OPTIMIZATION OF SOLAR DISINFECTION SYSTEM FOR HOUSEHOLD WATER TREATMENT

By

Awrajaw Dessie Zeleke

A thesis submitted to the Department of Environmental Health Sciences and Technology, College of Public Health and Medical Sciences, Jimma University in partial fulfillment of the requirements for the degree of Master of Science in Environmental Science and Technology, *specialty in Environmental Technology*

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Jimma, Ethiopia

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ABSTRACT

Waterborne diseases are still common in developing countries as drinking water sources are contaminated and feasible means to reliably treat and disinfect these water sources are not available. Many of these developing countries are in the tropical regions of the world where sunlight is plentiful. The objective of this study was to optimize solar disinfection system for household water treatment. An experimental study was carried out from April1 to June7, 2011 at the laboratory of Environmental Health Sciences and Technology, Jimma University. Inactivation of microbes was tested at different water and environmental conditions (turbidity, pH, water depth, dissolved oxygen concentration, water temperature, container type, color of container, solar intensity) using fecal coliform as test organism. Optimization of solar disinfection (SODIS) system was done by testing the efficiency of SODIS at optimized conditions (at turbidity of 2NTU, pH 7, dissolved oxygen concentration of 6.52mg/L, half-surfaced black colored PET bottle, and water depth of 10 cm). Fecal coliform enumeration was performed by pour plate method. The results showed that complete fecal coliform inactivation was found on clear water samples having 2nephlometric turbidity unit (NTU) with six hour exposure time. On the contrary, complete inactivation was not found for a water sample having turbidity of 13NTU. Statistically significant difference on the rate of fecal coliform inactivation was not found on water samples having different pH value in the range of 5.5 to 9 ($p=0.05$). Depth of water has shown significant impact on inactivation of fecal coliform ($p=0.015$). After 3 hour of exposure time, higher log inactivation (2.91 ± 0.001) was found on water depth of 5.5 cm and the least log inactivation (0.474 ± 0.044) was found on water depth of 10 cm. Higher log inactivation (0.79 ± 0.03) was found on colorless Polyethylene terephthalate (PET) bottle and the least log inactivation (0.16 ± 0.03) was found on black colored PET bottles. Aerating raw water samples prior to exposure enhanced the inactivation rate by a factor of 2.2 even if the difference was not statistically significant ($p=0.05$). Exposing raw water under half-surfaced black colored PET bottle has shown significant increment on the rate of fecal coliform inactivation. Place of bottle exposure didn't show statistically significant effect on SODIS. Intensity of light has also shown significant effect on the rate fecal coliform inactivation. After 3 hour of exposure, 1.65 ± 0.05, 0.95 ± 0.03 and 0.2 ± 0.01 log inactivation was observed on raw water

samples exposed to sunlight having a cumulative solar irradiance of 3.99kWh/m^2, 2.77kWh/m^2 and 0.6026kWh/m^2 respectively. Complete microbial inactivation was observed within exposure time of 3 to 4.5 hour, on raw water samples having 820CFU/mL under optimized conditions for water disinfection. Bacterial re-growth was not observed after solar disinfection, confirming that the inactivation was irreversible. The results demonstrated that under optimized conditions for water (at turbidity of 2NTU, pH 7, dissolved oxygen concentration of 6.52mg/L, half-surfaced black colored PET bottle, and water depth of 10 cm). Complete fecal coliform inactivation can be achieved within an exposure time of less than four hour in all parts of the world which are receiving solar irradiance of 3.99kWh/m^2 and above.

Key words: *Bacteriologically contaminated water, water disinfection, household water treatment, solar radiation*

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ACRONYMS

CIS	Corrugated Iron Sheet
DEHA	Di (2-ethylhexyl) adipate
DEHP	Di (2-ethylhexyl) phthalate
DNA	Deoxyribonucleic acid
DO	Dissolved oxygen
E.coli	Eshershia coli
FC	Fecal Coliform
FDRE	Federal Democratic Republic of Ethiopia
Hr	Hour
MDGs	Millennium Development Goals
MOFED	Ministry of Finance and Economic Development
MoH	Ministry of Health
MoWR	Ministry of Water Resources
NOM	Natural Organic Matter
NTU	Nephlometric Turbidity Unit
PET	Polyethylene terephthalate
SODIS	Solar disinfection
THMs	Trihalomethanes
UN	United Nation
UNICEF	United Nations International Children's Emergency Fund
UV	Ultra Violet
WaSH	Water, Sanitation and Hygiene
WHO	World Health Organization

CHAPTER ONE
INTRODUCTION

1.1. Background

Safe drinking water, sanitation and good hygiene are fundamental to health, survival, growth and development. However, these basic necessities, WaSH in general and safe drinking water in particular is still a problem for many of the world's poor people. Globally more than 1.1 billion and about 2.6 billion people are deprived of safe drinking water and basic sanitation respectively. Access to safe drinking water and basic sanitation are basic inputs in realizing concrete work of prevention of death or reduction of the burden of diseases like, cholera, diarrhea, ascaris, dracunliasis, hookworm, schistosomiasis and trachoma (WHO and UNICEF, 2006).

As Thomas (2009) stated in his finding, providing safe, reliable, piped-in water to every household is an essential goal, yielding optimal health gains while contributing to the Millennium Development Goal (MDG) targets for poverty reduction, nutrition, childhood survival, school attendance, gender equity and environmental sustainability. While strongly committed to this goal and to incremental improvements in water supplies wherever possible, the World Health Organization (WHO) and others have called for targeted, interim approaches that will accelerate the heath gains associated with safe drinking-water for those whose water supplies are unsafe.

So, as part of its MDGs, the UN expressed its commitment by 2015 to reduce by half the proportion of people without "sustainable access to safe drinking water" (UN, 2000). By this measure, progress is being made, with many countries on track to meet the targets. Nevertheless, current trends will leave hundreds of millions unserved by the target date (WHO and UNICEF, 2006). Three quarters of these will live in rural areas where poverty is often most severe and where the cost and challenge of delivering safe water are greatest. In sub-Saharan Africa, where many countries are falling short of MDG targets, current trends will actually result in a 47 million person increase in the number of unserved. Thus, the health benefits of safe drinking water, especially in preventing diarrhoea, which kills 2.2 million annually, including 17% of fewer than five children in

developing countries (WHO, 2010) will remain elusive for vast populations for years to come.

Ethiopia is one of the developing countries which strive in achieving the millennium development goal on the area of safe water and sanitation. It has already established a £75 million budget programme that will provide water and sanitation to 3.2 million people and schools in small towns and rural areas (MOFED and UN, 2004). Though such encourageable efforts are carried out, water sources in Ethiopia are potentially liable to biological contamination due to improper protection and treatment, lack of periodic maintenance and sanitary survey. The problem is also highly rampant in Jimma, Ethiopia where this particular study is taken place.

