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Performance Evaluation of a Modified SODIS under Sub-tropical Climate Conditions in Bangladesh

by

Md. Habibur Rahman Bejoy Khan

Student No: 191051015

A thesis submitted to the Department of Civil and Environmental Engineering (CEE) in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering

Supervised by

Prof. Dr. Md. Rezaul Karim

Department of Civil and Environmental Engineering (CEE)
Islamic University of Technology (IUT)
Gazipur-1704, Bangladesh

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The thesis titled "**Performance Evaluation of a Modified SODIS under Sub-tropical Climate Conditions in Bangladesh**" submitted by Md. Habibur Rahman Bejoy Khan, Student ID 191051015 of Academic Year 2019-2020 has been found as satisfactory and accepted as partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering.

1. Prof. Dr. Md. Rezaul Karim
Professor
Department of Civil and Environmental Engineering,
Islamic University of Technology (IUT)
— Chairman (Supervisor)

2. Prof. Dr. Hossain Md. Shahin
Professor
Department of Civil and Environmental Engineering,
Islamic University of Technology (IUT)
— Member (Ex-Officio)

3. Prof. Dr. Shakil Mohammad Rifaat
Professor
Department of Civil and Environmental Engineering,
Islamic University of Technology (IUT)
— Member

4. Asst. Prof. Dr. Amimul Ahsan
Assistant Professor
Department of Civil and Environmental Engineering,
Islamic University of Technology (IUT)
— Member

5. Prof. Dr. Jahir Bin Alam
Professor
Department of Civil and Environmental Engineering
Shahjalal University of Science and Technology (SUST)
— Member (External)

Declaration of Candidate

It is hereby declared that this thesis has not been submitted elsewhere for the award of any Degree or Diploma.

Name of Supervisor:
Dr. Md. Rezaul Karim
Professor and Head
Department of Civil and Environmental Engineering (CEE)
Address: Room NO. 406, 1st Academic Building, Department of CEE, Islamic University of Technology, Board Bazar, Gazipur 1704,
Date 5·06·2023

Name of Candidate:
Md. Habibur Rahman Bejoy Khan
Student No.: 191051015
Academic Year: 2019-2020
Date: 5·06·2023 .

Dedication

I dedicate this thesis to my parents, siblings, wife, daughter, in-laws and teachers.

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List of Acronyms

ANOVA	Analysis Of Variance
AOP	Advanced Oxidation Process
CFU	Colony Forming Unit
CI	Confidence Interval
D.F.	Degree Of Freedom
DALY	Disability-Adjusted Life Years
DNA	Deoxyribonucleic Acid
DO	Dissolved Oxygen
EC	Electrical Conductivity
ECR	Environmental Conservation Rules
EPA	Environmental Protection Agency
$FADH_2$	Flavin Adenine Dinucleotide
H_2O_2	Hydrogen Peroxide
HWT	Household Water Treatment
HWTS	Household Water Treatment and Safe Storage
IR	Infrared
IRR	Incidence Rate Ratio
LMCT	Ligand-To-Metal- Charge Transfer
LRV	Log Reduction Value
MSE	Mean Square Error
MSR	Mean Sum of Residuals
NRMSE	Normalized Root Mean Square Error
NTU	Nephelometric Turbidity Unit
OR	Odds Ratio
PB	Plastic Bag
PET	Polyethylene Terephthalate
POU	Point-Of-Use
PSF	Pond Sand Filters
PVC	Poly Vinyl Chloride
RCT	Randomized Controlled Trials
RMSE	Root-Mean-Squared Error
RNA	Ribonucleic Acid
ROS	Reactive Oxygen Species
RWH	Rainwater Harvesting
SOD	Superoxide Dismutase
SODIS	Solar Disinfection
SSE	Sum of Square Error
SSR	Sum of Squared Residuals
SST	Total Sum of Squares
TW-1	Test Water 1
TW-2	Test Water 2
UN	United Nations
UV	Ultraviolet
VIF	Variable Inflation Factor
WASH	Water, Sanitation and Hygiene
WHO	World Health Organization

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Abstract

Solar disinfection (SODIS) is a low-cost, effective, sustainable, and easy-to-use method recognized by the World Health Organization (WHO) as an HWT option for eradicating different microorganisms in drinking water. Studies have shown that the main limitations of SODIS are prolonged exposure time (>6h), ineffective during the monsoon and winter seasons and the regrowth of microorganisms after treatment. To overcome these limitations, the performance of a modified SODIS with a photocatalyst (H_2O_2) was evaluated in this study by the photo-Fenton process using test water and drinking water collected from restaurants, slums, and household areas following the WHO protocol during the monsoon and winter seasons in sub-tropical climatic conditions of Bangladesh. In addition, to predict the bacterial disinfection rate using the modified SODIS with H_2O_2, regression analysis was performed. Two types of test waters were prepared according to the WHO protocol. The SODIS experiment was conducted using reactors (polyethylene terephthalate (PET) bottles and plastic bags) of 500 ml capacity. 5 ml of H_2O_2 were added to each PET or plastic bag (PB). In each batch, six PET or PB with test water or collected drinking water samples were used and exposed to sunlight using a fabricated SODIS chamber for 6 h in both the monsoon (June-October, 2022) and winter (November-February, 2023) seasons. Before the SODIS experiment, the physicochemical and bacteriological water quality parameters were measured. In every test, physicochemical parameters such as dissolved oxygen (DO), electrical conductivity (EC), pH, turbidity, and water temperature were assessed along with bacteriological parameters such as Escherichia coli (E. coli) testing. During each hour of the SODIS experiment, one sample was taken for physicochemical and bacteriological testing along with the measurement of solar irradiance at an interval of 1 min. After 6 h, the SODIS-treated water was kept in the dark at room temperature for 12 and 24 h to check the regrowth potential of

the microorganisms. Drinking water samples were also collected from restaurants, slums, and household establishments in Dhaka City to evaluate the modified SODIS. The physicochemical parameter variations before and after SODIS illustrated that there were no significant changes except in the EC values. The efficacy of modified SODIS with H_2O_2 illustrates only 2 h was required by the PET bottle to inactivate bacteria, and 1 h was required for PB in the monsoon season, where a 6.7 log reduction value (LRV) was achieved. On the other hand, in the winter season, 2 h was required to inactivate bacteria in a PET bottle and PB, where a 5.49 LRV was achieved. There was no regrowth after the 12 and 24 h post-SODIS periods in the monsoon and winter seasons, respectively. The performance of SODIS with H_2O_2 was termed "Highly Protective" based on microbial inactivation (LRV >4). The Weibull bacterial inactivation model fits well with the data of PET bottles and PB in the monsoon and winter seasons, with an R^2 value of 0.95-0.98. The safe exposure time for achieving the four LRV was 1 h as the minimum and 2 h as the maximum. In terms of regression analysis, the maximum accuracy was illustrated by PB (TW-1) with an R^2 value of 0.79 (79%), where the equation coefficients are turbidity, water temperature, solar irradiance, and DO. Regression analysis showed that the disinfection rate increased when the water temperature, solar irradiance and DO increase and decreased when the turbidity increased. The statistical analysis results from the regression analysis also illustrated the fit of the model to the data obtained in this study. Drinking water samples from restaurants, slums, and household areas water parameter results illustrate that most of the water was microbially contaminated and that iron was present in the water. The application of the modified SODIS with H_2O_2 and conventional SODIS illustrates that the modified SODIS performs better, and there was no regrowth in the modified SODIS. This study's outcome shows data similar to the literature available on SODIS for inactivating bacteria. SODIS, if promoted properly, can be a potential

method for drinking safe water and providing access to water in the water stressed areas of Bangladesh and other developing countries. The results of this study will help people acknowledge the efficacy of SODIS in Bangladesh and other developing countries, and use SODIS for potable water.

CHAPTER 1: INTRODUCTION

1.1 General

According to a recent report by the United Nations, the world's population approached 8 billion in 2022, posing serious challenges for water shortages and access to potable water on a global scale (UN, 2022). These issues require immediate attention, as out of 8 billion people, more than 2 billion reside in water stressed nations, and 785 million people lack access to a basic and safe water supply (UNICEF and WHO, 2022a). Though the United Nations' Sustainable Development Goal 6.1 has taken aims to provide universal and equitable access to safe and low-cost drinking water for all by 2030, overpopulation, climate change, and pandemics are impeding its progress. Unsafe drinking water causes water-borne diseases such as cholera, diarrhea, dysentery, hepatitis A, polio, and typhoid, of which only diarrhea results in 829,000 global mortalities, 90 % of which are children under the age of five. Moreover, approximately 2 billion people drink water contaminated with feces, with the majority of these people living in developing countries, notably those who have poor incomes (WHO, 2022a). In these countries, conventional drinking water treatment and distribution networks are inadequate, forcing the population to rely on highly microbially contaminated water from shallow wells, lakes, rivers, and springs (Chaúque et al., 2021). To tackle this issue, Household Water Treatment (HWT) options which are inexpensive, user-friendly, and sustainable can be promoted (Hunter, 2009; Meierhofer and Landolt, 2009). Numerous HWT interventions exist, including boiling, filtration, UV disinfection, chemical disinfection, chlorination, and Solar disinfection (SODIS). SODIS has been demonstrated in many developing countries as a sustainable, low-cost, and simple-to-manage intervention that is also recognized by

the WHO (Brockliss et al., 2022; Figueredo-Fernández et al., 2017; McGuigan et al., 2012; WHO, 2011).

SODIS process is simply done by placing water in a clean polyethylene terephthalate (PET) bottle, plastic bag (PB), or transparent glass, shaking to enhance dissolved oxygen (DO), and exposed it to direct sunlight for 6 h on a sunny day; on a cloudy day, it may require 48 h or 2 days for complete microbial inactivation of microorganisms (Meierhofer, and Wegelin, 2002; Oates et al., 2003; McGuigan et al., 2012; Karim et al., 2021). Microbial inactivation occurs due to the strong synergistic effect between solar irradiance and the temperature of water exceeding 45°C (McGuigan et al., 2012; Meierhofer and Wegelin, 2002). UVB light (280-320 nm) is absorbed directly by the deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) of microorganisms, resulting in their inactivation (Mbonimpa et al., 2012). Visible and UVA light (>320 nm) that is absorbed by endogenous chromophores functioning as sensitizers and stimulates the generation of reactive oxygen species (ROS), which are responsible for the 70 % indirect inactivation (Castro-Alférez et al., 2017). ROS destroys the lipids and proteins of microorganisms, and alters membrane permeability, resulting in DNA breaks (Berney, 2006). SODIS has been shown to be effective against all groups of microorganisms, including bacteria (E. coli, Salmonella typhimurium, Pseudomonas aeruginosa, Campylobacter jejuni, Vibrio cholera, etc.), fungi (Fusarium solani), viruses (Bacteriofage f2, Polio, Rota, and Noro, etc.) and protozoa (Giardia spp., N. Guberi, and Acanthamoeba castellanii etc.) (McGuigan et al., 2012, Heaselgrave and Kilvington, 2010; Polo-López et al., 2020). Furthermore, field trials of SODIS in Uganda, Mexico, Kenya, India, and Bolivia demonstrated that when administered correctly, infant diarrhea can be significantly reduced (Asiimwe et al., 2013; Boyle et al., 2008; du Preez et al., 2011; Martín-Domínguez et al., 2005; Mäusezahl et al., 2009; Pal et al., 2010).

Despite being highly encouraged, SODIS has a number of drawbacks, including the need for high levels of solar irradiation and higher water temperatures, which makes it highly climate dependent; it requires a longer exposure time to disinfect the water in the monsoon and winter seasons, and its limited water treatment capacity. Furthermore, regrowth of microorganisms also occurs after application of SODIS (Mäusezahl et al., 2009; Giannakis et al., 2014, 2015; McGuigan et al., 2012; Martínez-García et al., 2020; Reyneke et al., 2020; Rosa e Silva et al., 2022). In Reyneke et al. (2020) study, experiments were conducted in South Africa and Uganda with rainwater and found regrowth of bacteria after 8 h of solar exposure in sunny weather condition by acrylic glass tubes. In Rosa e silva et al. (2022) study in Brazil, they apply SODIS in stream water by laying PET bottles in zinc corrugated tin sheets and after 25 h of solar exposure in cloudy weather conditions, they found regrowth of bacteria. Moreover, Martínez-García et al. (2021) study in Spain also found regrowth of bacteria using isotonic and demineralized water spiked with E. coli in transparent tubes after 5 h of solar exposure in sunny weather conditions. Thus, increased disinfection time and regrowth of microorganism's post SODIS are becoming some of the biggest obstacles to the widespread implementation of SODIS. Recently, numerous additives have been introduced to SODIS to improve disinfection time and efficiency through the generation of reactive oxygen species (ROS) such as the hydroxyl (•OH) radical, superoxide ($\bullet O_2^-$), hydrogen peroxide (H_2O_2), and singlet oxygen ($^1O_2$) (Fisher et al., 2008, 2012; Spuhler et al., 2010; Ndounla et al., 2013; Rubio et al., 2013; Fisher and Nelson, 2014). In photoinactivation of E. coli, oxygen plays the most significant role in the generation of reactive oxygen species (ROS), and the addition of H_2O_2 enhances this photoinactivation (Reed,1997; Fisher, 2004; Rincón and Pulgarin, 2004). In addition, Hoerter et al. (1996) found that photoinactivation of E. coli in the presence of H_2O_2 occurred through an intracellular Fenton-like process. The characterization of the photo-Fenton

process is the iron-dependent breakdown of H_2O_2 illustrated in Equation 1.1 (Fisher et al., 2008). When compared to other additive addition techniques, this photo-Fenton process is the most effective in producing reactive oxygen species (ROS) and killing microorganisms (Villar-Navarro et al., 2019; Garcia-Fernández et al., 2012). The Fenton process occurs because dissolved iron ions in water rapidly react with added H_2O_2 and breakdown hydroxyl radicals (•OH) via the Haber-Weiss reaction (Haber et al., 1934; Sychev et al., 1995). The synergistic action of solar radiation and H_2O_2 reacting with dissolved irons in water causes oxidative stress and inactivation of microorganisms by diffusion of H_2O_2 across the cell membrane (Halliwell and Gutteridgde, 1999; Polo-López et al., 2011). The Fenton process utilizes primarily Fe^{2+}/Fe^{3+} present in water and added hydrogen peroxide and reacts rapidly to release •OH radicals to oxidize DNA, proteins, and cell membranes of microorganisms, resulting in inactivation, as shown in Equations 1.1 and 1.2 (García-Fernández et al., 2012; Rincón and Pulgarin, 2007; Sciacca et al., 2010).

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + \bullet OH \quad (k = 63\ L\ mol{-}1\ s{-}1) \qquad (1.1)$$

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + HO_2 \bullet + H^+ \quad (k = 3.1 \times 10{-}3\ L\ mol{-}1\ s{-}1) \qquad (1.2)$$

Bangladesh is a developing nation with an alarming rate of population growth. Bangladesh has a population of 165 million people, yet 1.8 million lack access to improved water sources, and 36 million lack access to improved sanitation (Water, 2022). In addition, according to a recent assessment, 41% of the improved water sources contained feces, and 68.3 million people lack access to potable water (World Bank, 2018; UNICEF, 2021). In the coastal region of Bangladesh, rain-fed ponds, rainwater harvesting (RWH), and pond sand filters (PSF) are the primary sources of drinking water (Karim, 2010; Islam et al., 2011). As a result, drinking contaminated water is the leading cause of waterborne diseases in water-stressed areas. As a subtropical nation like Bangladesh where, solar exposure is high throughout the year, a low-cost, sustainable system like

SODIS could be an excellent solution for preventing the use of contaminated water. The majority of this country's population relies on groundwater as a drinkable water source, and the median iron concentration of water is 0.91 mg/l (Stewart et al., 2019). This probable presence of iron in water could result in a photo-Fenton reaction when exposed to sunlight and combined with H_2O_2. Recent research by Karim et al. (2021) and Islam et al. (2015) demonstrates the significance of SODIS in the lab and field conditions. However, the primary obstacle identified by these researches is that during the monsoon and winter seasons, the disinfection time is >6 h and the regrowth of bacteria is prevalent following the SODIS treatment, demonstrating the need for the improvement of the SODIS system. As residents of a developing nation, the poor are averse to adopting new health practices. Therefore, for the population of this country that has not yet recognized SODIS, it could be a successful technique for bacterial inactivation and a lifesaver against drinking contaminated water. No research has been conducted in Bangladesh to improve the effectiveness of SODIS for reducing disinfection time and the regrowth of microorganisms during the monsoon and winter seasons, indicating a significant research need.

In order to improve the effectiveness of SODIS in terms of decreasing disinfection time and microbial regrowth, the use of H_2O_2 was evaluated in this study. Furthermore, the photo-Fenton process's potential for killing E. coli was assessed, and the results was compared to those of the current SODIS system. These findings can be used as scientific evidence for promoting the modified SODIS as an HWT strategy for assessing safe drinking water supplies in water-stressed communities.

1.2 Objectives

The specific objective of this study are as follows:

1. To evaluate the performance of a modified SODIS with photocatalyst (H_2O_2) under sub-tropical climate conditions in Bangladesh using both test water and drinking water collected from households, restaurants and slums.
2. To assess the bacterial regrowth potential in the post-SODIS treated water.
3. To develop a regression model to predict the disinfection rate of the modified SODIS under different climate conditions.

1.3 Scope of the Study

The scope of this research to attain the objectives are as follows:

1. Development of a modified SODIS with the addition of H_2O_2.
2. Effectiveness of the modified SODIS with H_2O_2 assessed during the monsoon and winter season in 6-h solar exposure by two types of water:
    a. Test water
    b. Drinking water collected from households, restaurants and slums.
3. Post SODIS regrowth potential evaluation of the modified SODIS with H_2O_2 and compared with the published conventional SODIS processes.
4. Disinfection rate prediction of the modified SODIS with H_2O_2 using regression analysis.
5. Comparative performance analysis between the modified SODIS and conventional SODIS with the water collected from restaurants, households, and slums.
6. Mechanism for promoting the modified SODIS for field applications in the rural and urban areas with unsafe water supply.

1.4 Layout of the Thesis

In six chapters, the thesis presents the relevant literature, the modified methodology, the modified SODIS with photocatalyst, and the study's findings. The references are also included in this study.

Chapter 1 discusses the background, objectives, scope, and contribution of this study.

Chapter 2 describes the disinfection mechanism of the conventional SODIS system and various constraints, the efficiency of SODIS by various microorganisms, climate and weather influences on SODIS, various SODIS enhancement steps already established, SODIS health impacts, limitations, and applications in field trials.

Chapter 3 presents the prototype construction with locally available and affordable materials for conducting SODIS, laboratory experiment steps and water parameters outcomes and collection point locations, bacterial and regression models, and the statistical analysis applied in this study.

Chapter 4 presents the performance analysis of the modified SODIS under laboratory conditions (using test water) following the WHO guidelines in the monsoon and winter seasons with PET and plastic bags as containers, the outcomes of the regrowth potential of the modified SODIS, along with bacterial inactivation models and regression analysis for prediction of the disinfection rate. Cost analysis was done for implementation of the modified SODIS

Furthermore, the physicochemical parameter variation of drinking water collected from restaurants, households, and slums. In addition, the application of the modified SODIS in various establishments, and a comparison with conventional SODIS are discussed. Moreover, regrowth potential is also assessed in post SODIS treated water.

Chapter 5 presents the laboratory and water collected from restaurants, slums, and households' experimental conclusions drawn from the results of this study and the scope for the future work.

CHAPTER 2: LITERATURE REVIEW

2.1 General

This chapter presents a literature review on the state of SODIS mechanisms, efficacy, enhancement, influence of climate and weather, health impact, advantage, disadvantage, and field application, as well as the guidelines for assessing the performance evaluation of various HWT options comprehensively following the most recent studies.

2.2 Solar Disinfection (SODIS)

There are a number of useful HWT technologies for purifying drinking water, and one of them is solar water disinfection, or SODIS. Millions of people are said to have been instructed on how to use it (Luzi et al., 2016) because it has been adopted in so many different nations. Water was used to be stored in copper containers after being exposed to sunlight, filtered through charcoal, and used in rituals as early as 2000 B.C. in Sanskrit writings (Baker, 1981). Downes and Blunt published the first controlled investigation on sunlight's antibacterial effects in 1877, showing that it may inactivate bacteria and slow their development in nourishing broth (Downes, 1877). The first quantitative research on the near-UV inactivation of E. coli was undertaken by Hollaender in 1943 (Hollaender, 1943), and in 1946, Lukiesh showed that sunlight may kill E. coli (Luckiesh, 1946). Recent research by Calkins et al. found that in sunlight-exposed Kentucky waste stabilization ponds, simulated solar UV-B rapidly inactivated E. coli and other indicator species (Calkins et al., 1976).

In the 1980s, Acra et al. at the American University of Beirut, Lebanon, did the first quantitative studies on how the sun can disinfect drinking water and oral rehydration solutions (Acra et al., 1980; Acra, 1984). Based on the results of this study, Escherichia coli should be used as an

indicator organism for SODIS, just like the presence of viable fecal coliforms is used to measure how well traditional methods of disinfection work. Since then, other research teams have looked at the SODIS procedure, with the Swiss Federal Institute of Environmental Science and Technology (Wegelin et al., 1994) being a leader in many aspects of the applied study and spread of practical SODIS information. Twenty nations in Africa, Asia, and Latin America have used and researched SODIS thus so far (Luzi et al., 2016). Millions of people in over 50 Asian countries use it to purify their drinking water (McGuigan KG, 2012). As evidenced by statistics from ventures backed by EAWAG, a minimum of 5 million individuals have implementing the strategy to increase the safety of their potable water. Improved water sources are frequently polluted with organisms that can cause infectious diseases like cholera and enteric fever, so even in areas with ample water supplies, access to microbiologically safe water may be limited (Sobsey, 2008). Water that has been tainted is placed in clear bottles (ideally PET) and exposed to sunlight for at least 6 h. After being exposed, the water is safe to drink since the number of pathogens that are still alive is much reduced. In Fig. 2.1, some elementary instructions for operating SODIS are shown.

Solar water treatment is one of the most promising new technologies for making safe water in a way that is sustainable and less harmful to the environment. To produce potable water, the WHO endorses the use of solar disinfection (SODIS). It has been pushed for both on its own and as part of bigger programs like HWTS (Household Water Treatment and Safe Storage) or WASH (Water, Sanitation, and Hygiene). There are a variety of HWTS techniques that have been around for decades (ceramic filtration and chlorination), years (bio-sand filtration and SODIS), or even longer (boiling). Continual innovation in the form of newly released technology is introduced. However, the idea of treating water before bringing it into the home is still not widely adopted. There are drawbacks to every standard approach to HWTS, which is why none of them has gained

widespread acceptance thus far. Only in relation to other HWTS technologies can the SODIS approach's niche be assessed, and its benefits may vary considerably depending on the setting. Particularly among the poor and in locations where no other HWTS technologies are offered, SODIS has comparative benefits as a low-cost alternative that is autonomous of PET bottle supply chain operations. Since the execution of the approach requires nothing more than sunlight and PET bottles, SODIS promotion consists mostly of actions aimed at a change in the behavior of the target community. Since the marketing of HWTS techniques necessitates the construction of supply network for particular items, SODIS promotion is more readily scalable. The market for SODIS is likely to decrease as more competitive, low-cost HWTS technologies with greater practicality, efficiency, and aspirational appeal replace it in a given area. The same holds true as a community's income rises. The effectiveness of SODIS relies on its ease of use: filling a clear container with the available water and leaving it in the sun for one day (under normal irradiation circumstances) or two days (under cloudy skies) to purify the water (McGuigan et al., 2012). Economically and environmentally, SODIS stands out for a number of reasons, including its low operating costs for the user (based solely on the replacement of the bottles), its simplicity of operation and reliance on sunlight, and the fact that it does not alter the water's organoleptic properties, call for additional chemicals, or produce any residues. Furthermore, SODIS has been shown to be effective against a wide range of water-borne pathogens, including E. coli, Salmonella, Vibrio cholerae, Enterococcus faecalis, Bacteriophage MS2, Hepatitis A virus, and Cryptosporidium parvum (Sansaniwal, 2019). In rural areas where water sources are contaminated and sanitation is lacking, contaminated water is a leading cause of illness, particularly diarrhea and other gastrointestinal issues (Caslake, 2004). Due to its low cost, SODIS has great potential for application in disaster relief efforts and in rural areas (McGuigan, 1998).

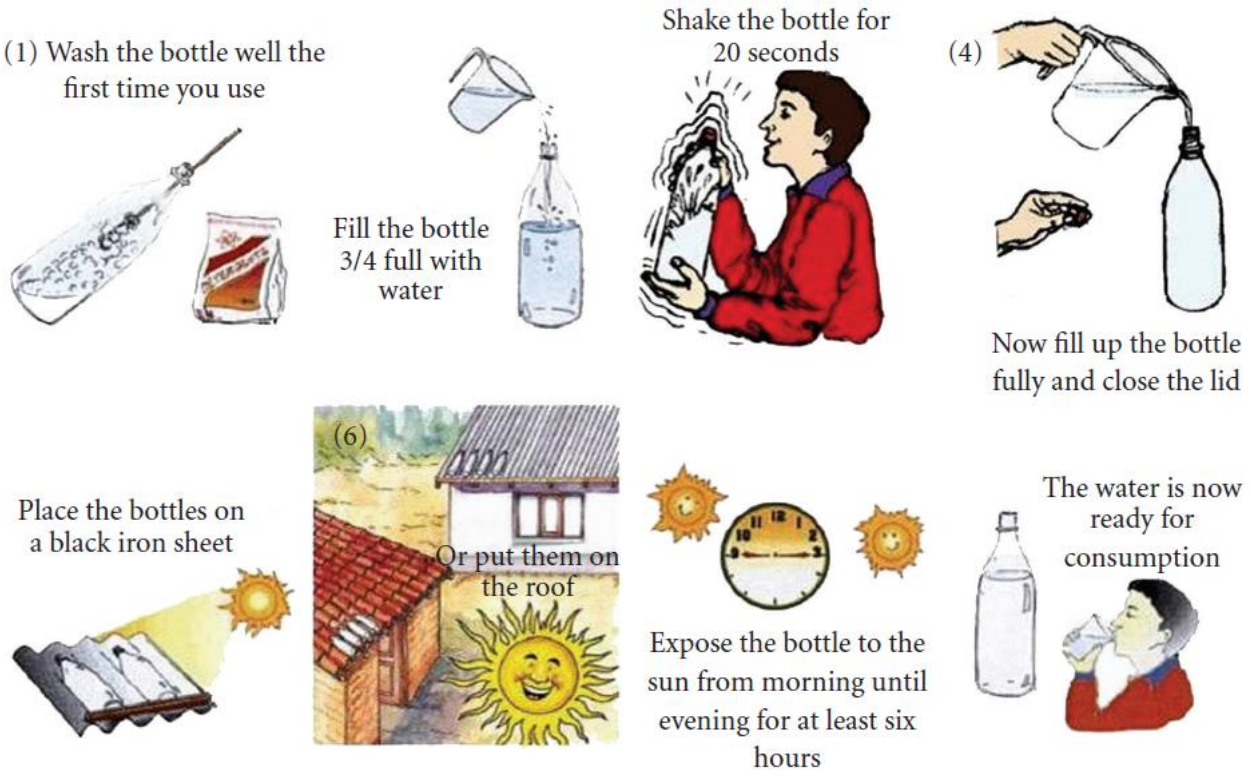


Fig. 2.1 Typical SODIS process (SODIS, 2022)

However, the time after sun irradiation has been studied insufficiently, with the exception of the disinfecting impact SODIS has. There is a wide range of systems that utilize various mechanisms of solar energy conversion and recent advances in material science and engineering reactor technologies, including solar stills (Karimi et al., 2015; Bhardwaj et al., 2015; Malaeb et al., 2016; Gad et al., 2015; Ibrahim and Eshhamarka, 2015), desalination systems (Sua'rez et al., 2015; Sankar et al. (SODIS, 2002); and solar stills (Kar, 2015; Gad et al., 2016; Sua'rez et al., The main principle of solar water disinfection is to expose water infected with microorganisms to the disinfecting UVA and UVB radiation of natural sunlight in transparent containers for at least 6 h. Laboratory and field investigations have shown that this approach is effective at killing waterborne pathogens (Wegelin et al., 1994; Sommer et al., 1997; McGuigan et al., 1998; Oates et al., 2003; Dejung et al., 2007; Graf et al., 2010; Figueredo-Fernández et al., 2017).

2.3 Solar Radiation as a Disinfection Mechanism

Pathogens in water can be killed by exposing them directly to sunlight, which is what solar water disinfection does. It works on the top layer of bodies of water and can be used to disinfect drinking water. Radiation that reaches the Earth's surface includes ultraviolet (UV), visible (visible), and infrared (IR) waves. Radiation in the UV-B, UV-A, and maybe the lesser visible spectrum causes active or passive disruption to the organisms' proteins and DNA, rendering them inactive during solar disinfection. There are two aspects of sunlight that SODIS utilizes to disinfect water. First, there is the germicidal impact of UV-A light. Second, infrared radiation heats the water, a process called pasteurization when the water temperature reaches between 70 and 75°C. When UV-A radiation and heat are used together, a synergistic impact increases the process's effectiveness (McGuigan et al., 2012).

2.3.1 Effect of Solar Radiation

There are ultraviolet (UV) rays, visible light, and infrared rays in the spectrum of solar radiation. UV light includes UV C rays (which do not penetrate Earth's atmosphere), UV B rays, UV A rays, and visible and infrared light (IR). UV rays are invisible to the naked eye. This type of radiation is extremely harmful, as it can kill cells and cause severe skin and eye damage. Fortunately, the ozone (O_3) layer in the atmosphere absorbs most of the UV-C and UV-B rays between 200 and 320 nm, shielding the Earth from radiation from space. UV-A radiation with wavelengths between 320 and 400 nm, close to the violet end of the visible light spectrum, is the only kind that reaches the Earth's surface. Human pathogens in water are killed by UV-A light. Because of the unique conditions that exist in the human digestive system, many infections are poorly adapted to withstand environmental stress. That's why you'll notice they're more sensitive to sunlight than most common creatures. UV-A radiation causes cellular damage and death by interacting with a

cell's DNA, nucleic acids, and enzymes on a molecular level. Highly reactive forms of oxygen are also created when ultraviolet light reacts with oxygen in the water (oxygen free radicals and hydrogen peroxides). Light absorption events through biomolecules like chromophores result in the production of reactive oxygen species (ROS), such as peroxy radicals (HO_2), hydrogen peroxide (H_2O_2), and hydroxyl radicals (•OH), which are damaging to cells. Furthermore, the presence of intracellular iron and hydrogen peroxide may be traced back to the Fenton and Haber-Weiss reactions, which are responsible for the generation of •OH radicals inside the cell (Imlay, 2008). To eliminate the infections, these reactive chemicals also disrupt their cell structures. Visible light is abundant but almost harmless to microorganisms, while IR increase temperature of water; however, some materials used for SODIS vessels (such as polycarbonate or PET) are partially or totally opaque to UVB (Wegelin et al., 2001). Each wavelength's associated mode of action has been recently examined (Giannakis et al., 2016b; Nelson et al., 2018). Briefly, ultraviolet (UV) light (Oppezzo, 2012; Pfeifer et al., 2005) acts directly on the microorganism genome, causing mutations in its genetic material, and ultraviolet (UV) light (in bacteria) initiates oxidative chain reactions within the cell (Berney et al., 2006; Bosshard et al., 2010a, 2010b; Giannakis, 2018; Hoerter et al., 2005). Recent reports indicate blue light-mediated bacterial inactivation (Halstead et al., 2019; Maclean et al., 2014), but visible light in the received intensities does not contribute much to oxidative processes in the matrix (Hessling et al., 2017; Ng et al., 2016), and the heat from IR light denatures proteins, causing lethal damage (Baatout et al., 2005; Blaustein et al., 2013). This illustration shows how the responses of individual bacterial cells alter in the presence and absence of sunlight.

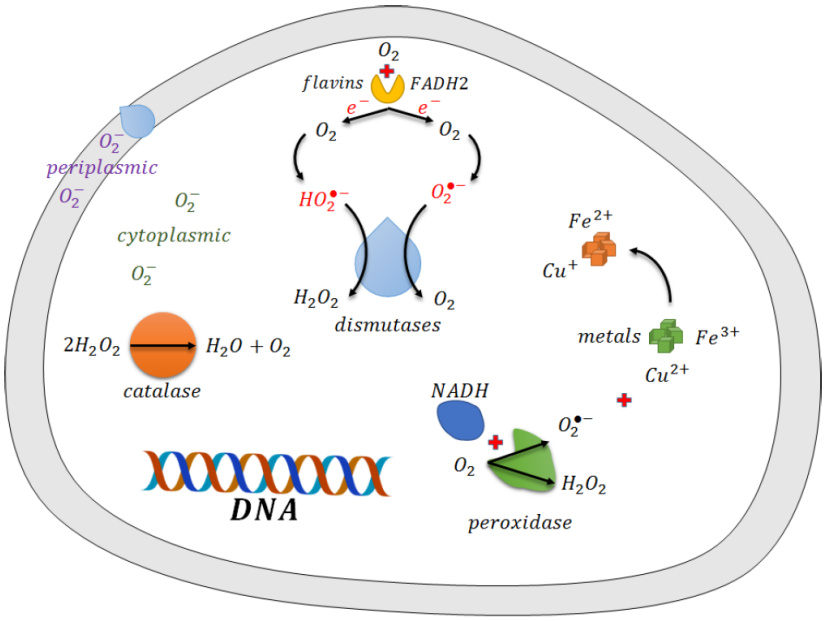


Fig. 2.2 Bacteria cell state prior to light exposure (Giannakis et al., 2016a)

Internal ROS cycle seen in Fig. 2.2 prior to the presence of light. Here reactive oxygen species (ROS) is being spontaneously generated, with the most reactive species being the superoxide radical anion ($O_2\cdot$) and the hydroperoxyl radical ($HO_2\cdot$). Through either direct damage (oxidation) or indirect generation of highly reactive ROS in reduced-metal catalyzed interactions with H_2O_2, their scavenging efficiency influences the degrees of auto-damage. Cell homeostasis was also shown to be disturbed by light, as shown in Fig. 2.3 where UVB-induced DNA damage and Catalase (CAT) function impairment; UVA-induced oxidant stress and accumulation of ROS due to UVA's effect on enzymes and proteins involved in ROS production (flavins, $FADH_2$ (Flavin Adenine Dinucleotide), SOD (Superoxide Dismutase), peroxidases, porphyrins); light-induced iron release and reduction and LMCT (Ligand to Metal Charge Transfer)-driven iron reduction and internal photo-Fenton initiation.

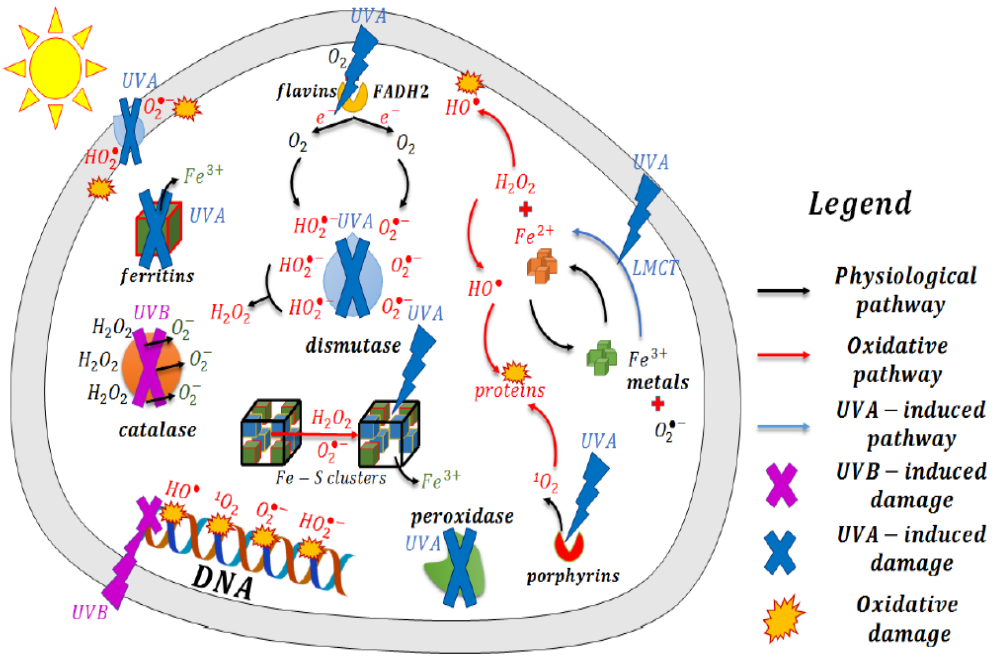


Fig. 2.3 Bacteria cell state after light exposure (Giannakis et al., 2016b)

Evidence of the efficacy of SODIS in both sunlight and lab-induced tests is shown in Appendix I (Table A1), which illustrates the solar irradiation of several research projects.

2.3.2 Effect of Temperature

Solar disinfection needs a certain amount of time to reach a target log reduction. This time depends on a number of parameters. Solar irradiance and energy dose, wavelength, water temperature during treatment, turbidity, salt concentration, dissolved oxygen, dissolved organic matter in the contaminated water, and the 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- Solic and Krstulovic,1992). Wegelin et al. (1994) investigated the impact of temperature on the persistence of fecal coliforms in saltwater, both singly and in combination with sun radiation. However, at temperatures of 50°C or higher, the needed fluences to inactivate E. coli were three times smaller than at lower temperatures (Wegelin et al., 1994). To back up their findings, Berney and colleagues tested the heat effect on E. coli in

the dark and found a small rate of inactivation even at 48 ℃ (Berney et al., 2006b). As a result of this potent synergy, a variety of improvements have been proposed to achieve this water temperature value for SODIS acceleration. One method is to paint the bottles black, another is to employ absorptive materials, a third is to cycle the water over a black surface inside a container that is transparent to UVA light, and a fourth is to utilize sun collectors or solar reflectors to heat the water (McGuigan et al., 2012). Infrared, a type of long-wave radiation, is yet another facet of sunlight. Light with a wavelength longer than 700 nm is invisible to the human eye but can be felt as heat. It is the infrared light absorbed by the water that causes the temperature to rise.

Studies have shown that after the water temperature reaches 45°C, the radiation and heat from the water work together to kill any germs present (McGuigan et al. 2012). Other research at low temperatures (less than 40°C; Polo-López et al., 2019) has only looked at UV deactivation. Temperatures of 60–70°C have been previously reported for the thermal deactivation of E. coli without UV in laboratory-controlled biology tests (Collis O'Neill and Middelberg 1995). Solar cookers, which typically heat water to temperatures of about 65°C without the use of UV light, have also been the subject of studies into water purification (Ciochetti and Metcalf 1984). The use of nanoparticles for thermal deactivation, the focus of recent innovative work, was found to be effective, as water temperatures were not significantly affected.

In doing so, they absorb photons in the UV-A and visible spectra, reaching an excited state that results in the generation of highly reactive species such as singlet oxygen and hydroperoxyl radicals, which inhibit cell reproduction and destroy microbes (Nelson et al. 2018). Furthermore, infrared radiation, with a wavelength of around 800 nm, can increase the temperature of a liquid and kill any microbes that are sensitive to heat. Marques et al. (2013) validated this by measuring the temperature of irradiated water and finding that it reached 50°C, killing 99% of E. coli. In

addition, a recent study showed that the inactivation rate was higher in water with a temperature of 6°C compared to water with a temperature of 22°C (Villar-Navarro et al. 2021). While severely turbid waters can be treated, doing so demands temperatures of at least 55°C (Joyce et al. 1996). Only pasteurization, that is, thermal processes, can inactivate microorganisms at these temperatures and turbidities. McGuigan et al. (2008) demonstrated that 99 % inactivation of E. coli occurred only 1 cm into the optical path, even in severely turbid water (200 NTU). In order to treat water more quickly using solar disinfection, there is a pressing need for a low-cost, effective way of lowering turbidity in the source water.

Table 2.1 Effect of temperature on various microorganisms (Feachem et al., 1983)

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

Heat kills microorganisms and other pathogens. Table 2.1 details the required temperature and exposure duration to kill various types of microbes. As demonstrated here, boiling water is not necessary to destroy 99.9 % of bacteria and other germs. For the same result, heat the water to 50 to 60°C for an h.

2.3.3 Synergetic Effect of UVA Radiation and Temperature

The combination of solar ultraviolet (UV) light and low-level infrared heating of the water is commonly cited as the mechanism by which solar radiation kills bacteria (McGuigan et al., 1998; Berney et al., 2006a). Already at 45°C, synergistic effects are present in the inactivation process, and they grow stronger as the temperature rises (Vivar et al. 2017). It has been reported by Wegelin et al. (1994) that temperatures between 20 and 40°C do not kill bacteria, but that beyond 45°C, UV-A and visible light have a synergistic impact. In Fig. 2.4, the synergistic effect of SODIS and its impact on the inactivation rate of pathogens are illustrated. To kill bacteria like E. coli, water must be heated to at least 50°C.

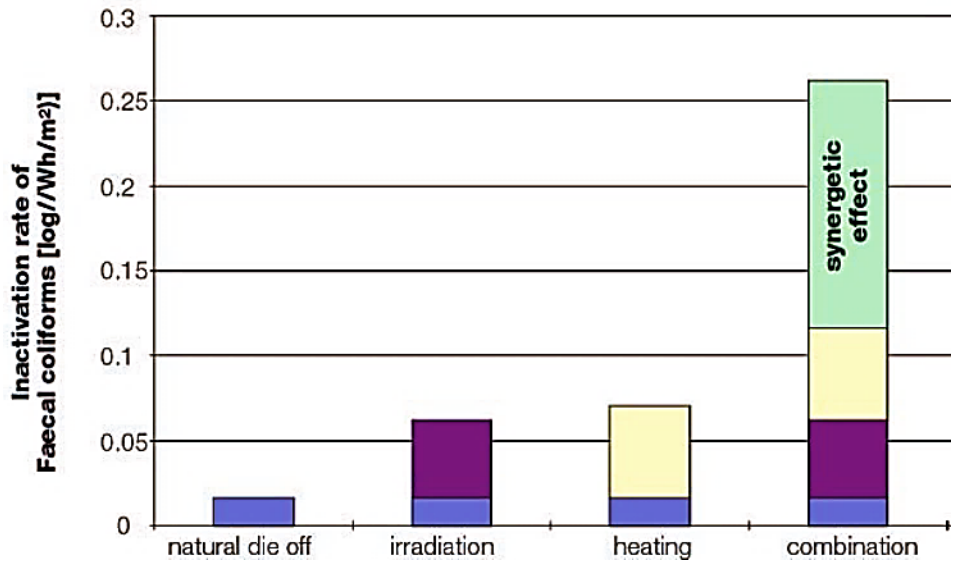


Fig. 2.4 Inactivatoin rate of fecal coliforms

But the death rate of fecal coliforms exposed to sunlight goes up dramatically when UV-A radiation and high-water temperature are also present. A synergistic impact between UV-A radiation and temperature occurs at 50° water temperature, requiring just 140 W.h/m^2 of UV-A radiation to achieve a 3-log reduction in fecal coliforms (Wegelin et al. 1994).