The study area (Jimma town) is characterized with annual average maximum temperature of 27.69^{o}C to 28.17^{o}C and annual minimum temperature of 11.27^{o}C to 12.7^{o}C. And it has shown seasonal variation, in which higher maximum temperature has been seen in January, February; March, October, November and December. Whereas, in May, June, July, August and September, the lowest minimum temperature has been registered (Kumela, personal communication, 2010). The five year temperature profile of Jimma town is found attached in Annex II.

The solar duration profile of the study area is characterized by annual average solar duration in the range of 6.51 hour (Hr) to 6.97 Hr. Longest sunshine duration has been observed in January, February; march, April, October, November and December and the shortest sunshine duration has been observed in June, July, August and September (Personal communication, Kumela, December 13, 2010). The five year sun shine duration profile of Jimma town is found attached in Annex II. A water treatment technology, which uses the advantage of optimum ambient temperature and sunshine duration, can be planned as best alternative treatment option in Jimma and similar areas.

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1.2. Statement of the Problem

Worldwide over 1.1 billion people are at risk due to lack of access to safe drinking water (WHO, 2003a). And about 5000 young children are dying due to water borne diseases every day (WHO, 2004); this problem is very severe in developing countries especially in Ethiopia (FDRE AND MoWR, 2004).

Conventional water treatment plants in Ethiopia which are supposed to curb the prevailing water borne diseases are found in limited number and concentrated in large towns and cities and even the existing plants are vulnerable for frequent supply interruption and technical malfunction. Expanding treatment plants in rural areas and small towns is unthinkable, due to geographical location, limited availability of chemicals, energy, investment costs and lack of know-how (SANDEC/EAWAG, 2002).

Different literatures illustrated that some household treatment systems are also found to be unsatisfactory. According to James (2004), Darby and his colleagues (1995) and Lawrence et al, (2005) chlorination is not consumer friendly due to chemical toxicity, production of THMs and its non effectiveness against intestinal parasites *Cryptosporidium parvum, Giardia lambia* and *Entamoeba histolytica*. Boiling is also not always feasible, due to cost and its indoor air pollution effect (McGuigan et al, 1999). Commercially produced filters are relatively costly, and filters made of locally available material are generally of limited treatment efficiency with regard to microbiological water quality improvement (Meierhofer, 2006).

The problems described above call for the development of alternative treatment technique that are technically simple, practical and easy to apply at household level. Solar disinfection can be one of the alternative household treatment methods that are effective, practical and simple enough to be applied by individuals or households. This technology can be applicable in Ethiopia where the peoples are enjoying 13 months of sunshine and receiving a cumulative solar irradiance of 5.26 kWh/m^2 (GTZ Eastern Africa Energy Resource Base, 2010) if detailed study is carried out. Studies regarding solar disinfection in Ethiopia are very limited; one study done by Ambelu (2001) in Jimma has shown that,

there is a conducive condition for applying the technology if enhancement of the efficiency of bacterial elimination done.

Therefore, optimization of the SODIS system for household water treatment technology is very important to achieve better efficiency at optimized condition and to answer questions such as at what intensity of solar radiation, turbidity, temperature and pH of water, exposure time and in which color and type of container SODIS is effective in Ethiopian weather condition. In this regard, this research was tried to address such gaps and related problems seen in household water treatment systems or technologies.

CHAPTER TWO

LITERATURE REVIEW

2.1. Disinfection Options

Water disinfection is the removal, deactivation or killing of pathogenic microorganisms. It is an important step in ensuring that water free from pathogenic microorganisms and safe to drink. In most of the cases, water systems add disinfectants to destroy microorganisms that can cause disease in humans (National Environmental Services Center, 2009).

Water treatment system can be established at central place, but when large community-wide water treatment and distribution systems are not available, people may treat water individually or for their families. There are several water disinfection options available for small-scale use. These disinfection methods can be divided into two categories. The first category is chemical disinfection which includes methods such as chlorination and iodine treatment. Chlorine is the most common method of drinking water treatment due to its effectiveness by inactivating several types of pathogens and its low chemical cost. Chlorinated water also retains a residual that further protects from recontamination after the water is treated (Burch and Thomas, 1998). Iodine is a second chemical treatment option and one that is commonly used by hikers and backpackers in different countries as an effective and transportable method of water treatment. However, iodine is not used to treat large amounts of drinking water because; it costs approximately 20 times more than chlorine (Ellis, 1991). Chemical costs may render such options unavailable to low-income families. Other reasons chemical treatment is undesirable include the training needed to calculate proper chemical dosages and the unpleasant odor and taste of the drinking water. An additional disadvantage with all chemical treatment methods is that chemicals oxidize over time and therefore have limited shelf lives.

The other treatment method is physical treatment which includes boiling water and UV treatment. Boiling water is a simple process, but requires resources that may not be readily available. This is especially true for areas concerned with the effects of desertification and deforestation because boiling one liter of water requires approximately

one kilogram of wood. The process is also, time consuming and boiling water has been found to impart a disagreeable taste (Acra *et al*, 1984 and Ellis, 1991). UV radiation is the process where water is exposed to a lamp generating light at a wavelength of approximately 250 nm. This wavelength is in the middle of the germicidal band and is responsible for damaging the DNA of bacteria and viruses. However, UV treatment is only effective for low turbidity waters and therefore pretreatment such as filtering is required for poor water quality sources. Also, developing and maintaining UV radiation treatment requires the initial cost of purchasing equipment, a knowledgeable operator to properly use the equipment, and sufficient funds for maintenance. For areas that are unable to financially support such a treatment scheme, UV radiation is not a viable treatment option (Burch and Thomas, 1998).

2.2. Solar disinfection

Solar disinfection is a simple water treatment method using natural solar radiation to inactivate pathogens commonly found in drinking water (Figure 1). This technology involves simply filling transparent PET bottles with contaminated water and exposing them to direct sunlight. SODIS utilizes the power of the sun to inactivate microorganisms using UV-A radiation and increased temperature. Because this technology is so simple, both in concept and application, it is easily applicable in the developing world where safe water resources are scarce. However, the success of SODIS is dependent on a number of conditions, including climate and water clarity.

Figure 1. SODIS water treatment using sunlight (Doekhie, 2008)

The SODIS methodology utilizes both the infrared and ultraviolet spectra of radiation to disinfect water (McGuigan *et al*, 1999). Wegelin and his colleagues (1994) described

that, visible violet and blue light have little disinfection capability. However, the other components of sunlight, UV-A, UV-B, and UV-C radiation, are able to inactivate organisms. UV-C radiation, at approximately 260 nm, has the greatest potency because it corresponds to maximum absorption by DNA. Some countries use UV-C (at 254 nm) in their municipal treatment plants to disinfect drinking waters and secondary wastewater effluents because of its germicidal ability to initiate changes in nucleic acids and other structures such as enzymes and immunogenic antigens. However, near ultraviolet (UV-A) light has been found to be the most significant component of sunlight that is responsible for the inactivation of microorganisms, with an increase in effectiveness due to the synergistic effects of UV-A and violet light. This is because the UV-C component of solar radiation does not reach the earth.

Acra *et al* (1984) compared the germicidal effects of different wavelengths of light by measuring the average number of coliforms inactivated upon exposure to the varying wavelengths. They found that the most significant decrease in viable bacterial organisms occurred when they were exposed to wavelengths between 260 to 350 nm (compared to inactivation at wavelengths between 550 to 850 nm).

Natural sunlight has been shown to have germicidal properties. Wegelin *et al* (1994) found that a fluence of natural light of approximately 2000 kJ/m^2 or 555 Wh/m^2 resulted in a 3-log inactivation of *E. coli*. This is equivalent to 5 hours of midday summer sun as measured at Duebendorf, Switzerland. Virus's required higher fluences than bacteria for the same inactivation level: F2 coliphage, rotavirus and encephalomyocarditis virus required 9,000, 6,800, and 34,300 kJ/m^2 for 3-log inactivation. Davies and Evison (1991) also found solar disinfection to be effective, with 1 log inactivation of *E. coli* in 10 hours of exposure to sunlight, and 4 log inactivation of *Salmonella typhimurium* in 4 hours of exposure.

2.2.1. Mechanisms of Solar Disinfection

Microbial inactivation is contingent on the disinfection mechanisms of DNA alteration, photo-oxidative destruction, and thermal pasteurization damaging cellular defenses.

Thermal inactivation

The first mechanism of disinfection utilized by SODIS is thermal inactivation of microorganisms. Microorganisms can only function within certain temperature ranges because of limitations of their metabolism. When these temperatures are exceeded, proteins and other macromolecules are denatured and the microorganism loses its ability to function properly (Madigan, 2000). It is possible to disinfect drinking water without reaching boiling temperatures. This process, known as pasteurization, is different from sterilization in that sterilization inactivates all microorganisms, including heat-resistant spores. However, heat-resistant spores are harmless for humans to eat, and thus pasteurized water is sufficient for drinking purposes. For *E.coli*, a pathogen causing diarrhea, pasteurization occurs above 70^{o}C (Wegelin *et al*, 1994).

Microbial inactivation is also possible at temperatures below pasteurization temperatures. Between 20 to 40^{o}C, the inactivation rate of fecal coliforms remains constant (Wegelin *et al*, 1994). Above temperatures of 50^{o}C, microbial inactivation is enhanced through the synergistic effects of UV and temperature. However, at temperatures lower than 20^{o}C, the thermal inactivation effects are negligible and therefore photo biologic effects (i.e. UV and photo-oxidative) are the main modes of disinfection.

The temperature of the SODIS system is increased by the absorbance of both long and short wave radiation by the bottle and the water, which then generates heat in the system. Some of this heat is re-emitted as back-radiation from the bottle into the atmosphere. Additionally, the system gains or looses heat through convective exchange with the air. The addition of wind can enhance convective exchange, thus increasing the rate of heating/cooling. In order to prevent rapid cooling, a wind-shield would be desirable to protect the bottles from heat loss, provided the shield does not shade the bottles. Additionally, uneven exposure can cause uneven heating, which causes a thermal gradient and induces circulation in the bottle (Wagelin *et al*, 1994).

Because it is difficult to determine when water reaches pasteurization temperatures without thermometers, a device known as a Temperature Sensor has been developed for

use in developing countries (SANDEC/EAWAG, 2002). This device contains soy wax, which melts just below pasteurization temperatures. When the wax melts it drops to the bottom of the indicator, so that even if the water cools again it is obvious that the threshold temperature was reached.

DNA Alteration by UV

The second mechanism of solar disinfection is alteration of DNA. According to Raven and Johnson (1996), to assure eradication of pathogenic organisms, DNA must be damaged faster than microbes can repair it. DNA has a maximum UV absorbance at around 260 nm that causes mutagenesis and results in cellular death. Absorbed UV light causes adjacent thymine bases to covalently bond together, forming thymine dimers.

When this damaged DNA replicates, nucleotides do not complementary base pair with the thymine dimers and this terminates replication. Organisms may also replace thymine dimers with faulty base pairs, which causes mutations, leads to faulty protein synthesis, and may result in death.

The effect of thymine dimer formation may be reversed to some extent by exposure to visible light in a process called photoreactivation. Visible light can activate the enzyme DNA photolyase that breaks the bond joining the thymine bases. DNA can also be repaired by excision, where DNA polymerase and DNA ligase cut out damaged DNA and replaces it with a stretch of error-free DNA (Mathews and Van Holde, 1996).

When DNA damage is too extensive for photoreactivation and excision mechanisms, the cell coordinates the expression of a large number of unlinked genes, which enhance capacity for DNA repair and inhibit cell division. This orchestrated activation of diverse metabolic functions to repair damaged DNA damage has been called the SOS response (Mathews and Van Holde, 1996). The manifestation of the SOS response eventually leads to DNA repair and returns the cell to its normal growth cycle. Extreme UV-resistance of some bacteria is a result of efficient DNA repair machinery along with powerful scavenging activity of cells toward various reactive oxygen species generated by UV

irradiation. To ensure UV-A radiation overpowers pathogenic cellular defense mechanisms; a sunlight intensity of 500 W/m^2 should be applied for 3 to 5 hours to induce lethal effects (SANDEC/EAWAG, 2002).

Photo-oxidative Disinfection

Photo-oxidative disinfection is the third mechanism of microorganism destruction by sunlight. UV-induced reactive oxygen species can be lethal if they are present in numbers higher than the organism is capable of attenuating. Natural dissolved organic matter can absorb ultraviolet radiation to induce photochemical reactions (Miller, 1998). The energy transfer of a high-energy photon to absorbing molecule produces highly reactive species such as superoxides (O_2^-), hydrogen peroxides (H_2O_2), and hydroxyl radicals (OH^-) (Stumm and Morgan, 1995; Miller, 1998). These highly reactive species in turn oxidize microbial cellular components such as nucleic acids, enzymes, and membrane lipids, which kill the microorganisms (McGuigan *et al,* 1999).

In their defense, microorganisms have evolved powerful scavenging activity toward various reactive oxygen species (Yun & Lee, 2000). A common defense against superoxide is carried out by a group of enzymes called superoxide dismutase. Superoxide dismutase catalyzes the following reaction, which decreases the lifetime of superoxide by a factor of 10^9.

$$O_2^- + O_2^- + 2H^+ \longrightarrow H_2O_2 + O_2 \quad \ldots\ldots 1$$

Microbes cope with hydrogen peroxides using two groups of enzymes called catalases and peroxidases. Catalases eliminate hydrogen peroxide formed in reaction 1, by:

$$2H_2O_2 \longrightarrow O_2 + 2H_2O \quad \ldots\ldots 2$$

while peroxidase uses the reducing power of *NADH*:

$$H_2O_2 + 2NADH \longrightarrow 2NAD^+ + 2H_2O \quad \ldots\ldots 3$$

In addition to superoxide dismutases, catalases, and peroxidase, there is an additional orchestrated defense observed in *E. coli* (Yun & Lee, 2000).