2.3.4 Effect on SODIS on Pathogen

UV-A irradiation resistance varies widely between pathogen kinds. UV radiation from the sun is generally more damaging to viruses and spore or cyst-forming protozoa than it is to pathogenic bacteria. UV-B radiation, which has a little impact in the SODIS process with PET bottles but has a profound effect on many viruses, is a byproduct of the process. When compared to viruses and protozoa, the variation in solar radiation resistance shown between various species of harmful bacteria is minimal.

Human pathogens have evolved to survive in the dark, humid conditions and 36°C to 37°C temperatures found in the human intestines. The infections are extremely vulnerable to the unforgiving environment after they have been released. They have no defenses against the effects of UV light, and they wilt in even mildly warm conditions. This means that the pathogens can be rendered harmless by subjecting them to either heat or ultraviolet light.

It has been established through scientific investigation that SODIS is effective at killing dangerous germs and viruses. The efficiency of SODIS against various microorganisms is detailed below:

2.3.4.1 Bacteria

Cholera and bacterial dysentery are two of the worst kinds of diarrhea that bacteria can cause. Pathogens that don't make spores, like bacteria that cause diarrhea, are more likely to die when they are exposed to sunlight. SODIS cuts the amount of these pathogens by many orders of magnitude on an average day in the tropics or subtropics. The rate at which a species becomes inactive varies considerably. When compared to the dose and time required to kill E. coli (1210 kJ/m^2 to the extent of 350–450 nm, equating to 182 min in the experiment performed by Berney, 2006), the dose and time required to kill Vibrio cholerae (165 kJ/m^2 to the extent of 350-450 nm)

are significantly lower. The average rates of elimination for several types of harmful bacteria are shown in Table 2.2 of the scientific literature.

Based on the information in the literature about E. coli, it appears that bacteria isolated from sewage are more resistant to solar radiation than bacteria grown in the lab (for instance, Fisher et al. 2012). Thus, the disinfection efficacy of SODIS in field applications is probably overestimated in lab-cultured organism SODIS tests; the results of this research should be viewed with caution.

Table 2.2 Inactivation rate of various bacteria

Pathogen	Log reduction value (6h)	Reduction of pathogen concentration (6h)	Approx. time required for 3 log reduction	References
Escherichia coli (E. coli)	2-5	99 – 99.999%	1 day	McGuigan et al. 1998; Kehoe et al. 2001; Fujioka and Yoneyama 2002; Berney et al. 2006; Boyle et al. 2008; Fisher et al. 2008; Fisher et al. 2012; Kruti and Shilpa 2012, Castro-Alférez et al., 2018; Yin et al., 2020; Karim et al., 2021
Vibrio cholera	3-5	99.9-99.999%	3h	Kehoe et al. 2004; Berney et al. 2006; Cano Ssemakalu et al., 2020
Salmonella spp.	2-4	99 – 99.99%	1 day	Smith et al. 2000; Kehoe et al. 2004; Berney et al. 2006; Bosshard et al. 2009, (Santos et al., 2020)
Shigella flexneri	2-4	99 – 99.99%	1 day	Kehoe et al. 2004; Berney et al. 2006; Bosshard et al. 2009
Shigella dysenteriae	>4	>99.99%	< 1day	Kehoe et al. 2004
Campylobacter jejuni	>4	> 99.99%	< 1 day	Boyle et al. 2008; Chihomvu, 2019
Yersinia enterocolitica	>3	> 99.9%	1 day	Boyle et al. 2008
Enterococcus feacalis	2-5	99 – 99.999%	1 day	Reed 1997; Fujioka and Yoneyama 2002

Studies were conducted to see if SODIS was effective at disinfecting against a variety of potentially harmful microorganisms. Since it's harder and more expensive to measure viruses and protozoa, most SODIS studies focus on pathogenic bacteria, indicator bacteria like E. coli, or indicator groups (total coliforms, thermotolerant coliforms). SODIS efficacy for E. coli cannot be

easily generalized to other pathogen forms. Moreover, the SODIS efficiency for E. coli overestimates the efficiency for most spore-forming bacteria, viruses, and protozoa, while underestimating the efficiency for less resistant diseases (such as Vibrio cholerae). Some coliforms are more resistant to sun radiation than others; hence, studies of SODIS inactivation based on the concentration of total coliforms likely underestimate the efficacy against pathogenic organisms.

2.3.4.2 Virus

Rotavirus, caliciviruses, coxsackievirus, enterovirus (e.g., poliovirus, echovirus), adenovirus, hepatitis A and E virus, coronavirus, and astrocystis virus are all major viruses that can be spread by water (Susana 2009). A sizable proportion of all cases of diarrheal illness are caused by viruses. Although rotavirus, the virus responsible for most occurrences of viral diarrhea in children, can be spread through contaminated water, research suggests that it is spread primarily through contaminated hands or other surfaces (Percival et al., 2004). Data on the effectiveness of SODIS in eliminating viruses is scarcer than data on its effectiveness against bacteria because infectious viruses are more difficult to quantify. In addition, not all accessible SODIS research adheres to the standard SODIS procedure in PET bottles because they use bacteriophages as human virus models instead of genuine pathogens and non-standard experimental setups (i.e., not eliminating the UV-B radiation). The information in Table 2.2 is assumed to be typical for the SODIS approach. Solar radiation kills viruses such as encephalomyocarditis, bacteriophage F2, and bovine rotavirus at roughly the same rate as bacteria, i.e., 3–4 log reduction value (LRV) for 6 h, according to an early study on solar disinfection (Wegelin et al. 1994).

Table 2.3 Inactivation rate of various virus

Pathogen	Log reduction value (6h)	Reduction of pathogen concentration (6h)	Approx. time required for 3 log reduction (h)	Remarks	References
Bovinerotavirus	0.5-1	70% - 90%	>20	Lab experiments with cut off filter for UVB	Wegelin et al. 1994
Coliphage f2	1	90%	>15	Lab experiments with cut off filter for UVB	Wegelin et al. 1994
EMCV	>0.5	Very low	>50	Lab study with cut off filter for UV-B	Wegelin et al. 1994
Wild ccoliphages	<1	50%	>30	Field study with PET bottles	Dejung et al. 2007
Polio Virus	Very low	Very low	>50	Lab study with cut-off at 360nm or UV-B	Fujioka and Yoneyama 2002; Silverman et al. 2013
Murine norovirus	1.3	95%	1.8	PET bottles	Harding and Schwab 2012
MS2 coliphage	1-4	90-99.99%	<6 - 33	PET bottles. High values for swiss tap water, low values for Indian tap and groundwater in the study by Caldao	Fisher et al. 2012; Harding and Schwab 2012; Dionisio Calado 2013
Echovirus	1	90%	>12	PET bottles. Indian groundwater.	Fujioka and Yoneyama 2002; Dionisio Calado 2013
Coxsackievirus	Very low	Very low	>50	Cut-off at 360nm	Fujioka and Yoneyama 2002
PhiX174 bacteriophage	0-0.5	0 – 70%	>12	PET bottles	Dionisio Calado 2013
Adenovirus	Very low	Very low	>40	PET bottles (Dionisio Calado 2013)	Gall 2010; Dionisio Calado 2013; Silverman et al. 2013

Later research validated this for echovirus, coxsackievirus, and poliovirus, as well as for poliovirus (Heaselgrave et al. 2006), poliovirus, and hepatitis A virus (Heaselgrave and Kilvington 2012), and poliovirus (Fujioka and Yoneyama 2002). However, the relatively tiny amount of UV-B radiation from the sun that reaches the surface of the Earth is likely to be to blame for the reported high inactivation rate. Since most UV-B radiation is blocked by PET bottles, SODIS studies utilizing these containers have shown much lower inactivation rates (> 30 h of exposure time needed for 3 LRV for Rotavirus, equal to just 0.5 LRV in 6 h) (Fisher et al. 2012). According to a recent study, the inactivation rate of viruses in PET containers is highly dependent on the virus

type and water composition (Dionisio Calado 2013). The greater amounts of dissolved organic material in Indian groundwater prevent the production of reactive oxygen species, although the inactivation rates were greater in Swiss tap water than in tap and groundwater from Chennai. In Swiss tap water, oxidant-sensitive viruses (echovirus and bacteriophage MS2) were inactivated effectively (4 log eradication in 6 h), whereas in India, inactivation was substantially slower (1 log removal in 6 h).

Viruses that are more resistant to treatment (bacteriophage phi X174, adenovirus) were inactivated at considerably lower percentages across the board. Higher temperatures were found to be significantly more effective in disinfecting viruses in this study, but further research is required to discover which viruses are effectively inactivated at the temperatures normally attained in SODIS bottles in tropical areas (about 40°C) for various water compositions. Table 2.3 displays results from experiments where UV-B radiation was blocked by using PET bottles or alternative setups. The higher inactivation rates are not shown for the complete solar spectrum because they aren't typical of the SODIS approach often implemented with PET bottles.

2.3.4.3 Protozoa

Amoeba, Giardia, and Cryptosporidium are the most common protozoa responsible for diarrhea. Cysts and oocysts, the protective cellular encasements that some protozoa can develop into, are often highly resistive to environmental stress, as well as, in some circumstances, chemical treatment of drinking water. Cryptosporidiosis is a severe health danger for immunocompromised patients, such as those living with HIV or AIDS, despite the fact that the symptoms of protozoal-caused diarrhea are typically less immediately life-threatening than those of viral or bacterial illnesses.

Table 2.4 Inactivation rate of various protozoa

Pathogen	Log reduction value (6h)	Reduction of pathogen concentration (6h)	Approx. time required for 3 log reduction (h)	References
Giardia spp	2 - >3	99 – >99.99%	< 6 - 9	McGuigan et al. 2006; Heaselgrave and Kilvington 2010
Cryptosporidium spp.	0.3 - >0.4	45- >92%	>10 - 70	Mendez-Hermida et al. 2005; McGuigan et al. 2006; Mendez- Hermida et al. 2007; King et al. 2008; Gomez-Couso et al. 2009; Heaselgrave and Kilvington 2010
N.Guberi	3.6	> 99.99%	< 6	Heaselgrave and Kilvington 2010
Entamoeba invadens	1.9	< 99.99%	> 9	Heaselgrave and Kilvington 2010
Acanthamoeba polyphaga / histalogica		Inactivation only > 50ºC		Lonnen et al. 2005; Heaselgrave et al. 2006; Mtapuri- Zinyowera et al. 2009
Acanthamoeba castellanii	>2	> 99%	< 9	Heaselgrave and Kilvington 2010

Rates of protozoa inactivation are listed in Table 2.4. SODIS is about as effective at killing Giardia species cysts and other types of protozoa as it is at killing bacteria that cause diarrhea (Table 2.2). Cysts from species of Cryptosporidium need a much stronger irradiation dose than E. coli does. At temperatures exceeding 50°C, the sun's ultraviolet rays have a considerable impact on amoeba.

2.3.4.4 Other microorganisms

Research into SODIS's efficacy against various pathogens is summarized in Table 2.5. Below are the outcomes for preventing the development of helminth eggs (Ascaris suum) and two different kinds of fungi. Although the results for fungi are somewhat inconclusive, i.e., Lonnen (2005) vs. Haeselgrave (2007), the reported data indicate that only under normal SODIS settings are anticipated elimination values in the range of 1 LRV (2010). These microorganisms are relatively minor contributors to the health burden of aquatic diseases as compared to bacteria, viruses, and protozoa.

Table 2.5 Inactivation rate of other microorganisms

Pathogen	Log reduction value (6h)	Reduction of pathogen concentration (6h)	Approx. time required for 3 log reduction (h)	References
Ascaris suum	1	90%	>15	Heaselgrave and Kilvington 2011
Fusarium solani	0.7	70%	>20	Heaselgrave and Kilvington 2010
Candida albicans	1	90%	>15	Heaselgrave and Kilvington 2010

2.4 SODIS Efficiency

Several studies examined the efficacy of SODIS across a spectrum of water quality, container types, and environmental conditions using pathogens with differing levels of virulence. The efficiency of the application of laboratory ideas and findings to field studies is briefly reviewed.

2.4.1 Physicochemical Water Quality

2.4.1.1 Effect of turbidity

Suspended particles in the water decrease the penetration of solar radiation into the water and protect microorganisms from being bombarded. Therefore, SODIS is less effective at disinfecting muddy water. It is proposed that a turbidity level of not more than 30 NTU should be maintained before application of SODIS (Meierhofer and Wegelin, 2002). The potential disinfection efficacy of SODIS may also be diminished by dissolved organic material, i.e., big molecules like humic acids. Besides acting as an internal UV screen by soaking up UV-A rays, dissolved organic materials can also protect against harmful ROS by neutralizing them. The production and quenching of reactive oxygen species (ROS) by dissolved organic matter are contradictory effects that are not well understood and may vary greatly depending on the organic matter's type and concentration (Wilson and Andrews 2011). Some dissolved organic substances absorb visible light and function as water colorants, whilst others do not affect the water's appearance. Further, Kehoe

et al. (2001) reported that in high turbidity waters (> 100 NTU), the UV radiation necessary to achieve complete inactivation increased, but was still attainable with exposures of up to 8.5 h. They came to the conclusion that water with an NTU value greater than 300 may require pre-treatment by filtering or decanting before being treated by SODIS. Keogh et al. (2015) tested 19-L polycarbonate containers with low turbidity water at PSA in Bahrain and India, finding that UV dosages of 250, 730, and 750 kJ/m^2 achieved a 4-log reduction in E. coli. When using SODIS, turbidity is crucial since it affects how much light is able to enter the water and thus how effective the process is (Marques et al. 2013). Dessie et al (2014) research confirmed that increasing turbidity significantly reduces disinfection efficacy. The authors report that 0.93 log units of turbidity were removed from water at 2 NTU after being exposed to the material for 3 h, while just 0.05 log units were removed from water at 81 NTU. E. coli inactivation was reduced from 5 log units to 1 log as turbidity increased from 0 to 200 NTU (Amirsoleimani and Brion, 2021). In addition, they discovered that turbidity levels of 30 and 200 NTU resulted in around 1 log of removal of E. coli concentrations, whereas turbidity values of 0 NTU resulted in the largest inactivation (almost 5.03 logs of elimination as bacterial counts were below detection) of 95.31 and 89.04 %, respectively. As turbidity grew, the temperature rose because the antibacterial effects of sunlight were diminished by clay particles, indicating that the solar insolation had shifted from the ultraviolet (UV) to the infrared (IR). Even though higher temperatures were reported in these turbid waters during sun exposure, they inferred that thermo-tolerant indicator bacteria (E. coli) survived better at higher turbidity levels (100 and 200 NTU). It appears that thermotolerant bacteria may survive at slightly increased temperatures for extended periods of time thanks to turbidity, which protects them from UV irradiation. Incomplete inactivation of E. coli at the higher turbidities was established in this work, making the use of SODIS for hygiene water unadvisable

for waters with turbidities greater than 30 NTU, even if the turbidity induces a rise in temperature. However, if SODIS is to be used efficiently, attention must be paid to the reduction of turbidity before treatment. Because UV radiation is entirely absorbed after a few centimeters in highly turbid waters, the efficacy of SODIS is reduced (Gómez-Couso et al. 2009; McGuigan et al. 1998). This suggests that filtration of turbid waters prior to exposure is strongly recommended. SODIS performance drops dramatically when turbidity levels are greater than 30 NTU. Increased turbidity in water necessitates preliminary treatment, such as settling and decanting, cloth or sand filtration, or flocculation. Alternative water treatment procedures that also improve water aesthetics should be investigated in places when drinking water is murky (below or over 30 NTU), since they are more likely to be accepted and used on a long-term basis by residents.

If a normal newspaper headline can be read through the mouth of a full bottle, the turbidity is below 30 NTU. As seen in Fig. 2.5, the amount of UVA radiation decreases as turbidity rises. Reduced turbidity allows more UVA to pass through, which aids in killing microorganisms.

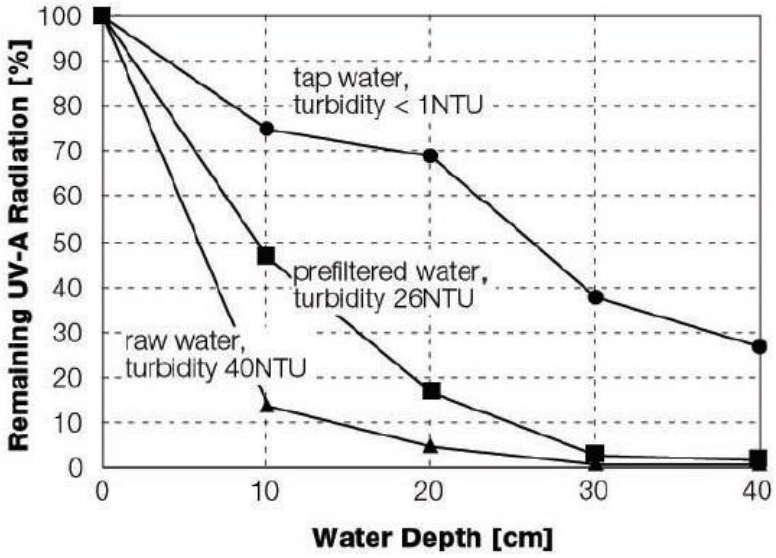


Fig. 2.5 Effect of turbidity in water (Sommer et al., 1997)

Fig. 2.7 SODIS turbidity test (Meierhofer and Wegelin, 2002)

Fig. 2.6 Simple turbidity test (Meierhofer and Wegelin, 2002)

Prolonging the use of raw water by a day allows larger particles and solids to settle to the bottom, reducing turbidity. The water is then emptied through a decanter. Filtration can be used to separate solids, typically with a sand layer or a cloth. Crushed Moringa oleifera seed or aluminum sulfate can be used for flocculation or sedimentation to lessen turbidity. According to Meierhofer and Wegelin (2002), anyone may evaluate the turbidity of water and do a pretreatment with a fine cloth before SODIS by using the basic turbidity test method depicted in Figs. 2.6 and 2.7.

2.4.1.2 Effect of Dissolved Oxygen

The sun makes oxygen free radicals and hydrogen peroxides, which are very dangerous forms of oxygen, form in the water. This makes SODIS work better in water with this kind of oxygen. These reactive chemicals react with cell structures and kill the pathogen (Reed, 1997). Aeration of the water can be performed by shaking the ¾ filled bottle for about 20 seconds before the bottle is filled entirely and exposed to the sun (Meierhofer and Wegelin, 2002). The water in ponds, cisterns, and wells that has been sitting for a long time and has a low oxygen content should be

aerated before being exposed to sunlight (Reed, 1997). Elevated dissolved oxygen content helps the generation of ROS, which is responsible for oxidative disinfection processes (Reed et al. 1997). Recent studies, however, indicated that the bottles should be shaken just at the beginning of the SODIS process. It is important to leave the bottles in one place once they have been placed in the sun, as moving them around too much will cause the solar exposure to be less effective (Kehoe et al., 2001). The damaging effect of sunlight on skin radiation and cell structures is mediated by the reactive oxygen species (ROS) produced by photosensitizers. The molecules of the pathogenic cell or dissolved organic chemicals (exogenous route) make up photosensitizers (endogenous pathway). Due to the essential role of ROS, the SODIS process is ineffective in anaerobic (oxygen-free) water. At 50 % oxygen saturation, the disinfection rate for E. coli and Enterococcus faecalis is approximately half that at full oxygen saturation (Reed, 1997). Early SODIS application recommendations advocated shaking half-filled bottles for oxygen saturation before solar exposure.

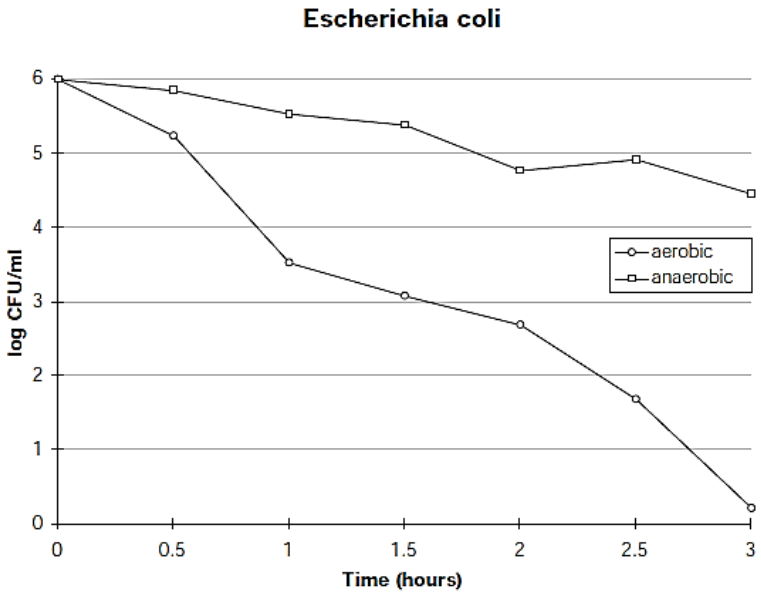


Fig. 2.8 Inactivation of E.coli with time (Reed, 1997)

This guideline is no longer upheld as shaking the bottles complicates the process, and water is oxygenated during the process of filling the bottles prior to solar exposure. Fig. 2.8 compares the rates of E. coli inactivation in aerobic and anaerobic settings over time, demonstrating that aerobic inactivation rates are higher.

2.4.1.3 Effect of color

According to tests, the time it takes to kill the pathogens increases when there is a lot of color in the water (Reed,1997).

2.4.1.4 Effect of water temperature

In the absence of ultraviolet light, high temperatures eliminate harmful microorganisms (pasteurization). Pathogens can be killed in 60 min at temperatures ranging from 45°C (Vibrio cholerae) to 63°C (Enteroviruses) (Berney et al. 2006). The effectiveness of SODIS dramatically rises with greater temperatures, even below pasteurization levels. The inactivation rates are weakly and approximately linearly temperature dependent below 45°C (Wegelin et al. 1994; Fisher et al. 2008). Wegelin et al. (1994) found that treating at 50°C can cut the necessary irradiation dose and/or exposure duration by as much as two thirds, leading to a three-log difference in pathogen reduction compared to the calculated sum of the separate effects of radiation and heat (Theitler et al. 2012). This indicates that under ideal conditions (high temperatures and enough radiation), full disinfection can be attained in less than the stipulated day (6 h minimum). However, the temperature of the water contained within SODIS bottles is not readily apparent to consumers. Therefore, even if the irradiation parameters and temperature appear favorable, it is not advised to reduce the exposure time. Also, if bottles are to be put on a dark surface to enhance the heat effect, it is not advisable to decrease the exposure duration. Fig. 2.9 shows the synergistic effect of UV-temperatures and irradiation over 50°C on the fecal coliform's inactivation curve in glass bottles

with a turbidity of 17 NTU. To a large extent, the effectiveness of the process is determined by atmospheric temperature and wind speed, both of which are influenced by the temperature of the water. Countries with cold or mild climates are also suitable for SODIS, provided that sufficient sun exposure is available, according to field testing conducted in the north-west plateau of China and the highlands of Bolivia (UNICEF, 2005).

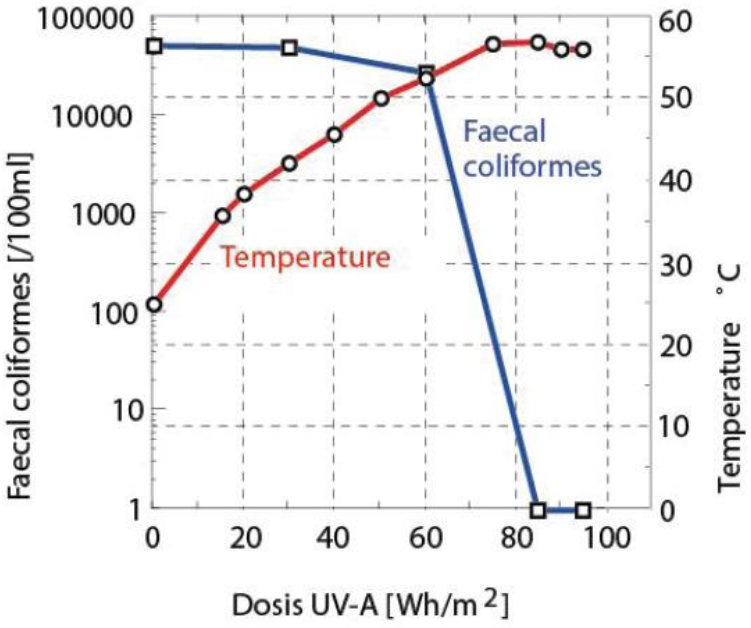


Fig. 2.9 Effect of temperature on fecal coliform (Sommer et al., 1997)

2.4.2 Microbiological Water Quality

In Section 2.3.4, the microbiological water quality is discussed. This shows how well SODIS works against bacteria, viruses, protozoa, and other harmful microbes.

2.4.3 Material and Shape of Container

In SODIS applications, the way pathogens are killed depends a lot on the container's material and shape, both of which are very important. Because the different properties of the material and shape help to make the process better, these properties should be understood and used in the SODIS application.

2.4.3.1 Plastic bottles: PET or PVC

Many kinds of clear plastic are good at letting both ultraviolet (UV-A) and visible (visible) light through. Typically, PET (Poly Ethylene Terephthalate) or PVC (Poly Vinyl Chloride) is used to create plastic bottles. Both have additives, including UV-stabilizers, that protect them and their contents from oxidation and UV radiation and make them more stable.

The difference between PVC and PET can be done in the following way:

- PVC bottles almost always have a bluish shine to them. This bluish shine is most noticeable along the cut edges of a piece of bottle material that has been removed.
- When PVC is burned, it produces a smoke that has a strong, unpleasant odor, but the smoke produced when PET is burned has a pleasant aroma.
- PET is more likely to catch fire than PVC.

It is advised that bottles made from PET be used rather than bottles made from PVC because PET has a great deal fewer additives than bottles made from PVC. Field tests show that the best way to transport SODIS is in clear PET bottles with a capacity of 2 liters. Both returnable and one-way bottles do well in lab tests, but one-way bottles are better because they let more UV light through. The transmission coefficient of one-way bottles does not change noticeably with time. UV light don't pass through colored bottles and so colored bottles are not recommended to use for SODIS (Wegelin, 2000; Quispe, 2000).

2.4.3.2 Glass bottle or Plastic Bottle

The amount of iron oxide in glass determines how much UV light it lets through. Ordinary window glass of 2 mm thickness transmits almost no UV-A light. Therefore, it cannot be used for SODIS. Certain specific glasses (Pyrex, Corex, Vycor, and Quartz) transmit significantly more UV-light

than ordinary window glass. As a result, glass bottles shouldn't be used (Lawand et al., 1990; Sommer et al., 1997; UNICEF, 2005).

The advantage and disadvantage of glass bottle and plastic bottle is given in Table 2.6.

Table 2.6 Pros and cons between plastic and glass bottle

Plastic Bottle	Glass Bottle
Advantages	Advantages
• Characteristics of low density • Brittleness • Transparency • Tastelessness • Chemical stability	• Heat tolerant • Won't scratch • Unable to produce any photos as byproducts.
Disadvantages	Disadvantages
• Brittleness at temperatures exceeding 65°C • Scuffs, dents, and other signs of wear and tear	• Easily broken • Heavier • More expensive

2.4.3.3 SODIS and Plastic bag

Specially created SODIS plastic bags have a higher efficiency as a result of a superior surface-to-volume ratio; however, it is not recommended to use these bags because they are not readily available locally, they are difficult to handle, and they shatter more easily than plastic bottles (Sommer et al., 1997). Transparent polyethylene plastic bags that are easy to find in the area have been tested and shown to have a very high disinfection efficiency. However, using these bags is not recommended for the same reasons that UNICEF (2005) list for the SODIS bag.

2.4.4 Regrowth of Microorganisms

The possibility of bacterial regrowth following inactivation during solar disinfection storage is one of the hazards that prohibits its widespread application. Due to the lack of a residual biocide agent in the disinfected water following SODIS, unlike after sodium hypochlorite disinfection with

residual free chlorine (WHO, 1996), bacterial regrowth may occur, posing a health risk to the final user, depending on the storage water conditions (primarily room temperature), water nutrient content, and level of disinfection achieved (CFU/100 ml). For as long as there have been studies on SODIS, beginning with Acra et al. (1984), regrowth has been a major issue. The first set of experiments showed no signs of regrowth after disinfected water was stored at room temperature for 5 days with a laboratory strain of Escherichia coli. Later, after the first SODIS workshop was held in Montreal (Canada) in 1988, Lawand et al. (1990) summarized the key findings and open questions regarding solar disinfection, including a number of those pertaining to possible regrowth. One finding was that "non-turbid water stored for long periods of time in dark opaque containers eventually becomes almost totally free of pathogenic bacteria," though the exact length of storage time or other conditions were not specified. The question of "whether inactivated pathogenic bacteria that were undetectable would recover if placed in a proper environment, such as the human body," was also raised as a potential area of future research.

Moreover, investigations that incorporated post-irradiation regrowth analyses on SODIS yielded a variety of conclusions. On one hand, there are studies that have not detected regrowth, such as that of Wegelin et al. (1994), which stored the treated water at 20°C after sun exposure and did not detect any E. coli; or that of Sommer et al. (1997), which used 30°C as storage temperature and did not observe any fecal coliform regrowth within 24 h after exposure and complete inactivation. Berney et al. (2006) did not observe any recovery of E. coli cells during the 5 days after irradiation, showing with different viability indicators that the damage caused by UVA in E. coli is irreversible, and Oates et al. (2003) in Haiti also stored the water for 1 day with no regrowth, though the storage conditions are unknown. Recent studies that support this claim and show that there is no regrowth of bacteria after complete total inactivation typically store the water for 2-3

days (Alrousan et al., 2012; Boyle et al., 2008; Giannakis et al., 2014; Helali et al., 2014; Nalwanga et al., 2014; Navntoft et al., 2008; Ndounla et al., 2013). However, there is a body of research that has found bacterial growth again after SODIS treatment. Regrowth of E. coli was observed after 24 h of total inactivation in turbid water (100 NTU) (Kehoe et al., 2001), though a detection limit was not provided and some remaining bacteria might have been present after sun exposure. Gelover et al. (2006) came to the same conclusion after seeing regrowth of coliform bacteria after sun exposure with an initial residual concentration of 10 CFU/100 ml during 7 days of storage but then seeing the bacteria die off for good on day 7. In addition, Mustafa et al. (2013) found that 51% of samples in water that had not been completely disinfected grew again after being stored for 1 week at room temperature. In a more recent study by Keogh et al. (2015) using 19-L polycarbonate plastic water cooler containers and PET bottles, there was no regrowth after 24 h at room temperature (25°C) in the large containers (detection limit of 2 CFU/mL). The regrowth of E. coli K12 in partially inactivated water was also studied by other authors who incubated samples in the dark at 37°C for 24 h (Rincón and Pulgarin, 2004; 2007). Furthermore, the regrowth of microorganisms occurs after the SODIS application for 8 h in the winter and monsoon seasons, showing that appropriate measures should be taken to minimize it, as shown by the study conducted in Bangladesh by Karim et al., 2021. Total bacterial inactivation is achieved when no colony-forming bacteria units are detected in 100 ml of water (0 CFU/100 ml) using standard detection and enumeration methods, as outlined in the World Health Organization's Drinking-Water Guidelines (WHO, 2022b). Because this threshold was never reached in any of the studies reporting regrowth, it is possible that some bacteria were still present and were able to multiply again in the presence of favorable conditions. These storage conditions are rarely mentioned in the literature, with the exception of the vague reference to "room temperature," without clarification

as to whether or not this refers to the standard, controlled temperature of a laboratory (25°C). Recent research by Giannakis et al. (2014) suggests that water temperature storage, in addition to water nutrient content and level of injury in the cells, may play a role in the regrowth process, either suppressing potential regrowth or increasing it (related to sun exposure period). Water quality is at risk due to the presence of nutrient sources in wastewater, which can affect the likelihood of microbial regrowth and lead to recontamination if proper precautions are not taken (Giannakis et al., 2015). As an added bonus, recent SODIS application results suggest that this technology can be efficiently applied to different types of waters, such as wastewater effluents, for regeneration (Gutiérrez-Alfaro et al., 2018). SODIS water should be consumed within 24 h because pathogens can grow again after being exposed to the sun (McGuigan et al., 2012).

2.4.5 Adoption and Adherence to SODIS

Implementation rates of SODIS have not been studied extensively. But there have been a few field trials that have monitored participants' adherence to protocols throughout the trial. There have been claims that users are very compliant with the system (Conroy et al., 1996), but a randomized trial of 425 households found mean compliance rates of 32% (Mäusezahl et al., 2009), and other groups have found sustained adoption rates as low as 9%, with up to 85% of users also regularly consuming untreated water (Rainey and Harding, 2006). Possible reasons for the varying of user compliance in the Conroy study include the backing and participation of key opinion leaders.

Because so little research has been performed and published on SODIS in Bangladesh, there is a great chance that people will adopt it and have access to water that is free of microorganisms. Karim et al. (2021) study on SODIS is the only feasible study that is known to exist, and it demonstrates that it may be utilized effectively and provides useful outcomes.

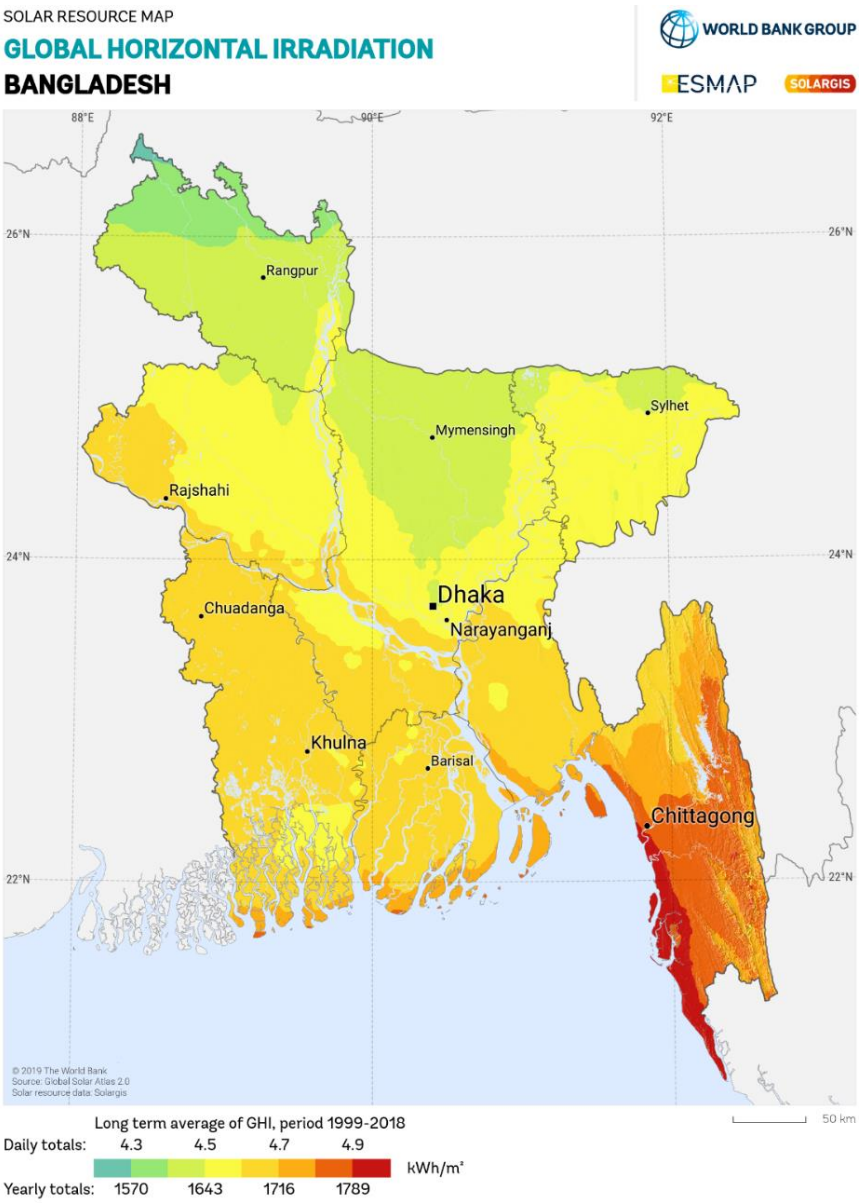


Fig. 2.10 Solar irradiance condition of Bangladesh (World Bank, 2020)

2.5 Influence of Climate and Weather on SODIS

There is a one-to-one relationship between the amount of sunshine that is readily available and the performance of SODIS. Because the intensity of solar radiation changes based on latitude, season, and time of day, it is not possible to say what effects solar radiation has on Earth as a whole. There is a one-to-one relationship between the amount of sunshine that is readily available and the

performance of SODIS. Because the intensity of solar radiation changes based on latitude, season, and time of day, it is not possible to say what effects solar radiation has on Earth as a whole.

2.5.1 Solar Radiation Geography

Latitudes from 15°N to 35°N (and 15°S to 35°S) are optimal for SODIS. The highest levels of solar radiation are seen in these semiarid zones. Due to low cloud cover and low yearly precipitation (less than 250 mm of rain and typically more than 3000 h of sunshine), more than 90% of sunlight reaches Earth as direct radiation.

Beyond the equator, the area between 15 ° north and south is the second-most favorable. Scattered radiation is particularly abundant in this area because of the high humidity and frequent cloud cover (about 2500 h of sunshine annually). The majority of the world's poorest countries can be found between latitudes 35 degrees north and south. They can, therefore, use solar radiation to sterilize water for human consumption. The sun irradiation of Bangladesh during 1999–2018 is shown in Fig. 2.10, demonstrating that the country is within the optimal SODIS zone.

2.5.2 Solar Radiation Seasonal and Daily Changes

There are daily and seasonal shifts in the amount of UV-A emitted by the sun. Most of the climate is set by how the seasons change, which is in turn set by the latitude. There is less seasonal variation in the brightness of the sun's rays in latitudes close to the equator than there is in the northern or southern hemispheres. To give an idea, the UV-A radiation intensity peaks at 18 W/m^2 in June in Beirut (latitude: 33°N) and drops to 5 W/m^2 in December.

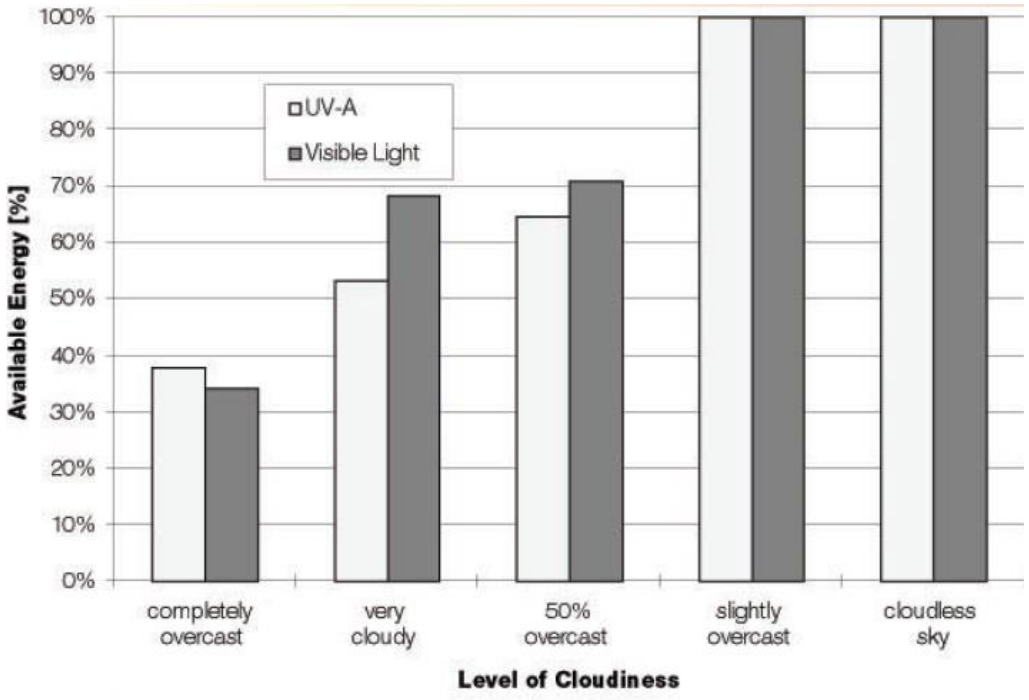


Fig. 2.11 UVA and visible light penetrance in different weather conditions (Sommer et al., 1997)

To know if solar water disinfection is possible, how solar radiation changes throughout the year need to be known. Seasonal radiation intensities must be determined before deploying SODIS in a given area. The minimum solar radiation intensity needed for SODIS to function is 500 W/m^2 for around 6 h. Solar radiation levels also fluctuate during the day. When there are more clouds in the sky, less solar radiation can penetrate. Complete cloud cover reduces UV-A radiation by three-quarters compared to the intensity measured on a clear day. Fig. 2.11 is a representation of the available losses of solar radiation that occur during the monsoon and winter seasons as a result of cloudy sky conditions. Sommer et al. (1997) study illustrate that the SODIS bottles must be left outside for two days in a row on very cloudy days in order to get the right amount of radiation and make sure that all of the pathogens are killed. The administration of SODIS for three days is represented in Fig. 2.12, where they observed that the inactivation of many pathogens does not occur when sunlight is absent from the environment.