Superoxide and hydrogen peroxide are not themselves dramatically devastating, but they can produce hydroxyl radicals, which form a juggernaut of oxidative power, in two ways as it is expressed in equation 4 and 5, below:

1. $H_2O_2 + e^- + H^+ \longrightarrow H_2O + OH$……4

2a .$M^{3+} + O_2^- \longrightarrow M^{2+} + O_2$……5(1)

2b. $M^{2+} + H_2O_2 \longrightarrow OH^- + M^{3+} + OH$……5(2)

where M is a metal

After the hydroxyl radical is formed, it reacts extremely fast with almost every type of molecule found in living cells causing tremendous damage.

For photo-oxidative disinfection to occur, sufficient levels of oxygen need to be initially present. This was demonstrated by Reed in 1997 by comparing aerobic and anaerobic inactivation rates of *E. coli* and *Ent. faecalis* using solar disinfection. The aerobic rates of disinfection are much faster than the anaerobic rates, indicating that the presence of oxygen is essential for the rapid solar destruction of *E. coli* and *Ent. faecalis.*

Desired aeration can be achieved on a practical level by vigorously shaking the SODIS containers before sunlight exposure. This is especially important for stagnant water sources where the levels of dissolved oxygen are questionable (SANDEC/EAWAG, 2002).

2.2.2. Inactivation of Indicator Organisms and Pathogens

SODIS efficacy is usually established through the inactivation of indicator organisms, due to time scarcity, financial constraint and difficulty of monitoring the inactivation of each and every pathogen, but effects on actual pathogens have also been investigated by different investigators. The criteria to be selected as indicator organism and organisms commonly used as indicator is discussed as follows, below:

Indicator Organisms

Indicator organisms are a basic monitoring tool used to measure both changes in environmental water quality or conditions, and the potential presence of hard-to-detect

pathogenic organisms. An indicator organism provides evidence of the presence or absence of a pathogenic organism that survives under similar physical, chemical, and nutrient conditions (WHO, 2001). Billions of organisms can be generated from one person a day that is very difficult to isolate and identify and it is time and money consuming. Due to this very reason indicator organisms which are easily identifiable organisms is used to suggest the existence of pathogenic ones are becoming utilized for identification of pathogenic organisms from am environmental sample(Oates, 2001).

According to Gerba (2009), ideal indicator organisms have the following characteristics:

- The organism should be useful for all types of water
- The organism should be present whenever enteric pathogens are present
- The organism should have a reasonably longer survival rate than the hardest enteric pathogen
- The organism should not grow in water
- The testing method should be easy to perform
- The density of the indicator organism should have some direct relationship to the degree of fecal pollution
- The organisms should be a member of the intestinal microflora of warm-blooded animals

Unfortunately, no single group of organism meets all of the above criteria. Consequently, multiple indicator organism groups are often used. The two most common ones are total and fecal coliform.

Total coliform

The coliform group includes a number of genera and species of bacteria which have common biochemical and morphological attributes that include gram negative, non-spore forming rods that ferment lactose in 24 to 48 hours at 35^{o}C (WHO,2001)

According to Oates (2001) the absence of coliform bacteria in 100 ml of drinking water indicates the absence of other pathogenic microorganisms. So, it serves as pollution indicator or microbial inactivation efficiency indicator.

Fecal coliform

According to New Hampshire, Department of Environmental Services (2003); the presence of fecal coliforms is a reliable indicator of fecal contamination. However, the absence of fecal coliforms does not equate to the absence of fecal contamination, which is one of the shortcomings of using fecal coliforms. The source of the contamination could be animal excreta, wastewater, sludge, septage, or biosolids. As Maier (2000) described, each of these wastes is derived entirely or at least in part from the feces and urine of warm-blooded animals. Since enteric pathogens and fecal coliforms are also excreted by warm-blooded animals, detection of fecal coliforms indicates the potential presence of pathogens. Generally both total coliform and fecal coliform can be used to determine the efficiency of solar disinfection.

2.2.3. Factors affecting solar disinfection efficiency

Induced DNA alteration, photo-oxidative destruction, and thermal effects are the commonest working principle of solar disinfection. For effectiveness of these parameters, the environment must be sunny and hot enough, the water must be clear enough to allow the light to penetrate, and the type of bottle being used must not substantially hinder these processes. In addition, for this technology to become a reality, people must be able to afford it, and they must believe in it, or it would never be applied.

According to Mahafooz (2009), there are factors that enhance or reduce the efficiency of solar disinfection. These factors are:

a) <u>factors reducing the efficiency of SODIS;</u>
    1. Turbid Water,
    2. Bottles with low UV-transmittance (old, scratched, blind and colored bottles),
    3. Low UV-A radiance like cloudy sky & low air temperature,
    4. Bottles placed upright instead of horizontal,
b) <u>factors enhancing the efficiency of SODIS;</u>
    1. Using raw water of low turbidity,
    2. Placing bottles horizontally or at a flat angle toward the sun,
    3. Placing bottle on a corrugated iron sheet or underground which reflects sunlight,

4. Exposing the bottle during 2 consecutive days if the sky is 100% cloudy,
5. Avoiding falling shadow on the bottles, and
6. Using simple solar collector which can be constructed from Aluminum and bucket

Effect of Weather and Climate

The efficiency of the SODIS process is dependent on the amount of sunlight available. Solar (UV-A) intensity shows both seasonal (because of changes in the earth's angle of tilt) and daily variation. This variation is depends on the latitude and is mainly responsible for the climate in that region (SANDEC/EAWAG, 2002).

Cloudy sky

As Sommer and his colleagues (1997) stated that the UV dose received during one day exposure may not be sufficient for satisfactory water quality achievement if the sky is covered with cloud. The result, he and his colleagues has obtained shows that there was about three times more energy available for heating and irradiation on a day with a clear sky than on a completely overcast day. Same result also obtained in the study undertaken in Kenya by Joyce and his colleagues in 1996; as there result indicated that a complete range of cloud and sunshine conditions was encountered during these experiments. So, due to the variation of weather conditions in Kenya, solar power levels varied from a maximum of 89mW/cm^2 during full sunshine to a minimum of 3mW/cm^2 during overcast.

Air Temperature and Wind

Air temperature and wind are the two climatic factors influencing the water temperature, which has a direct impact on the efficiency of the process. According to Wegelin(1998),water temperatures between 20 and 40 °C do not affect the inactivation of bacteria exposed to UV-A and visible light radiations. Synergetic effects were observed at a threshold water temperature of 50°C. Compared to lower water temperatures, the required fluence to inactive E. coli is more than 3 times smaller at this temperature. Viruses, however, are more sensitive to water temperature changes. By the increment of

water temperature from 20 to 40^{O}C, the inactivation rate of sunlight for bacteriophages was increased by a factor of three. Enteroviruses and rotaviruses are even more sensitive to the same water temperature change; i.e., the inactivation rates increased by a factor 2.4 and 3.7, respectively.

Geographical Variation of Solar Radiation

According to Mahafooz (2009), the most favorable regions for SODIS are located between latitude 15 °N and 35 °N (as well as 15 °S and 35 °S). These semi-arid regions are characterized by the highest amount of solar radiation. Over 90% of the sunlight touches the earth as direct radiation due to the limited cloud cover and rainfall (less than 250 mm rain and usually more than 3000 hours of sunshine annually).

Developing countries including Ethiopia which are deprived of safe water supply are located between latitudes 35 °N and 35 °S. This can be taken as a good opportunity for them to rely on solar radiation as an energy source for disinfection of drinking water. The following figure shows, effective areas of solar disinfection.

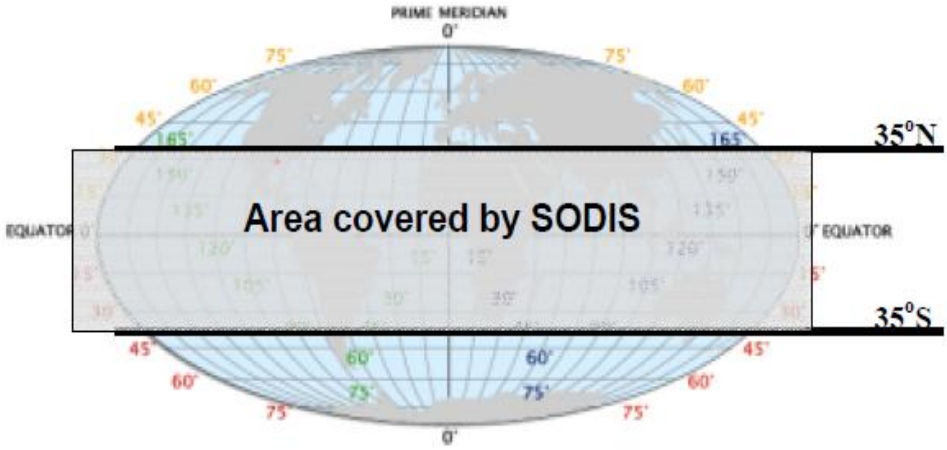

Figure 2. Effective area for SODIS application (Parsons, 2001)

For practical application of SODIS in developing countries, where there is no accurate way of judging cloud cover or bottle water temperature, an exposure time of two days has been recommended as the standard SODIS procedure (Oates, 2001). Outside of the regions mentioned above, SODIS works sub-optimally because of the limited availability

of solar radiation and the colder climate. Often longer exposure can ensure the effectiveness of SODIS under these conditions, as the UV and photo-oxidative effects of the sunlight dominate the disinfection process, as opposed to thermal effects. However, the optimal length of exposure under different conditions has not been extensively investigated in the literature.

Seasonal and Daily Variations of Solar Radiation

A seasonal and daily variation of solar radiation is one of the parameter that affects the effectiveness of solar radiation. Because of changes in the earth's angle of tilt, the intensity of UV-A, shows both seasonal and daily variation. This variation is depends on the latitude and is mainly responsible for the climate in that region (SODIS technical note n^{o} 6). Regions near the equator encounter lower variance of light intensity during the year than regions in the northern or southern hemisphere (Mahafooz, 2009).

According to SANDEC/EAWAG (2002) the seasonal differences of solar radiation are important for the applicability of solar water disinfection. Prior to the implementation of SODIS in a specific place, the seasonal radiation intensities need to be assessed. A total solar radiation intensity of at least 500 W/m^2 is required for approximately 6 hours for SODIS to be effective. The average daily radiation reaching the ground in Ethiopia as it is described in GTZ Eastern Africa Energy Resource Base (2010) is 5.26 kWh/m^2. This varies significantly during the year, ranging from a minimum of 4.55 kWh/m^2 in July to a maximum of 5.55 kWh/m^2 in February and March. On regional basis, the yearly average radiation ranges from values as low as 4.25 kWh/m^2 in the areas of Itang in the Gambella regional state (western Ethiopia), to values as high as 6.25 kWh/m^2 around Adigrat in the Tigray Regional state (northern Ethiopia). The intensity solar radiation in Ethiopia has shown, as there is a room for applying SODIS technology and it is comparable with the recommended radiation intensity for inactivation of microbes, which is 555Wh/m^2.

And according to Sommer and his colleagues (1997) the solar radiation intensity is also subject to daily variations. With increasing cloudiness, less radiation energy is available. During completely overcast days, the UV-radiation intensity is reduced to one third of the intensity recorded during a cloudless day. During very cloudy days, the SODIS bottles

have to be exposed for two consecutive days to reach the required radiation dose and to ensure the complete inactivation of the pathogens.

Generally, the SODIS efficiency is dependent on the amount of solar energy available:

1. Expose the bottle to the sun for 6 Hr if the sky is cloudless or up to 50% cloudy (SANDEC/EAWAG, 2002).
2. Expose the bottle to the sun for 2 consecutive days if the sky is more than 50% cloudy (SANDEC/EAWAG, 2002).
3. At a water temperature of at least 50 °C, one hour exposure time is sufficient (Mahafooz, 2009).

Effect of Physical and Chemical Water Quality

Water Turbidity

Turbidity is a principal physical characteristic of water and is an expression of the optical property that causes light to be scattered and absorbed by particles and molecules rather than transmitted in straight lines through a water sample. It is caused by suspended matter or impurities that interfere with the clarity of the water. These impurities may include clay, silt, finely divided inorganic and organic matter, soluble colored organic compounds, and plankton and other microscopic organisms (USEPA, 1999).

Due to inhibition of light penetration by highly turbid water, the efficiency of SODIS process becomes deteriorated (Oates, 2001). Study done in Jimma, Ethiopia has shown turbidity and perpendicular depth of water during sunlight exposure was found to be a predictor of solar disinfection efficiency on FC reduction (Ambelu, 2001). This may be in part due to shielding of organisms by particles (Kehoe *et al.*, 2001, McGuigan *et al.*, 1999 and Sommer *et al.*, 1997). According to the study done by Sommer and his colleagues (1997) the percent UV-A radiation remained at different depths of water sample found to be highly correlated with turbidity level of water samples; the percent UV-A radiation remained along the water depth becomes drastically reduced in water samples that has higher turbidity level than the water sample with lower turbidity level. Therefore, for effective solar disinfection, the turbidity level of waters should be less than

30NTU (Nephelometric Turbidity Units) to ensure safe drinking water (SANDEC/EAWAG, 2002).