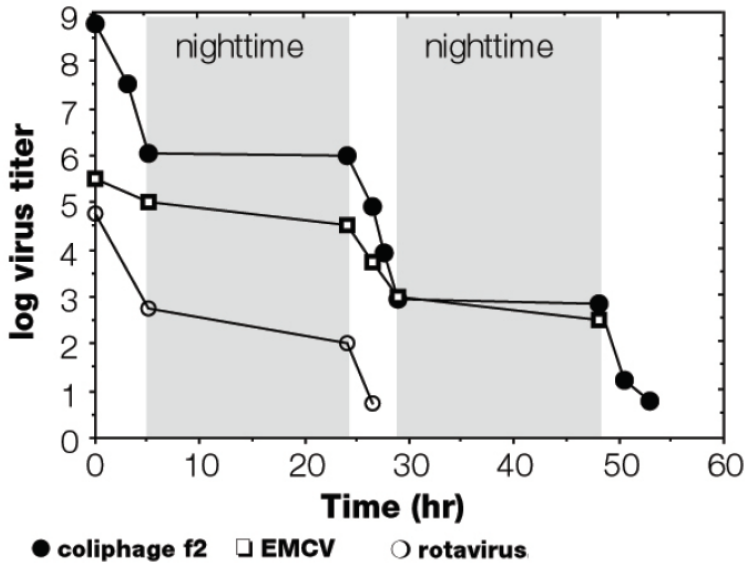


Fig. 2.12 Log Reduction of virus with respect to time (Wegelin et al., 1994)

The strength of the sun's ultraviolet light has a lot to do with how quickly pathogens are killed by solar disinfection. Figure 2.13 shows a typical inactivation curve for E. coli concentrations against the total irradiation dose (or fluence). Following an initial "shoulder" or "lag" phase during which the concentration of viable cells is roughly constant, the concentration of viable cells drops exponentially as a function of the UV dose received.

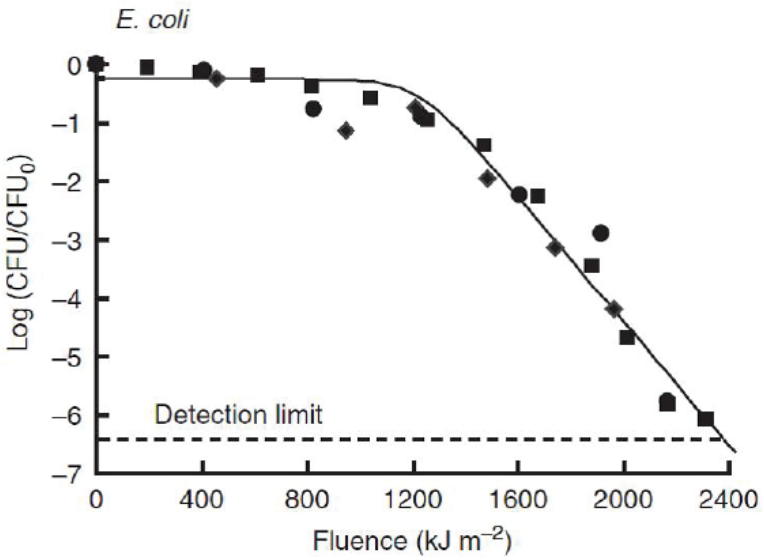


Fig. 2.13 E. coli inactivation rate at 37°C (Berney et al., 2006a)

Even though the amount of irradiation is a key part of how well SODIS works, it is hard to guess what the minimum dose needs to be for effective disinfection. Part of the reason for this is that the effectiveness of treatment depends on a wide range of other factors, such as the type, source, and health of the pathogens in the water, as well as the temperature and chemical composition of the water. But it is hard to compare the rates of inactivation that have been seen because the different experiments that have been performed on SODIS have used different settings. Natural sunlight (which varies by season, location, and duration of day) and filters and artificial lamps of variable radiation spectra were both used in various experiments. Doses of irradiation may be stated for the entire solar spectrum, for a subset of the spectrum (e.g., UV, UV-A), or as an intensity (mean, maximum, or range) for a given treatment duration. There is not yet a complete model for how the effectiveness of SODIS varies with irradiation dose and other parameters.

According to Meierhofer and Wegelin's (2002) recommendations, the following measures need to be taken in order to make SODIS more effective:

- Keep the bottle out in the sun for 6 h if the sky is clear, or for 3 h if there are clouds.
- If the sky is less than 50% cloudy, leave the bottle out in the sun for a single day.
- One h of exposure in water at least 50°C is sufficient.
- Water temperatures of at least 50°C for one h will do the trick.

Even though the amount of radiation is so important for a high level of disinfection, it is still important to follow the rules about how much time should be spent in the sun. In places closer to the equator and during the summer, solar irradiation can easily be stronger than what is needed. This creates a buffer zone that lets exposure times be shorter without affecting how well the disinfectant works. This buffer zone narrows throughout the winter and at higher latitudes away from the equator. A substantial risk of infection exists if the exposure duration is shortened, for

example, either consuming treated water after lunch or treating two batches of water using the same bottles in a single day. Therefore, it is essential that the promotion emphasize the need to apply according to the rules.

2.5.3 Water Temperature and its Influencing Factors

The air temperature and wind speed, which are both affected by the water temperature, have a direct effect on how well the process works. Nonetheless, field tests conducted on the northwest plateau of China and in the highlands of Bolivia show that countries with cold or temperate temperatures are equally acceptable for SODIS if sufficient sun radiation is available (UNICEF, 2005).

2.6 SODIS Enhancement

The "traditional" SODIS technology has a number of deficiencies that need to be addressed. The use of PET bottles makes it possible to treat only very small volumes (two to three liters), and the efficiency of the process is dependent on a wide range of environmental parameters, such as the solar irradiance (which varies depending on the latitude, time of day, and atmospheric conditions), the initial water quality, such as organic loading, turbidity, level, and the type of bacterial contamination. Variations in treatment times are a direct result of the resistance shown by bacteria to the disinfecting effects of sunlight. To improve the efficiency of the solar disinfection process, a variety of different process improvements have been investigated. These kinds of initiatives have included doing periodic agitation, employing foil to boost reflectivity, utilizing different containers, utilizing different additives, using solar collectors, and painting half the bottle black in an effort to raise the temperatures that may be reached.

2.6.1 Additives

Experts have shown that incorporating additives like titanium dioxide (TiO_2) and hydrogen peroxide (H_2O_2) into SODIS can improve the treatment's overall effectiveness (Byrne et al., 2011). Some of these supplements greatly improve the treatment's efficiency. But there are two key obstacles to their widespread promotion and implementation in target countries. The first problem is that the added chemical makes using the water much more difficult for the user without providing anything in the way of tangible benefits. Exposing the bottles for only one or two h (midday) still presents a logistical difficulty for persons who work outside the home, even if the time required to do so is reduced to that extent. Second, steady consumption of a SODIS catalyst calls for established and trustworthy distribution channels for the substance. When a chemical disinfectant like chlorine can be purchased and used for the same purpose (the elimination of harmful microorganisms in water), there is no persuasive incentive for water consumers to acquire and utilize a solar disinfection catalyst.

Several chemical additions, like the photocatalyst TiO_2, have been looked at as possible ways to make SODIS less harmful. There has been a lot of interest in citrus-based flavor enhancers. Inactivation of MS2 coliphage, E. coli, and Enterococcus spp. was hastened by the addition of 125 mg/l sodium percarbonate in conjunction with either citric acid or copolyphosphate plus ascorbate, as reported by Fisher et al. (2012). SODIS plus lime juice or pulp can drastically lower E. coli counts in as little as 30 min, as demonstrated by Harding and Schwab (2012). The treatment period (30 min) is comparable to boiling and other HWT procedures; however, they show reductions of 6 log units for E. coli in improved bottles compared to 1.5 log units in normal SODIS. Riboflavin was studied by Heaselgrave and Kilvington, who found that it significantly increased the efficacy of simulated solar disinfection (SODIS) at 150 W/m^2 against a variety of microorganisms, such as

E. coli, F. solani, C. albicans, and A. polyphaga trophozoites (>3-4 LRV after 2-6 h; P:0.001). In the presence of riboflavin and 250 W/m^2 irradiation, A. polyphaga cysts were killed (3.5 LRV after 6 h) (Heaselgrave and Kilvington, 2010). In addition to the improved inactivation with riboflavin (SODIS-R), they found that the inactivation of Acanthamoeba castellanii cysts was increased from 2.16 LRV with SODIS alone at 6 h to 3.84 LRV with SODIS plus riboflavin.

2.6.1.1 H_2O_2

Advanced oxidation processes (AOPs) can improve the effectiveness of ultraviolet light in killing microorganisms. In these reactions, hydroxyl radicals (•OH) are produced. Additives that boost SODIS therapy by creating reactive oxygen species (ROS) like the hydroxyl (•OH) radical, hydrogen peroxide (H_2O_2), superoxide (O^{-2}), and singlet oxygen ($^1O_2$) have been the subject of recent research (Fisher et al., 2008). In order to purify polluted water, AOPs have been hailed as a potentially effective method for getting rid of harmful microbes and chemical substances. Sustainable drinking water and irrigation water treatment may benefit from solar-powered AOPs, which should be more affordable (Malato et al., 2009). The generation of reactive oxygen species, such as •OH radicals, speeds up the inactivation of microbes by UVA light in solar-powered AOPs. There are two types of AOPs that occur after exposure to light: heterogeneous and homogeneous. Homogenous oxidative processes (liquid phase reaction) require high concentrations of reactive species to inactivate microorganisms effectively. This can have a huge health impact on the human body owing to the addition of high concentrations of oxidants. They can react with harmful and beneficial microorganisms. It is expensive to implement and operate, and it can also produce harmful by-products after chemical reactions. In contrast, heterogeneous oxidative processes (liquid-solid phase reaction) are more efficient, low-cost, environmentally friendly, and do not kill beneficial microorganisms. Moreover, it is easy to implement and effective against inactivating

microorganisms, as the ROS produced in this process have strong oxidative properties that damage the cell membranes, proteins, and DNA of microorganisms. The most extensively researched are done with heterogeneous process for the destruction of microorganisms as a photocatalysis such as titanium dioxide and hydrogen peroxide with iron salts (Malato et al., 2009). However, photo-Fenton has gained significant attention because of its effectiveness in producing •OH radical. Both heterogeneous and homogeneous occurs in water by the addition of hydrogen peroxide with dissolved iron and iron salts in water. The following equations (Pignatello et al., 2007) describe the Fenton process.

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + \bullet OH \quad (k = 63\ L\ mol{-}1\ s{-}1) \tag{2.1}$$

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + HO_2 \bullet + H^+ \ (k = 3.1 \times 10{-}3\ L\ mol{-}1\ s{-}1) \tag{2.2}$$

$$\bullet OH + H_2O_2 \rightarrow HO_2 \bullet + H_2O \quad (k = 3.3 \times 107\ L\ mol{-}1\ s{-}1) \tag{2.3}$$

$$\bullet OH + Fe^{2+} \rightarrow Fe^{3+} + OH^- \ (k = 3.0 \times 108\ L\ mol{-}1\ s{-}1) \tag{2.4}$$

$$Fe^{3+} + HO_2 \bullet \rightarrow Fe^{2+} + O_2 + H^+ \ (k = 2.0 \times 103\ L\ mol{-}1\ s{-}1) \tag{2.5}$$

$$Fe^{2+} + HO_2 \bullet + H^+ \rightarrow Fe^{3+} + H_2O_2 \ (k = 1.2 \times 106\ L\ mol{-}1\ s{-}1) \tag{2.6}$$

$$HO_2 \bullet + HO_2 \bullet \rightarrow H_2O_2 + O_2 \ (k = 8.3 \times 105\ L\ mol{-}1\ s{-}1) \tag{2.7}$$

Second-order rate constant is denoted by k. UV-vis radiation up to 600 nm significantly boosts •OH generation. Photo-Fenton describes the final step in the catalytic cycle, which is represented by Equation 2.8 (Mailhot et al., 2002):

$$Fe(OH)^{2+} \xrightarrow{h\nu} Fe^{2+} + \bullet OH \quad (2.8)$$

The synergistic effect of H_2O_2 and UV light from the sun is another photo-induced effect that has recently drawn attention for killing pathogens in water. Jones (1999) and Goldstein et al. (2007) wrote in Equation 2.9 that photons with wavelengths shorter than 300 nm photolyze H_2O_2 to make •OH.

$$H_2O_2 \xrightarrow{h\nu} 2 \bullet OH \quad (2.9)$$

But solar energy isn't enough to make •OH through this pathway because there are no photons with wavelengths below 280 nm at the Earth's surface. In 1977, it was written that hydrogen peroxide and ultraviolet light can kill phage T_7 (Ananthaswamy et al., 1979). Few studies have documented the deleterious impact of H_2O_2/sunlight on aquatic microorganisms. The combined disinfection effectiveness of near UV or visible light and hydrogen peroxide has been demonstrated experimentally utilizing a variety of targets, including Escherichia coli and Streptococcus mutans (Feuerstein et al., 2006; Hartman and Eisenstark, 1978). As a result of the microbial cells' inherent iron content and the diffusion of H_2O_2 across their membranes, a synergistic effect is produced when hydrogen peroxide and solar photons are combined (Polo-López et al., 2020).

Microorganisms exposed to oxidative stress exhibit a spectrum of reactions, beginning with increased mitosis and ending with apoptosis or necrosis (Cadenas and Davies, 2000). Reagent oxidative species (ROS) such as O_2, H_2O_2, or derived oxygen species created during photosynthesis cause this stress (Imlay, 2008). During photolysis, cell death is mediated by a variety of inactivation mechanisms (Spuhler et al., 2010). Additional hydroxyl radicals (•OH) are

produced, and the disinfection process is quickened when an advanced oxidation treatment is applied, such as solar photo-Fenton, to kill bacteria in water. By triggering a chain reaction of lipid peroxidation, which is then absorbed by the cell membrane, reactive oxygen species (ROS) are able to damage cells from the outside. This raises permeability across membranes, which in turn disrupts normal cellular activity and shortens their lifespan (Kiwi and Nadtochenko, 2005). For instance, hydrogen peroxide (H_2O_2) can freely pass through cell membranes and has the potential to generate •OH via Fenton reactions with free iron already present in the cells (Imlay, 2008). This suggests that H_2O_2 may be extremely harmful to aerobic metabolism within cells, as it can cleave DNA molecules at their amine bases (Jones, 1999). Another type of foreign species that might cause damage on the inside is Fe^{2+}. Being easily able to pass through cell membranes, Fe^{2+}can cause damage to cells on the inside through interactions with metabolic hydrogen peroxide (Imlay, 2008; Sichel, 2009; Spuhler et al., 2010).

The process through which microorganisms are rendered inert Since iron is believed to be present as dissolved organic complexes of ferric iron (Clarizia et al., 2017; Yuegang and Jürg, 1992) in waters with a natural organic matter content and a pH of 8.04. The generation of reactive oxidation species under solar irradiation is thus boosted by the presence of naturally occurring iron and natural organic matter as well as additional H_2O_2. Seawater had an iron concentration of 14.3 g/L. Somewhat surprisingly, photo-Fenton may occur at extremely low iron concentrations in some situations (Ndounla and Pulgarin, 2014). H_2O_2 causes an increase in the generation of harmful ROS in the presence of iron ions, resulting in full inactivation without dark re-growth, even for a more resistant Salmonella sp. This insight is crucial for really putting this method to use in the real world. In this situation, the presence of iron at concentrations as low as 0.3 mg/l could be deemed sufficient to produce the photo-Fenton reaction, a potential method of bacterial inactivation.

Experiments of a similar nature have been carried out in a laboratory batch photoreactor with deionized water and at pilot scale in a CPC with natural surface water from Leman Lake (Rincón and Pulgarin, 2006, 2007a, 2007b). A concentration of 0.3 mg/l of iron or 10 mg/l of H_2O_2 was sufficient to inactivate the complete E. coli charge and preserve the bacterial water quality for 24 h at room temperature and in the dark (also called the "efficient disinfection time after 24 h or "EDT24"). The bactericidal effect of sunlight occurs due to (Giannakis et al., 2016b): (1) the damaging effects of sunlight (mainly UVB) on bacterial DNA and on the enzymes that repair it, and (2) the oxidative stress within bacteria as a result of the disruption of the normal balance between the reactive oxygen species (ROS). The cytoplasmic direct oxidation and Fe release processes that react with H_2O_2 (a natural result of bacterial metabolism) would generate hydroxyl radicals (•OH). In the cytoplasm, photo-Fenton reactions occur at low peroxide concentrations.

The bactericidal effect of hydrogen peroxide occurs in the presence of only hydrogen peroxide for two reasons (Giannakis et al., 2016b): (1) H_2O_2 affects the bacterial membrane, initiating its auto-oxidation, and (2) oxidative stress is generated inside the bacteria, due to the penetration of H_2O_2 and the increase of intracellular reactive oxygen species. Again, OH is produced via direct oxidation processes in addition to the release of Fe in the cytoplasm. When there is an abundance of peroxide in the cytoplasm, the Fenton reaction is triggered. The above-mentioned factors may explain the mechanism of enhanced Vibrio spp. inactivation by SODIS/ H_2O_2.

- Light has a deleterious effect on both bacterial DNA and the enzymes that may repair it;
- Disruption of the membrane from the outside (the H_2O_2 causes auto-oxidation in the bacterial membrane);
- Light-induced cellular imbalance and H_2O_2's incomplete penetration lead to oxidative stress within the bacterium.

Because of this, the cytoplasm has a lot of peroxide, both from the outside and from the metabolism of the bacteria, which causes photo-Fenton reactions. In the presence of naturally dissolved iron, SODIS/ H_2O_2 can boost the production of hydroxyl radicals in the bacterial cytoplasm (the photo-Fenton process). This may account for the observed synergistic impact. However, the potential role of the photo-Fenton process in the formation of •OH radicals in the bacteria's external watery media does not appear to be significant. The low amounts of naturally existing iron and the difficulty of iron to activate the Fenton reaction in the marine environment due to trapping processes may account for this phenomenon (Giannakis et al., 2016b). (Sajiki and Yonekubo, 2004).

The main advantage of an H_2O_2/solar light system is the low cost of the reagent (H_2O_2) and the very low amounts needed for disinfection. It does not require a post-treatment because the auto-decomposition of hydrogen peroxide in water and oxygen avoids concerns about secondary pollution due to the disinfectant itself. This is not the case for other advanced oxidation processes like titanium dioxide, which require a post-treatment to remove the catalyst from the water, or the photo-Fenton process, which requires pH neutralization and iron removal.

The large amount of extracellular •OH created during SODIS with H_2O_2 (Equations 2.1–2.8) is the key to the process's high efficiency. These radicals mostly target the membranes of pathogens (Jones, 1999), but they can also reach DNA and cause breaks in the strands, alterations to the nucleic bases, and even death (Henle and Linn, 1997). (McGuigan et al., 1998). As revealed by Rincón and Pulgarin (2006), the significant generation of oxidative species both inside and outside the cell is responsible for the increased efficiency of the system Fe^{3+}/ H_2O_2/solar light compared to $Fe^{3+/}$solar light alone. Spuhler et al. (2010) found similar findings with E. coli when they utilized genuine water from Switzerland's Lemans Lake and supplemented it with 10 mg/l of iron from

iron-sulfur and 10 mg/l of H_2O_2 at a neutral pH. In addition, 0.6 mg/l of Fe^{2+}or Fe^{3+} and 10 mg/l of H_2O_2 were used to grow E. coli in a solar simulator exposed to UVA radiation in the range of 330-390 nm. The time to inactivation was determined to be 180 min.

The effects of light on bacteria are discussed in the previous section (2.3.1). Two basic methods of cellular inactivation were discussed: direct light action (mutations, strand breakage, etc.) and indirect light-initiated pathways (ROS formation, iron release, and the subsequent internal Fenton and photo-Fenton reactions). Superoxide and H_2O_2 have been identified as pivotal mediators of the internal photo-Fenton reaction, which contributes to both the direct destruction of biomolecules and the indirect exacerbation of ROS generation. Here, the inner and outer workings processes inside the bacteria are shown when light is present or absent, and evaluated how the addition of H_2O_2 can increase UV induced inactivation of bacteria.

2.6.1.1.1 Prior to light exposure

Hydrogen peroxide (H_2O_2) has a potential of 1.8 volts at pH 0 and a potential of 0.87 volts at pH 14. (Venkatadri and Peters, 2009). H_2O_2 was linked to disinfection and regulating biofilm formation in contexts related to biology (Venkatadri and Peters, 2009). Auto-oxidation of bacterial respiratory dehydrogenases (Imlay, 2003) produces H_2O_2 as a natural byproduct of respiration; catalases and peroxidases keep ROS concentrations in check and at nanomolar levels (Seaver and Imlay, 2001). H_2O_2, being an uncharged molecule, is known to diffuse across membranes and enter cells if it is present in the microorganism's environment (Seaver and Imlay, 2001). Because of this delicate balancing act between its intracellular synthesis, the potential diffusion from external sources, and the scavenging effectiveness of the enzymes, a steady state concentration is maintained (Cadenas and Davies, 2000). Indicators of steady-state concentrations can vary across a range of physiological conditions (Sichel et al., 2009). According to reports, 20% of the

extracellular concentration of H_2O_2 is possible to diffuse into the cell, ultimately leading to cell death (Seaver and Imlay, 2001). This imbalance can be scavenged or inactivated by enzymes. H_2O_2 can cause cell death via multiple mechanisms; determining which one is at play requires evaluating the mode of action and the underlying mode of action. There is a wide range of concentrations of H_2O_2 that can be encountered from the outside, as it can be created naturally or added on purpose. Experiments with mm (miliMolar) doses of H_2O_2 by Imlay and Linn revealed a connection between H_2O_2 addition and cell inactivation (Imlay and Linn, 1986, 1988). Concentrations as low as 1-3 mm H_2O_2 and as high as >20 mm can be broadly classified into two groups. Mode I and Mode II categories were reported to have experienced internal and exterior damage, respectively (Uhl et al., 2015). By reacting probably directly with the cellular membrane, H_2O_2 from the outside can enhance its permeability and allow higher amounts of H_2O_2 into the cell, which can have a severe effect on the cell's viability in mode II (Halliwell and Aruoma, 1991). At concentrations up to 100 mm, a linear relationship has been seen (Imlay and Linn, 1986). The processes entangled in Mode I damage, however, are much more intriguing. In sum, the internal Fenton reaction described in the prior chapter is being bolstered by these measures. Specifically, it was shown in Park et al. (2005) that M concentrations destroyed Fe/S clusters, causing cellular catabolic and biosynthetic processes to be disturbed (Jang and Imlay, 2007; Keyer and Imlay, 1996; Liochev and Fridovich, 1994; Touati et al., 1995). Excess H_2O_2 will kick off Fenton reactions, and the broken cluster helps liberate free iron. Although H_2O_2 is an oxidant, it is not the only oxidant that may scavenge electrons. Hydroxyl radicals ($HO\cdot$) are specifically created through one-electron transfer. Mode A killing will also occur, albeit the routes taken may be direct or indirect (Imlay and Linn, 1986). H_2O_2 can scavenge $HO\cdot$, creating the less reactive superoxide anion (Imlay and Linn, 1986), which has a reduced oxidative potential but is physiologically relevant due to its great

affinity with bacterial components (Halliwell and Gutteridge, 1984). It is also significantly more stable than HO. The addition of a large volume of H_2O_2 to the bulk under saturated conditions has intriguing Fenton-related ramifications.

2.6.1.1.2 After light exposure

Because very small amounts of H_2O_2 are usually used in experiments (Garcia-Fernández et al., 2012; Rincón and Pulgarin, 2004; Spuhler et al., 2010), these kinds of additions are called Mode I killing. Scientists at concentrations below 15 mg/l (0.44 mm) discovered no inactivation; at 10 mg/l (0.29 mm), Sciacca et al. observed a 2-log reduction; and researchers at concentrations of 8.5 mg/l (0.25 mm) reported only minimal inactivation in the dark (Ndounla et al., 2013; Sciacca et al., 2010). Still, the conditions for efficient internal photo-Fenton reactions and speedy regeneration of ferric iron back to ferrous can be provided by diffusion into the cell and the input of light into the sample. Synergistic inactivation by near-UV light and H_2O_2 was originally established for phages by Ananthaswamy and Eisenstark (1976) and for E. coli by Hartman and Eisenstark (1980). Fisher et al. (2008), Garcia-Fernández et al. (2012), Ng et al. (2015), Sciacca et al. (2010), and Spuhler et al. (2010) are only a few examples of the many subsequent works that have been generated to evaluate the H_2O_2-enhanced photokilling modes and factors that are involved. The vast majority of studies agree that an internal photo-Fenton reaction, boosted by illumination, and the causes of dominant mechanism are the following:

- The direct damage of the light affects the DNA and the enzymes responsible for its reparation (direct action).
- Light is disrupting the normal ROS-scavenging enzymes into the cells such as catalase, superoxide dismutase, peroxidases etc. (indirect action)
- H_2O_2 penetrates the cell, causing imbalance of ROS into the cells.

- ROS and light release iron into the cytoplasm, with reacts with H_2O_2 to create ●OH. Other ROS are involved into the reduction of iron, or directly attack susceptible moieties (oxidative stress).
- Added H_2O_2 affects bacterial membrane (outer damage), initiating its auto-oxidation.
- Light reduces ferric iron to ferrous directly, through ligand-to-metal charge transfer (LMCT) or indirectly, through the reactive intermediates available by the light-induced malfunctioning into the cell, initiating a photo-catalytic cycle.

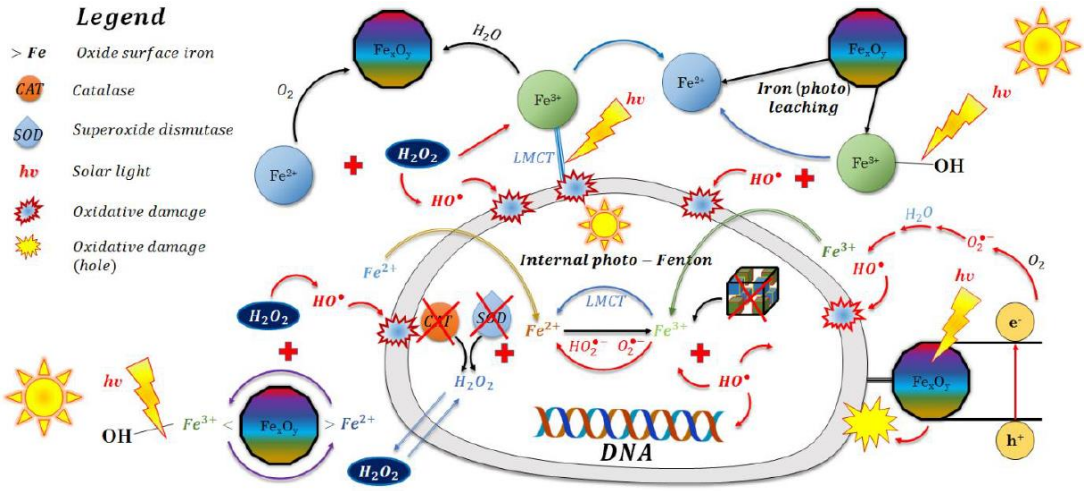


Fig. 2.14 Effect of H_2O_2 in bacterial disinfection (Giannakis et al., 2016b)

A number of indicators support the majority of these hypotheses or restrict them to some degree. For instance, Fisher and Nelson (2014) proposed that at aerobic, near-neutral conditions, the ligand-to-metal charge transfer could not proceed for h, implying that iron supplies must be supplied. Even though this period of time is not required for bacterial inactivation, it is expected that Fe^{3+} will precipitate under these conditions and no longer play a role in the inactivation mechanism. When the concentration of H_2O_2 was increased from 0 to 500 mm (Fisher et al., 2008) or from 0 to 10 mg/l (García-Fernández et al., 2012), the inactivation kinetics increased linearly. As a result, it is hypothesized that the internal Fenton reaction is occurring and that Fe^{2+} is not the

limiting reagent. As a result, an effective catalytic cycle is always at work, releasing and reducing iron continuously. The following reactions with bacteria take place as a result of the addition of H_2O_2 to the water, and they are depicted in Fig. 2.14. The use of hydrogen peroxide, which disinfects bacteria in a relatively short amount of time when exposed to solar irradiation, causes total cell destruction. Therefore, combining SODIS with H_2O_2 can expedite the killing of bacteria in water within the allotted time for disinfection and produce bacterium-free water as a result.

2.6.1.1.3 Advantages of Hydrogen Peroxide in Various Applications

Applying hydrogen peroxide (H_2O_2) in SODIS process to inactivate microorganisms has various advantages:

Enhanced disinfection: Hydrogen peroxide is a strong oxidizing chemical that can inactivate a variety of microorganisms, including bacteria, viruses, and protozoa. Its significant oxidative properties contribute to the destruction of cellular structures and components, rendering microbes nonviable.

Broad-spectrum activity: H_2O_2 exhibits broad-spectrum antibacterial activity, allowing it to be effective against a wide variety of microbes. This adaptability is essential for guaranteeing thorough disinfection and lowering the danger of waterborne illnesses.

Simplicity and accessibility: The utilization of hydrogen peroxide in SODIS is simple and readily available. It does not require complicated equipment or significant technical experience, making it suited for resource-constrained environments or emergency situations in which conventional water treatment technologies may be unavailable.

Rapid action: The rapid action of hydrogen peroxide on germs promotes speedy disinfection. This is particularly helpful for SODIS, as solar exposure times are often longer, and the addition of H_2O_2 can accelerate the inactivation of microorganisms.

Environmental compatibility: Hydrogen peroxide easily breaks down into water and oxygen, leaving no hazardous byproducts in the treated water. This makes it an eco-friendly option for water disinfection because it does not introduce extra chemical contaminants.

Cost-effectiveness: Hydrogen peroxide is readily available and very inexpensive, making it a cost-effective choice for microbial inactivation using SODIS. Its price promotes its use in communities with limited access to clean water.

Storage stability: Properly stored hydrogen peroxide can retain its efficacy for an extended duration, ensuring a dependable and stable means of disinfection for SODIS applications.

Therefore, hydrogen peroxide provides a number of benefits in the context of microbial inactivation using SODIS. Its improved disinfection capabilities, broad-spectrum activity, simplicity, rapid action, environmental compatibility, cost-effectiveness, and storage stability make it a powerful instrument for promoting safe and accessible water disinfection, especially in settings with limited resources. For this reason, many researchers choose H_2O_2 as a photocatalyst for inactivating microorganisms (Sciacca et al., 2010; Rubio et al., 2013; Navarro et al., 2019)

2.7 Health Impact of SODIS

Every effort made to spread awareness of SODIS or HWTS should lead to a decrease in the population's vulnerability to diarrheal illness. Most HWTS project impact studies compare populations before and after an intervention, or compare the intervention population to a control group, to measure the success of the project in reducing the prevalence of diarrhea or the risk of infection. Diarrhea reductions have been inconsistent among trials of SODIS's health effects (Table 2.7). Disease incidence reductions of 26–37% have been observed in the vast majority of randomized controlled trials (Sobsey et al., 2008). One of the earliest SODIS randomized controlled trials (RCTs) was undertaken by Conroy et al. (1996), and they found a 34% reduction

in diarrhea and a 35% reduction in severe diarrhea after 12 weeks. A year later, the same team conducted a follow-up trial and discovered that the rate of diarrhea cases had decreased by 16%. (Conroy et al., 1999). In addition, the same authors found that the incidence of cholera was reduced by 88% in children younger than 6 years old after SODIS was implemented during an outbreak (95% confidence interval (CI): 35%–98% reduction), while the effect was not statistically significant in children aged 6-15 years old (95% CI: 42% reduction-105% increase) (Conroy et al., 2001). In rural Pakistan, South Africa, India, Bolivia, Guatemala, rural Cambodia, and the periurban Kibera slum in Nairobi, Kenya, the number of cases of diarrhea in children dropped by 41%, 31%, and 42%, respectively (Gurung et al., 2009), and by 47% in rural Uzbekistan (Grimm, 2004). The studies may not have been sufficiently powered to detect effects at the levels they reported, or others may have been observational in nature and lack suitable controls. In addition, several of the earlier SODIS studies were carried out in high-compliance settings, such as Massai communities, where the buy-in of Massai elders assured high compliance rates among community members (Conroy et al., 1996, 1999, 2001). Positive but minor decreases in diarrheal illness were shown in a recent experiment with inadequate compliance (Mäusezahl et al., 2009). Intentionally treating persons with an intervention is unlikely to alter health outcomes unless the intervention is actually employed by research participants; therefore, this is not surprising. Another subsequent meta-analysis reached the same conclusion: there was insufficient evidence to determine that SODIS's preventive effects were greater than zero after 1 year of adoption (Hunter, 2009). However, this does not mean that after a year, SODIS is useless. Instead, the report recommends more long-term blinded studies of SODIS and other therapies to properly evaluate their health impacts. In sub-Saharan Africa and some East Asian nations, the drinking of SODIS water has decreased the prevalence of water-borne diseases such as dysentery, typhoid, and cholera (Conroy

et al., 1996, 2001; du Preez et al., 2010). Solar UV radiation's capacity to kill off pathogenic bacteria like poliovirus and Giardia cysts is mostly responsible for this (Heaselgrave et al., 2006; Quinones et al., 2006). Infectious microorganisms are equally susceptible to the killing effects of solar UV radiation, regardless of whether or not they are currently being treated with antibiotics. And in areas where waterborne diseases are common, sunlight—the principal source of solar ultraviolet radiation—is abundant. Besides the chemistry and biology of microbial inactivation, there are additional factors that contribute to the positive health effects of drinking SODIS water (Berney et al., 2006). One of the many potential advantages of drinking SODIS water is a boost to human immune system. Water after SODIS may contain a wide variety of microbial antigenic determinants or epitopes, while their precise nature is unclear (Bosshard, Bucheli, et al., 2010; Bosshard et al., 2009). Consumption of SODIS water may trigger an immunological reaction or response, depending on how the microbial epitopes are recognized and processed by the immune system. There is substantial evidence linking the provision of drinking water via SODIS with a decrease in the incidence and severity of diarrhea, particularly in children (Clasen et al., 2004; du Preez et al., 2011a; McGuigan et al., 2011a; Rai et al., 2010); these outcomes are thought to be attributable to the ingestion of water free of viable pathogens. Few studies have looked into the immunogenicity of sun-inactivated pathogens in water or the immunological consequences for people who consume SODIS-treated water. This disagreement among researchers, however, is not about the efficacy of SODIS in neutralizing the etiological agents of diarrhea; rather, it concerns the influence of SODIS-based therapies on lowering the prevalence of diarrhea. So, while the discussion can and should center on the methodological quality of the field trials, the delivery of SODIS to people and their reception and use of it over time should be the conversation's central focus. Conventional SODIS relies on individual and household behavior to disinfect water

properly on a daily basis, which is one of its major limitations. This means that it might have a positive or negative effect on the prevalence of diarrhea. Recent works (Azamzam et al., 2021; Chaque and Rott, 2021; Garca-Gil et al., 2021) have discussed the shortcomings of traditional SODIS and proposed solutions. However, in the same manner that high-quality studies are essential to evaluate the effect of SODIS-based treatments on diarrhea prevalence. In addition, more research is essential to determine the most effective means of bringing SODIS technology to communities. In these efforts, the evaluation of alternative technology approaches to improve upon the shortcomings of traditional SODIS should also be taken into account. Priority should be given to suggestions that either boost SODIS's output or lessen the burden caused by the daily ritual of filling bottles and setting them in the sun. The process of microbial inactivation by the sun is connected to the potential of SODIS-inactivated pathogens to generate immunological alterations that result in protective effects. Sun ultraviolet (UV) radiation (both A and B) or the combination of UV and solar heat is responsible for the biocidal impact that kills microorganisms during SODIS (Nelson et al., 2018). Photosynthetically active radiation contributes only a little amount (Muela et al., 2002). These pathways are responsible for the diminished metabolic activity and cytotoxicity of water-borne bacteria (Chihomvu, 2019b). It has been shown that during SODIS, a wide range of cellular structural and enzymatic proteins are damaged in a fashion similar to that caused by the oxidative process, through carbonylation and aggregation (Bosshard et al., 2010). These alterations are made without significantly reducing the microbes' immunogenic potential (Cano Ssemakalu et al., 2020).

Table 2.7 SODIS efficiency in different countries

Location	Duration	Sample Size	Population	Age	Outcome	Results	Reference
Pakistan			Rural		Diarrhea	Mean 41% (95% Confidence Interval)	Gurung et al., 2009
Kenya			Kibera slum, Periurban		Diarrhea	Mean 42% (95% Confidence Interval)	Gurung et al., 2009
Cambodia			Rural		Diarrhea	Mean 31% (95% Confidence Interval)	Gurung et al., 2009
India				Children<5y	Diarrhea	IRR 0.64 (40% reduced risk of infection)	Rose et al., 2006a
South Africa				Children<5y	Diarrhea	Dysentery: IRR 0.64, 95% CI 0.39-1.0, P 0.071) Non-dysentery: no statistically significant effect	du Preez et al., 2010
Kenya				Children 6 months to 5y	Diarrhea	Dysentery IRR = 0.56 (95% CI 0.40 to 0.79) Dysentery episodes IRR = 0.55 (95% CI 0.42 to 0.73) non dysentery days IRR = 0.70 (95% CI 0.59 to 0.84) non dysentery episodes IRR = 0.73 (95% CI 0.63 to 0.84). Median height-for-age: higher by an average of 0.8 cm over a 1-year period in SODIS group (95%CI 0.7 to 1.6 cm, P = 0.031). Median weight-for-age: higher by average of 0.23 kg over a 1-year period in the SODIS group (95% CI_0.02 to 0.47 kg, P = 0.068).	du Preez et al., 2011a
Cameroon				Children<5		OR (intervention group vs control group): 0.63 OR (SODIS users vs none users): average 0.45)	Graf et al., 2010a
Uzbekistan	2 years	419	Rural	All	Diarrhea	Mean 47% (95% Confidence Interval)	Grimm, 2004
Bolivia	52 weeks	735 children	Rural	Children<5y	Diarrhea	Relative rate of diarrhea: 0.81 (95%CI 0.59–1.12	Mäusezahl et al., 2009
Kenya	52 weeks	349 children	Massai, Rural	Children<6y	Diarrhea	Odds ratio 0.69, 95% CI 0.63 to 0.75	Conroy et al., 1999
Kenya	8 weeks	299 children	Massai children M6, Rural	Children<6y	Cholera	Odds ratio 0.12, 95% CI 0.02 to 0.65 81% less cholera cases among children <5	Conroy et al., 2001a
Kenya	12 weeks	206 children	Massai, children	Children 5-15y	Diarrhea	Diarrhea (odds ratio 0·66 [0·50–0·87]), severe diarrhea (0·65 [0·50–0·86])	Conroy et al., 1996
Cambodia				Children 5 months to 5y	Diarrhea	Dysentery: IRR 0.50 (95% CI 0.27_0.93, p= 0.029) Non-dysentery: IRR of 0.37 (95%CI 0.29_0.48, p < 0.001)	McGuigan et al., 2011a
Guatemala				Children<5y	Diarrhea	No difference between the intervention and control villages in the prevalence of child diarrhea or child growth	Arnold et al., 2009

Measures for the magnitude of the effect of an intervention:
- Incidence rate ratio (IRR): Rate of illness occurrence in the population as a ratio to the total population. Diarrhea cases were halved in the intervention group compared to the control group, based on an IRR of 0.50.
- Odds Ratio (OR): Comparative risk of infection amongst populations (the odd is the ratio between people with and without disease). If the =R is less than 1, the intervention families have a significantly reduced risk of contracting diarrhea (e.g., a 5-fold reduction at a =R of 0.20).
- Relative risk: Probability of the incident occurring in the intervention group as compared to the control group.

2.8 Several Positive Aspects of SODIS

The relative ease of use of SODIS is one of its main benefits. Supporters of this strategy point out that plastic bottles are relatively cheap or even free in many third-world countries. Since no extra chemicals, equipment, or fuel are needed, it also has the added benefit of being inexpensive. Proponents argue that the fact that SODIS does not change the water's smell, flavor, or appearance and poses no risks of overdosing is the most important factor in its general acceptability. What follows is an illustration of the many other benefits to be mentioned (Luzi et al., 2016; Meierhofer, 2006), which are given below:

- Drinking water treated with SODIS has a higher microbiological quality.
- The SODIS system results in an overall improvement in the family's health.
- SODIS can be used as a jumping off point for education regarding health and hygiene.
- Water purification systems are often inadequate or nonexistent in public water supply systems in developing countries. SODIS provides users with a straightforward technique that can be implemented at the household level under their own direction and accountability.
- The concept behind SODIS is simple.
- Solar-powered, disposable water containers (SODIS) are accessible to all budgets due to the fact that the only inputs required are sunlight (at no cost) and plastic bottles.
- SODIS is easily replicable in self-help projects because it does not necessitate a sizable and expensive infrastructure.
- SODIS lessens dependence on firewood, kerosene, and other fossil fuels.
- Deforestation is a major environmental issue in many developing countries, but by switching to SODIS, the air pollution can be lessened which caused by burning fossil fuels.

- Most of the work of gathering firewood falls on the shoulders of women and children. Less time is spent gathering firewood thanks to SODIS.
- When the health of the user's family improves, the user can save money because fewer resources will be needed for medical care. Furthermore, the costs of conventional fuels like gas, kerosene, and firewood are diminished. Getting hands on some clear plastic bottles won't take a lot of money. Since this is the case, even the poorest can afford SODIS.
- Integral safeguards against recontamination of stored water in SODIS bottles
- There was no change in taste quality of the water.
- No reliance on third-party distributors for items other than PET bottles

As a household water intervention that makes safe water available to more people, SODIS has enormous benefits.

2.9 The Drawbacks of SODIS

Labor requirements, bottle scarcity, and varying disinfection efficacy—especially in overcast conditions—are all potential SODIS drawbacks that could slow the technology's widespread adoption (Fisher et al., 2008; Oates, 2001). Low user adherence to the SODIS procedure is another issue (Mäusezahl et al., 2009). Regions between 35 degrees north and south have the optimal exposure to sunlight for the solar disinfection process, with about 300 sunny days and clear skies per year being ideal (Acra et al., 1984). A decrease in the intensity of sunlight that reaches the earth due to cloud cover, however, reduces the sun's germicidal effects. Though this limitation exists, Acra et al. (1984) state that increasing the exposure time more than makes up for the diminished solar intensity. Materials required for solar disinfection may be hard to come by, which is another issue. Solar water purification works best in clear, cylindrical bottles because more light can enter the container, but these may be hard to come by for widespread use in rural areas where

plastic water bottles are not commonly sold. Foil, for example, is an enhancement used by many researchers, but it can be expensive to buy in large quantities (Kehoe et al., 2001). Solar panels, copper piping, and thermostat valves were all needed to build the solar panel described by (Fjendbo Jrgensen et al., 1998). Solar water heaters are impractical for widespread use in developing countries due to a lack of access to the necessary materials and knowledge of how to construct one. However, the use of plastic bottles on an individual basis is a treatment method that requires neither extensive infrastructure nor specialized personnel. In addition to the already-mentioned drawbacks, some others mentioned by Luzi et al. (2016) and Meierhofer (2006) are discussed here.

- It is necessary to have enough sunlight for SODIS to function. Consequently, it is conditional upon the weather and climate.
- Safe water is necessary for SODIS.
- Chemically speaking, the quality of the water is not affected by using SODIS.
- When dealing with large quantities of water, SODIS is ineffective.
- Very low efficacy against some types of dangerous viruses and protozoa
- Depending on the availability of enough empty PET bottles
- Different microorganisms have different sensitivities to solar disinfection, so the time needed to reach a certain disinfection level is affected by factors such as solar irradiance (which, in turn, depends on latitude, time of day, and atmospheric conditions), organic loading turbidity of the water, and the load and nature of the microbial contamination.
- There is a high daily demand for laborers.
- The length of time needed for treatment with SODIS is subjective and there is no way to guarantee the process's efficacy.

- Fewer opportunities for aspirational fulfillment (a technique of the poor). Anxieties about the system's general acceptability among users due to the time and space constraints of water treatment.
- Efficacy is less in monsoon and winter season due to cloudy weather.

2.10 Uses of SODIS in the Field

SODIS is a method for disinfecting water that is used by about 5 million people around the world. Since 1.5- to 2-liter PET bottles are inexpensive and widely available in low-income countries, they are often used for this purpose. Researchers in Africa, Latin America, and Southeast Asia have examined the effectiveness of PET bottles for microbial inactivation and their impact on human health in terms of lowering the occurrence of diarrhea (McGuigan et al., 2012). Table 2.8 compiles findings from a number of recent field studies that have reported on the efficacy of SODIS using PET bottles. All these studies, mostly conducted on children younger than 5, show that people who use SODIS have fewer bouts of diarrhea, which has positive effects on their health. A double-blind, randomized, controlled trial of SODIS would be ideal in order to rule out the placebo effect or bias (reporter, observer, courtesy, or recall), but such a study has not been conducted. A SODIS study of this scope is currently impossible due to the high overhead involved in conducting the study. Median height-for-age was significantly increased in Kenyan children under 5 years old using SODIS, corresponding to an average increase of 0.8 cm over a period of 1 year for the group as a whole (95% CI 0.7-1.6 cm, P = 0.031). Although this method has been shown to be effective, there are still a number of challenges that must be overcome before it can be used in the field. These include the low efficiency in cloudy conditions and turbidity (which can increase treatment times up to 48 h), the potential for post-treatment regrowth of bacteria during storage, and the resistance to inactivation of some pathogens like E. coli (McGuigan et al.,

2012). However, when thinking about rural communities in low-income countries, the high cost remains the main barrier to implementation. Concerns have been raised about the feasibility of post-project maintenance. In 2008, a single-pass continuous-flow SODIS CPC-reactor was installed in a rural area of Kenya to treat the contaminated surface water there.

Table 2.8 Recent findings of SODIS efficiency

Author	Location	Results
Islam et al. (2015)	Khulna, Bangladesh	SODIS effectively decreased fecal coliform and E. coli contamination in normal household settings. More than 96% of health risks were reduced in lake water and 90% in rainwater thanks to SODIS.
Boyle et al. (2008)	Cochabamba, Bolivia	Campylobacter jejuni (20 min), Yersinia enterocolitica (150 min), enteropathogenic Escherichia coli (90 min), Staphylococcus epidermidis (45 min), and Bacillus subtilis endospores are all killed by this treatment (2 days)
Mäusezahl et al. (2009)	Totora, Cochabamba, Bolivia	The results of this study showed a negligible effect, with the incidence rate of gastrointestinal illness in the SODIS children's users being 3.6 episodes/year, compared to 4.3 episodes/year in the control group.
McGuigan et al. (2011b)	Prey Veng and Svay Rieng, Cambodia	A 1-year study found that children in the SODIS group had a lower rate of dysentery and were protected from non-dysentery diarrhea.
Bitew et al. (2018)	Dabat, Ethiopia	Diarrhea occurred 8.3 times per 100 person-weeks in the SODIS group, while it occurred 15.3 times per 100 person-weeks in the control group.
Rose et al. (2006b)	Vellore, India	Diarrhea in children younger than 5 years old reduced by more than half when they were given half-black 1 L-PET bottles.
Narain et al. (2012)	Roorkee, India	Total coliforms were reduced by 79%, turbidity by 66%, total dissolved solids by 41%, and E. coli by 40% in just 8 h of sun exposure.
Rai et al. (2010)	Mazegoan, India	SODIS users saw a 75% reduction in diarrhea episodes after 8 weeks of intervention.
Mahvi (2007)	Tehran, Iran	After 8 h of sun exposure, fecal coliforms have decreased by 3 logs.
Conroy et al. (1996)	Kajiado Province, Kenya	Reduction in Diarrhea Cases in Children Ages 5 to 16 Using SODIS Over a 12-Week Testing Period
Conroy et al. (2001b)	Kajiado Province (Maasai communities), Kenya	Only 3% of SODIS users (children younger than 6) experienced diarrhea, compared to 20% (control group)
du Preez et al. (2011)	Nakuru, Kenya	Users of SODIS saw a significant decrease in the incidence rate ratios of both dysentery and non-dysentery diarrhea episodes and days. Weight and height measurements above the age-standard were found to be significantly higher in SODIS users.
Martín-Domínguez et al. (2005)	Chihuahua, Mexico	Total coliform and E. coli inactivation within clear, half-black, and black PET bottles.
Asiimwe et al. (2013)	Ndagwe, Uganda	Comparable effectiveness in disinfecting both turbid and clear water in both glass and PET bottles when tested in tropical conditions

During this research, a flow rate of 10 liters per minute was used to successfully inactivate bacteria from 100 to 0 CFU/ml after 20 min in a single pass, providing safe drinking water (Gill and Price, 2010). It was reported not too long ago that, five years after it had been installed, this CPC reactor was still operating normally (including replacement of lost and degraded material). Damaged severely in 2013, the system has since been repaired and upgraded with the help of local stakeholders so that it can once again provide safe water for human consumption (mac Mahon and Gill, 2018).

Other options besides PET bottles have been looked into so that the amount of exposed surface area and solar radiation can be increased. These alternatives include SODIS bags made of low-density, food-grade polyethylene. Some SODIS bags were found to have good disinfection performance, but the bags were too cumbersome to be used as a standard household treatment. However, the bags' portability, durability, and low price make them a viable option in the event of a natural disaster (McGuigan et al., 2012). Therefore, field application is also limited everywhere, and more applications of it are required to encourage the public to use SODIS for disinfecting water.

2.11 Guidelines for Assessing the Effectiveness of HWT Technologies

The absence of harmful microorganisms is a crucial quality indicator for drinking water. Pathogenic contamination can occur at multiple points in the water's distribution chain, reducing its quality for everyone from the water's source to the final user. Pathogenic pollution must be treated, and the risk of infection must be minimized through a combination of strategies. Ingestion of water tainted with pathogenic bacteria, viruses, protozoa, or helminths poses the greatest microbiological danger.

The WHO recommends many different ways to treat water to make sure it is safe, each one based on the specific conditions in each country. Many organizations and NGOs have come up with their own ways to safe water in order to protect their members and the public from the dangers of drinking water that contains pathogens. Household water treatment (HWT) is becoming a public health issue because some types of water, like pipe water and other supply water, are no longer considered safe due to contamination at different stages (WHO, 2019). Point-of-use (POU) treatment is highly successful against contaminated source water at the household level. HWT and POU have been designated by the WHO as being interchangeable. It has been established that a variety of technologies, devices, or methods, to be known as household water treatment (HWT) or point of use (POU) treatment, can be used to treat water at the household level or at the point of use in other settings, such as schools, healthcare facilities, and other community locations (WHO, 2011).

2.11.1 Log Reduction Value (LRV)

Log Reduction Value (LRV), also called log10 reduction, is a measure of a technology's ability to kill microorganisms. It is used to describe the potential for killing microorganisms. Reduction factor (LRV) is a straightforward mathematical instrument for assessing microbe concentration relative to source water quality. The term "logarithmic reduction of microorganisms" (LRV) is commonly used to indicate how many times more dead germs were removed from a surface after disinfection than live ones.

The following is a brief record of the LRV calculation:

Log_{10} reduction (LRV) = ($M_{\text{before treatment}} / M_{\text{after treatment}}$) or $\log_{10}(M_{\text{before treatment}}) - \log_{10}(M_{\text{after treatment}})$

where M = bacteria count in a water source.

All relevant standards and guidelines say that LRV must be used to measure how well water treatment technologies work. Therefore, experimental choices based on $\log_{10}$ reductions (LRVs) must be employed to validate through control measures in a wide variety of circumstances until epidemiological data are acquired and/or where epidemiological studies may not be possible or acceptable (WHO, 2011). This can be illustrated as follows:

- A 90% reduction corresponds to a 1 LRV, a 95% reduction to a 2 LRV, a 99.9% reduction to a 3 LRV, and so on. A 5-log10 decrease, or 99.999 %, is substantially more stringent than a 2-log10 reduction, or 99 %, requirement.
- Tech that can reduce bacterial numbers by 5 log10, or 100,000-fold, would be considered effective against bacteria.
- A 5-log10 reduction would bring the number of harmful germs in water from 100,000 to one.

The usefulness of a technology can be judged by how well it stops the spread of bacteria, viruses, and protozoa, which are three of the most dangerous pathogens. This means that the number of target organisms that have been eliminated must be part of any LRV evaluation. There is no universal set of standards by which treatment facilities are judged; instead, many different countries and organizations have developed their own criteria. In Appendix I (Table A2), many different LRVs are illustrated that have been proposed for use in various water purification techniques.

The Environmental Conservation Rule (ECR) of 2023 describes the physicochemical criteria and briefly discusses the microbiological criteria necessary to meet the criteria for the quality of drinking water in Bangladesh. However, there is no benchmark value established by Bangladeshi norms for assessing such water treatment facilities.

2.11.2 Each Organism's Performance Goal

Recommended performance levels for technologies to eliminate bacteria, viruses, and protozoa/spores (WHO, 2011a) are shown in Table 2.9.

Table 2.9 Performance analysis by WHO (WHO, 2011)

Target	Log_{10} reduction required: Bacteria	Log_{10} reduction required: Virus	Log_{10} reduction required: Protozoa
Highly protective	≥ 4	≥ 5	≥ 4
Protective	≥ 2	≥ 3	≥ 2
Interim*	Gains in health and protection against two types of infectious diseases		
* Treatment solutions classed as "interim" should only be advised when credible epidemiological research demonstrates that their use reduces the incidence of waterborne diseases.			

Bacteria, viruses, and spores all have diverse goals, as shown by these criteria. From a "highly protective" reference level of risk of 10^{-6} disability-adjusted life years (DALY) per person per year at the top to an "interim" target relevant to the performance of currently available, low-cost technologies that have demonstrated health improvements, there is a wide range of targets to choose from. Highly protective technologies are those that, when applied correctly and consistently over the course of an entire year, reduce the disease burden associated with drinking water to less than 10^{-6} disability-adjusted life years (DALYs) per person. When considering health, this is a very conservative goal, and the usage of such technologies should be strongly encouraged. In order to achieve the same goal of supplying high-quality, safer water, a second tier, presented as "protective," has been constructed with a higher standard for the allowable degree of disease

excess. The "protective" aim specifies pathogen eliminations necessary to reach a 10^{-4} DALY per person per year health-based goal. The health benefits of devices that fulfill the log removal parameters in the second tier would still be substantial in regions with a presumed high burden of waterborne illness. The elimination of all three groups of pathogens is the basis for both the "very protective" and "protective" objectives.

Targets that are both highly protective and protective are conservative, hence an "interim" target has been established to account for the fact that meeting both may not be the most cost-effective or realistic course of action. Technologies with a demonstrated impact on lowering diarrheal and waterborne diseases are eligible for the "interim" aim, which is defined as the eradication of two types of pathogens. Achieving this intermediate goal should serve as a springboard for further improvement toward the final "very protective" goal.

2.11.3 Measurement Procedure of SODIS's Effectiveness

Indirect detection approaches are available for many aquatic diseases; however, they are often time-consuming and costly to use. Pathogens can be measured indirectly by indicator organisms that show the presence of feces in the water. The following requirements should be met by any fecal indicator organism:

• It is found in high concentrations in the feces of humans,

• It can be identified using straightforward procedures.

• It does not develop in natural waters,

• It has the same resistance to water treatment as other water-borne diseases and is eliminated in the same way.

E. coli meets a good number of these requirements (E. coli, fecal coliforms). Therefore, if microbiological testing facilities are scarce, E. coli can serve as a useful indicator organism for

gauging the extent to which drinking water has been tainted by feces (WHO, 2011b). In under-resourced regions, testing for E. coli is a challenge and requires high-quality equipment and supplies. However, other microorganisms have proven to be more resilient than E. coli. In other words, the lack of E. coli does not necessarily suggest that the bacteria have been eradicated. Clostridium sulfide reductase spores are a diagnostic marker for sulfite-reducing bacteria (WHO, 2011b). However, such analytical approaches are too time-consuming and costly to be employed for routine tests in the field. Since total coliform bacteria are so prevalent in nature, they cannot be utilized as a gauge of the hygienic condition of raw water before it is treated. The total bacterial count also isn't a good indicator of SODIS performance because benign organisms like ambient bacteria and algae can flourish in an exposed SODIS container when exposed to sunlight.

CHAPTER 3: METHODOLOGY

3.1 General

This chapter deals with modified SODIS with H_2O_2 experiments using test waters and drinking water samples collected from restaurants, slums, and households. The experiments were conducted in the IUT Environmental Laboratory during the monsoon months of June through October and the winter months of November through February. This chapter also discusses the steps in the preparation of test waters following the WHO standards, E. coli culture and spiking, physicochemical and bacteriological parameter analysis, bacterial inactivation model, and statistical and regression analysis.

3.2 Design and Fabrication of SODIS Platform

3.2.1 Design of Prototype SODIS Platform

Typically, the SODIS platform was used to expose the SODIS reactors to sunlight with different backing conditions with different materials to absorb the maximum possible solar energy or maximum heat. Fig. 3.1 shows the design of the prototype SODIS platform. The inclination of corrugated tin sheets can be varied from 10° to 16° (Chidya et al., 2021; Siriwong et al., 2006). The design was made similar to that of a rural household with tins. The corrugated tin sheet was placed horizontally at an angle of 16° on the SODIS platform.

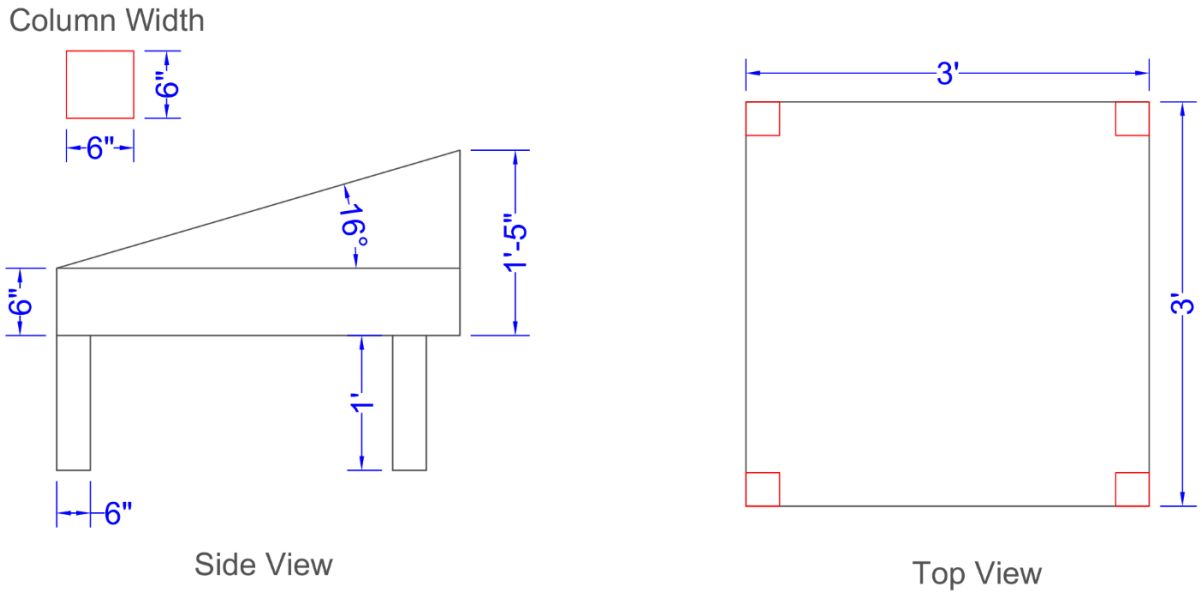


Fig. 3.1 SODIS platform and inclination

To evaluate the material producing maximum heat, locally available corrugated tin sheets of various materials (zinc and aluminum steel) and thicknesses (32, 22, and 12 mm) were collected from the local market. The materials used for fabrication of the of SODIS platform are listed in Table 3.1. The heat absorbance of tins with different thicknesses was measured by exposing them to sunlight under different conditions, as shown in Fig. 3.2 and the temperature was measured.

Table 3.1 Materials specification

S.No.	Materials	Specification
1	Zinc corrugated tin sheets	32 and 12 mm
2	Aluminum corrugated tin sheets	22 and 12 mm
3	Wooden board	6.5 feet sq.
4	Wooden column	6 inches sq.
5	Pins (Steel)	30 pieces
6	Black enamel paint	1 piece
7	Insulation sheets	1 piece
8	Foil paper	4 packets
9	PET Bottle	360 pieces
10	Plastic Bag	360 pieces
11	Hydrogen Peroxide	2 liters
12	Disposable gloves	4 boxes
13	Paint brush	4 pieces

a) Black enamel painted tins

b) Foil paper laid on black enamel painted tins

c) Foil paper laid on tins

d) Tins

Fig. 3.2 Various corrugated tin sheets for maximum solar irradiation evaluation

The results of the experiment are provided in Table 3.2 and Figs. 3.3, 3.4, 3.5, and 3.6

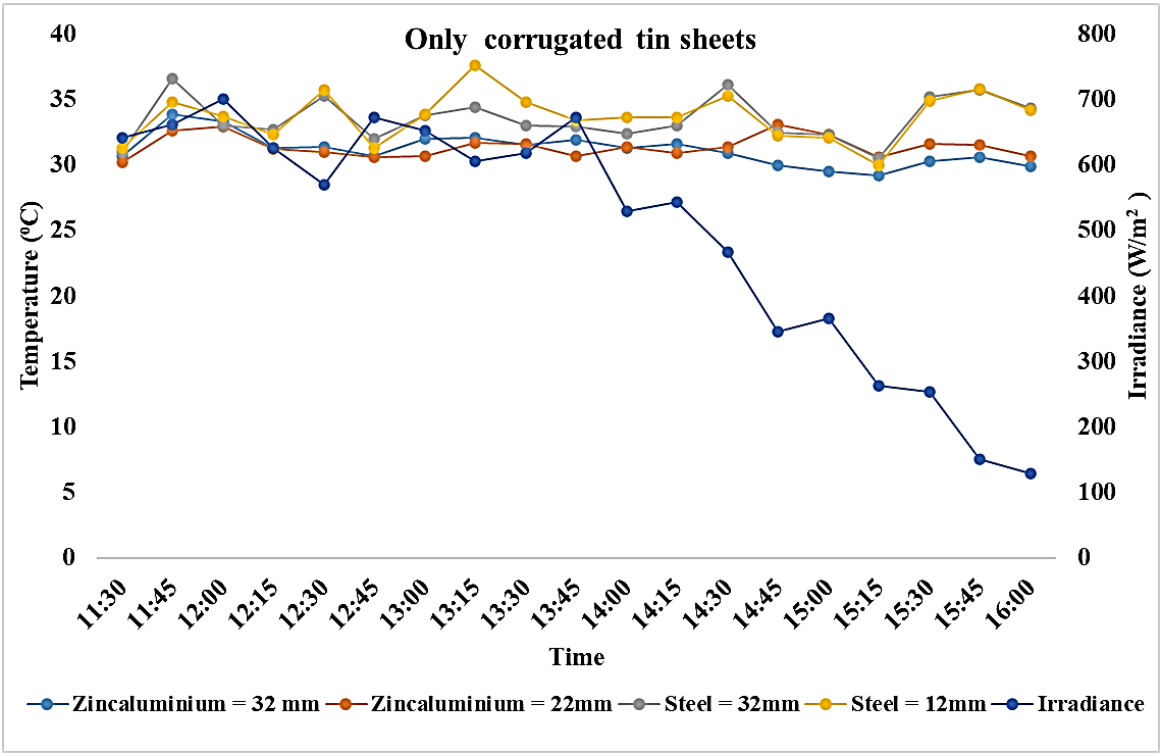


Fig. 3.3 Variation of temperature with respect to solar irradiance in corrugated tin sheet settings

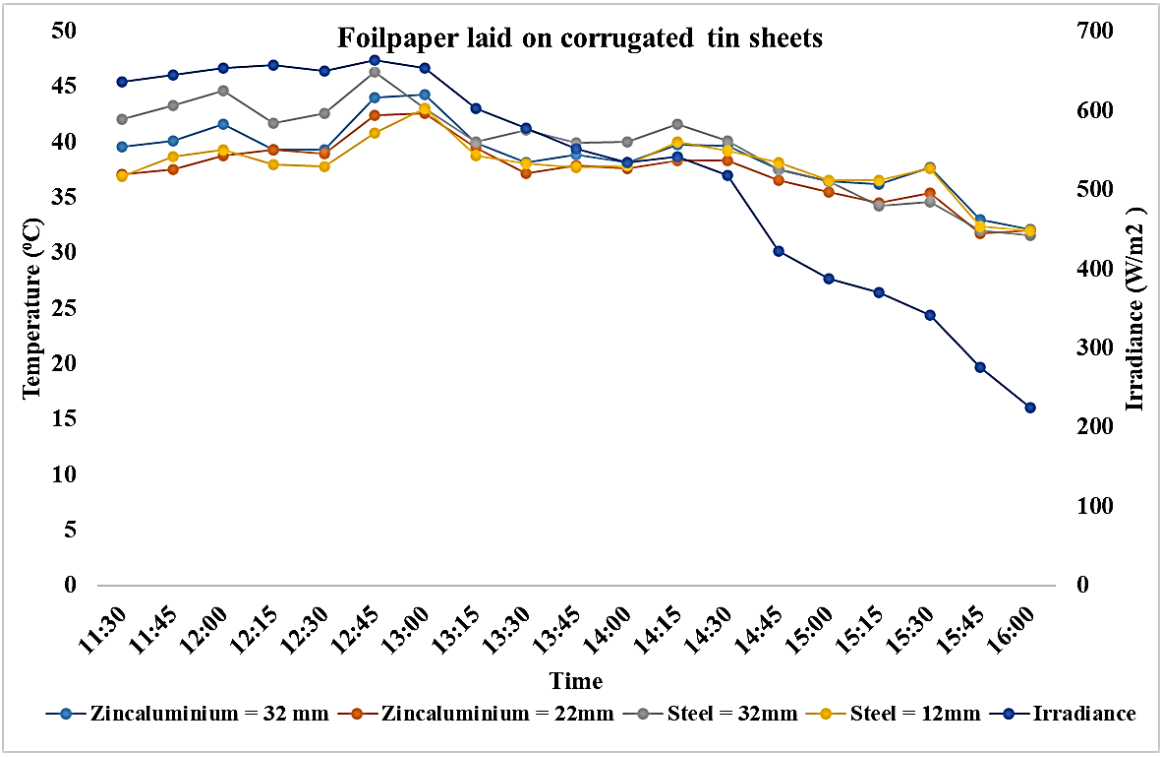


Fig. 3.4 Variation of temperature with respect to solar irradiance in foil paper laid on corrugated tin sheet settings

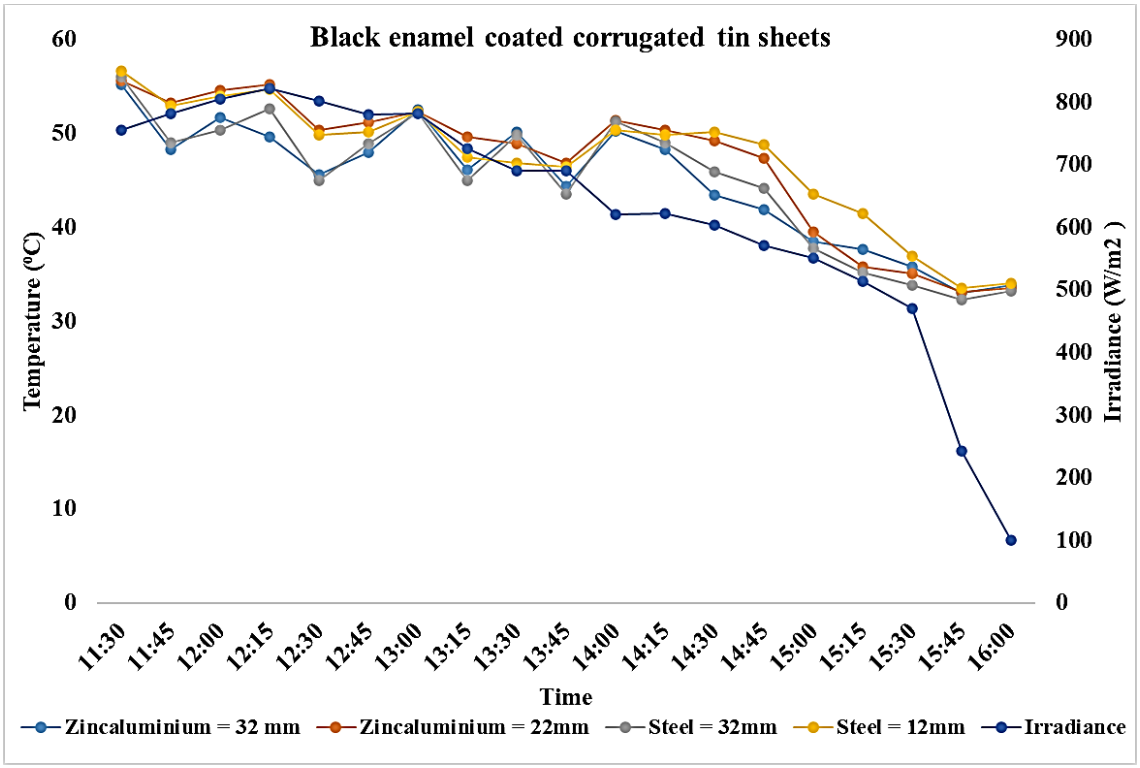


Fig. 3.5 Variation of temperature with respect to solar irradiance in black enamel coated corrugated tin sheet settings

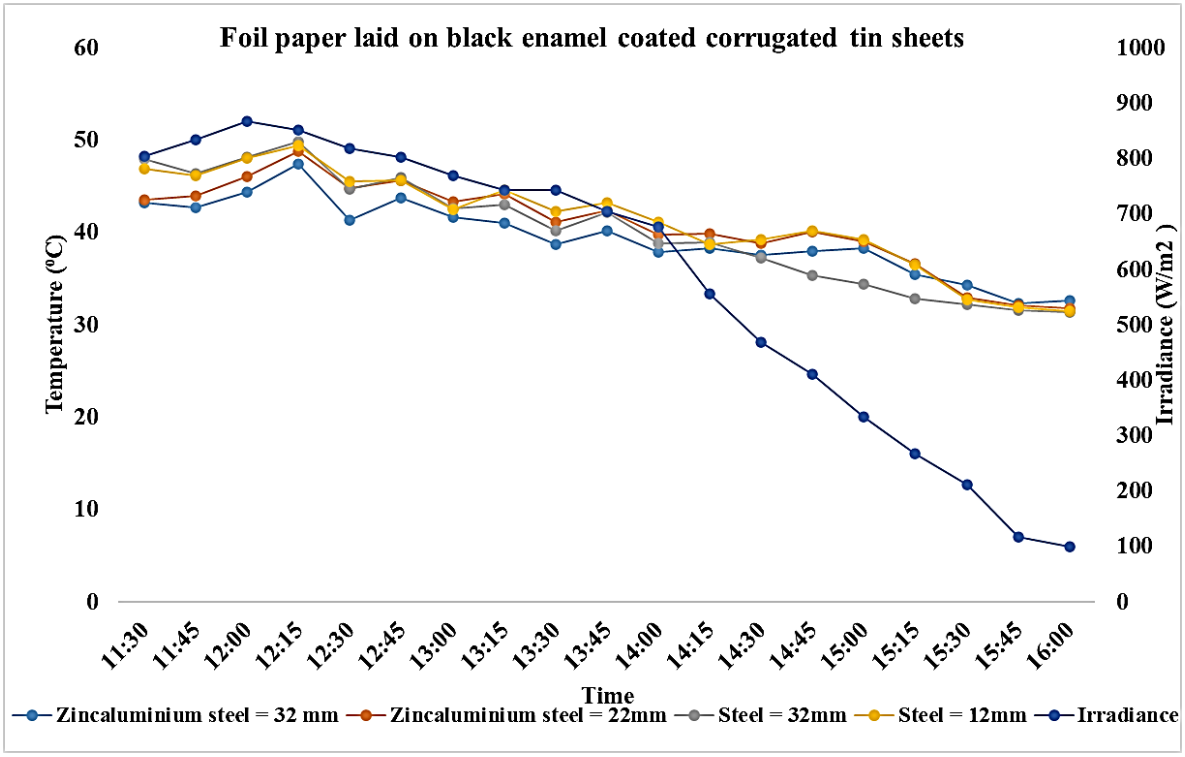


Fig. 3.6 Variation of temperature with respect to solar irradiance in foil paper laid on black enamel coated corrugated tin sheet settings

Table 3.2 Summary of various setting temperature absorbance

Setting system	Material type	Thickness (mm)	Average Solar Irradiance (W/m^2)	Temperature (°C)			
				Minimum	Maximum	Average	Standard Deviation
Only corrugated tin sheet	Zinc aluminium coating steel	32	498	29.20	33.90	31.20	1.16
		22		30.20	33.10	31.40	0.80
	Steel	32		30.50	36.60	33.50	1.65
		12		30	37.60	33.70	1.81
Foil paper laid on corrugated tin sheets	Zinc aluminium coating steel	32	521.37	32.1	44.3	38.74	2.95
		22		31.8	42.6	37.44	2.76
	Steel	32		31.6	46.3	39.87	4.04
		12		32	46.9	39.97	2.45
Black enamel-coated corrugated tin sheets	Zinc aluminium coating steel	32	627.79	33	55.2	44.95	6.39
		22		33.1	55.6	47.01	7.39
	Steel	32		32.3	56	45	7.10
		12		33.5	56.6	47.35	6.52
Foil paper laid on black enamel-coated corrugated tin sheets	Zinc aluminium coating steel	32	583.51	32.3	47.4	39.44	3.94
		22		31.8	48.8	40.81	4.68
	Steel	32		31.4	49.9	40.22	5.92
		12		31.5	49.5	41.36	5.22

It reveals from the graphs and table that 12 mm thick corrugated tin sheets can be used for the fabrication of the prototype SODIS platform to increase the efficiency of SODIS experiments.

3.2.2 Fabrication of Prototype SODIS Platform

To fabricate the prototype system, specialized labor was required to cut the tin and assemble a wooden frame. Using a variety of tools, the fabrication was performed using insulation sheet, black enamel coating, and tin sheet placement on the wooden frame. Fig. 3.7 illustrates the entire process of prototype fabrication.

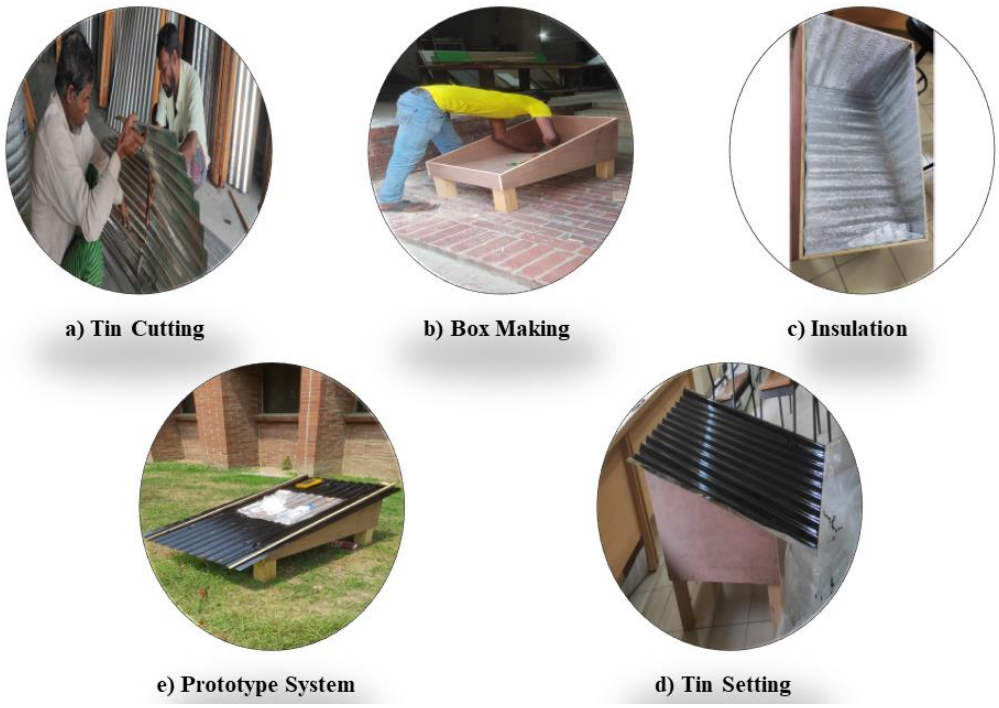


Fig. 3.7 Fabrication process for SODIS Prototype

In Step a, the required size of the tin sheets was cut to determine the amount of heat that could be produced by sun irradiation. In Step b, a wooden board was cut to create a box that resembled the upper half of a house made of tin sheets. Step c involves pinning the insulation sheets so that heat can be built up within the tin layer. In step d, tin was set, and in step e, the prototype system was

utilized to evaluate the effectiveness of the SODIS system in various containers. Moreover, Karim et al. (2021) study found that laying foil paper on top of tin sheets increased the efficiency of the SODIS system; therefore, foil paper was used as a reflective batch reactor in conducting the experiment.

3.3 Preparation of Test Water

3.3.1 E. coli Culture and Spiking

E. coli was cultured similarly following the procedure as described by Karim et al. (2021). The Environmental Microbiology Laboratory of the International Centre for Diarrheal Disease Research, Bangladesh (icddr, b), Dhaka, provided the E. coli used throughout the investigation. The strain of the sample was subculture on MacConkey agar. The prepared culture was incubated for 24 h at 37°C. On mTEC agar, colonies were separated and subculture. The sample was then incubated at 37°C for 2 h, followed by 18 to 24 h at 44°C. For the differentiation and enumeration of E. coli, modified mTEC agar was utilized in a single-step, single-medium procedure. This procedure was recommended by EPA Method 1603, which was released in 2002. Using an overnight culture of E. coli ATCC 25922 established on mTEC agar, a suspension of E. coli was prepared in normal saline. 100 ml of diluted solution was cultivated using a drop plate technique. It was determined that the E. coli was in the range of 10^7 CFU/100 ml. Before spiking, the saline was placed in a water bath to bring its temperature down from its storage temperature of approximately -15°C to room temperature.

3.3.2 Reactors (PET bottles and Plastic Bags)

Aquafina and Kinley water bottles (500 ml capacity) were purchased from the local market and IUT canteen, respectively. Plastic polymer bags were purchased from scientific shops at Hatkhola, Motijheel. All labels were removed from the bottles to obtain sufficient UV-visible light

transmission. The purchased PET bottles were sterilized to ensure the absence of bacteria. Plastic bags were sterilized with 75% ethanol. During the experiment, both containers were checked to determine whether UV rays could pass through them unhindered. Owing to the global availability of PET bottles and plastic bags of various sizes, photostability, and transparency, these containers were chosen for testing.

3.3.3 Test Water

The WHO suggested using two test waters to test a variety of possible untreated water sources for the laboratory verification of HWT technologies. The present study followed these guidelines. Table 3.3 displays the requirements for the test waters.

Table 3.3 Test water specification (WHO, 2011)

	Test Water 1 (TW-1)	Test Water 2 (TW-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 (NTU)	< 5	> 30
pH	7.0-9.0	6.0-10.0
Temperature (°C)	20°C ± 5	4°C ± 1
NTU= Nephelometric Turbidity Unit		

To prepare the test water, two 10-liter water containers were cleaned, rinsed with sterile distilled water, and sterilized with 100% ethanol. Then, 10 L containers were filled with groundwater used in the IUT water supply. The following methods were used to prepare the test water samples:

Test water 1:

TW-1 turbidity <5 NTU and the pH ranged between 7.0-9.0 was achieved from the IUT groundwater. The water was then poured into six PET bottles and six plastic bags, which were spiked with 10^7 CFU/100 ml of E. coli 2 h before exposure to sunlight for the SODIS experiment.

Test water 2:

The same groundwater was mixed with 1% by volume of sewage water collected from the IUT sewer line and sterilized in an autoclave at 121°C for 24 h. TW-2 must have a turbidity more than 30 NTU which was achieved by adding clay that was passed through a 200 mm sieve. This clay was obtained from an undisturbed soil sample at a depth of 30 m beneath the ground surface along the Dhaka–Chittagong highway and was examined at the Geotechnical Laboratory. Clay was obtained by passing this sample through a 200-mm sieve. The water had a turbidity of over 30 NTU and a pH between 6.0 and 10.0. TW-2 was poured into six PET bottles and six plastic bags and spiked with 10^7 CFU/100 ml of E. coli bacteria 2 h before each SODIS experiment.

Batch reactors:

Reflective food-grade foil papers were attached to the back surfaces of the PET bottles and plastic bags as reflective reactors.

H_2O_2:

According to the U.S. According to the Environmental Protection Agency (EPA), the minimum dose of H_2O_2 in drinking water is 25–50 mg/l. Moreover, Sciacca et al. (2010) found that 10 mg/l of H_2O_2 showed a strong inactivation rate of the bacteria under solar exposure. Based on the available literature, 10 mg/l of 30 % EMSURE ® ISO H_2O_2 was added to each PET bottle PB one h before exposure to the sun for the SODIS experiment. To assess the effect of H_2O_2 as an oxidizing agent on bacterial inactivation, an E. coli test was performed before each experiment after the addition of H_2O_2 to determine the initial bacterial count before solar exposure.

3.3.4 SODIS Experiment

Both sets of PET bottles and PB were then placed on the fabricated prototype system and exposed to sunlight. All the SODIS experiments were conducted on the IUT campus. Reactors (PET bottle

and PB) were shaken before solar exposure, maintaining an air space of approximately 15% of the container capacity to allow for air circulation and aeration (Reed, 1997). In all cases, containers were left out in the sun for 6 h, beginning at 10 a.m. (+/- thirty min) and ending at 4 p.m. (+/- thirty min). The Solar Survey 200R Pyranometer (Seward Group, UK) was used to record the irradiance and temperature of the sun at 1-minute intervals throughout the experiments. Six containers of TW-1 and six containers of TW-2 were exposed simultaneously, for a total of 12 containers in each trial, as illustrated in Figs. 3.8 and 3.9. Six-h exposure studies were carried out during the monsoon and winter months, with each sample water container being collected from the solar irradiation exposure chamber every h for testing. All experiments were conducted in duplicate for each condition during the monsoon and winter.

Fig. 3.8 SODIS experiment setting

Fig. 3.9 SODIS experiment setting (zoom view)

3.3.5 E. coli Testing

After each hr. of solar exposure during the monsoon and winter seasons, samples were collected from the SODIS platform. The samples were maintained in sterile beakers to ensure their sterility. For each experiment, six PET bottles and six PB from TW-1 and TW-2 were sampled for E. coli testing. Post-SODIS water was also then placed in a dark environment for 12 and 24 h at room temperature to check the regrowth of microorganisms (Giannakis et al., 2015). 100 ml of each sample was filtered through 0.22-micron-pore filter paper (Millipore Corp., Bedford, MA, USA). The filter paper was then placed in a broth comprising m-TEC agar in a glass Petri dish following the membrane filtration method (APHA 1998). The samples were incubated at 37°C for 24 h. The typical white-grey appearance of E. coli colonies makes it possible to visually count the total number of colonies. Following incubation, the total number of E. coli colonies in each sample was counted. E. coli counts were expressed as CFU/100 ml and all the tests were performed twice for accuracy. The average of the two tests was then determined.

3.4 Physicochemical Testing

Four physicochemical parameters like pH, turbidity, dissolved oxygen (DO), iron (Fe) and electrical conductivity (EC) were assessed during the SODIS experiments. These parameters were measured for both the test water and filtered water. The methodology used to measure the physicochemical parameters is presented in Table 3.4.

Table 3.4 Assessment procedures for physicochemical parameters

S. No.	Parameters	Unit	Instrument / Reagents Used
1.	pH	-	HACH® pH meter (HACH sensION+ PH31)
2.	Turbidity	NTU	HACH® turbidity meter (HACH 2100Q)
3.	DO	mg/l	HACH® probe (HACH HQ 40D)
4.	EC	µs/cm	HACH® conductivity probe (HACH CDC40101).
5.	Iron (Fe)	mg/l	FerrVer ® Iron Reagent and the Hach Spectrophotometer DR 3000

3.5 SODIS Experiments using Drinking Water collected from Slums, Restaurants and Households

The drinking water used in different establishments (households, restaurants, and slums) was collected from different places of Dhaka city as shown in Fig. 3.10 and Table 3.5 indicate the locations of them. The primary sources of drinking water in the Dhaka city include piped water from the Dhaka Water Supply and Sewerage Authority (DWASA), jar water from private company and tube wells, and hand-pumped ground water.