As it is indicated in SANDEC/EAWAG (2002) if the water turbidity is higher than 30NTU, the water needs to be pretreated before being exposed. Bigger particles and solids can be eliminated by storing the raw water for one day and letting the particles settle to the bottom. Afterwards the water is decanted. Solid matter can be separated by filtration, using a sand layer or a cloth. Turbidity can also be reduced by flocculation /sedimentation using aluminium sulphate or crushed *Moringa oleifera* seed (Bina *et al*, 2007).

Oxygen

SODIS is more efficient in water containing high levels of oxygen. Sunlight produces highly reactive forms of oxygen (oxygen free radicals and hydrogen peroxides) in the water. These reactive molecules react with cell structures and kill the pathogens (Reed, 1997).

Findings has shown that inactivation of bacteria (*E.coli*, *Enterococcus faecalis*, *Streptococcus faecalis*, faecal coli forms) is much more efficient in aerobic than in anaerobic conditions. Field tests confirmed that the shaking of bottles enhances SODIS efficiency (Mahafooz, 2009).

According to Reed (1997) and Kehoe and his colleagues (2001) aeration of the water can be achieved by shaking the ¾-filled bottle for about 20 seconds before the bottle is filled completely and exposed to the sun. Recent research revealed that the bottles should be shaken only at the beginning of the SODIS process. Once the bottles are exposed to the sun, they should not be moved anymore, as continuous shaking of the bottles during the solar exposure will reduce the efficiency of the process.

Material and Shape of Containers

Container shape and color may have significant impacts on the effectiveness of solar disinfection. The bottle shape may interfere with the sun's disinfection capabilities; as the sun moves across the sky, the intensity will change and may be reduced depending on the bottle shape. Acra *et al* (1984) recommend using round, conical bottles as opposed to square or irregularly shaped containers. However, the major limiting factor is the availability of the bottles themselves, with variables such as plastic thickness and light transmittance characteristics being difficult to assess in the field.

Acra *et al* (1984) also noted that colorless containers allow the most transmittance of ultra-violet wavelengths and are therefore the optimal choice for use in solar disinfection. Blue and violet tinted containers also transmit radiation, yet other colors, such as orange, yellow, red and green, will absorb wavelengths with the most lethal bactericidal effects and therefore must be avoided (IDRC, 1998). With regard to pasteurization, a water sample exposed to sunlight increases in temperature due to the red and infrared components of sunlight. Blue containers would therefore absorb these components and minimize any temperature increases (Acra *et al.*, 1984). Therefore, to maximize the effects of both solar radiation and heating, colorless containers are recommended.

Container size may also be an important parameter in the solar disinfection process. Acra *et al* (1984) specifies that container size is a variable that affects solar disinfection. However, their studies do not specifically test the effect of volume size on solar disinfection. Kehoe *et al* (2001) found no significant difference in the population dynamics of 0.5 and 1.5 L samples. In contrast, Reed *et al* (2000) compared the time needed to achieve a 99.9% reduction in the initial fecal coliform counts of 22 L and 25 L samples and found that exposure times of 150 minutes and 290 minutes were required, respectively. A more extensive study on volume variations may be useful.

For solar disinfection mostly transparent bottles, mostly PET bottles are used. The reason why these test containers are chosen due to the worldwide availability PET bottles in varying sizes (Mahafooz, 2009), so the abundance of plastic bottles increases the

likelihood of employing the solar disinfection process. The other major reason is the traces of the plasticizers DEHA and DEHP leaching from PET bottles upon SODIS (solar water disinfection) treatment do not pose a significant cancer risk and are below the respective limits for drinking water fixed by the WHO, as it is investigated by Schmid and his colleagues (2008).

2.2.4. SODIS application in Ethiopia

Ethiopia has enjoyed 13 months of sunshine and its altitudinal and longitudinal location is found in the region where for application of SODIS is suitable (Parsons, 2001). Though favorable conditions are found for SODIS application, progress in this area is very limited. In fact promising conditions are seen regarding SODIS. From the 34th WEDC International Conference, which was held in Addis Ababa, Ethiopia, one paper was presented regarding User acceptance: the key to evaluating SODIS and other methods for household water treatment and safe storage, important inputs were grasped (Luzi, 2009). One encouraging project was also launched that promotes the application of SODIS in Ethiopia. From this project 33 countries are benefited which was coordinated by Swiss Federal Institute of Aquatic Science and Technology (Eawag), through the Department of Water and Sanitation in Developing Countries (Sandec). For the fruitfulness of such encourageable projects, undergoing research, that can be useful as an input for the projects are essential.

2.3. Significance of the study

Supply of safe drinking water in the urban and rural parts of Ethiopia can be achieved either by improving the existing water supply system or by promoting water treatment methods at household level. SODIS technology, which is technically simple and economically viable, becomes an alternative choice for enhancements of the coverage of safe drinking water.

This study has the following significances, for a scientific ground and for different stakeholders:

- To provide alternative water disinfection options specifically for the communities who are using unprotected spring and well water.
- Introducing SODIS as household water purification technology which is universally available and free of charge, without minimal installation cost and no operational cost
- The study will also be an input in diversification of the implementation of clean technology in supplement of the widely known hydropower generation in our country.
- Furthermore, the study can be baseline information for different stakeholders and policy makers for policy and plan revision and for researchers for further research and investigation.

CHAPTER THREE

OBJECTIVES

3.1. General objective

The general objective of this study was to optimize solar disinfection system for household water treatment.

3.2. Specific objective

1. To determine the efficiency of solar disinfection under different water depth, exposure time, pH, water temperature, turbidity level, color and type of container and radiation intensity
2. To determine the efficiency of solar disinfection at optimized conditions for water disinfection
3. To evaluate the possibility of bacterial re-growth after solar disinfection

3.3. Hypothesis

Water depth, turbidity, PET color and pH could affect SODIS negatively whereas exposure time and radiation intensity could affect it positively.

CHAPTER FOUR

METHODS AND MATERIALS

4.1. Study area and period

The study site is located at 7°40′N 36°60′E, at an altitude of 1763 m above sea level in Jimma town (Desta, 2006). The site is found within the most favorable region, 35°N and 35°S, for solar disinfection (Parsons, 2001); and known by a sunshine duration of about 2500 hours per year (Personal communication, Kumela, December 13, 2010). The study was conducted from April to June 7, 2011.

4.2. Study design

A laboratory based experimental study was conducted to optimize solar disinfection system for household water purification technology by testing SODIS efficiency at different conditions; water factors such as turbidity, pH, dissolved oxygen concentration and water temperature and environmental factors such as solar intensity and ambient temperature.

4.3. Experimental design

Containers were filled with raw water and exposed to sunlight for 6 Hr under different conditions to achieve the intended objective of the study. The exposure time was determined by undertaking preliminary experiment. The preliminary experiment was run from 9AM to 4:30PM. Within this time interval the strongest sunlight intensity was observed (Yohannes, personal communication on February 26, 2011). The preliminary experiment result showed 0.87±0.11 log inactivation within 3 Hr of sunlight exposure and no colony forming unit (CFU) count was observed after 6 hour of exposure time. Hence, 6 Hr exposure from 10AM to 4PM was found to be an optimum exposure time for the subsequent experiments undertaken in this study.