Table 3.5 Locations of water sources for sampling

No.	Establishment Type	Source	ID	Location	
				Latitude (Decimal Degrees)	Longitude (Decimal Degrees)
1.	Slum	Piped water	S-1	23.829929	90.377347
2.	Slum	Piped water	S-2	23.829591	90.377390
3.	Slum	Tubewell	S-3	23.829969	90.377279
4.	Slum	Piped water	S-4	23.827956	90.378214
5.	Restaurant	Filtered Jar water	R-1	23.829920	90.376566
6.	Restaurant	Piped water	R-2	23.829181	90.375344
7.	Restaurant	Drum water	R-3	23.829756	90.375376
8.	Restaurant	Piped water	R-4	23.87986	90.401
9.	Household	Piped water	H-1	23.831455	90.374773
10.	Household	Piped water	H-2	23.756879	90.415067
11.	Household	Piped water	H-3	23.863760	90.403168
12.	Household	Piped water	H-4	23.812926	90.452894

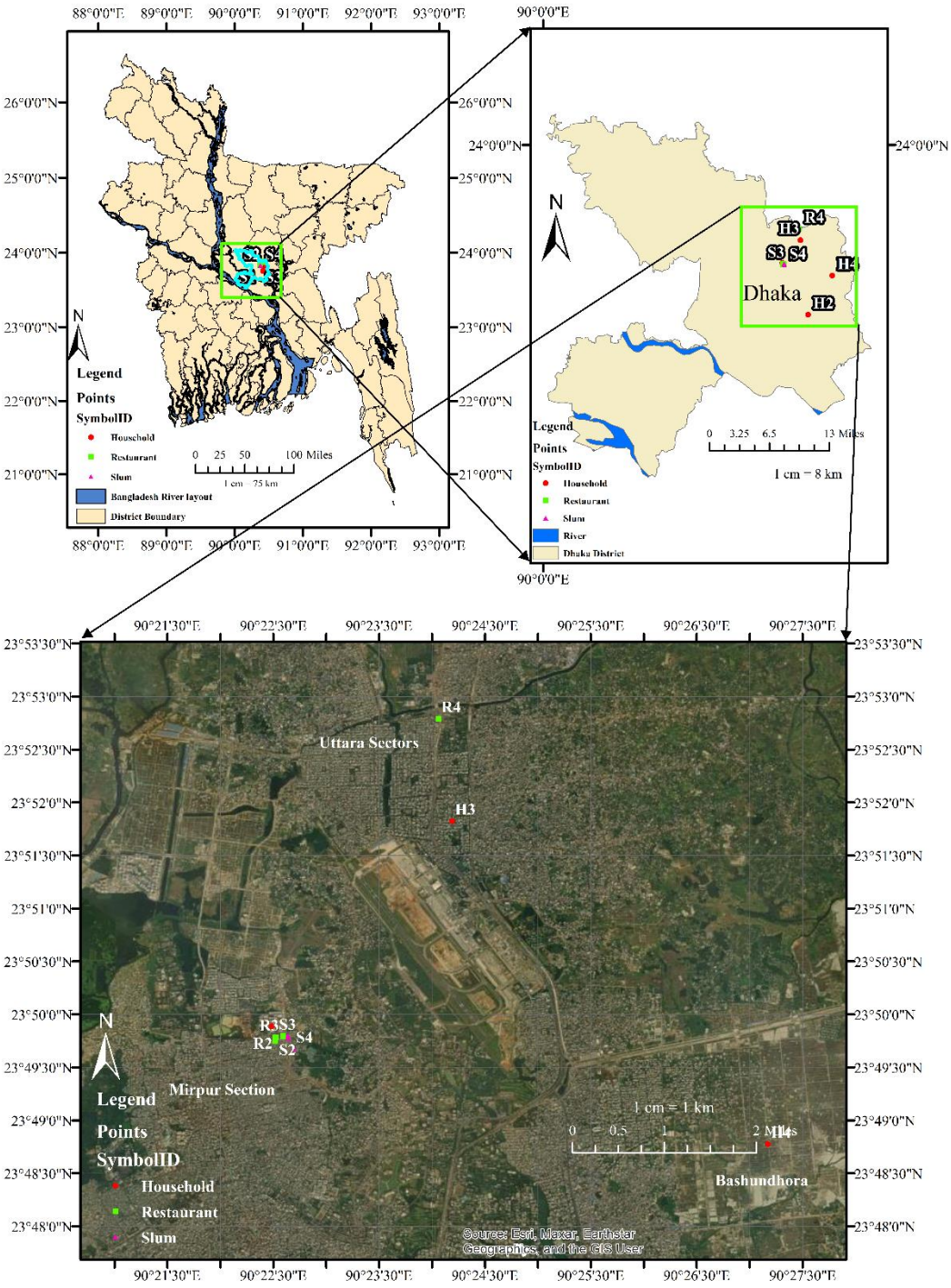


Fig. 3.10 Drinking water sampling at 12 locations in Dhaka city

Different establishments were randomly selected from various locations to collect the drinking water samples. The drinking water was collected in PET bottles (2-L) and placed in a cloth bag so that it did not receive any sunlight. Water samples were transported on the same day of collection

by an air-conditioned car to the laboratory. To compare the treatment efficiency, SODIS experiments were conducted with the collected drinking water samples with H_2O_2 and without H_2O_2 during 6 h of solar exposure. Reactors (PET and PB) were used during the winter under cloudy weather conditions. The H_2O_2 dosage was 10 mg/l. Physicochemical, and E. coli tests were performed similarly to the test water experiment. In addition, post-SODIS regrowth analysis of bacteria was performed in all experiments.

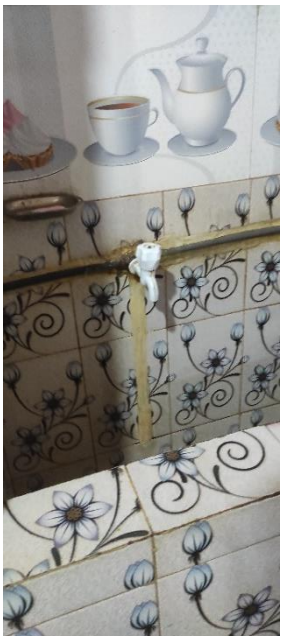
3.5.1 Water quality of the Drinking Water Samples

The drinking water samples were analyzed for various physicochemical and bacteriological parameters before the SODIS experiment. Table 3.6 shows the results of the water quality of the collected drinking water samples before the SODIS experiment. In each sample, drinking water was labeled with an ID, such as R 1–4 for restaurants, S 1–4 for slums, and H 1–4 for households.

Table 3.6 Analysis of collected drinking water quality parameters

Type	Location	Source	ID	Temperature (℃)	Turbidity (NTU)	DO (mg/l)	pH	EC (µS/cm)	E. coli (CFU/100ml)	Fe (mg/l)
Restaurant	Mirpur	Jar Water	R-1	22.8	0.63	8.06	7.67	297	500	0.82
Restaurant	Mirpur	Piped	R-2	22.3	1.64	7.59	7.42	286	3000	0.56
Restaurant	Mirpur	Drum	R-3	22.3	1.33	6.22	7.8	294	980	0.24
Restaurant	Uttara	Piped	R-4	22.4	1.25	8.29	7.36	209	1980	0.15
Slum	Mirpur	Piped	S-1	25.5	7.53	3.56	7.38	296	721	0.64
Slum	Mirpur	Piped	S-2	25.6	6.25	5.45	7.22	297	634	0.45
Slum	Mirpur	Tubewell	S-3	25.6	3.42	3.31	7.12	297	1890	0.29
Slum	Mirpur	Piped	S-4	24.6	0.45	6.78	7.28	222	1520	0.13
Household	Mirpur	Piped	H-1	25	3.1	7.64	7.27	245	840	0.18
Household	Malibagh	Piped	H-2	24.7	0.56	7.17	7.17	329	540	0.22
Household	Uttara Sector 4	Piped	H-3	25	0.84	7.2	7.32	237	470	0.20
Household	Bashundhora	Piped	H-4	24.9	0.48	7.41	7.32	226	890	0.11

Most physicochemical parameters of the water were within the drinking water standards as per ECR (2023) and WHO (2022b). The iron test results of the drinking water samples were within 0.3–1.0 mg/l, as the standard set by ECR (2023). All the water contains higher E. coli level; thus, the water is not safe for drinking. Based on available literature, the risk levels for E. coli are classified as low (1 CFU/100 ml), moderate (1–10 CFU/100 ml), high (11–100 CFU/100 ml), and very high (>100 CFU/100 ml). The collected drinking water samples poses an extremely high risk to human health according to the risk categories as E. coli counts were more than 100 CFU/100ml. Similar results were reported by UNICEF, where they found 32 % of piped water and 30.4% of tube well water had E. coli risk levels (Charles et al, 2021). Under these conditions, SODIS can be used for improving human health by reducing the risk of water-related illnesses, and can be HWT option to disinfect water before consumption.



a) Supply water source

b) Drum water source

c) Tubewell water source

Fig. 3.11 Hygienic conditions of the collected drinking water sources

The hygienic conditions of the drinking water supply systems of different establishments are shown in Fig. 3.11. E. coli contamination occurred through unsanitary storage facilities and storage

of water. Analysis of the drinking water quality parameters revealed that the state of the water supplied to the mass population is contaminated and may pose a significant threat to the overall health of the human population.

3.6 Bacterial Inactivation and Modelling

Bacterial inactivation by the solar irradiation was calculated using the GInaFiT freeware add-on in Microsoft Excel (Geeraerd et al., 2005) and LRV. The Weibull frequency distribution model (Mafart et al., 2002) and bacterial decay model (Chapra, 2008) were chosen because they produced the best fitting curves across all cases examined. The smallest root-mean-squared error (RMSE), and highest correlation coefficient (R^2) were chosen to assess the best model.

3.6.1 Weibull Inactivation Model

The GInaFiT freeware add-on in Microsoft Excel was used to determine the bacterial response to solar irradiation (Geeraerd et al., 2005). The Weibull frequency distribution model (Mafart et al., 2002) curves were selected because they had the highest R^2 and lowest RMSE of all the models that were applied.

$$\frac{N}{N_0} = 10^{\left(-\left(t/\delta\right)^p\right)} \quad (3.1)$$

For identification purposes reformulated as:

$$\log_{10} N = \log_{10} N_0 - \left(t/\delta\right)^p \quad (3.2)$$

Where:

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

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

t: the investigated time (s).

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

The scale's parameter δ indicates when the reading is rounded down to the nearest decimal place. For p <1, a concave curve is illustrated, whereas for p > 1, a convex curve is illustrated. Last but not least, the model structure dictates that d and p are not unrelated to one another; rather, they exhibit a high link, as proposed by van Boekel (2002); Geeraerd et al. (2005), and Mafart et al. (2002). Moreover, according to Raes et al. (2012), model fitting can be considered poor if NRMSLE >30%, fair if 30%>NRMSLE>20%, good if 20%>NRMSLE>10%, and excellent if NRMSLE <10%.

3.6.2 Bacterial Decay Model

The rate at which N decays was calculated using the following equation, which was based on the assumption that the water inside the container of the prototype SODIS system was well mixed and that the death of bacteria followed first-order kinetics (Chapra, 2008).

$$N = N_o \times e^{-kt} \quad (3.3)$$

Where:

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

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

t: the investigated time (h).

k: decay rate constant (h^{-1})

Regression analysis was performed using the k or decay rate constant to assess the SODIS experiments.

3.7 Regression Analysis Model

In accordance with the methodology of Suárez et al. (2017), a regression model was utilized in the present investigation. By applying the model, it is possible to approximate the relationship between the response variable and predictor variables using a regression model, where Y is the parameter to be predicted (response variable), and X1, X2,..., Xm denote the parameters utilized to forecast the response variable (predictor variables).

$$Y = f(X_{1,}X_{2,} \dots \dots, X_m) + \epsilon \quad (3.4)$$

The relationship between Y, the response variable, and X_1, X_2,..., X_m, the predictor variables, is described by the function f (X_1, X_2,..., X_m), where an is the number of predictor variables and 1 is the error term representing the disagreement in the approximation. The general form of the regression model is as follows.

$$y_i = \beta_o + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + \beta_4 x_{i4} + \dots \dots \dots \dots + \beta_m x_{im} + \epsilon_i \text{ , i = 1, 2, 3 ……, n.} \quad (3.5)$$

where n represents the number of observations. All the terms in Equation 3.6 can be written in matrix form as shown below.

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ . \\ y_n \end{bmatrix} \quad ; \quad X = \begin{bmatrix} 1 & x_{11} & x_{12} & \dots & x_{1m} \\ 1 & x_{22} & x_{22} & \dots & x_{2m} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ . & . & . & \cdots & . \\ 1 & x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix}; \quad \beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ . \\ \beta_m \end{bmatrix}; \qquad \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ . \\ \varepsilon_n \end{bmatrix} \quad (3.6)$$

Which can be derived as

$$Y = \beta X + \varepsilon \quad (3.7)$$

$Y\ (n \times 1)$ is a vector of response variables; $X\ (n \times (m+1))$ is a matrix of predictor variables, which includes the constant predictor (intercept); $\beta((m+1) \times 1)$ is a vector of regression

coefficients to be estimated; and e is an $n \times 1$ vector of random errors. By minimizing the error vector (e), the coefficient vector (β) can be estimated using the least-squares approach.

Equation 3.8 illustrates the least squares approach proposed by (Suárez et al., 2017).

$$\varepsilon = Y - \beta X \tag{3.8}$$

In matrix notation, if a derivative of e is set with respect to b equal to zero $[(Y - \beta X)^T (Y - \beta X)]$, found,

$$(X^T X)\beta = X^T Y \tag{3.9}$$

Multiplying both sides of Equation 3.10 by $(X^T X)^{-1}$ yields the coefficients vector (b), which in turn yields

$$\hat{\beta} = (X^T X)^{-1} X^T Y \tag{3.10}$$

After controlling for correlation between predictors, each element of the vector ($\hat{\beta}$), reflects the contribution to Y per unit change of the related predictor variables (X). Because high levels of correlation among predictor variables are so frequently encountered, and because such correlation might result in misleading correlation coefficient estimates, this correction is crucial. Using multicollinearity diagnostics like the variable inflation factor (VIF) might help researchers find overlapping relationships between predictors.

$$VIF_j = \frac{1}{1 - R_j^2} \tag{3.11}$$

where, R_j^2 is the model's coefficient of determination for the regression of X_j, against the other $(m - 1)$ predictor variables.

$$X_j = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ ... + \beta_{m-1} x_{m-1} + \varepsilon_j \tag{3.12}$$

Values of VIF_j, larger than 5 imply that X_j depends on other predictor factors (Montgomery et al., 2021). The goodness of fit is evaluated using the coefficient of determination (R^2), which indicates the amount of variance in the response variable that can be attributed to the predictor variables.

$$R^2 = \frac{SSR}{SST} \tag{3.13}$$

That can also be stated as

$$R^2 = 1 - \frac{SSE}{SST} \tag{3.14}$$

where, SSR=$\sum(\hat{y}_i - \overline{y}_i)^2$, SSE=$\sum(y_i - \hat{y}_i)^2$, and SST= $\sum(y_i - \overline{y}_i)^2$. SST=SSR + SSE may be proved mathematically. *R*, the multiple correlation coefficient, is calculated by taking the square root of the coefficient of determination (R^2).

Alternatively, the adjusted R-square (R_a^2), which adjusts R-square by dividing SSE and SST by their respective degrees of freedom, can be used as a measure of fit quality (D.F.). You can use it to evaluate the relative merits of models with different numbers of predictor variables.

The value of the adjusted R-squared is

$$R_{adj}^2 = 1 - \frac{n-1}{n-m-1} \times (1 - R^2) \tag{3.15}$$

The hypothesis that the regression coefficients ($\hat{\beta}$), are all zero can be tested using the F-test in analysis of variance (ANOVA).

$H_0: \beta_1 = \beta_1 \ldots . \beta_1 = 0$ against $H_1: \beta_j \neq 0$ for at least one *j*.

The F-statistics is given by

$$F = \frac{MSR}{MSE} \tag{3.16}$$

Where, MSR = SSR/*m* and MSE= SSE/*(n-m-1)*.

If F is larger than the crucial F_{crt}, which varies with the specified significance level (a), then H_0 can be disregarded. If the F-test indicates that any of the regression coefficients are significant, the

focus shifts to determining which ones. Following the method outlined by Chatterjee and Hadi (2006), the student's t-statistic is utilized to compare the alternative hypothesis, H_1: $\beta_j \neq \beta_j^0$, with the null hypothesis, H_0: $\beta_j = \beta_j^0$.

$$t_j = \frac{\beta_j - \beta_j^0}{s.e.(\hat{\beta}_j)} \tag{3.17}$$

where β_j is tested regression coefficient; β_j^0 is arbitrary; s:e: $(\hat{\beta}_j)$ is the standard error of $(\hat{\beta}_j)$. The standard error s:e: $(\hat{\beta}_i) = \sqrt{Var(\hat{\beta}_i)}$, where Var $((\hat{\beta}_i)$ are the diagonals of the variance and covariance matrix of $(\hat{\beta}_i)$ provided by $\sigma^2(X^T X)^{-1}$. Models mean square error (MSE) is calculated using the term σ^2. There must be no linear connection ($\beta_j^0 = 0$) between the variables,

$$t_j = \frac{\beta_j}{s.e.(\hat{\beta}_j)} \tag{3.18}$$

3.8 Statistical Analysis

The microbiological analysis and effectiveness of several materials were compared using Microsoft Excel® ver. 16.1 (Microsoft Corporation, Redmond, WA, USA) and R Studio (R Coding). A paired t-test was performed to determine the significance of the dataset using pairs of datasets comprising aluminum foil paper, corrugated steel sheets, PET bottles, or plastic bags. Additionally, analysis of variance (ANOVA) was performed to compare each sample for seasonal fluctuations. All tests were considered significant if their p-values were less than 0.05, and the significance level for hypothesis testing was set at 5% (Clark, 1974).

Further, Equation 3.19 states the ‘safe exposure duration' needed to achieve the desired degree of bacterial inactivation to be maintained throughout SODIS application to avoid the re-growth of microorganisms in photo-treated water, as introduced in a study by Castro-Alférez et al. (2018).

$$t_{safe\ exposure} = t_{model} + 0.2\ t_{model} + 30 \tag{3.19}$$

CHAPTER 4: RESULTS AND DISCUSSION

4.1 SODIS Performance in Test Waters

The WHO's recommendations for HWT methods were followed for the test water experiments in this section. Experiments were conducted throughout two cloudy seasons in Bangladesh (monsoon and winter) to test the effectiveness of the SODIS. A prototype SODIS system was developed using foil paper to improve SODIS performance over a wide range of solar exposure times and conditions, including cloudy days. The reactors used in the experiments were polyethylene terephthalate (PET) bottles and plastic bags. Solar irradiation and several physicochemical parameters were evaluated using a standardized protocol. Here, the findings from different experimental tests are discussed.

4.1.1 Physicochemical Parameters

A comparison of the physicochemical parameter before and after SODIS with H_2O_2 application was conducted. During the monsoon and winter seasons in Bangladesh, the pH, DO, turbidity, EC, and temperature of the test water were measured. In these seasons, the IUT groundwater iron concentration was between 0.3 and 0.7 mg/l. Test waters prepared in accordance with WHO (2011) guidelines provide ideal (TW-1) and worst-case (TW-2) scenarios that can be used to quickly compare different HWT efficiencies. The mineral concentration and low organic content of the water used in the TW-1 preparation are notable features. Furthermore, TW-2 with added sewage water contained colloidal and organic components that induced changes in physicochemical characteristics. Appendix II (Tables A3, A5, A7, and A9) display the average values of TW-1 (PET bottle and PB) and TW-2 (PET bottle and PB) for the monsoon and winter seasons, as determined by the pre SODIS assessed parameters. The statistics revealed that there was a seasonal difference in water temperature, and all other values

were consistent with the standards set forth by the WHO (2011). This study results are consistent with those of another study by Clarizia et al. (2017), which also revealed that iron in water causes a rise in pH to 8.04, principally because of the oxidation of water. In Appendix II (Tables A4, A6, A8 and A10) show the post SODIS parameters based on the average results from SODIS over the course of 6 h. Temperature shifts were apparent due to solar exposure, and the presence of iron in the water cause the subsequent rise in EC. According to the literature, lowering the pH of water involves mixing of the photocatalyst and allowing iron to react with the hydrogen ions in the water. It was also discovered that the cause of DO level decreased may be attributable to the chemical reaction of the photocatalyst with iron or other organic content in the water, or to the inactivation of bacteria. The turbidity of TW-2 decreased after the SODIS experiment, which Karim et al. (2021) also reported.

4.1.1.1 Comparison between Pre and Post SODIS PET bottle and Plastic bag test waters

Table 4.1 illustrates a comparison of the physicochemical parameters using PET bottles and plastic bags for two types of test waters during the monsoon and winter seasons, allowing the average value of several physicochemical characteristics to be analyzed rapidly and effortlessly before and after the application of SODIS with H_2O_2. Following the use of the SODIS during the monsoon and winter seasons, the EC value and turbidity of both test waters increased. The physicochemical parameters of both containers exhibited temperature-dependent changes; however, neither DO nor pH were affected. The parameters with the greatest variations in both test waters (TW-1 and TW-2) were EC, temperature, and turbidity. An increase in the temperature of water increases the mobility of ions by dissociation of molecules, resulting in an increase in conductivity (Barron and Ashton, 2005). Moreover, conductivity can also be increased in this study because of the presence of iron ions as the reaction of H_2O_2 and iron in water occurs due to sunlight (Mathur, 2015). Thus, the increase in EC in this study was due to

an increase in temperature and the presence of Fe ions in water. In addition, the lowest variation was illustrated by pH and DO in both test waters during the monsoon and winter seasons. Similar results were reported by Karim et al. (2021).

Table 4.1 Comparison of the physicochemical parameters using PET and plastic bag in pre and post SODIS conditions

Season	Parameters		TW-1			TW-2		
			Pre SODIS	Post SODIS	Deviations (%)	Pre SODIS	Post SODIS	Deviations (%)
Monsoon (June-October, 2022)	pH	Average	8.13	7.96	2.09	8.32	8.05	3.25
	DO (mg/l)		7.56	7.14	5.56	7.99	7.42	7.13
	EC (µS/cm)		374.53	756.42	101.97	403.51	768.12	90.36
	Turbidity (NTU)		3.25	2.49	23.38	46.11	37.05	19.65
	Temperature (°C)		29.11	38.32	31.64	29.13	38.37	31.72
Winter (November-February, 2023)	pH	Average	7.94	7.91	0.38	8.29	8.23	0.72
	DO (mg/l)		7.73	7.18	7.12	8.28	7.67	7.37
	EC (µS/cm)		425.83	784.68	84.27	419.23	794.88	89.60
	Turbidity (NTU)		3.58	2.45	31.56	44.02	35.15	20.15
	Temperature (°C)		25.72	40.16	56.14	25.72	40.16	56.14
Sample size (N): 30 in monsoon and 30 in winter seasons								

4.1.2 E. coli Inactivation

In this section, the effectiveness of E. coli inactivation by SODIS with H_2O_2 in PET bottles and plastic bags using test water (TW-1 and TW-2) during the monsoon and winter seasons is discussed.

4.1.2.1 Monsoon Season

4.1.2.1.1 PET Bottle

Figs. 4.1 and 4.2 demonstrate the results of bacterial inactivation of TW-1 and TW-2 under identical conditions of solar exposure and temperature, microorganisms were found to be inactive within 2 h. Bacteria were inactivated within 2 h at temperatures above 50°C and solar radiation levels greater than 700 W/m^2. This demonstrates that during the monsoon season, bacteriological inactivation was attained in less than 2 h using the PET reactors for both test waters. The SODIS system can function at such a high level of efficiency because of the

incorporation of a photocatalyst, which triggers the photo-Fenton process owing to the presence of iron in water.

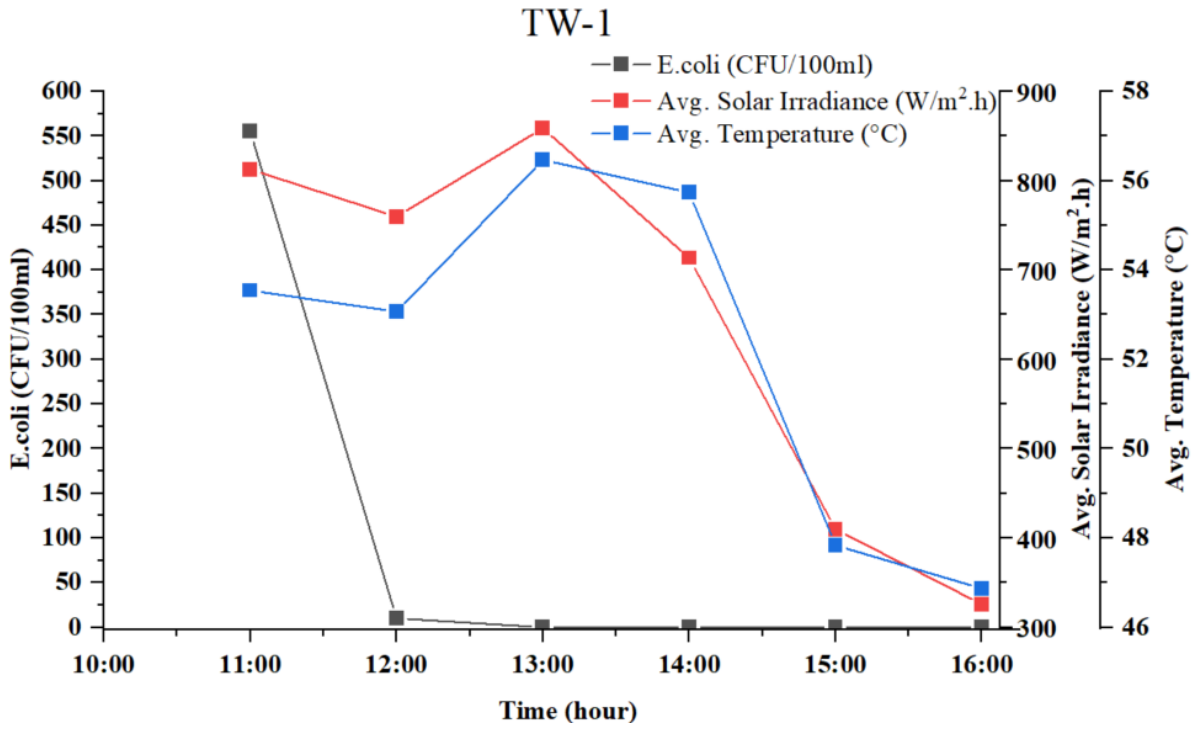


Fig. 4.1 Bacterial inactivation of TW-1 in 6 h solar exposure in PET bottle (Date:20/10/2022)

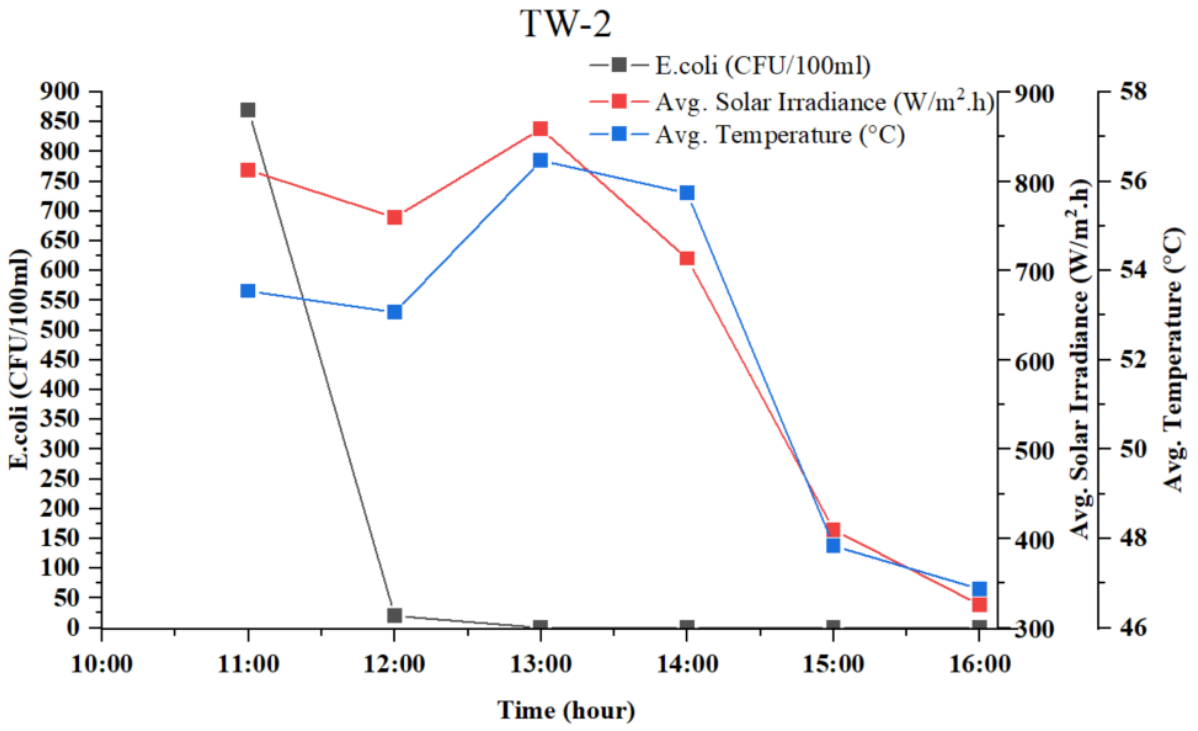


Fig. 4.2 Bacterial inactivation of TW-2 in 6 h solar exposure in PET bottle (Date:20/10/2022)

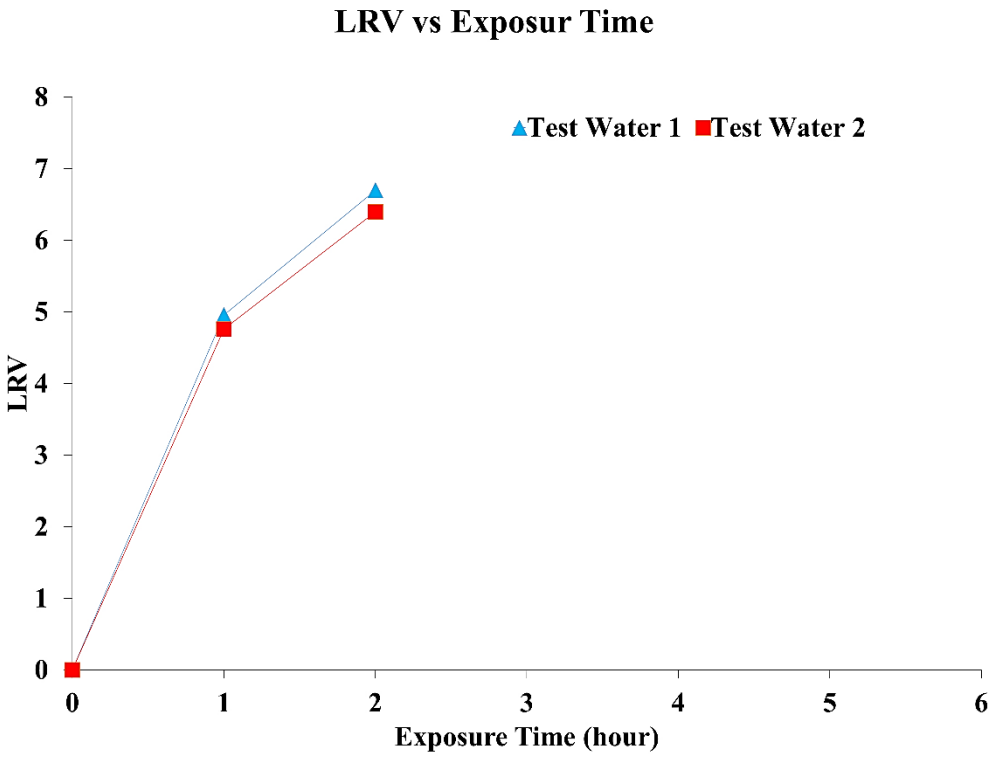


Fig. 4.3 LRV of PET bottle in the monsoon season

As shown in Fig. 4.3, the LRV value of the two test waters was greater than 6 within 2 h of solar exposure. Since it has an LRV >4 in bacterial inactivation, this SODIS system with H_2O_2 is termed “highly protective” according to the WHO (2011) standards.

4.1.2.1.2 Plastic Bag

Similar experiments were conducted in plastic bag reactors. Bacterial inactivation after 6 h of solar exposure in TW-1 due to solar irradiance and temperature is shown in Fig. 4.4. When bacteria were exposed to temperatures above 50°C and solar irradiation levels of more than 700 W/m^2**,** they were killed off within 1 h. The photocatalyst used in the SODIS system facilitated the photo-Fenton reaction, which increased the efficiency of the system. The results of the bacterial inactivation of TW-2 are shown in Fig. 4.5, which reveals that under the same conditions of solar exposure and temperature as TW-1, bacterial inactivation also occurs within 1 h. This shows that bacterial inactivation can be performed within 1 h using a plastic bag reactor in the prototype during the monsoon season.

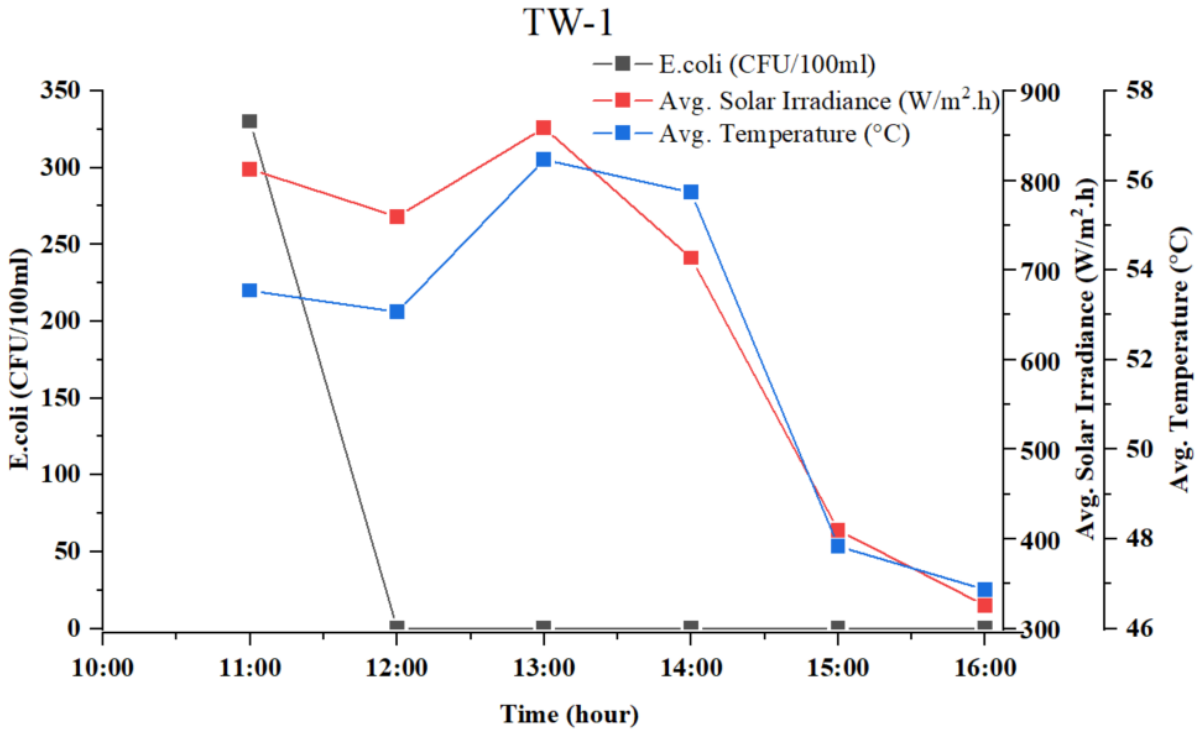


Fig. 4.4 Bacterial inactivation of TW-1 in 6 h solar exposure in plastic bag (Date:20/10/2022)

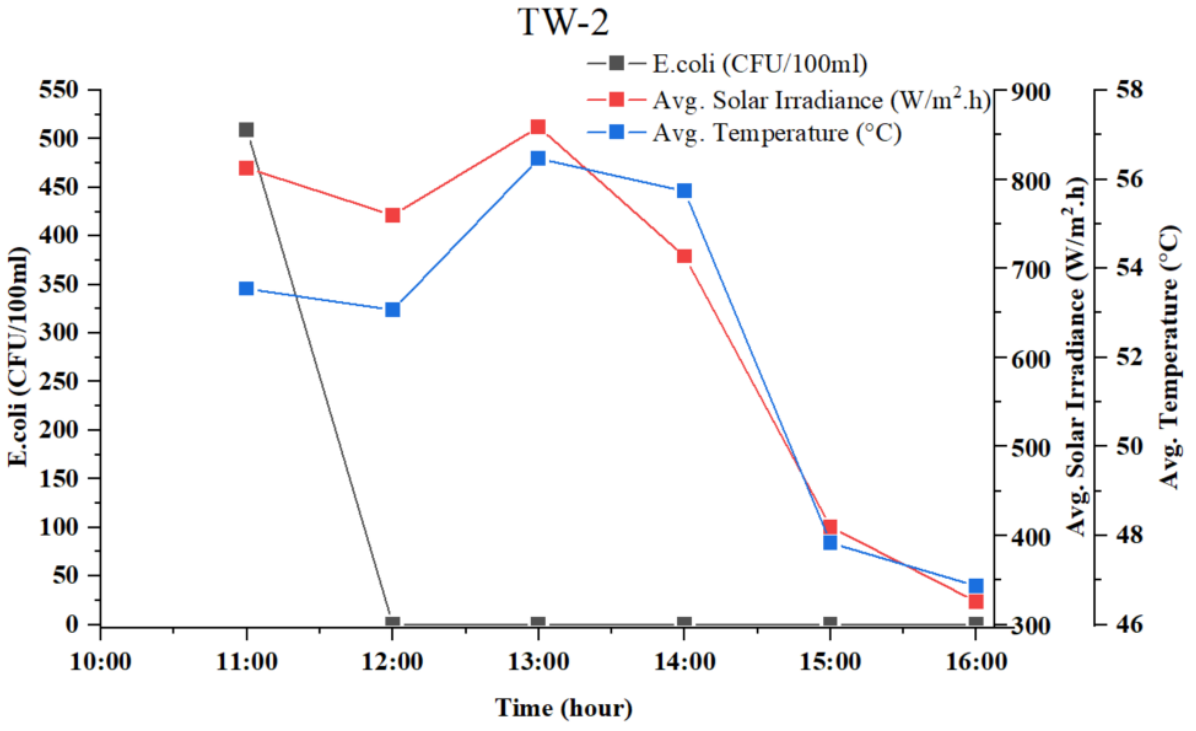


Fig. 4.5 Bacterial inactivation of TW-2 in 6 h solar exposure in plastic bag (Date:20/10/2022)

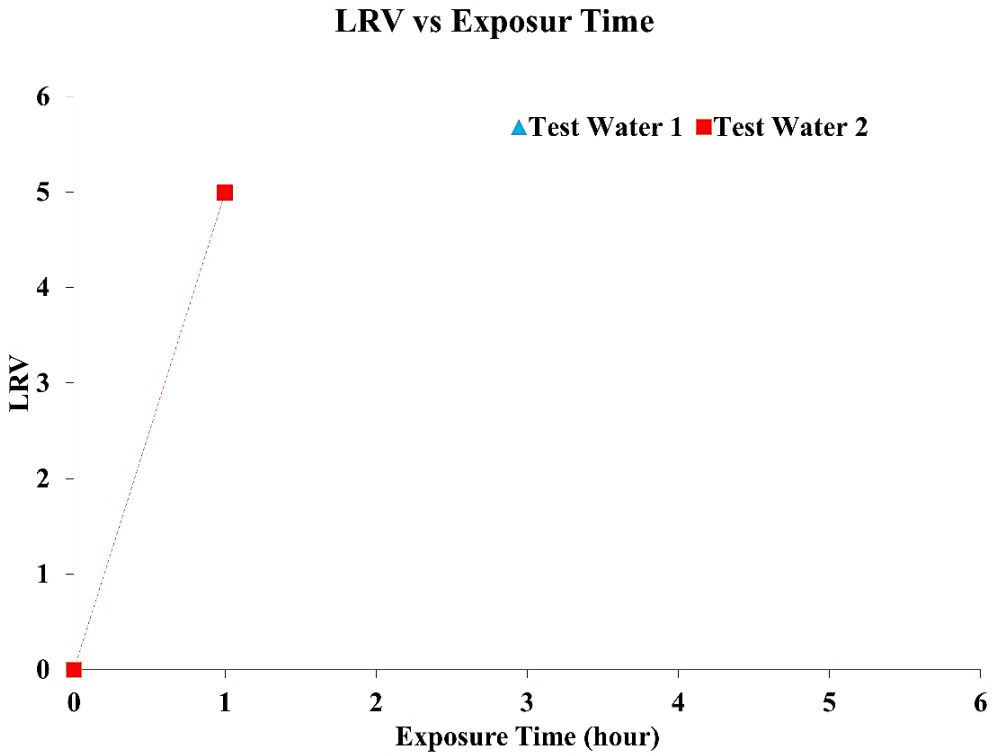


Fig. 4.6 LRV of plastic bag in the monsoon season

As shown in Fig. 4.6, the LRV values of the two test waters increased > 5 LRV after only 1 h of solar exposure. Since it has an LRV > 4 in bacterial inactivation, this SODIS system with H_2O_2 is termed “highly protective” according to the WHO (2011) standards.

4.1.2.2 Winter Season

4.1.2.2.1 PET Bottle

Bacterial inactivation of TW-1 is shown in Fig. 4.7 after exposure to the sun for 6 h. The bacteria were inactivated within 2 h during this season when the temperatures were over 45°C and solar irradiation was greater than 500 W/m^2. Similarly, the photocatalyst used in the SODIS system increased the efficiency of the system.

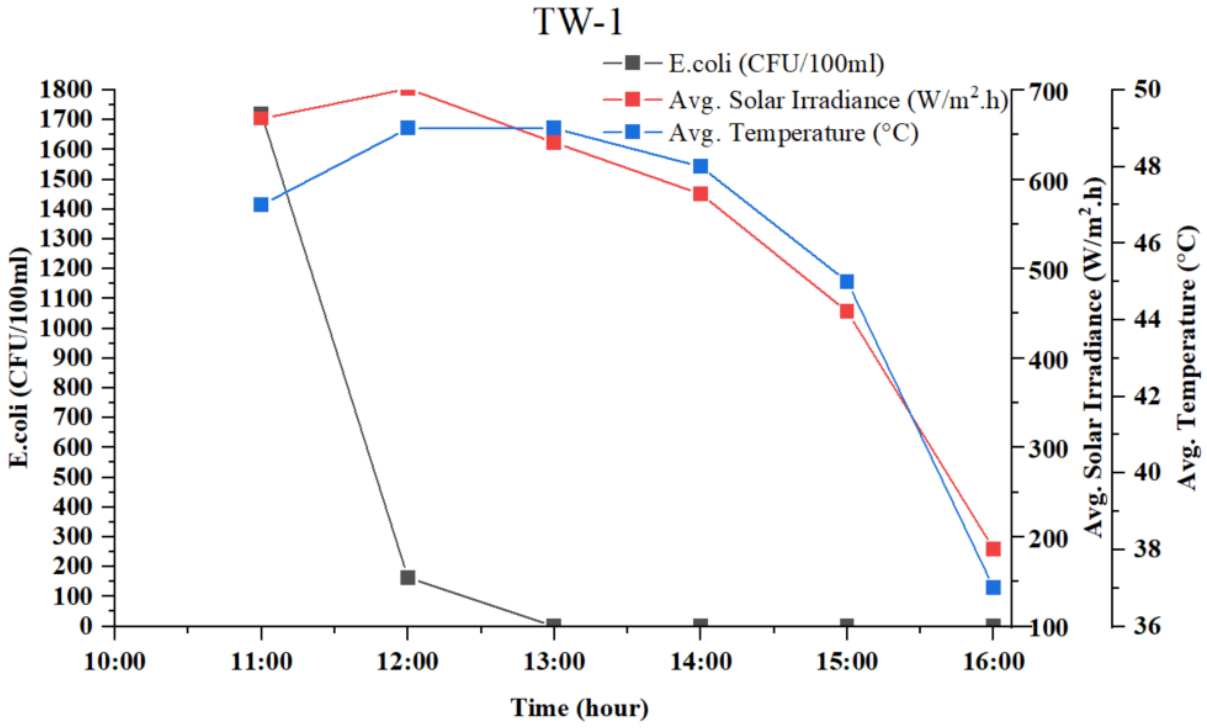


Fig. 4.7 Bacterial inactivation of TW-1 in 6 h solar exposure in PET bottle (Date:17/11/2022)

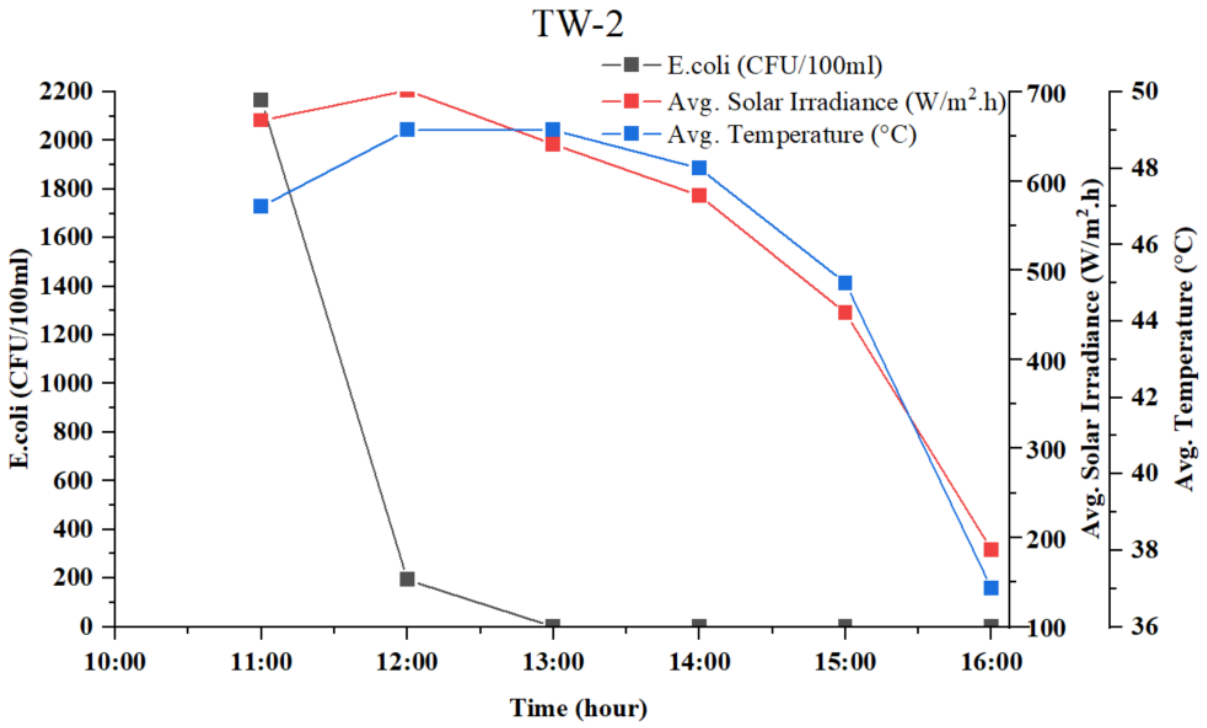


Fig. 4.8 Bacterial inactivation of TW-2 in 6 h solar exposure in PET bottle (Date:17/11/2022)

Fig. 4.8 (which depicts TW-2 bacterial inactivation) shows that bacteria are inactivated within 2 h under the same solar exposure and temperature as TW-1. This demonstrates that bacterial

inactivation can be achieved within 2 h using a PET bottle reactor in the prototype, even in winter. In Fig. 4.9, an illustration of the LRV values is shown for the two test waters. More than 5 LRV were obtained after only 2 h of sun exposure. Since it has an LRV >4 in bacterial inactivation, this SODIS system with H_2O_2 is termed "highly protective" according to the WHO (2011) standards.

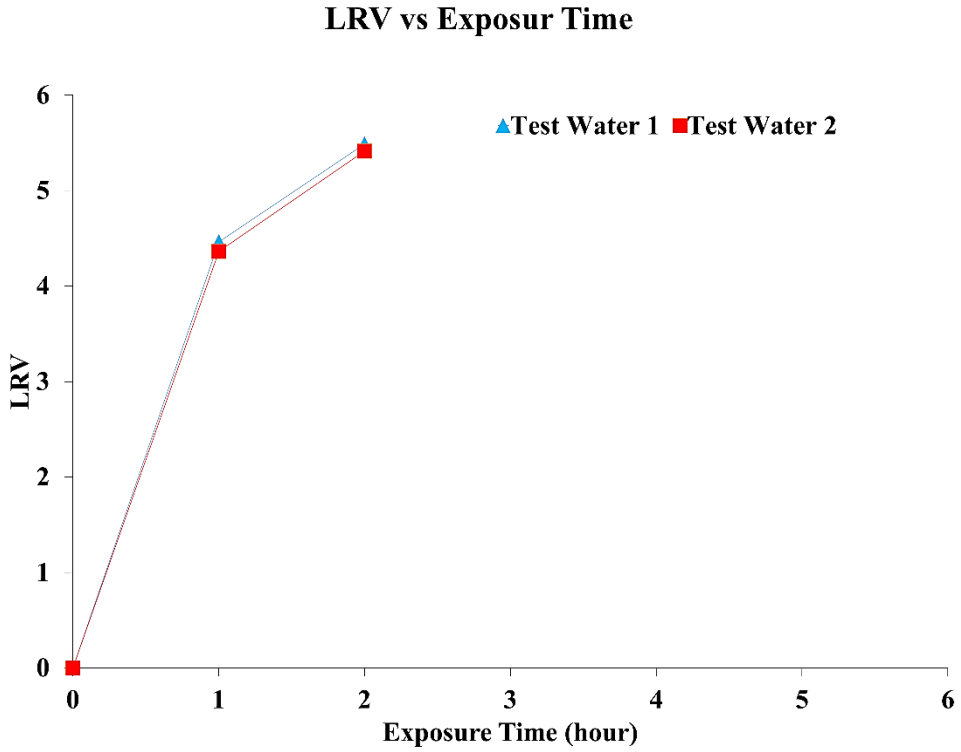


Fig. 4.9 LRV of PET bottle in the winter season

4.1.2.2.2 Plastic Bag

Fig. 4.10 depicts the inactivation of bacteria after 6 h of sun exposure in TW-1. As the highest solar exposure was more than 350 W/m^2 and the temperature was more than 35°C, bacterial inactivation was achieved within 2 h of solar exposure in this season. The SODIS system uses a photocatalyst to enable the photo-Fenton reaction, which contributes to this efficiency. The bactericidal efficacy of TW-2 is depicted in Fig. 4.11, which shows that under the same sunlight and temperature conditions as TW-1, bacterial inactivation was achieved within 2 h. This demonstrates that bacterial inactivation can be achieved within 2 h by utilizing a plastic bag reactor in the prototype during the winter season.

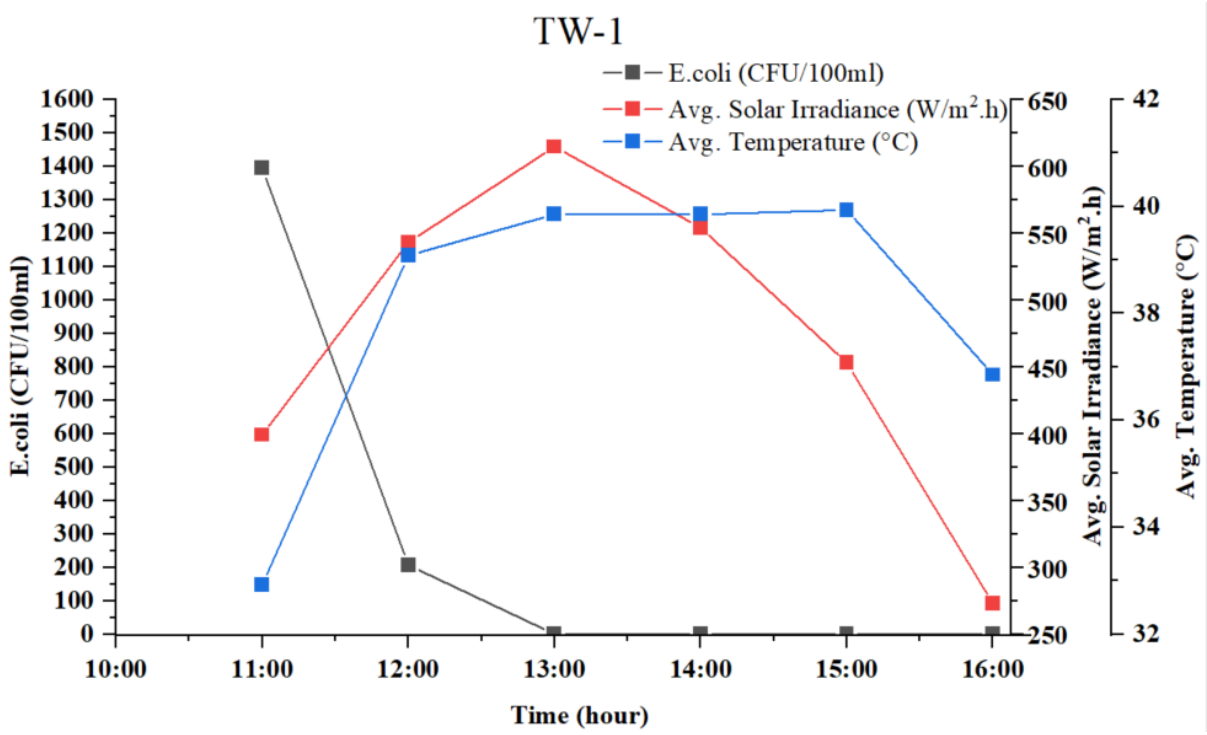


Fig. 4.10 Bacterial inactivation of TW-1 in 6 h solar exposure in plastic bag (Date:19/12/2022)

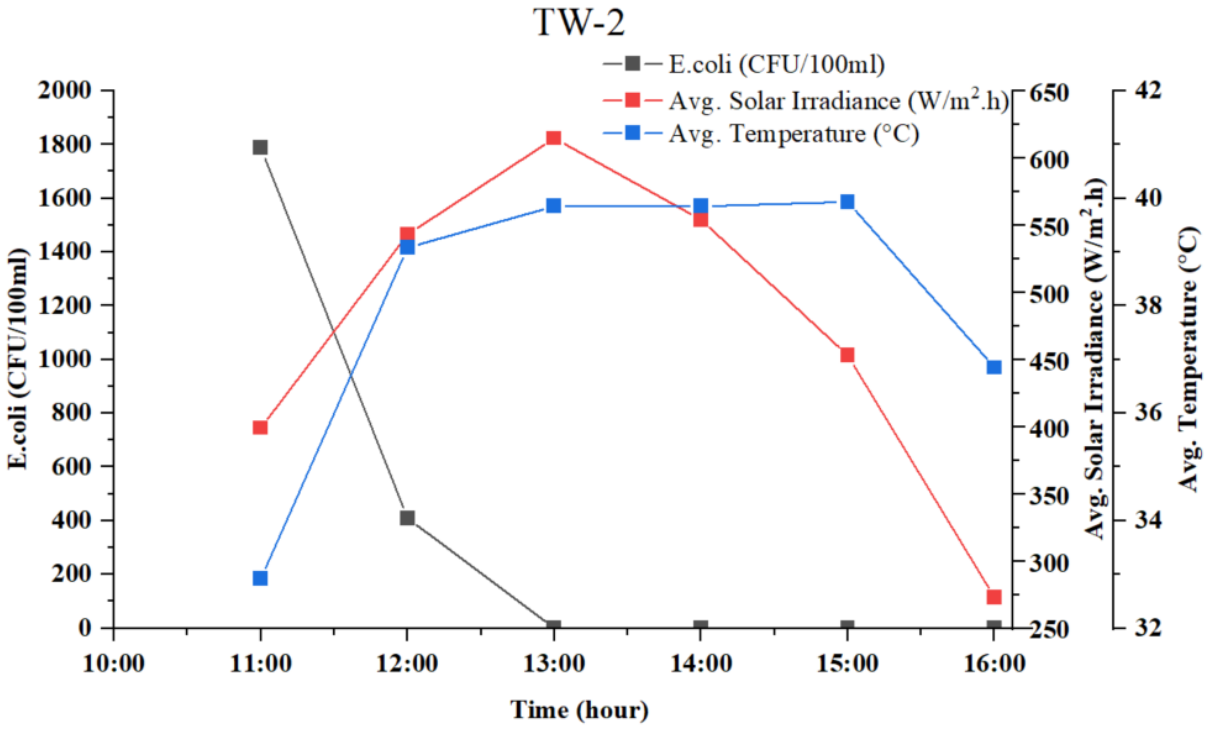


Fig. 4.11 Bacterial inactivation of TW-2 in 6 h solar exposure in plastic bag (Date:19/12/2022)

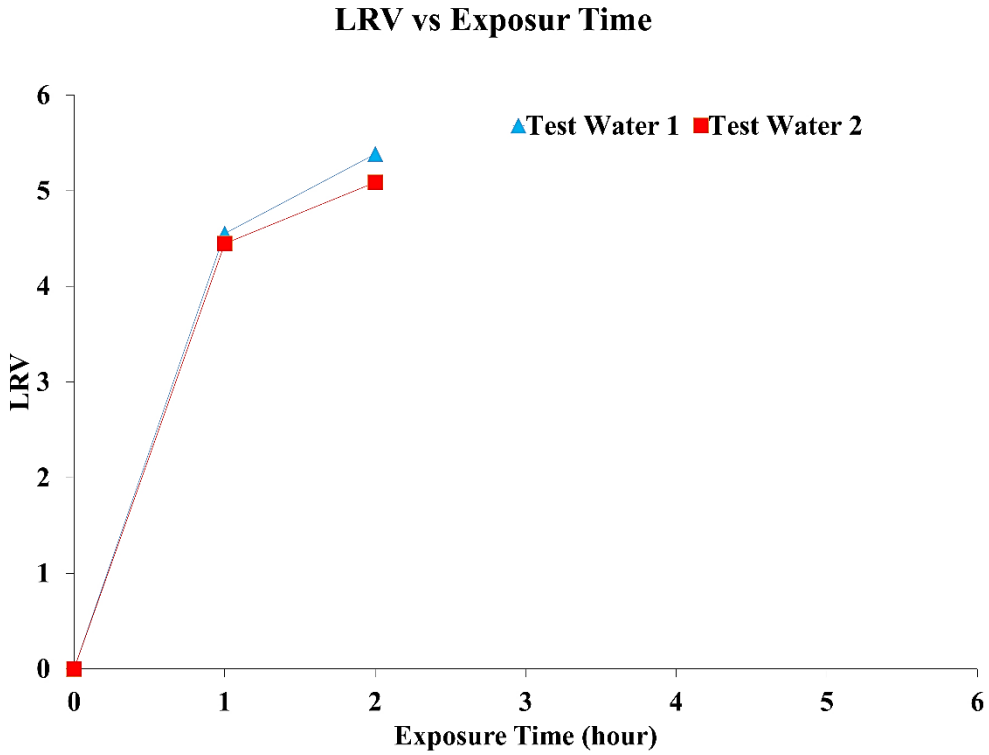


Fig. 4.12 LRV of plastic bag in the winter season

Fig. 4.12 displays the LRV values of the two test waters, which were > 5 LRV within 2 h of solar exposure. Since it has an LRV >4 in bacterial inactivation, this SODIS system with H_2O_2 is termed “highly protective” according to WHO (2011) standards.

4.1.2.3 Summary of Bacterial Inactivation in Monsoon and Winter Seasons

The WHO (2011) classifies HWT alternatives as "highly protective" for ≥ 4 LRV and "protective" for ≥ 2 LRVs based on an evaluation of their efficacy in inactivating bacteria. Table 4.2 provides an overview of the bacterial inactivation results in both monsoon and winter. The modified SODIS with H_2O_2 showed that the performance is rated as "highly protective" in both monsoon and winter. In the case of plastic bag reactors, a greater surface area was exposed to sunlight and shallower water depth make it more effective for disinfection of microorganisms. Thus, the plastic bag reactor is more efficient in bacterial inactivation in both the monsoon and winter seasons using the fabricated prototype SODIS platform.

Table 4.2 Summary of SODIS performance according to WHO (2011) protocols

Season	Reactors	Test waters	Exposure (h)	LRV	Bacterial Inactivation time (h)	Performance Level
Monsoon (June-October, 2022)	PET	TW-1	6	6.7	2	Highly Protective
		TW-2	6	6.4	2	Highly Protective
	Plastic Bag	TW-1	6	5.17	1	Highly Protective
		TW-2	6	4.99	1	Highly Protective
Winter (November-February, 2023)	PET	TW-1	6	6.07	2	Highly Protective
		TW-2	6	5.82	2	Highly Protective
	Plastic Bag	TW-1	6	6.40	2	Highly Protective
		TW-2	6	5.94	2	Highly Protective
Sample size (N) = 30 in monsoon and 30 in winter seasons						

As mentioned by Karim et al. (2021), that SODIS process is not effective as it would require more than 6h of exposure to sunlight and also regrowth of microorganisms was found to occur in post-SODIS water. This study demonstrated that a complete inactivation of microorganisms could be achieved using this modified SODIS. This can eliminate all shortcomings of the conventional SODIS process. The bacterial inactivation outcomes of the remaining 60 experiments are illustrated in Appendix II, (Tables A11 and A12) for the monsoon and winter.

4.1.3 Microorganisms' Regrowth

There are a number of causes for microbial regrowth, and some of these are discussed in the literature review sections. Regrowth is a concern right from the commencement of SODIS and occurs after treatment is performed. Table 4.3 shows that modified SODIS with H_2O_2 is effective in preventing the regrowth of bacteria, as shown in this study. Regrowth after SODIS-treated water, as shown by the study of Karim et al. (2021) in Bangladesh, is a serious problem. People suffering from waterborne infections will not benefit from SODIS, if regrowth of microbes in the water occurs after SODIS. Therefore, reducing the regrowth of bacteria is a significant challenge in SODIS-treated water. Both Giannakis et al. (2015) and Gutiérrez-Alfaro et al. (2018), who have conducted extensive prior research on the topic, illustrated the regrowth of microorganisms as one of the major challenges of SODIS.

Table 4.3 Regrowth potential of modified SODIS

Season	Containers	Test Waters	LRV	Solar Intensity (W/m^2)		Maximum Temperature (°C)	Disinfection Time (h)	Regrowth after 12 h	Regrowth after 24 h	Delta (LRV)	WHO (2011) Treatment Classification
				Average	Maximum						
Monsoon (June-October)	PET	TW-1	6	669.01	995	45.3	2	0	0	6	HP
		TW-2	5	669.01	995	45.3	2	0	0	5	HP
	PB	TW-1	5	646.91	918	52.7	1	0	0	5	HP
		TW-2	5	646.91	918	52.7	1	0	0	5	HP
Winter (November-February)	PET	TW-1	6	539.1	756	43.9	2	0	0	6	HP
		TW-2	5	539.1	756	43.9	2	0	0	5	HP
	PB	TW-1	5	577.43	874	46.4	2	0	0	5	HP
		TW-2	5	577.43	874	46.4	2	0	0	5	HP
Delta (LRV) = LRV (after disinfection) − LRV (after 24 h of storage). HP= Highly Protective											

The results of this study show that photocatalyst-based SODIS reduces the risk of microbial regrowth, making the treatment more acceptable to the low-income people. In PET and plastic bag containers, test water (TW-1 and TW-2) had LRV values greater than 4 throughout the monsoon and winter seasons (PET and PB). It is clear from the delta (LRV) readings that SODIS with H_2O_2 is more effective than conventional SODIS (Karim et al., 2021). According to WHO criteria (2011), the SODIS with H_2O_2 system is considered "highly protective."

4.1.4 Weibull Inactivation Model

Many authors, including Giannakis et al. (2015), Castro-Alférez et al. (2018), and Karim et al. (2021), used the Weibull bacterial inactivation model. The effectiveness of the SODIS system, time required for disinfection, and 4-LRV of the SODIS experiment can be easily demonstrated using this model. The model fits well with the experiment data using both the plastic bag, and PET bottle during the winter and monsoon seasons, as shown in Figs. 4.13 and 4.14, respectively. The results illustrate that the data of this study significantly fit the Weibull inactivation model.

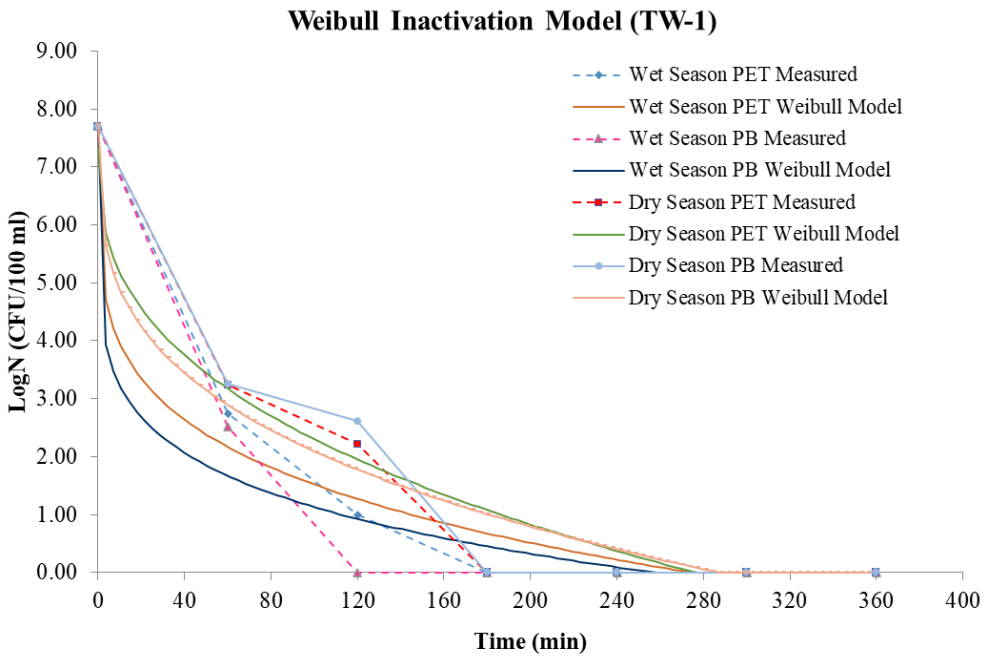


Fig. 4.13 Weibull bacterial inactivation model of TW-1 of the monsoon and winter season

Table 4.4 shows the values of p and δ, which show that p is less than 1, indicating that the bacterial inactivation curve is concave and decreased. R2 values were found between 0.96 (96%) and 0.98 (98%) and RMSE values were between 0.54 and 0.77.

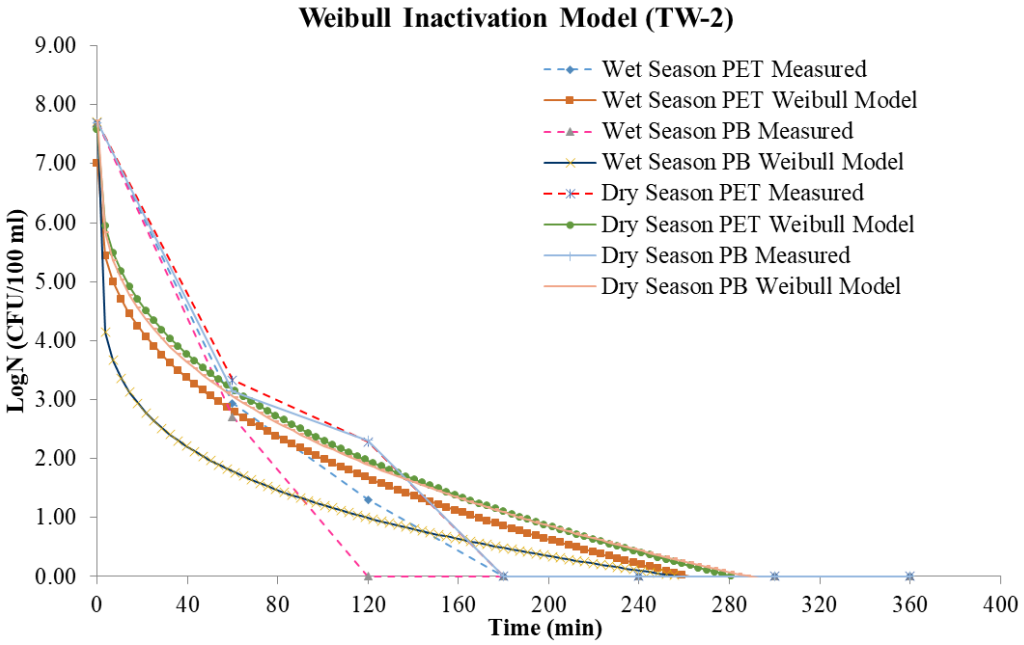


Fig. 4.14 Weibull bacterial inactivation model of TW-2 of the monsoon and winter seasons

In addition, the ratings supplied by Raes et al. (2012) show that the model fits are outstanding, as NRMSLE values are <10% in all experiments performed throughout the winter and monsoon seasons. Across the seasons, the 4-log exposure duration was less than 1 h, demonstrating that the established SODIS prototype with H_2O_2 was more effective. Furthermore, Castro-Alférez et al. (2018) introduced a safe exposure time to prevent the regrowth of microorganisms in photo treated water; the safe exposure time in the monsoon and winter seasons is less than 3 h, which is also more effective than any other study conducted in Bangladesh. During the monsoon season, solar exposure averages 646.91 W/m^2, with a peak of 918 W/m^2. Conversely, during the winter months, the average solar exposure was greater than 450 W/m^2, and the maximum temperature exposure was greater than 600 W/m^2. The modified SODIS with H_2O_2 is rated as a highly protective technique that can be easily implemented by anyone in Bangladesh to safely consume drinking water.

Table 4.4 Summary of the Weibull inactivation model in test water (TW-1 and TW-2) of the monsoon and winter seasons

Season	Reactor	Test Water	Delta, δ (min)	p	$logN_0$ (CFU/100ml)	Root MSE	NRMSE	R^2	R^2-(adj)	4 log (99.99%) removal per intensity and model time required				Safe Exposure time for 4 LRV (h)
										Solar Intensity (W/m^2)		Weibull model required time (h)	Exposure dose ($W\text{-}h/m^2$)	
										Average	Maximum			
Monsoon (June-October)	PET	TW-1	0.02	0.2	7.72	0.54	6.95	0.98	0.97	646.91	918	0.18	117.59	1
		TW-2	0.97	0.4	7.01	0.74	9.62	0.96	0.93	646.91	918	0.85	549.08	2
	PB	TW-1	0.001	0.2	7.71	0.71	9.24	0.96	0.94	646.91	918	0.06	37.52	1
		TW-2	0.003	0.18	7.72	0.77	9.97	0.95	0.93	646.91	918	0.11	71.55	1
Winter (November-February)	PET	TW-1	0.89	0.35	7.31	0.73	9.52	0.96	0.94	539.10	756	0.78	506.48	1
		TW-2	1.33	0.37	7.58	0.71	9.25	0.96	0.94	539.10	756	0.94	419.84	2
	PB	TW-1	0.31	0.3	7.73	0.68	8.8	0.96	0.94	472.35	666	0.52	247.94	1
		TW-2	0.49	0.3	7.73	0.75	9.76	0.96	0.93	472.35	666	0.62	293.59	1

4.1.5 Regression Analysis

Monsoon and winter season data statistics were analyzed together, with assessments made for both PET bottles and plastic bags (TW-1 and TW-2) in this section. Maximum water temperature (Tmax), turbidity (Turb), dissolved oxygen (DO), and ultraviolet radiation (UV) are the four dependent variables (UV) utilized here for the regression analysis. Four, three, two, and one dependent variables per container and test water were used to evaluate the regression model. The coefficient of determination (R^2), standard error (S. E.), and adjusted R^2 were calculated for each experiment. Regression significance was determined using analysis of variance (F-test) and Student's t-test. In the two significant hypothesis tests, both use a p-value of 0.05 as the threshold for statistical significance. Table 4.5 shows the results of the two-sample regression analysis models for the PET bottle and plastic bag accuracy. All regression models were significant for predicting the disinfection coefficient and may be used in the monsoon and winter seasons for PET bottles and plastic bags because the R^2 values of all four dependent variables (Tmax, Turb, DO, and UV) were above 0.50, or 50%. Standard errors of less than 1 in all tests of combinations of dependent variables in the regression analysis indicate that the experiment was successfully evaluated. For the same set of seasonally dependent variables, the modified R^2 values were similarly statistically significant. The variables that are strongly associated with the disinfection coefficient are demonstrated by the significant combination of the regression model, which can be utilized by anyone to develop a model for bacterial inactivation.

Table 4.5 Regression analysis of PET bottle and plastic bag in the monsoon and winter seasons of TW-1 and TW-2

PB TW-1					
Predictor Variables	Model	R	R^2	R^2adj	S. E
Tmax, Turb, DO, and UV	k= -1.64+0.05Tmax-.37 Turb+0.25 DO +0.002UV	0.80	**0.79**	0.75	0.45
Tmax, Turb and DO	k= -3.71+0.10 Tmax-0.37 Turb+0.46 DO	0.68	**0.68**	0.64	0.50
Tmax and Turb	k= -1.17+0.12 Tmax-0.36 Turb	0.29	0.38	0.13	0.60
Tmax	k= -1.82+0.11Tmax	0.56	0.32	0.30	0.65
Turb	k= 3.74-0.31Turb	0.31	0.10	0.10	0.75
DO	k= -4.77+1.08DO	0.40	0.20	0.20	0.70
UV	k= 0.89+0.004UV	0.70	**0.53**	0.50	0.60
PB TW-2					
Predictor Variables	Model	R	R^2	R^2adj	S. E
Tmax, Turb, DO, and UV	k= -0.46+0.05Tmax-0.01 Turb-0.04 DO +0.003UV	0.70	**0.78**	0.72	0.60
Tmax, Turb and DO	k= -1.86+0.10 Tmax-0.01 Turb+0.05 DO	0.53	**0.58**	0.50	0.65
Tmax and Turb	k= -1.55 +0.11 Tmax-0.01 Turb	0.53	0.35	0.30	0.70
Tmax	k= -1.88+0.1Tmax	0.52	0.30	0.30	0.70
Turb	k= 2.73-0.003Turb	0.03	0.01	0.01	0.80
DO	k= -2.74+0.71DO	0.30	0.10	0.10	0.80
UV	k= 0.57+0.004UV	0.70	**0.56**	0.51	0.60
PET TW-1					
Predictor Variables	Model	R	R^2	R^2adj	S. E
Tmax, Turb, DO, and UV	k= -1.94+0.05Tmax-.01 Turb+0.19 DO +0.003UV	0.71	**0.70**	0.65	0.40
Tmax, Turb and DO	k= 0.24+0.01 Tmax-0.002 Turb+0.26 DO	0.58	0.45	0.42	0.50
Tmax and Turb	k= 1.68 +0.02 Tmax+0.01 Turb	0.26	0.30	0.09	0.50
Tmax	k= 1.68+0.02Tmax	0.21	0.04	0.01	0.50
Turb	k= 2.60+0.06Turb	0.09	0.00	0.00	0.50
DO	k= 0.36+0.33DO	0.26	0.07	0.03	0.50
UV	k=1.63+0.002UV	0.54	0.35	0.30	0.45
PET TW-2					
Predictor Variables	Model	R	R^2	R^2adj	S. E
Tmax, Turb, DO, and UV	k= -1.27+0.03Tmax-.01 Turb+0.02 DO +0.003UV	0.70	**0.73**	0.70	0.40
Tmax, Turb and DO	k= -0.68+0.04 Tmax+0.02 Turb+0.11 DO	0.44	**0.50**	0.45	0.40
Tmax and Turb	k= 0.04 +0.04 Tmax+0.02 Turb	0.43	0.20	0.12	0.50
Tmax	k= 0.50+0.04Tmax	0.40	0.14	0.12	0.50
Turb	k= 1.73-0.02Turb	0.25	0.06	0.02	0.50
DO	k= 1.20+0.16DO	0.14	0.02	0.01	0.50
UV	k=1.05+0.003UV	0.65	**0.55**	0.50	0.40
R: Multiple R; R^2: coefficient of determination; R^2adj: Adjusted coefficient of determination; S.E: Standard Error					

The models demonstrate that the disinfection rate in PET bottles and plastic bags (TW-1 and TW-2) is proportional to the water temperature, dissolved oxygen, and UV radiation. In addition, the rate of disinfection was negatively related to water turbidity. The results of the regression analysis indicated that as the turbidity of the water increased, the SODIS disinfection rate decreased. In contrast, if the water temperature, dissolved oxygen, and ultraviolet radiation

are increase, the disinfection rate will increase. Several studies have been cited in the literature, including McGuigan et al. (2012), Marugán et al. (2020), Amirsoleimani et al. (2021), and Karim et al. (2021), demonstrated the same occurrence in the increment and decline of the SODIS disinfection rate.

Figs. 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, 4.21 and 4.2, respectively which show significant fittings of the regression model for PET bottles and plastic bags (TW-1 and TW-2) during the monsoon and winter seasons.