4.3.1. Source of raw water

Both synthetic water and natural water were used as raw water. Synthetic water was prepared by purposely contaminating distilled water with fecal matter. Whereas, the

natural water was abstracted from unprotected shallow well found in the *Ginjo-Guduru kebele* near Jimma University (Figure 3). The well water was taken using sterile containers and transported in darkness, within one hour of duration, to the Environmental Health Laboratory. Afterwards, analysis of physicochemical parameters (pH, DO and turbidity) and faecal coliform enumeration was performed prior to solar experimentation (Reed *et al*, 2000).

Figure 3. Unprotected well found in *Ginjo guduru* kebele near Jimma University

4.3.2. Variables

Variables of the study are:

Dependent variable

- Efficiency of solar disinfection

Independent variables

- Turbidity

- pH
- Dissolved oxygen concentration
- Depth of water
- Type and color of container
- Solar intensity
- Exposure time
- Water temperature

4.3.3. Conceptual framework

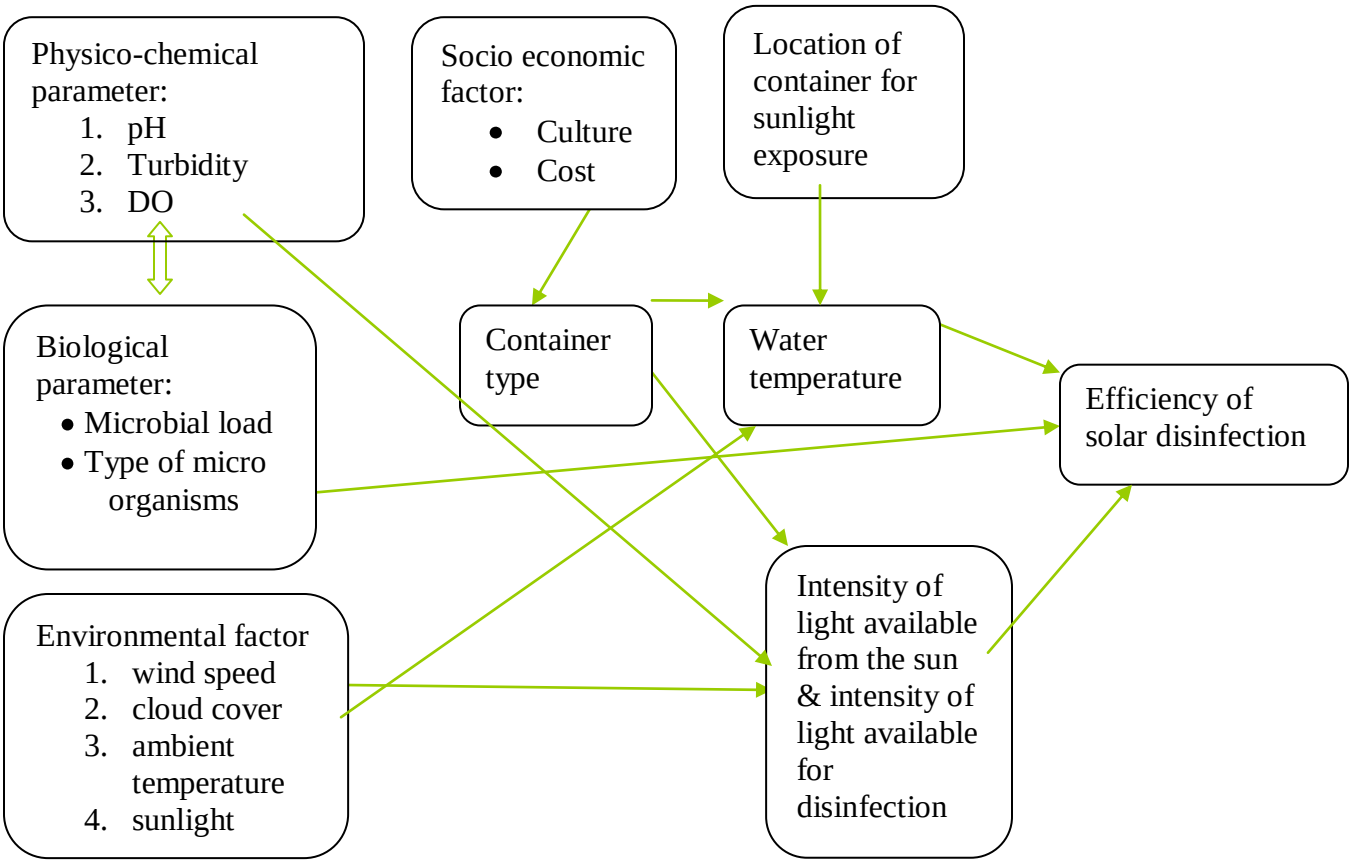

Figure 4. Conceptual frame work of Solar Disinfection

4.4. Experimental setup

The general setup of the experiment is demonstrated in Figure 5. CFU count, pH, ambient temperature and water temperature was measured before sunlight exposure and within 1.5 Hr interval of sunlight exposure while bacteriological samples were taken.

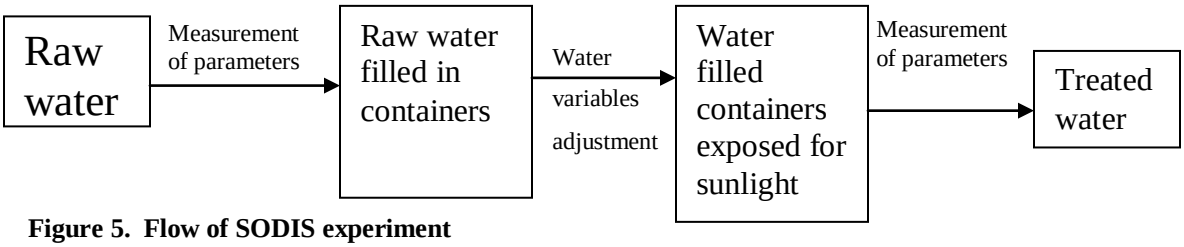

Figure 5. Flow of SODIS experiment

The level of microbial inactivation was determined in the form of log inactivation. Log inactivation is defined as level of microbiological inactivation or the degree of destruction of a microbial population (vegetative forms or spores) of known concentration, subject of a process of inactivity. It is computed as follows based on Badea *et al, (2011)*:

Log inactivation= $Log_{10}N_t/N_0$

Where, N_t= count of microbes in CFU/mL at a time "t".

t= exposure time

N_0= initial count of microbes in CFU/mL

First order inactivation rate constant (k) of fecal coliform was computed based on Chick's law (WHO, 2004) by performing linear regression analysis on plots of Ln (N/N_0) vs. exposure time.