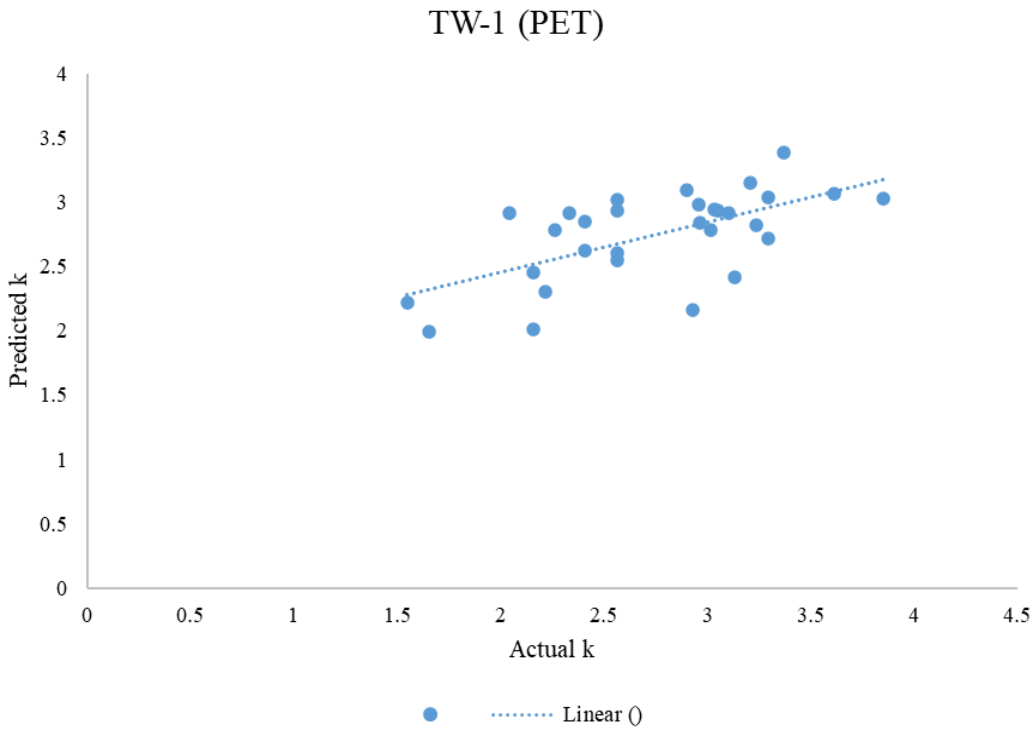


Fig. 4.15 Model fitting of TW-1 (PET) with Tmax, Turb, DO and UV as predictors

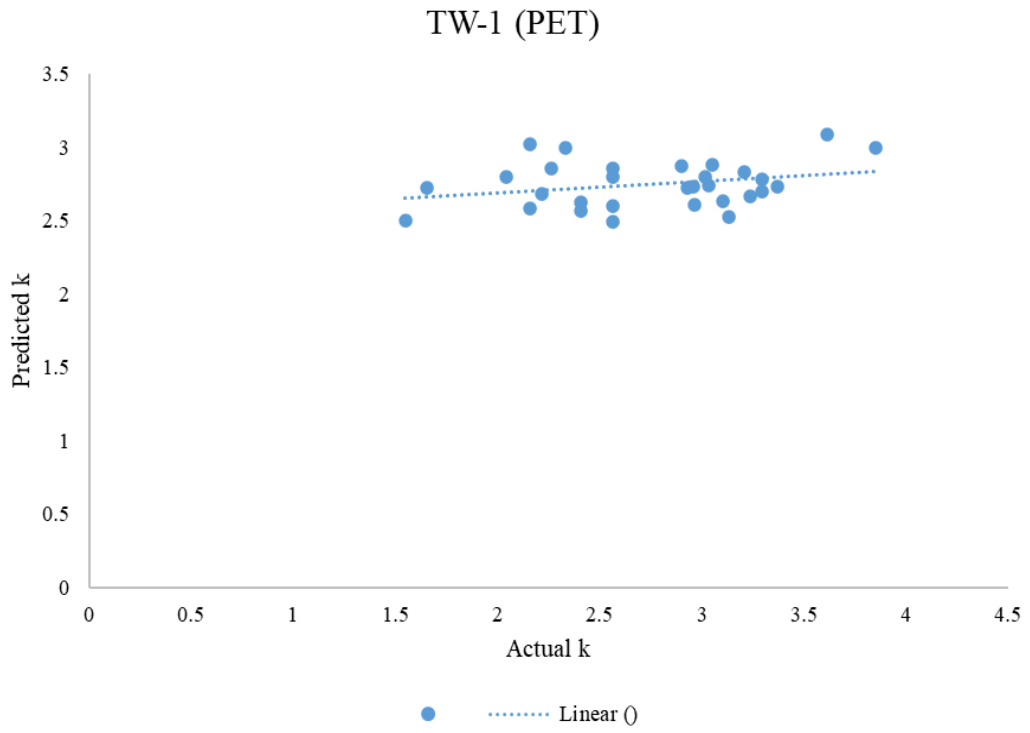


Fig. 4.16 Model fitting of TW-1 (PET) with Tmax, Turb and DO as predictors

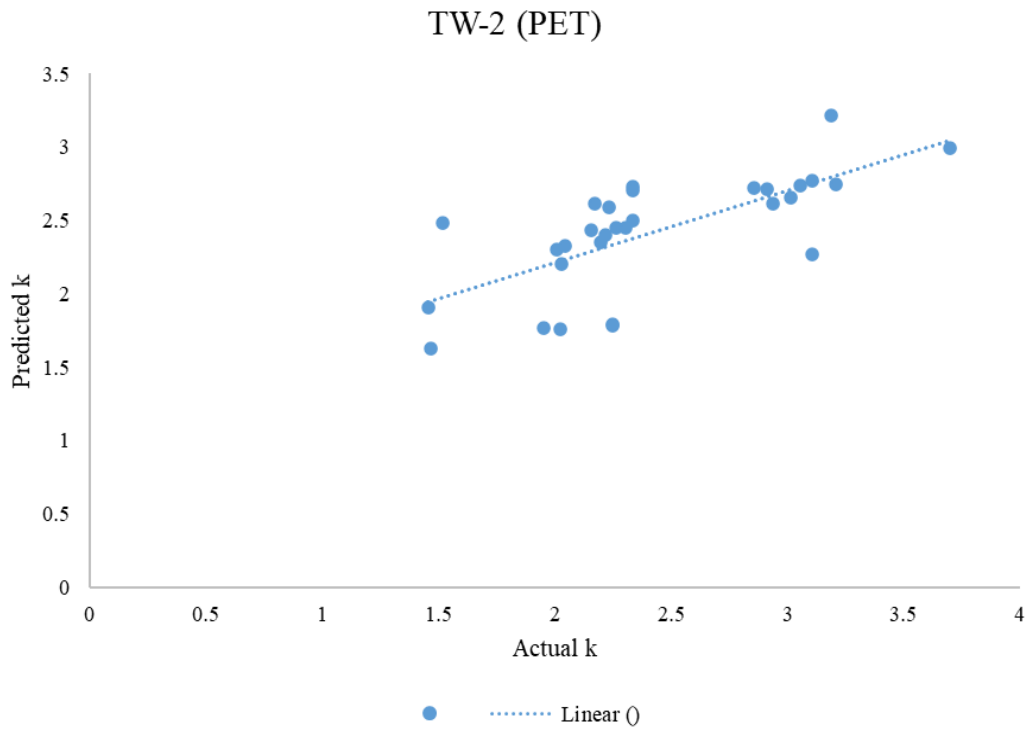


Fig. 4.17 Model fitting of TW-2 (PET) with Tmax, Turb, DO and UV as predictors

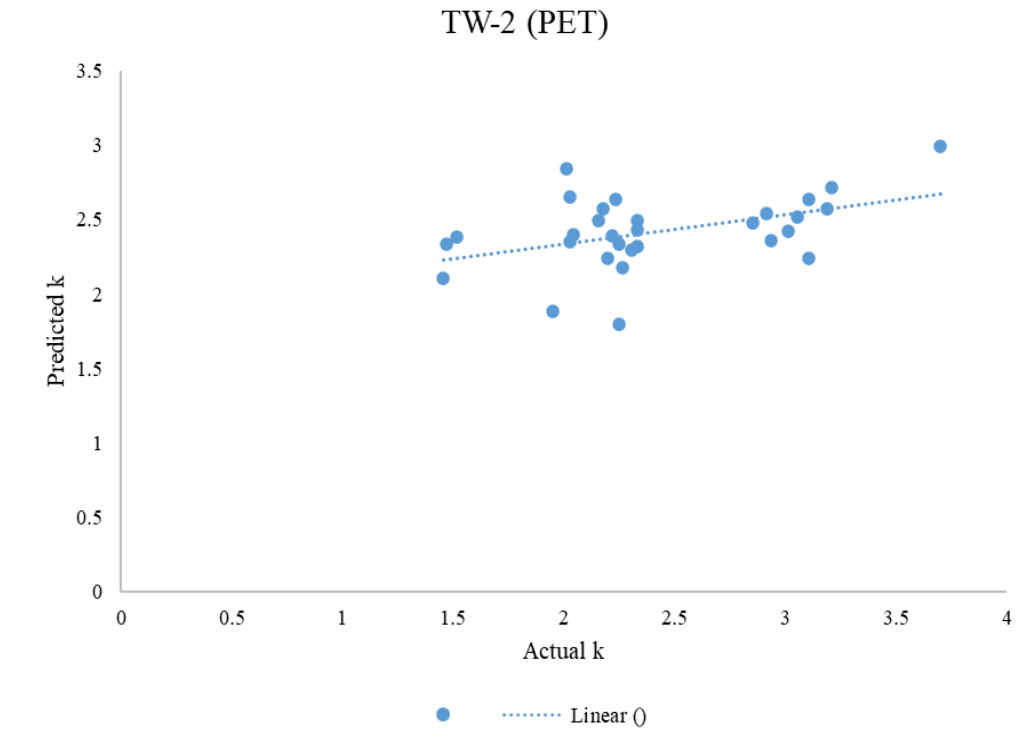


Fig. 4.18 Model fitting of TW-2 (PET) with Tmax, Turb and DO as predictors

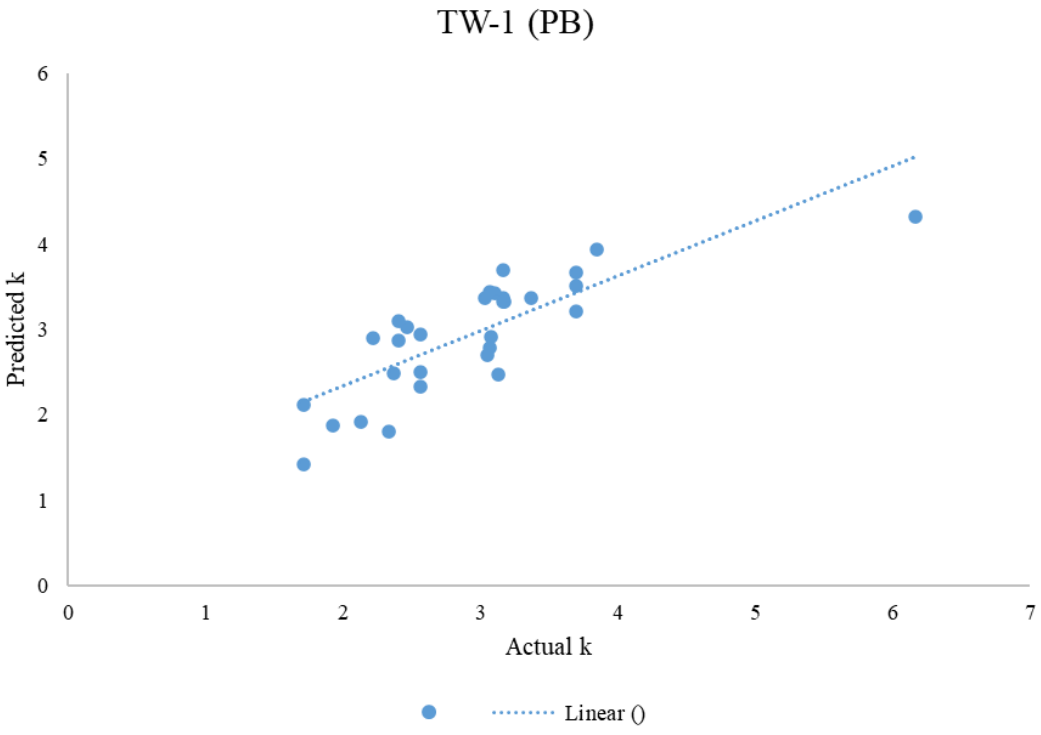


Fig. 4.19 Model fitting of TW-1 (PB) with Tmax, Turb, DO and UV as predictors

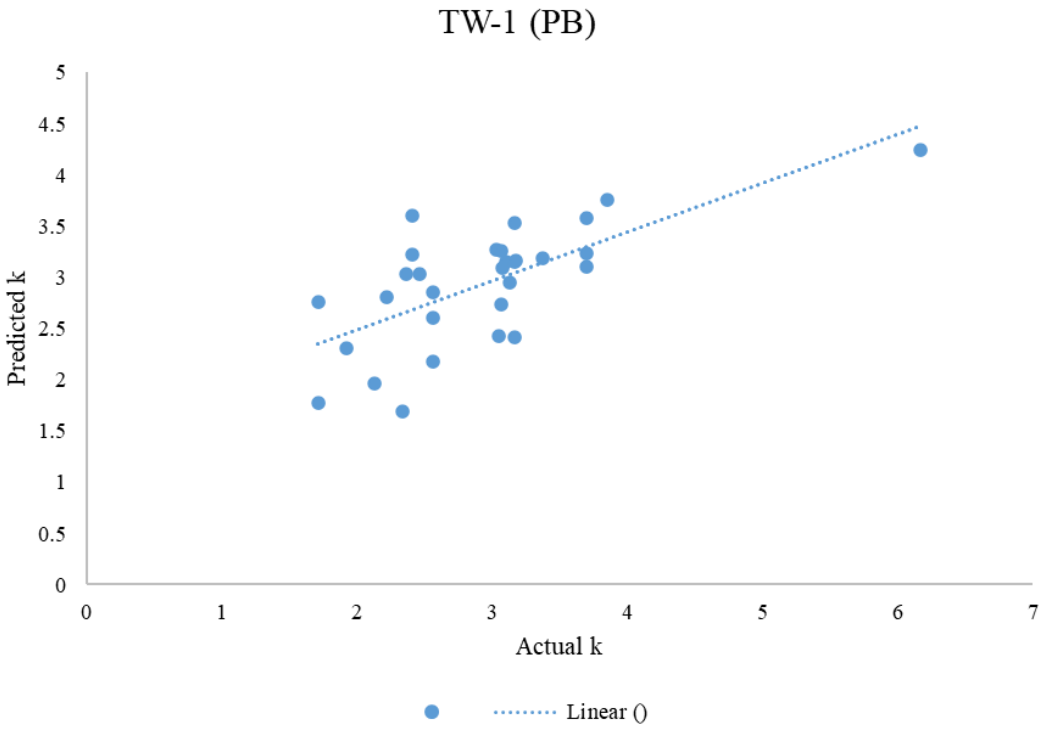


Fig. 4.20 Model fitting of TW-1 (PB) with Tmax, Turb and DO as predictors

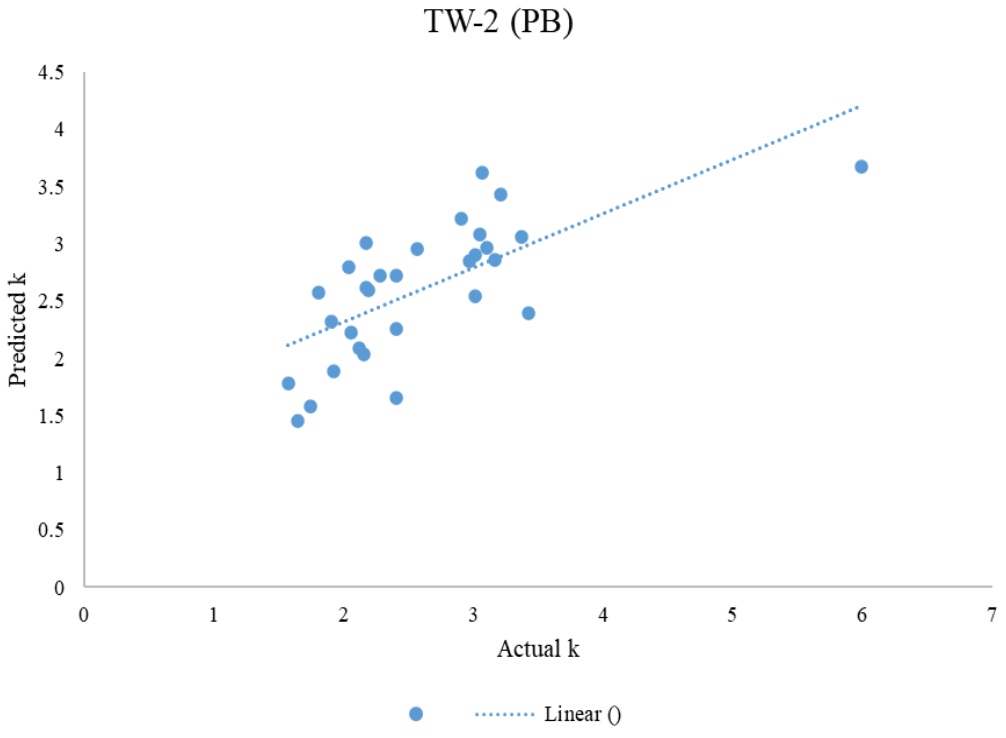


Fig. 4.21 Model fitting of TW-2 (PB) with Tmax, Turb, DO and UV as predictors

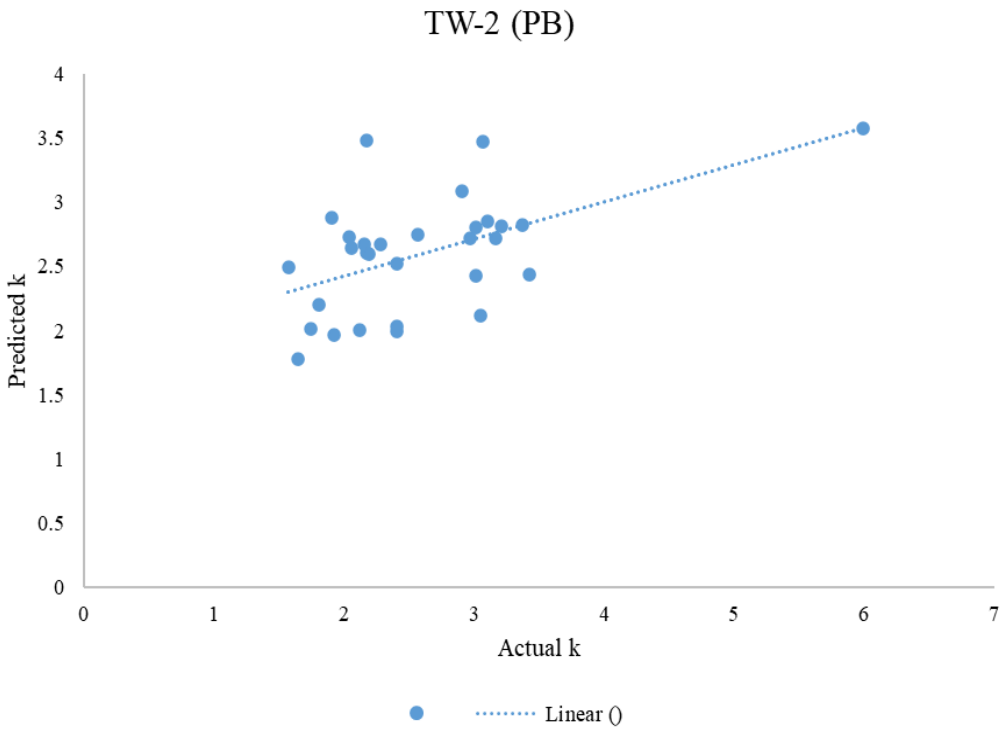


Fig. 4.22 Model fitting of TW-2 (PB) with Tmax, Turb and DO as predictors

Table 4.6 shows the results of an ANOVA F test performed on PB in TW-1 during the monsoon and winter seasons. The F-stat value is higher than F_{crit}, indicating that there is a significant relationship between the independent and dependent variables. The ANOVA F test revealed significant relationships between the variables and the disinfection die-off coefficient everywhere except in the Turb and DO regression models.

Table 4.6 ANOVA (F-test) Hypothesis test of PB TW-1 in the monsoon and winter seasons

PB TW-1					
Predictor variables: Tmax, Turb, DO, and UV	D.F	SS	MS	F-stat	F_{crit}
Regression	4.00	13.28	3.32	11.29	<0.0001
Residual	25.00	7.35	0.29		
Total	29.00	20.63			
Predictor variables: Tmax, Turb and DO	D.F	SS	MS	F-stat	F_{crit}
Regression	3.00	9.81	3.27	7.86	<0.0001
Residual	26.00	10.82	0.42		
Total	29.00	20.63			
Predictor variables: Tmax and Turb	D.F	SS	MS	F-stat	F_{crit}
Regression	2.00	9.33	4.67	11.16	<0.0001
Residual	27.00	11.29	0.42		
Total	29.00	20.63			
Predictor variables: Tmax	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	6.55	6.55	13.04	<0.0001
Residual	28.00	14.07	0.50		
Total	29.00	20.63			
Predictor variables: Turb	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	2.01	2.01	3.02	0.09
Residual	28.00	18.62	0.66		
Total	29.00	20.63			
Predictor variables: DO	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	3.47	3.47	5.66	0.02
Residual	28.00	17.16	0.61		
Total	29.00	20.63			
Predictor variables: UV	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	9.23	9.23	22.67	<0.0001
Residual	28.00	11.40	0.41		
Total	29.00	20.63			
D.F: Degree of freedom; SS: Sum of the square; MS: Mean sum of the square					

Table 4.7 shows the results of the ANOVA F test for PB in TW-2 during the monsoon and winter seasons. It shows that the most significant regression models are the 4 dependent variables combination model, the Tmax model, and the UV model. The ANOVA F test for the regression model with three and two dependent variables revealed that there was no significant relationship between turbidity and the die-off coefficient after disinfection.

Table 4.7 ANOVA (F-test) Hypothesis test of PB TW-2 in the monsoon and winter seasons

PB TW-2					
Predictor variables: Tmax, Turb, DO, and UV	D.F	SS	MS	F-stat	F_{crit}
Regression	4.00	9.84	2.46	5.64	<0.0001
Residual	25.00	10.91	0.44		
Total	29.00	20.75			
Predictor variables: Tmax, Turb and DO	D.F	SS	MS	F-stat	F_{crit}
Regression	3.00	6.01	2.00	3.54	0.03
Residual	26.00	14.74	0.57		
Total	29.00	20.75			
Predictor variables: Tmax and Turb	D.F	SS	MS	F-stat	F_{crit}
Regression	2.00	6.01	3.00	5.50	0.01
Residual	27.00	14.74	0.55		
Total	29.00	20.75			
Predictor variables: Tmax	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	5.80	5.80	10.88	<0.0001
Residual	28.00	14.94	0.53		
Total	29.00	20.75			
Predictor variables: Turb	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	0.02	0.02	0.03	0.87
Residual	28.00	20.73	0.74		
Total	29.00	20.75			
Predictor variables: DO	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	1.65	1.65	2.41	0.13
Residual	28.00	19.10	0.68		
Total	29.00	20.75			
Predictor variables: UV	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	9.02	9.02	21.51	<0.0001
Residual	28.00	11.73	0.42		
Total	29.00	20.75			
D.F: Degree of freedom; SS: Sum of the square; MS: Mean sum of the square					

Table 4.8 illustrates the ANOVA F test results for the PET bottle in TW-1 during the monsoon and winter seasons, which indicates that the UV model is a significant regression model. An ANOVA F test showed that there was no link between Tmax, Turb, and DO and the rate of death after disinfection in a regression model with four, three, and two dependent variables.

Table 4.8 ANOVA (F-test) Hypothesis test of PET bottle TW-1 in the monsoon and winter seasons

PET TW-1					
Predictor variables: Tmax, Turb, DO, and UV	D.F	SS	MS	F-stat	F_{crit}
Regression	4.00	3.50	0.87	4.02	0.01
Residual	25.00	5.44	0.22		
Total	29.00	8.94			
Predictor variables: Tmax, Turb and DO	D.F	SS	MS	F-stat	F_{crit}
Regression	3.00	0.71	0.24	0.75	0.53
Residual	26.00	8.23	0.32		
Total	29.00	8.94			
Predictor variables: Tmax and Turb	D.F	SS	MS	F-stat	F_{crit}
Regression	2.00	0.41	0.21	0.66	0.53
Residual	27.00	8.52	0.32		
Total	29.00	8.94			
Predictor variables: Tmax	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	0.41	0.41	1.35	0.25
Residual	28.00	8.53	0.30		
Total	29.00	8.94			
Predictor variables: Turb	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	0.08	0.08	0.24	0.63
Residual	28.00	8.86	0.32		
Total	29.00	8.94			
Predictor variables: DO	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	0.59	0.59	1.99	0.17
Residual	28.00	8.35	0.30		
Total	29.00	8.94			
Predictor variables: UV	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	2.65	2.65	11.79	<0.0001
Residual	28.00	6.29	0.22		
Total	29.00	8.94			
D.F: Degree of freedom; SS: Sum of the square; MS: Mean sum of the square					

Table 4.9 shows the results of an ANOVA F test performed on PET bottles sold in TW-2 in both summer and winter. The significant regression model was a four-factor arrangement using ultraviolet light (UV). The ANOVA F test for a regression model with three independent and two dependent variables showed that there was no link between Tmax, Turb, and DO.

Table 4.9 ANOVA (F-test) Hypothesis test of PET bottle TW-2 in the monsoon and winter seasons

PET TW-2					
Predictor variables: Tmax, Turb, DO, and UV	D.F	SS	MS	F-stat	F_{crit}
Regression	4.00	4.48	1.12	6.05	<0.0001
Residual	25.00	4.63	0.19		
Total	29.00	9.10			
Predictor variables: Tmax, Turb and DO	D.F	SS	MS	F-stat	F_{crit}
Regression	3.00	1.79	0.60	2.12	0.12
Residual	26.00	7.31	0.28		
Total	29.00	9.10			
Predictor variables: Tmax and Turb	D.F	SS	MS	F-stat	F_{crit}
Regression	2.00	1.72	0.86	3.15	0.06
Residual	27.00	7.38	0.27		
Total	29.00	9.10			
Predictor variables: Tmax	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	1.33	1.33	4.81	0.04
Residual	28.00	7.77	0.28		
Total	29.00	9.10			
Predictor variables: Turb	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	0.57	0.57	1.86	0.18
Residual	28.00	8.54	0.30		
Total	29.00	9.10			
Predictor variables: DO	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	0.19	0.19	0.60	0.45
Residual	28.00	8.91	0.32		
Total	29.00	9.10			
Predictor variables: UV	D.F	SS	MS	F-stat	F_{crit}
Regression	1.00	3.95	3.95	21.46	<0.0001
Residual	28.00	5.15	0.18		
Total	29.00	9.10			
D.F: Degree of freedom; SS: Sum of the square; MS: Mean sum of the square					

In addition, the significance of the regression model is determined by having the students perform a t-test hypothesis, where the null hypothesis shows that the means are the same and the alternate hypothesis shows that they are not. There is no significance or correlation between the variables in the model if the null hypothesis is not rejected, which means that all the variables are equal. However, if the null hypothesis is rejected, there is a correlation between the variables, which means that the regression model is valid.

The predictor variables in this study had a strong correlation with the response variable, as stated by Brockliss et al. (2022), Samoili et al. (2022) and Nwankwo et al. (2022). Normally,

an insignificant model is not illustrated in the outcome of any study, but due to the strong correlation between the predictor variables and the response variables, the insignificant relationship between the predictor variables in the student's t-test is illustrated to assess the probable change in the predictor variable due to the response variable. Moreover, the combination model of UV and Tmax is redundant as a predictor variable in a regression model, as there is a strong correlation between the parameters (Nwankwo et al., 2022). The confidence intervals of 90%, 95%, 98%, and 99%, and critical values of t for two-tailed tests were considered in the student's t-test in this study.

Table 4.10 Student's hypothesis t-test of PB TW-1 in the monsoon and winter seasons

PB TW-1					
Predictor variables: Tmax, Turb, DO, and UV	β	S. E	t-stat	p-value	Confidence level
Intercept	-1.64	2.34	-0.70	0.49	
Tmax	0.05	0.03	1.67	0.11	Insignificant
Turb	-0.37	0.12	-3.16	<0.0001	99.5%
DO	0.25	0.37	0.68	0.51	Insignificant
UV	0.002	0.00	3.44	0.00	99.5%
Predictor variables: Tmax, Turb and DO	β	S. E	t-stat	p-value	Confidence level
Intercept	-3.71	2.69	-1.38	0.18	
Tmax	0.10	0.03	3.08	<0.0001	99.5%
Turb	-0.37	0.14	-2.61	0.01	97.5%
DO	0.46	0.43	1.07	0.30	Insignificant
Predictor variables: Tmax and Turb	β	S. E	t-stat	p-value	Confidence level
Intercept	-1.17	1.23	-0.94	0.35	
Tmax	0.12	0.03	4.18	<0.0001	99.9%
Turb	-0.36	0.14	-2.58	0.02	97.5%
Predictor variables: Tmax	β	S. E	t-stat	p-value	Confidence level
Intercept	-1.82	1.32	-1.38	0.18	
Tmax	0.11	0.03	3.61	<0.0001	99.5%
Predictor variables: Turb	β	S. E	t-stat	p-value	Confidence level
Intercept	3.74	0.49	7.70	<0.0001	
Turb	-0.31	0.18	-1.74	0.09	90%
Predictor variables: DO	β	S. E	t-stat	p-value	Confidence level
Intercept	-4.77	3.24	-1.47	0.15	
DO	1.08	0.45	2.38	0.02	97.5%
Predictor variables: UV	β	S. E	t-stat	p-value	Confidence level
Intercept	0.89	0.45	1.99	0.06	
UV	0.004	0.00	4.76	<0.0001	99.9%
β : coefficient; S. E: Standard error					

Table 4.10 shows the standard errors and associated p-values for each variable included in the regression model for PB (TW-1) throughout the monsoon and winter seasons. This hypothesis test also evaluates the significance of the regression model coefficients. In this table where p value is less than 0.05, it is considered statistically significant. Moreover, two tailed tests t critical values are used in assessing the confidence interval and the insignificant model.

Table 4.11 Student's hypothesis t-test of PB TW-2 in the monsoon and winter seasons

PB TW-2					
Predictor variables: Tmax, Turb, DO, and UV	β	S. E	t-stat	p-value	Confidence level
Intercept	-0.46	2.82	-0.16	0.87	
Tmax	0.05	0.04	1.27	0.22	Insignificant
Turb	-0.01	0.02	-0.48	0.64	Insignificant
DO	-0.04	0.43	-0.10	0.92	Insignificant
UV	0.003	0.00	2.96	0.01	99%
Predictor variables: Tmax, Turb and DO	β	S. E	t-stat	p-value	Confidence level
Intercept	-1.86	3.17	-0.59	0.56	
Tmax	0.10	0.04	2.75	0.01	97.5%
Turb	-0.01	0.02	-0.60	0.55	Insignificant
DO	0.05	0.49	0.11	0.91	Insignificant
Predictor variables: Tmax and Turb	β	S. E	t-stat	p-value	Confidence level
Intercept	-1.55	1.48	-1.04	0.31	
Tmax	0.11	0.03	3.31	0.002	99.5%
Turb	-0.01	0.02	-0.61	0.55	Insignificant
Predictor variables: Tmax	β	S. E	t-stat	p-value	Confidence level
Intercept	-1.88	1.36	-1.38	0.18	
Tmax	0.10	0.03	3.30	<0.0001	99.5%
Predictor variables: Turb	β	S. E	t-stat	p-value	Confidence level
Intercept	2.73	0.85	3.21	0.003	
Turb	0.003	0.02	-0.16	0.87	Insignificant
Predictor variables: DO	β	S. E	t-stat	p-value	Confidence level
Intercept	-2.74	3.44	-0.80	0.43	
DO	0.71	0.46	1.55	0.13	Insignificant
Predictor variables: UV	β	S. E	t-stat	p-value	Confidence level
Intercept	0.57	0.45	1.26	0.22	
UV	0.004	0.0009	4.64	0<.0001	99.9%
β : coefficient; S. E: Standard error					

Table 4.11 illustrates the p values of various variables in the regression model, which determine whether or not the value is significant, as well as their respective standard errors in PB (TW-2) for the monsoon and winter seasons. Additionally, this hypothesis test additionally evaluates

the significance of the coefficient values produced by the regression model. In this table, any p-value with a decimal place less than 0.05 is considered significant. Moreover, two tailed tests t critical values are used in assessing the confidence interval and the insignificant model.

Table 4.12 Student's hypothesis t-test of PET bottle TW-1 in the monsoon and winter seasons

PET TW-1					
Predictor variables: Tmax, Turb, DO, and UV	β	S. E	t-stat	p-value	Confidence level
Intercept	1.94	1.54	1.26	0.22	
Tmax	-0.05	0.03	-1.87	0.07	90%
Turb	-0.01	0.10	-0.13	0.89	Insignificant
DO	0.19	0.22	0.87	0.39	Insignificant
UV	0.004	0.001	3.58	0.001	99.5%
Predictor variables: Tmax, Turb and DO	β	S. E	t-stat	p-value	Confidence level
Intercept	0.24	1.76	0.13	0.89	
Tmax	0.01	0.03	0.58	0.57	Insignificant
Turb	0.002	0.12	0.01	0.99	Insignificant
DO	0.26	0.26	0.97	0.34	Insignificant
Predictor variables: Tmax and Turb	β	S. E	t-stat	p-value	Confidence level
Intercept	1.68	0.94	1.78	0.09	
Tmax	0.02	0.02	1.03	0.31	Insignificant
Turb	0.01	0.12	0.08	0.93	Insignificant
Predictor variables: Tmax	β	S. E	t-stat	p-value	Confidence level
Intercept	1.68	0.92	1.81	0.08	
Tmax	0.02	0.02	1.16	0.25	Insignificant
Predictor variables: Turb	β	S. E	t-stat	p-value	Confidence level
Intercept	2.60	0.31	8.40	<0.0001	
Turb	0.06	0.12	0.49	0.63	Insignificant
Predictor variables: DO	β	S. E	t-stat	p-value	Confidence level
Intercept	0.36	1.69	0.21	0.83	
DO	0.33	0.23	1.41	0.17	Insignificant
Predictor variables: UV	β	S. E	t-stat	p-value	Confidence level
Intercept	1.63	0.34	4.82	<0.0001	
UV	0.002	<0.0001	3.43	0.002	99.9%
β : coefficient; S. E: Standard error					

Table 4.12 displays the p-values of the significant variables in the regression model and their standard errors in PB (TW-2) throughout the monsoon and winter seasons. Additionally, this hypothesis test evaluates the coefficient values of the regression model. In this table, all p

values less than 0.05 are significant. Moreover, two tailed tests t critical values are used in assessing the confidence interval and the insignificant model.

Table 4.13 Student's hypothesis t-test of PET bottle TW-2 in the monsoon and winter seasons

PET TW-2					
Predictor variables: Tmax, Turb, DO, and UV	β	S. E	t-stat	p-value	Confidence level
Intercept	1.27	1.51	0.84	0.41	
Tmax	-0.03	0.03	-1.14	0.27	Insignificant
Turb	0.01	0.01	1.27	0.22	Insignificant
DO	0.02	0.17	0.13	0.90	Insignificant
UV	0.004	<0.0001	3.81	<0.0001	99.5%
Predictor variables: Tmax, Turb and DO	β	S. E	t-stat	p-value	Confidence level
Intercept	-0.68	1.75	-0.39	0.70	
Tmax	0.04	0.02	1.69	0.10	Insignificant
Turb	0.02	0.01	1.27	0.22	Insignificant
DO	0.11	0.21	0.50	0.62	Insignificant
Predictor variables: Tmax and Turb	β	S. E	t-stat	p-value	Confidence level
Intercept	0.04	0.96	0.05	0.96	Insignificant
Tmax	0.04	0.02	2.05	0.05	95%
Turb	0.02	0.01	1.19	0.24	Insignificant
Predictor variables: Tmax	β	S. E	t-stat	p-value	Confidence level
Intercept	0.50	0.88	0.56	0.58	
Tmax	0.04	0.02	2.19	0.04	95%
Predictor variables: Turb	β	S. E	t-stat	p-value	Confidence level
Intercept	1.73	0.52	3.34	0.002	
Turb	0.02	0.01	1.36	0.18	Insignificant
Predictor variables: DO	β	S. E	t-stat	p-value	Confidence level
Intercept	1.20	1.58	0.76	0.45	
DO	0.16	0.20	0.77	0.45	Insignificant
Predictor variables: UV	β	S. E	t-stat	p-value	Confidence level
Intercept	1.05	0.31	3.45	0.002	
UV	0.003	<0.0001	4.63	<0.0001	99.9%
β : coefficient; S. E: Standard error					

Standard errors and p-values for the PB (TW-2) variables from the regression model across the monsoon and winter seasons are shown in Table 4.13. This hypothesis test also evaluates the significance of the regression model coefficients. In this table, p-values less than 0.05, it is considered statistically significant. Moreover, two tailed tests t critical values are used in assessing the confidence interval and the insignificant model.

The results of the regression analysis showed a strong linear association between turbidity, maximum water temperature, dissolved oxygen, UV radiation, and the die-off coefficient of bacteria. Brockliss et al. (2022), Nwankwo et al. (2022), and Samoili et al. (2022) showed similar connections between dependent variables and the bacterial death coefficient in their research. Significant results from the UV model show that ultraviolet radiation is a more accurate predictor of SODIS performance in this region than maximum water temperature. Moreover, when using SODIS, water turbidity must be considered a serious issue. Several studies (Amirsoleimani and Brion, 2021; Gómez-Couso et al., 2009; McGuigan et al., 1998) have demonstrated that, as water turbidity increases, SODIS disinfection efficiency drops dramatically. Amirsoleimani and Brion (2006) observed that a change in turbidity from 0 to 200 NTU reduced the death rate of E. coli by 5 - 1 log (2021). This is because SODIS processes are disrupted by the shallowness to which light can penetrate severely murky water (Marques et al., 2013). Although the importance of turbidity in the regression model cannot stand on its own, it does indicate a negative impact on the die-off coefficient of bacteria when combined with other variables, which is consistent with previous research. Regression models/analyses can be used to effectively demonstrate a functional link between SODIS therapy efficacy and treatment circumstances to explain the daily variation in the die-off rate constant of bacteria.

4.1.6 Cost Analysis

Table 4.14 shows the total cost of building the prototype system used in this study, where the only recurring costs are those for aluminum foil paper, PET bottles, and hydrogen peroxide, while the remaining materials are purchased only once. This can be performed by any low-income family for a one-time investment of only 3,530 BDT (approximately $35.3).

Table 4.14 Cost analysis of full SODIS setup

Materials	Amount	Unit Price (BDT)	Total Cost (BDT)
Aluminum Foil paper	1 roll	250	250
Insulation sheets	1	100	100
PET bottle	6 L	30	180
Corrugated tin sheets	1	200	200
Wooden board	1	650	650
Black enamel paints	1	150	150
Hydrogen peroxide (H_2O_2)	1 L	2000	2000
Total			3530

In addition, Table 4.15 illustrates that the SODIS system may be simply implemented by those living in homes made of corrugated tin sheets for approximately 2580 BDT, or USD 25.80, which is cheaper according to the present economy for maintaining health protection from water-borne diseases.

Table 4.15 Cost analysis of SODIS setup for house dwellers with corrugated tin sheets

Materials	Amount	Unit Price (BDT)	Total Cost (BDT)
Aluminium Foil paper	1 roll	250	250
PET bottle	6 L	30	180
Black enamel paints	1	150	150
Hydrogen peroxide (H_2O_2)	1 L	2000	2000
Total amount			2580

In addition, Table 4.16 illustrates that the initial cost of H_2O_2 was quite low and within the financial means of any family in a poor country.

Table 4.16 Cost analysis of yearly H_2O_2 expenses

Daily Consumption of per person	Per dose	Total daily dose	Total monthly dose	Total yearly dose	Total yearly dose in ml	Total yearly dose in liter	Yearly cost of H_2O_2
6 L	10 mg/l	60 mg	1800 mg	21900 mg	21.9	0.0219	43.8 BDT

4.2 SODIS Performance in Experiments using collected Drinking Water Samples

In this section, the SODIS performance was evaluated using drinking water quality samples collected from restaurants, households, and slums experiments with SODIS. The quality of the drinking water samples was analyzed, and post SODIS analysis of the samples was performed. This section also presents an analysis of the differences and similarities between SODIS and SODIS combined with H_2O_2.

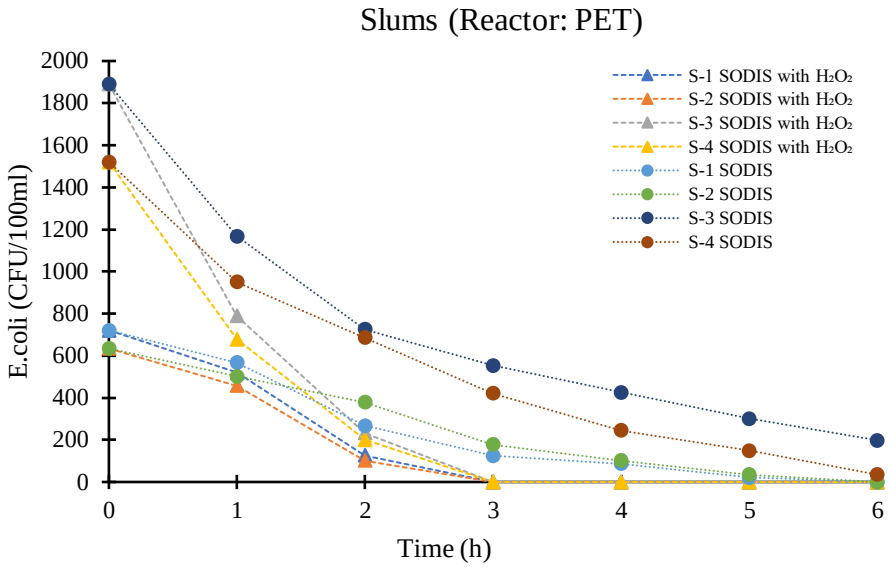
4.2.1 Physicochemical Variation

There were no differences in the physicochemical parameters of the treatment process between the experiments performed in the test waters and those performed on the collected drinking water samples when SODIS with H_2O_2 were used. In Appendix III (Tables A13 and A14), the physicochemical parameter changes in SODIS with H_2O_2 and SODIS are shown. The parameter changes followed a pattern similar to that observed in the test waters. All the drinking water sources have iron, indicating that the photo-Fenton process will occur by the addition of H_2O_2 in SODIS which will accelerate the inactivation of bacteria similar to the test waters.

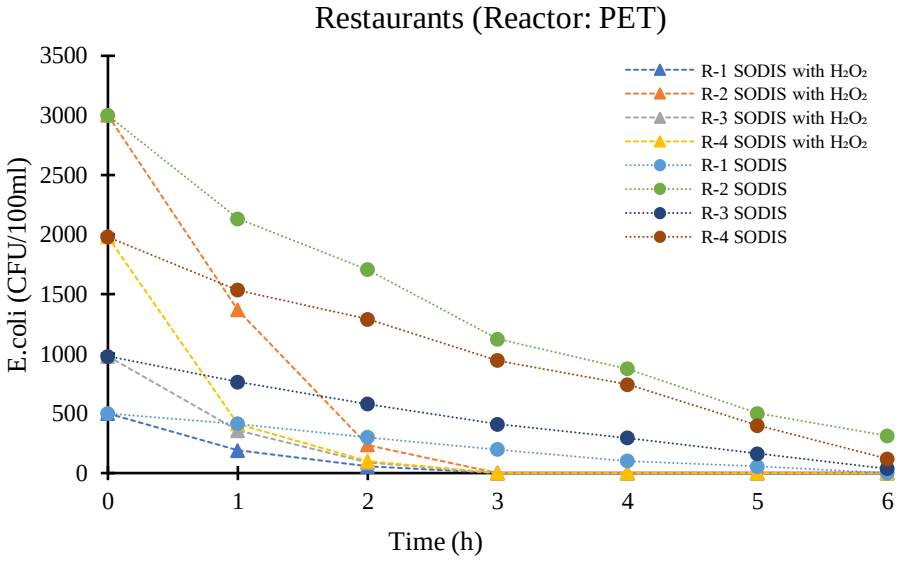
4.2.2 Comparison between SODIS with H_2O_2 and SODIS

This section is divided into two distinct sections: the first discusses the bacteriological examination of SODIS using H_2O_2, and the second discusses SODIS. PET bottles and plastic bags, two container types were used to analyze the drinking water sample collected from slums, restaurants, and households. The experiment was conducted during the winter under semi-cloudy conditions. The maximum temperature of the water was found to be 38.5℃ and the average solar exposure was 500-550 W/m^2 during this experiment. In Fig. 4.23, the inactivation efficiency of SODIS with H_2O_2 and SODIS alone to kill E. coli is depicted; using SODIS with H_2O_2 E. coli inactivated within 2 h in all drinking water samples, while using SODIS alone takes about 5-6 h. In a study by Karim

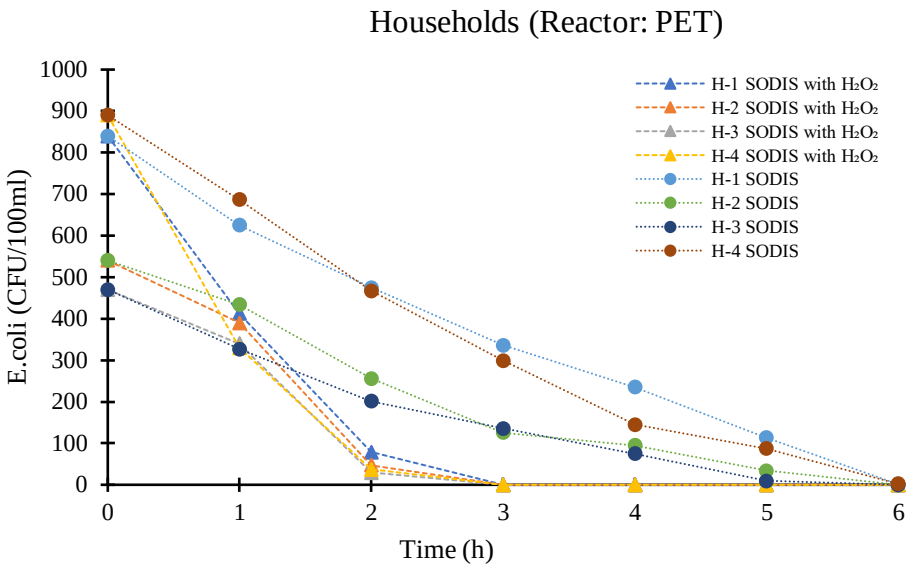
et al. (2021), it was demonstrated that the application of SODIS during the winter months under partly cloudy conditions requires more than six h, and this study data illustrate the same conclusion.



a) Slums



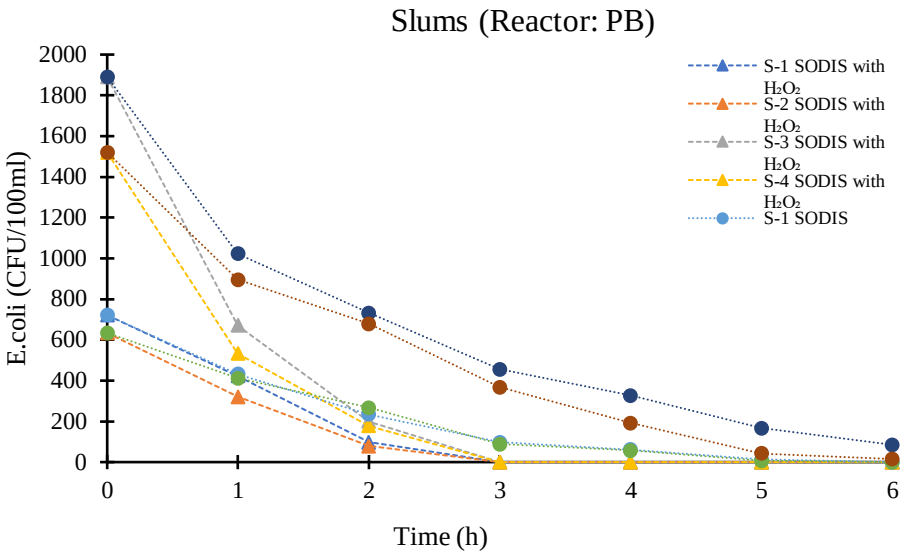
b) Restaurants



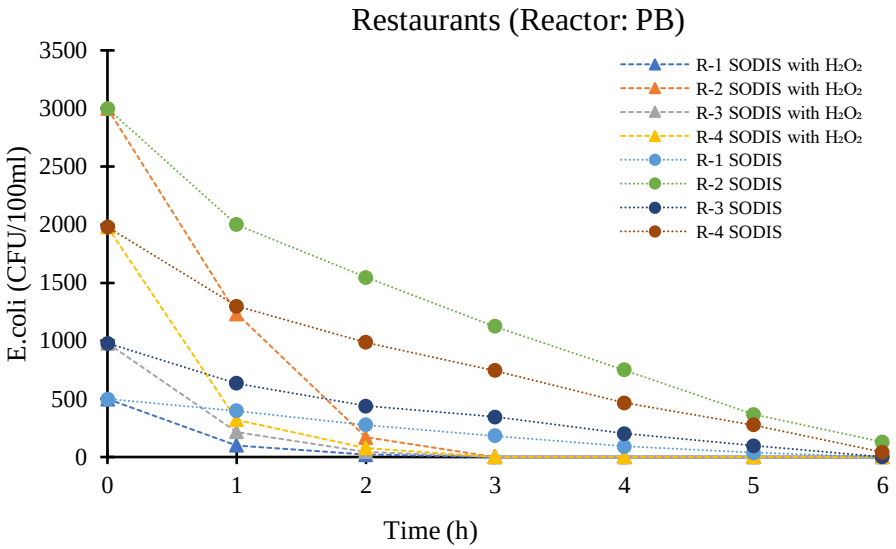
c) Households

Fig. 4.23 Comparison of E. coli inactivation between SODIS and SODIS with H_2O_2 in PET bottle of collected drinking water samples

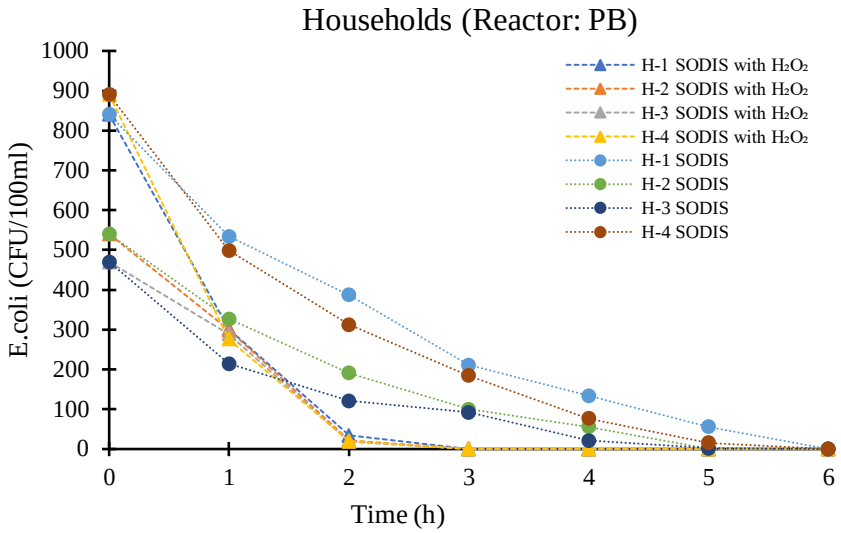
The effectiveness of SODIS with H_2O_2 in a PET bottle is shown now in Fig. 4.24. It takes 2 h for SODIS with H_2O_2 to completely inactivate microorganisms, and this efficiency has been observed across a variety of drinking water samples. In addition, SODIS experiments conducted in plastic bags were more efficient than those conducted in PET bottles. It is clear from the graphs that combining SODIS with H_2O_2 improves the performance of SODIS alone and has the potential to be implemented in the field. No fieldwork was performed outside the winter months, and vice versa. In summer, when temperatures are higher, SODIS treated with hydrogen peroxide is more effective, and bacterial inactivation can be observed after just 1 h.



a) Slums



b) Restaurants



c) Households

Fig. 4.24 Comparison of E. coli inactivation between SODIS and SODIS with H_2O_2 in PB of collected drinking water samples

4.2.3 Regrowth Potential

The regrowth potential of the drinking water samples collected from restaurants, slums and households was done by keeping them in a dark environment at room temperature which is presented in Table 4.17. However, in the case of SODIS alone, there was a significant presence of regrowth of bacteria because the complete bacterium was not inactivated throughout the 6-h exposure interval. All field studies were conducted during the winter season, and regrowth prevailed during cloudy weather, as discussed in the literature review section.

Table 4.17 Regrowth potential of collected drinking water samples

Test waters	Containers	SODIS with H_2O_2		SODIS	
		Disinfection Time (h)	Regrowth after 24 h (CFU/100ml)	Disinfection Time (h)	Regrowth after 24 h (CFU/100ml)
S-1	PET	2	0	5	343
	PB	2	0	5	145
S-2	PET	2	0	5	452
	PB	2	0	5	269
S-3	PET	2	0	>6	1289
	PB	2	0	>6	876
S-4	PET	2	0	>6	789
	PB	2	0	>6	601
H-1	PET	2	0	>6	498
	PB	2	0	5	98
H-2	PET	2	0	5	175
	PB	2	0	5	66
H-3	PET	2	0	5	235
	PB	2	0	5	134
H-4	PET	2	0	>6	459
	PB	2	0	5	245
R-1	PET	2	0	5	98
	PB	2	0	5	69
R-2	PET	2	0	>6	1200
	PB	2	0	>6	789
R-3	PET	2	0	>6	754
	PB	2	0	>6	104
R-4	PET	2	0	>6	2345
	PB	2	0	>6	567

Moreover, the regrowth of bacteria, which significantly hinders SODIS has been discussed by many researchers. This study results illustrate that in winter, SODIS application alone cannot reduce bacterial regrowth after SODIS application, and similar results were also obtained by Karim et al. (2021) in the winter season. Moreover, in Karim et al. (2021) results showed that it took more than 6 h to completely inactivate the bacteria and regrowth prevailed after SODIS application. Reyneke et al. (2020) study conducted experiment in South Africa and Uganda with rain water and found also regrowth of bacteria after 8-h solar exposure in sunny weather condition by acrylic

glass tubes. In a study in Brazil, SODIS was applied to stream water by laying PET bottles in zinc corrugated tin sheets and regrowth of bacteria was observed after 25 h of solar exposure in cloudy weather (Rosa e silva et al., 2022). Martínez-García et al. (2021) also found regrowth of bacteria using isotonic and demineralized water spiked with E. coli in transparent tubes after 5 h of solar exposure in sunny weather condition. Studies conducted in various countries and Bangladesh have illustrated that the use of SODIS could be harmful to human health. Thus, the results of this study indicate that the addition of SODIS with H_2O_2 might inhibit the regrowth of bacteria after treatment and provide drinkable water after storage which can influence people to embrace SODIS as a feasible HWT option to kill bacteria.

4.3 Application Protocol

The modified SODIS experiments can be easily conducted in the rural and urban areas of Bangladesh. Modified SODIS with H_2O_2 can disinfect water within 3 h under cloudy weather conditions as demonstrated in the drinking water samples collected by both reactors (PET and PB). Moreover, the safe exposure duration for both reactors (PET and PB) was 2 h to achieve 4 LRV for bacterial inactivation. The materials required to conduct the experiment and their respective costs are discussed in Section 4.1.6. In rural areas, house dwellers use corrugated tin sheets as roofing materials and the modified SODIS can be easily applied following the protocols shown in Fig. 4.25 for safe drinking water. On the other hand, in urban areas, a prototype SODIS platform can be fabricated with only 3530 BDT, and the modified SODIS can be implemented as per the protocols illustrated. Necessary precautions should be taken to ensure that the turbidity of the water is less than 100 NTU by applying the simple turbidity test shown in Fig. 2.7. If the turbidity of the water is greater than 100 NTU, cloth filtering can be performed to reduce turbidity as illustrated in Fig. 2.6. Moreover, H_2O_2 is corrosive to the skin, eyes and mucous membranes; therefore,

precautions should be taken while pouring it with a dropper in the reactors (PET and PB). The application protocol of the modified SODIS shows that it can be easily implemented at an affordable cost and can provide safe drinking water in the water-stressed communities.

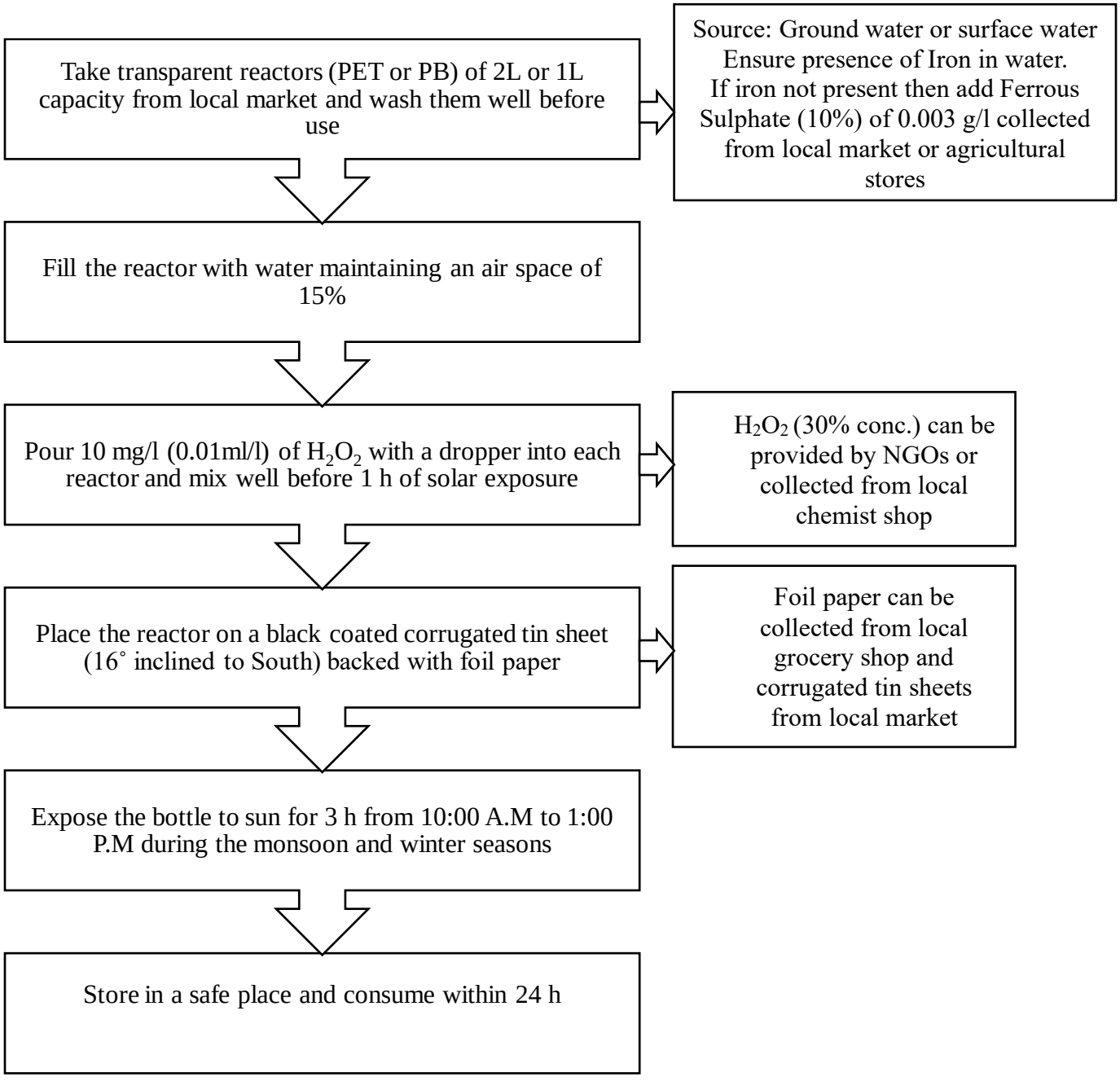


Fig. 4.25 Modified SODIS protocol

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 General

The conclusions of the research conducted in this study are discussed in this chapter, which is based on the results and discussion section. In addition, recommendations for carrying out SODIS in the subtropical climate conditions of Bangladesh are provided according to the guidelines provided by the WHO.

5.2 Conclusions

The conclusions from the evaluation of the test waters experiments are as follows:

1. Steel corrugated tin sheets of 12 mm thickness should be chosen from the market for SODIS applications as it retains the maximum temperature in solar exposure. Reflective reactors (foil paper) should be placed on top of the sheets to enhance the SODIS during the monsoon and winter seasons. SODIS's heating impact is a synergistic advantage that boosts the overall efficiency of the system.
2. During the monsoon and winter seasons, there was very little variation in the physicochemical parameters (temperature, turbidity, dissolved oxygen, and pH) of the test waters (TW-1 and TW-2) or the reactors (PET bottle and plastic bag). However, the EC value variation occurred before and after the experiment owing to the increase in temperature causing an increase in the number of ions in the water and the presence iron ions caused by the reaction of H_2O_2 with iron in the water.
3. The addition of H_2O_2 improved the inactivation of E. coli in the monsoon and winter.
4. During the monsoon season, LRV 5.2 the maximal efficacy was attained with a bacterial inactivation time of just one h in a plastic bag. And LRV 6.7 was found to be the most effective in a PET bottle, which takes only 2-h of bacterial inactivation time.

5. In the winter season, the best outcomes were obtained using LRV 5.49, which had a bacterial inactivation period of only 2 h in a PET bottle. However, the LRV for bacterial inactivation in the plastic bag was 2. This demonstrates that, in the winter season, the performance of SODIS with H_2O_2 in reactors (PET bottles and PB) was relatively similar.
6. During the monsoon season, solar exposure was greater regardless of the monsoon period than during the winter season, when mist predominates the majority of the time. Therefore, the disinfection rate during the monsoon season is higher than that during the winter season.
7. After 12 and 24 h of SODIS with H_2O_2, no microorganisms were found to have grown back in either of the test waters (TW-1 and TW-2) or in either of the reactors (PET bottle or plastic bag), indicating that the application of the photocatalyst resisted the regrowth potential of E. coli in the treated water. The combination of SODIS and H_2O_2 is one of the most effective strategies to prevent microbial growth after treatment has been proved in this study.
8. According to WHO recommendations, the regrowth potential Delta LRV value for PET and plastic bags in the monsoon and winter seasons was >5, making them a "highly protective" HWT system.
9. Based on the results of the Weibull bacterial inactivation model, it takes less than an h in both the monsoon and winter to achieve 4 log inactivation of bacteria in a PET bottle or a plastic bag. In all experiments, the R^2 values were greater than 0.95, which shows the accuracy of the SODIS experiment conducted in this study. All NRMSE values are less than 10%, which means that the experiment works excellently compared with other studies.
10. 2 h is the maximum acceptable exposure period for a 4 LRV PET bottle during the monsoon and winter seasons, but just one h is the safe exposure time for a plastic bag.

11. The best regression analysis models in the monsoon and winter seasons in the case of PB (TW-1) illustrates an R^2 of 0.79, PB (TW-2) illustrates an R^2 of 0.78, PET (TW-1) illustrates an R^2 of 0.70 and PET (TW-2) illustrates an R^2 of 0.73. The outcomes of all models are quite significant.
12. The regression model also showed that the disinfection rate was directly proportional to UV radiation, DO, and water temperature and negatively proportional to turbidity. So, if turbidity increases, the disinfection rate will decrease, and on the other hand, with the increase of UV radiation, water temperature, and DO, the disinfection rate will also increase.
13. The null hypothesis was not true because both the analysis of variance (F-test) and Student's t-test showed significant results (p=0.05). This means that there is a correlation between the variables that affect SODIS efficiency.
14. SODIS with H_2O_2 is reasonably priced at 3530 BDT for the total SODIS setting along with the prototype and 2580 BDT for those living in homes made of corrugated tin sheeting. Furthermore, the annual cost of H_2O_2 is merely 43.8 BDT.

The following is a synopsis of the findings from the analysis of the collected drinking water samples from restaurants, slums, and households:

1. The majority of restaurants, households, and slum water sources in the Dhaka city are polluted with E. coli, which is classified as a very high risk according to the existing research.

2. The WHO and ECR guidelines states that the turbidity and dissolved oxygen levels of water sources in slums are higher than the permissible limit. The iron level also exceeds WHO standards (0.3 mg/l) but is within ECR guidelines (0.3-1 mg/l).
3. In most slums and restaurants, the water collection site is unsanitary, which may be one of the potential causes of E. coli contamination in drinking water.
4. In all establishments, SODIS with H_2O_2 in reactors (PET bottles and plastic bag) illustrated a bacterial inactivation time of 2 h, and no regrowth of microorganisms prevailed after 12 h and 24 h of treatment.
5. SODIS application requires only 5–6 h for bacterial inactivation, and plastic bags are more effective than PET bottles for inactivating bacteria.
6. The comparison of SODIS to H_2O_2 and SODIS in households, restaurants and slums water source studies demonstrates that with the use of H_2O_2, the disinfection time was shortened by more than 50%, and there was no bacterial regrowth in the post-treated water.

5.3 Future Scopes

Microbial pollution of drinking water is one of the leading causes of various water-borne diseases in Bangladesh, and further research is required to eradicate it using available HWT alternatives such as SODIS. The following improvements can be made to SODIS.

1. Laboratory experiments are required to determine the efficacy of SODIS with H_2O_2 for inactivating organisms other than bacteria in drinking water, including protozoa and spore-forming organisms.

2. In SODIS with H_2O_2 application, appropriate precautions are required to assess for the presence of hydrogen peroxide after SODIS treatment, ensuring that no residual peroxide levels remain that could cause harm to human health.
3. In place of black enamel paints on corrugated tin sheets, heat-absorbing bitumen can be used to enhance the temperature of the corrugated tin sheets which will help increase the water temperature.
4. Future research could examine the inclusion of TiO_2 as a photocatalyst in SODIS and its performance in contrast to the climatic conditions in Bangladesh.
5. The photodegradation of PET bottles and plastic bags using the SODIS method should be examined in the future because microplastic are harmful to humans if ingested.
6. Appropriate government agencies in this country should raise public awareness, push for the adoption of long-term solutions, such as SODIS, to eradicate waterborne microorganisms, and work toward a future in which everyone has access to safe water.

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APPENDIX I: LITERATURE REVIEW

Table A 1 SODIS efficiency with respect to solar irradiance

Author	Irradiation type	Wavelength range reported	Dose	Intensity	Result (selected pathogens)	Remarks
Wegelin et al. 1994	Simulated sunlight	350-450nm	555 W.h/m^2	111 W/m^2	3- 4 LRV in five h for E. coli and St. faecalis,	
Heaselgrave and Kilvington 2010	Simulated sunlight	Wavelength range not specified		150W/m^2	E. coli: 5.7 log reduction after 4h	wavelength range unclear
Bosshard et al. 2009	Simulated and natural sunlight	350-450nm		various	E. coli: 1% survival at 1700kJ/m^2	
Dejung et al. 2007)	Natural sunlight	UV-A (320-400nm)		UV: 16.9Wm^2 (average day)	Minimum UV-A dosage for 3LRV bacteria, including E. coli: 60Wh/m2 (4h on average days)	Mean water temperature 44°C
Fisher et al. 2012)	Natural sunlight	UV-A (320-400nm)		73W/m^2 (calculated)	3 log reduction of lab-grown E. coli in 3h, 7h for wastewater-derived E. coli	
Reed 1997	Natural sunlight	Not specified: Full spectrum.		600-750W/m^2 (full spectrum?)	6log inactivation in 3h aerobically similar	Temperature < 28 °C
McGuigan et al. 1998	Simulated sunlight, 300-1020nm:		2900 kJ/m^2	700 W/m^2 (corresp. sunny weather) 400 W/m^2 (corresp. To partly cloudy weather) 100 W/m^2 (corresp. to overcast conditions	3 log inactivation, 2.5 log inactivation, 2 log inactivation	
Lonnen et al. 2005	Simulated sunlight	300-400nm		200W/m^2	E. coli: 5.5 log inactivation in 2.5h	
Berney et al. 2006	Natural sunlight	350-450nm	2400 kJ/m^2 in 6-7h		E. coli: 3 log reduction requires 2000kJ/ m2	
Boyle et al. 2008	Natural sunlight	295-385 nm		Maximum noon intensity: >1000 W/m^2 (full spectrum)	Inactivating 2 log E. coli takes 125 kJ/m^2 (295-385 nm). 4-log: Y. enterocolitica takes 150 min longer than enteropathogenic E. coli.	
Kehoe et al. 2001	Natural sunlight	300-20000nm			Full inactivation at 4-5 Mj(m2	High water temperature!
(Marques et al., 2013)	Natural sunlight	360-380nm		685.6 W/m^2	50°C water inactivates 99.9% of E. coli in 3 h.	High water temperature
(Kalt et al., 2014)	Natural sunlight	315-400 nm		24-36 W/m^2 UVA	34 L of water treated for 4 h reduces E. coli by 4 logs.	
(Giannakis et al., 2015)	Laboratory simulated intensity			500-1600 W/m^2	4 log reduction simulation is done.	
Karim et al., 2021	Natural Sunlight			Monsoon: 491-535 Winter: 356	Different seasons and durations achieve 4 log reduction.	

Table A 2 Different LRVs according to global standards (Andrew et al., 2012)

No.	Standard	LRV	Implementation	Remarks
1.	US EPA Guide Standard-1987	Bacteria: 6 Virus: 4 Cyst: 3	Multiple technologies; murky water conditions	It's a pioneering and well-known guide standard, although it's open to interpretation.
2.	Israel SI 1505 Part 1, Part 2	Bacteria: 7 Virus: N/A Cyst: N/A	Covers filtration, UV, and RO systems for safe, non-turbid water.	
3.	Japan JIS 3835	Bacteria: report results only Virus: N/A Cyst: N/A	Covers membrane filters, but not turbid water.	A membrane filter rating test.
4.	Mexico NOMISO-SSA	Bacteria: 4/1.3 Virus: N/A Cyst: N/A	Covers just safe-water applications, not turbidity reduction.	4-log E. coli and 1.3-log aerobic bacteria decrease.
5.	Australia/New Zealand AS/NZS 4348	Bacteria: 6 Virus: 4 Cyst: 3	Covers several technologies, including turbid water.	EPA Guide Standard-influenced.
6.	Brazil ABNT NBR 14908	Bacteria: 2 Virus: N/A Cyst: N/A	Covers plumbed-in filtering systems, but not turbid water.	
7.	Brazil ABNT NBR 15176	Bacteria: 2 Virus: N/A Cyst: N/A	Gravity-fed filtration devices, safe water exclusively, no turbidity	
8.	Venezuela COVENIN 3377	Bacteria: claims verification only Virus: N/A Cyst: N/A	Covers non-ceramic filtration and ozonation systems, but not turbid water.	Verifies assertions without pass/fail criteria.
9.	Venezuela COVENIN 2840	Bacteria: claims verification only Virus: N/A Cyst: N/A	Ceramic filtration systems, safe water only, no turbidity.	Only verifies claims; no pass/fail criterion.
10.	California Guidelines 2004	Bacteria: 6 Virus: 4 Cyst: 3.3	Covers several technologies, including turbid water.	EPA Guide Standard-influenced
11.	WQA ORD0901	Bacteria: 3 Virus: 3 Cyst: N/A	Gravity-fed filtration devices for pure, non-turbid water.	Developed nations-focused
12.	Proposed supplemental standard NSF/ANSI 244-3	Bacteria: 6 Virus: 4 Cyst: 3.3	Mechanical filtering systems, safe water exclusively, not turbid.	EPA Guide Standard-influenced. Certification for filtration systems that can prevent boil-water advisories.
13.	WHO HWT Guidelines 2011/ NSF P415	Highly protective Bacteria: 4 Virus: 5 Cyst: 4 Protective Bacteria: 2 Virus: 3 Cyst: 2	Covers several technologies, including turbid water.	EPA Guide Standard-influenced Designed for developing country local governments. WHO HWT Guidelines provide test methodology recommendations, but aren't prescriptive. NSF P415 employs NSF P231 and WHO HWT log reductions to make claims.

APPENDIX II: SODIS PERFORMANCE IN LABORATORY EXPERIMENTS

Table A 3 Initial physicochemical characteristics of TW 1 in bottle containers

Season	Parameters	Minimum	Maximum	Average	Standard Deviation	Variance
Monsoon (June- October, 2022)	pH	7.92	8.70	8.34	0.19	0.04
	DO (mg/l)	7.18	9.45	8.11	0.66	0.47
	EC (µS/cm)	326.00	606.00	409.95	73.84	5841.86
	Turbidity (NTU)	35.10	57.33	46.18	6.52	45.57
	Temperature (℃)	26.20	32.00	28.95	1.45	2.25
Winter (November-February, 2023)	pH	7.56	8.32	7.95	0.22	0.05
	DO (mg/l)	7.12	8.25	7.78	0.31	0.11
	EC (µS/cm)	314.00	543.00	397.53	62.06	4126.55
	Turbidity (NTU)	1.75	12.98	3.65	2.59	7.21
	Temperature (℃)	19.20	28.10	25.69	2.55	6.97
Sample size (N) = 30 in monsoon and 30 in winter seasons						

Table A 4 Final physicochemical characteristics of TW 1 in bottle containers

Season	Parameters	Minimum	Maximum	Average	Standard Deviation	Variance
Monsoon (June-October, 2022)	pH	6.77	8.48	7.81	0.42	0.18
	DO (mg/l)	6.12	8.45	7.25	0.58	0.34
	EC (µS/cm)	279.00	885.00	770.07	84.59	7235.50
	Turbidity (NTU)	0.38	4.54	2.50	1.22	1.51
	Temperature (℃)	26.90	52.70	38.37	5.40	29.49
Winter (November-February, 2023)	pH	7.41	8.34	7.90	0.23	0.05
	DO (mg/l)	6.14	8.12	7.25	0.42	0.18
	EC (µS/cm)	687.00	898.00	796.63	51.51	2682.80
	Turbidity (NTU)	0.68	4.12	2.22	0.77	0.59
	Temperature (℃)	23.50	51.20	40.16	4.82	23.54
Sample size (N) = 30 in monsoon and 30 in winter seasons						

Table A 5 Initial physicochemical characteristics of TW 2 in bottle containers

Season	Parameters	Minimum	Maximum	Average	Standard Deviation	Variance
Monsoon (June-October, 2022)	pH	7.92	8.48	8.32	0.16	0.03
	DO (mg/l)	7.18	9.45	8.11	0.66	0.47
	EC (µS/cm)	326.00	606.00	409.95	73.84	5841.86
	Turbidity (NTU)	35.10	57.33	46.18	6.52	45.57
	Temperature (℃)	26.20	32.00	28.95	1.45	2.25
Winter (November-February, 2023)	pH	8.06	8.47	8.31	0.11	0.01
	DO (mg/l)	7.98	8.67	8.35	0.19	0.04
	EC (µS/cm)	337.00	575.00	416.33	68.48	5024.95
	Turbidity (NTU)	32.50	56.00	41.55	5.97	38.22
	Temperature (℃)	19.20	28.10	25.69	2.55	6.97
Sample size (N) = 30 in monsoon and 30 in winter seasons						

Table A 6 Final physicochemical characteristics of TW 2 in bottle containers

Season	Parameters	Minimum	Maximum	Average	Standard Deviation	Variance
Monsoon (June-October, 2022)	pH	6.83	8.46	7.92	0.44	0.19
	DO (mg/l)	5.78	9.26	7.60	0.66	0.45
	EC (µS/cm)	511.54	955.00	785.00	69.06	4822.99
	Turbidity (NTU)	11.70	51.23	37.30	8.89	79.97
	Temperature (℃)	26.90	52.70	38.41	5.38	29.23
Winter (November-February, 2023)	pH	8.00	8.45	8.25	0.09	0.01
	DO (mg/l)	6.78	8.54	7.84	0.36	0.13
	EC (µS/cm)	698.00	896.00	808.69	51.10	2640.22
	Turbidity (NTU)	18.60	51.20	34.08	7.10	50.99
	Temperature (℃)	23.50	51.20	40.16	4.82	23.54
Sample size (N) = 30 in monsoon and 30 in winter seasons						

Table A 7 Initial physicochemical characteristics of TW 1 in plastic bag containers

Season	Parameters	Minimum	Maximum	Average	Standard Deviation	Variance
Monsoon (June- October, 2022)	pH	7.37	8.45	8.15	0.27	0.08
	DO (mg/l)	6.98	8.21	7.52	0.42	0.19
	EC (µS/cm)	312.00	584.00	380.73	73.90	5851.78
	Turbidity (NTU)	1.68	4.24	2.97	0.73	0.57
	Temperature (℃)	27.60	32.00	29.26	1.21	1.58
Winter (November- February, 2023)	pH	7.04	8.42	7.92	0.31	0.10
	DO (mg/l)	6.99	8.13	7.68	0.36	0.14
	EC (µS/cm)	341.00	684.00	454.13	91.07	8885.98
	Turbidity (NTU)	1.78	4.65	3.52	0.75	0.61
	Temperature (℃)	19.20	29.20	25.76	2.63	7.43
Sample size (N) = 30 in monsoon and 30 in winter seasons						

Table A 8 Final physicochemical characteristics of TW 1 in plastic bag containers

Season	Parameters	Minimum	Maximum	Average	Standard Deviation	Variance
Monsoon (June- October, 2022)	pH	7.21	8.83	8.11	0.34	0.12
	DO (mg/l)	6.25	8.04	7.03	0.39	0.15
	EC (µS/cm)	582.00	862.00	742.77	71.33	5144.92
	Turbidity (NTU)	0.25	4.42	2.48	0.97	0.95
	Temperature (℃)	31.90	52.70	38.27	4.14	17.32
Winter (November- February, 2023)	pH	7.02	8.45	7.92	0.31	0.10
	DO (mg/l)	6.09	8.03	7.11	0.44	0.19
	EC (µS/cm)	572.00	893.00	772.73	65.67	4360.69
	Turbidity (NTU)	0.99	4.24	2.69	0.87	0.76
	Temperature (℃)	23.50	51.20	40.16	4.82	23.54
Sample size (N) = 30 in monsoon and 30 in winter seasons						

Table A 9 Initial physicochemical characteristics of TW 2 in plastic bag containers

Season	Parameters	Minimum	Maximum	Average	Standard Deviation	Variance
Monsoon (June-October, 2022)	pH	7.90	8.70	8.32	0.22	0.08
	DO (mg/l)	7.28	8.47	7.87	0.31	0.19
	EC (µS/cm)	321.00	594.00	397.07	70.49	5851.78
	Turbidity (NTU)	35.00	65.40	46.05	8.45	0.57
	Temperature (℃)	27.60	32.00	29.31	1.18	1.58
Winter (November-February, 2023)	pH	7.92	8.48	8.27	0.16	0.03
	DO (mg/l)	7.47	8.47	8.21	0.26	0.07
	EC (µS/cm)	57.94	600.00	422.13	119.50	15301.53
	Turbidity (NTU)	30.78	69.40	46.50	9.61	98.95
	Temperature (℃)	19.20	29.20	25.76	2.63	7.43
Sample size (N) = 30 in monsoon and 30 in winter seasons						

Table A 10 Final physicochemical characteristics of TW 2 in plastic bag containers

Season	Parameters	Minimum	Maximum	Average	Standard Deviation	Variance
Monsoon (June-October, 2022)	pH	7.08	8.87	8.17	0.31	0.10
	DO (mg/l)	6.40	8.23	7.24	0.40	0.17
	EC (µS/cm)	529.00	872.00	751.24	70.63	5044.93
	Turbidity (NTU)	22.00	56.60	36.79	7.08	50.65
	Temperature (℃)	31.90	52.70	38.32	4.10	17.03
Winter (November-February, 2023)	pH	6.70	8.80	8.22	0.23	0.05
	DO (mg/l)	6.40	8.33	7.50	0.52	0.27
	EC (µS/cm)	57.95	896.00	781.08	105.24	11200.51
	Turbidity (NTU)	17.89	58.60	36.21	8.54	73.83
	Temperature (℃)	23.50	51.20	40.16	4.82	23.54
Sample size (N) = 30 in monsoon and 30 in winter seasons						

Table A 11 Plastic Bag E. coli test outcomes of the monsoon and winter seasons

Monsoon Season				**Winter Season**			
TW-1		**TW-2**		**TW-1**		**TW-2**	
Serial (h)	**E. coli (CFU/100 ml)**	**Serial (h)**	**E. coli (CFU/100 ml)**	**Serial (h)**	**E. coli (CFU/100 ml)**	**Serial (h)**	**E. coli (CFU/100 ml)**
Date: 10/8/2022				**Date: 1/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	80	1	170	1	3210	1	3950
2	20	2	130	2	630	2	970
3	10	3	30	3	30	3	150
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 17/8/2022				**Date: 2/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	500	1	750	Initial	2470	Initial	3210
2	150	2	220	1	430	1	780
3	10	3	120	2	0	2	0
4	0	4	30	3	0	3	0
5	0	5	0	4	0	4	0
6	0	6	0	5	0	5	0
Date: 24/8/2022				**Date: 3/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	800	1	1100	6	2700	6	4260
2	150	2	330	Initial	270	Initial	980
3	20	3	70	1	0	1	10
4	0	4	0	2	0	2	0
5	0	5	0	3	0	3	0
6	0	6	0	4	0	4	0
Date: 29/8/2022				**Date: 7/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	700	1	1030	5	2970	5	3780
2	230	2	390	6	1840	6	2010
3	0	3	0	Initial	530	Initial	930
4	0	4	0	1	70	1	250
5	0	5	0	2	0	2	0
6	0	6	0	3	0	3	0
Date: 19/9/2022				**Date: 8/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	500	1	870	4	1780	4	2980
2	220	2	310	5	670	5	1540
3	0	3	0	6	30	6	340
4	0	4	0	Initial	0	Initial	0

5	0	5	0	1	0	1	0
6	0	6	0	2	0	2	0
Date: 26/9/2022				**Date: 9/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	2500	1	3110	3	1590	3	2120
2	790	2	1250	4	350	4	1020
3	430	3	770	5	0	5	150
4	10	4	50	6	0	6	0
5	0	5	0	Initial	0	Initial	0
6	0	6	0	1	0	1	0
Date: 27/9/2022				**Date: 10/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	2980	1	4390	2	1690	2	2410
2	1650	2	2110	3	670	3	1840
3	780	3	980	4	40	4	170
4	70	4	130	5	0	5	0
5	0	5	0	6	0	6	0
6	0	6	0	Initial	0	Initial	0
Date: 29/9/2022				**Date: 14/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	2330	1	3950	1	1450	1	1890
2	850	2	1530	2	390	2	670
3	200	3	410	3	0	3	30
4	0	4	10	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 4/10/2022				**Date: 15/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	2450	1	3200	Initial	1870	Initial	2450
2	770	2	1670	1	20	1	950
3	50	3	210	2	0	2	130
4	0	4	0	3	0	3	0
5	0	5	0	4	0	4	0
6	0	6	0	5	0	5	0
Date: 5/10/2022				**Date: 16/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	1370	1	2780	6	1430	6	1760
2	410	2	890	Initial	310	Initial	470
3	10	3	30	1	0	1	0
4	0	4	0	2	0	2	0
5	0	5	0	3	0	3	0
6	0	6	0	4	0	4	0
Date: 10/10/2022				**Date: 17/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	870	1	1050	5	1370	5	1890

2	90	2	230	6	230	6	710
3	0	3	0	Initial	0	Initial	10
4	0	4	0	1	0	1	0
5	0	5	0	2	0	2	0
6	0	6	0	3	0	3	0
Date: 11/10/2022				**Date: 19/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	710	1	1150	4	1395	4	1788
2	30	2	190	5	206	5	409
3	0	3	0	6	0	6	0
4	0	4	0	Initial	0	Initial	0
5	0	5	0	1	0	1	0
6	0	6	0	2	0	2	0
Date: 13/10/2022				**Date: 2/1/2023**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	780	1	990	3	2300	3	3450
2	20	2	70	4	940	4	1430
3	0	3	0	5	110	5	370
4	0	4	0	6	0	6	0
5	0	5	0	Initial	0	Initial	0
6	0	6	0	1	0	1	0
Date: 17/10/2022				**Date: 9/1/2023**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	730	1	960	2	6990	2	7010
2	10	2	90	3	5450	3	5990
3	0	3	0	4	4670	4	3450
4	0	4	0	5	1560	5	1890
5	0	5	0	6	340	6	510
6	0	6	0	Initial	0	Initial	0
Date: 20/10/2022				**Date: 12/1/2023**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	330	1	509	1	1550	1	1890
2	0	2	0	2	230	2	370
3	0	3	0	3	0	3	0
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0

Table A 12 PET bottle E. coli test outcomes of the monsoon and winter seasons

Monsoon Season				**Winter Season**			
TW-1		**TW-2**		**TW-1**		**TW-2**	
Serial (h)	**E. coli (CFU/100 ml)**	**Serial (h)**	**E. coli (CFU/100 ml)**	**Serial (h)**	**E. coli (CFU/100 ml)**	**Serial (h)**	**E. coli (CFU/100 ml)**
Date: 8/8/2022				**Date: 1/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	1120	1	1350	1	3670	1	4270
2	120	2	320	2	1150	2	2010
3	30	3	80	3	170	3	470
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 24/8/2022				**Date: 2/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	930	1	1480	1	3170	1	3990
2	270	2	640	2	790	2	980
3	30	3	150	3	0	3	0
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 21/9/2022				**Date: 3/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	1780	1	2190	1	3260	1	5670
2	480	2	760	2	70	2	1230
3	10	3	90	3	0	3	90
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 27/9/2022				**Date: 7/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	3590	1	4980	1	3200	1	4200
2	2130	2	3230	2	2310	2	3120
3	1010	3	2320	3	560	3	2010
4	320	4	750	4	120	4	670
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 4/10/2022				**Date: 8/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	1100	1	1780	1	2120	1	2870
2	390	2	770	2	970	2	1320
3	10	3	130	3	110	3	410

4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 5/10/2022				**Date: 9/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	1450	1	1980	1	1820	1	1990
2	310	2	670	2	760	2	920
3	0	3	0	3	80	3	370
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 10/10/2022				**Date: 10/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	1100	1	1790	1	201	1	2890
2	170	2	310	2	85	2	1160
3	0	3	0	3	17	3	420
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 11/10/2022				**Date: 14/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	870	1	1450	1	1770	1	1920
2	90	2	210	2	610	2	470
3	0	3	0	3	0	3	0
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 12/10/2022				**Date: 15/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	980	1	4670	1	1570	1	1900
2	270	2	2230	2	460	2	730
3	0	3	700	3	0	3	100
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 13/10/2022				**Date: 16/11/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	1360	1	1890	1	1780	1	1930
2	130	2	310	2	590	2	610
3	0	3	0	3	0	3	50
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 17/10/2022				**Date: 17/11/2022**			

Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	980	1	1370	1	1719	1	2167
2	190	2	630	2	163	2	193
3	0	3	50	3	0	3	0
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 18/10/2022				**Date: 19/12/2022**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	1010	1	1730	1	189	1	213
2	390	2	730	2	53	2	89
3	0	3	110	3	1	3	06
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 20/10/2022				**Date: 2/1/2023**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	555	1	870	1	3460	1	4010
2	10	2	20	2	1450	2	2310
3	0	3	0	3	370	3	1010
4	0	4	0	4	0	4	430
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 26/10/2022				**Date: 9/1/2023**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	770	1	1070	1	1990	1	2470
2	30	2	190	2	430	2	750
3	0	3	0	3	0	3	0
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0
Date: 27/10/2022				**Date: 12/1/2023**			
Initial	50000000	Initial	50000000	Initial	50000000	Initial	50000000
1	1570	1	2140	1	2330	1	2570
2	52	2	1430	2	760	2	860
3	5	3	170	3	10	3	50
4	0	4	0	4	0	4	0
5	0	5	0	5	0	5	0
6	0	6	0	6	0	6	0

APPENDIX III: SODIS PERFORMANCE IN FIELD EXPERIMENTS

Table A 13 SODIS with H_2O_2 post-physicochemical parameters outcome

Location	Source	Test waters	pH	DO	EC	Temperature of water	Turbidity	Solar irradiance	Temperature panel
Mirpur	Piped	S-1	8.49	2.99	378	38.5	6.67	550.37	45.45
Mirpur	piped	S-2	8.4	4.88	367	38.1	5.59	550.37	45.45
Mirpur	tubewell	S-3	8.3	3.12	357	38.2	3.27	550.37	45.45
Mirpur	piped	S-4	8.3	6.34	326	38.5	0.4	550.37	45.45
Mirpur	piped	H-1	8.36	6.81	398	38.4	3.14	550.37	45.45
Malibagh	piped	H-2	8.24	6.7	406	38.5	0.21	550.37	45.45
Uttara sector 4	piped	H-3	8.33	6.76	329	38	0.42	550.37	45.45
Bashundhora	piped	H-4	8.28	7.24	399	38.1	0.28	550.37	45.45
Mirpur	Piped	R-1	8.49	7.15	350	37.2	1.93	503.64	40.08
Mirpur	piped	R-2	8.4	6.87	344	37.1	2.37	503.64	40.08
Mirpur	tubewell	R-3	8.3	4.99	344	37.2	1.27	503.64	40.08
Uttara	piped	R-4	8.3	7.43	262	37.5	1.85	503.64	40.08

Table A 14 SODIS post-physicochemical parameters outcome

Location	Source	Test waters	pH	DO	EC	Temperature of water	Turbidity	Solar irradiance	Temperature panel
Mirpur	Piped	S-1	7.96	6.93	332	37.4	6.25	681.87	49.16
Mirpur	piped	S-2	7.54	6.72	353	37.2	5.48	681.87	49.16
Mirpur	tubewell	S-3	7.43	6.8	348	37.1	3.26	681.87	49.16
Mirpur	piped	S-4	7.49	6.27	251	37	0.35	681.87	49.16
Mirpur	piped	H-1	7.47	6.72	270	37.2	3.02	681.87	49.16
Malibagh	piped	H-2	7.37	6.39	389	37.3	0.16	681.87	49.16
Uttara sector 4	piped	H-3	7.48	6.75	274	37.1	0.35	681.87	49.16
Bashundhora	piped	H-4	7.43	6.76	261	37.4	0.22	681.87	49.16
Mirpur	Piped	R-1	8.2	7.15	350	37.2	1.93	595.72	43.11
Mirpur	piped	R-2	8.15	6.87	344	37.1	2.37	595.72	43.11
Mirpur	tubewell	R-3	8.11	4.99	344	37.2	1.27	595.72	43.11
Uttara	piped	R-4	8.16	7.43	262	37.5	1.85	595.72	43.11