$N=N_0e^{-KCn *t}$

$KC^n=k$

K,n=empirical constants; C=disinfectant concentration

N_0=initial count in CFU/ml of the sample prior to treatment

N= residual bacterial count after treatment

t=exposure time

k=inactivation rate constant

Therefore, we can get a final formula, $N=N_0e^{-kt}$, and which can be converted in to linear form as Ln (N/N_0) =-kt. This formula was used to compute inactivation rate constant.

4.4.1. Testing the efficiency of solar disinfection at different conditions

Effect of raw water turbidity on SODIS

To determine the effect of raw water turbidity, raw water samples having turbidity levels of, 2, 13, 25, 46 and 81NTU were filled in triplicates with PET bottles. Then, bottles were closed and exposed for direct sunlight over concrete surface for six hours. Dissolved oxygen and pH were controlled and have similar value (7 and 5.24mg/L, respectively) in each test bottle. Afterwards, log inactivation of fecal coliform was enumerated based on the initial and final count of CFU.

Effect of pH on SODIS

PET bottles were filled, in triplicates, with raw water samples having pH value of 6, 7, 8 and 9 and exposed for direct sunlight over concrete surface to determine the effect of pH on SODIS. This pH range is in line with the directive of European Communities Council (1991), which dictated, the optimum pH of raw water for abstraction of drinking water is 5.5 to 9 as a guide and 6.5 to 8.5 as mandatory. Turbidity and dissolved oxygen concentration of the raw water were controlled and have similar value (0NTU and 5.24mg/L, respectively). Afterwards, log inactivation of fecal coliform was determined based on the initial and final count of CFU.

Effect of dissolved oxygen concentration on SODIS

Test and control water samples having initial dissolved oxygen (DO) concentration of 5.24mg/L were used to determine the effect of DO on SODIS efficiency. DO of test water samples were increased from 5.24mg/L to 6.52mg/L by aerating the water samples by aerator prior to sunlight exposure. Control water samples were exposed for sunlight without subjecting for aeration. Both control and test water samples in triplicates were filled with PET bottles and exposed for direct sunlight over concrete surface. Initial turbidity and pH of both control and test water samples were controlled and have similar value (0NTU and 7 respectively). Afterwards, log inactivation of fecal coliform was determined based on the initial and final count of CFU.

Effect of water depth on SODIS

To determine the effect of water depth on SODIS, a 0.5 L bottle with 5.5 cm water depth, 1.0 L bottle with 7.5 cm water depth, 1.5 L bottle with 8.5 cm water depth and 2.0 L with 10 cm water depth was filled with raw water having initial bacterial load of 810 CFU/mL and exposed for direct sunlight. The raw water samples were characterized and have DO 5.24mg/L, 0NTU turbidity level and pH 7. Then, raw water samples in triplicates, were exposed for direct sunlight over concrete surface at similar environmental condition on their sides. Subsequently, log inactivation of fecal coliform was determined based on the initial and final count of CFU.

Effect of water temperature on SODIS

The effect of water temperature on SODIS efficiency was determined by two mechanisms. The first mechanism was exposing bottles at different surfaces (concrete, CIS and cardboard) and the second one was using half-surfaced black colored PET bottles and exposing over concrete surface. Triplicates of water samples were filled with PET bottles and exposed to direct sunlight in the aforementioned surfaces. Dissolved oxygen concentration, turbidity, water depth and pH of water samples were controlled and have similar value (5.24 mg/L, 0NTU, 10 cm and 7, respectively). Afterwards, log inactivation of fecal coliform was determined based on the initial and final count of CFU.

Effect of container type on SODIS

Three different types of containers, namely, PET bottle, glass bottle and metal container (*coda*) were used to determine the influence of container type on SODIS efficiency (Figure 6). The containers were filled with raw water having turbidity value of 0NTU, pH 7 and DO 5.24mg/L and exposed for direct sunlight under similar environmental condition. Afterwards; log inactivation of fecal coliform was determined based on the initial and final count of CFU.

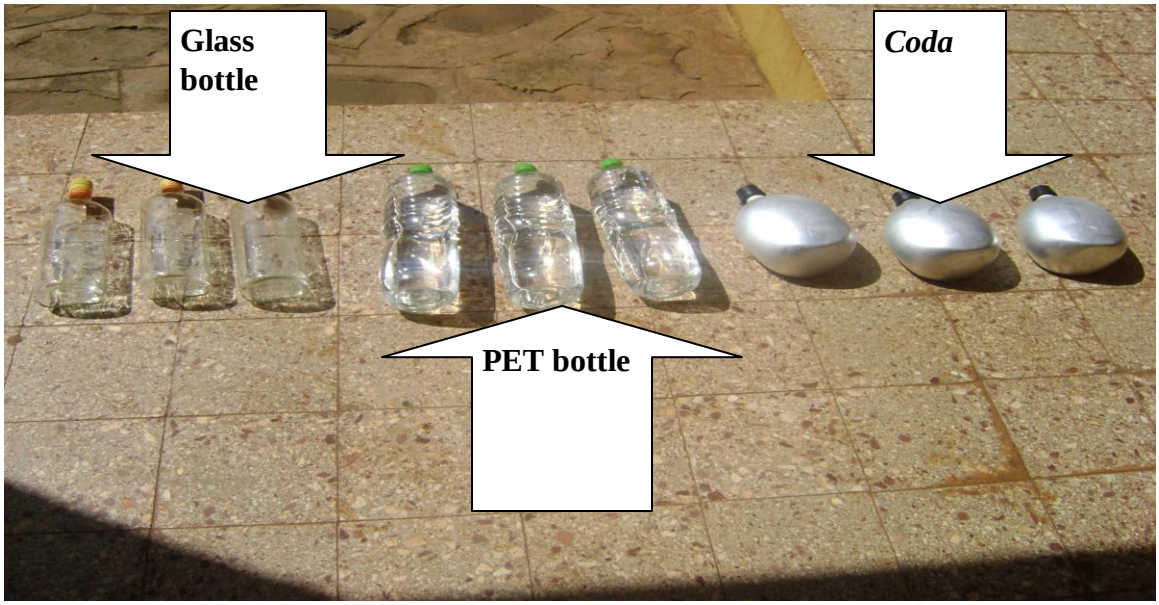

Figure 6. Three different container types (glass bottle, PET bottle and *coda*) tested for SODIS, June, 2011, Jimma, Ethiopia.

Effect of PET color on SODIS

Colorless, light-black and black colored PET bottles were used to determine the influence of color on SODIS efficiency (Figure7). Raw water samples at pH 7 were filled in triplicates with those PET bottles and exposed for direct sunlight at similar environmental condition. Turbidity, depth of water and DO of raw water samples were controlled with measured value of 0NTU, 10 cm and 5.24mg/L, respectively in each bottle.

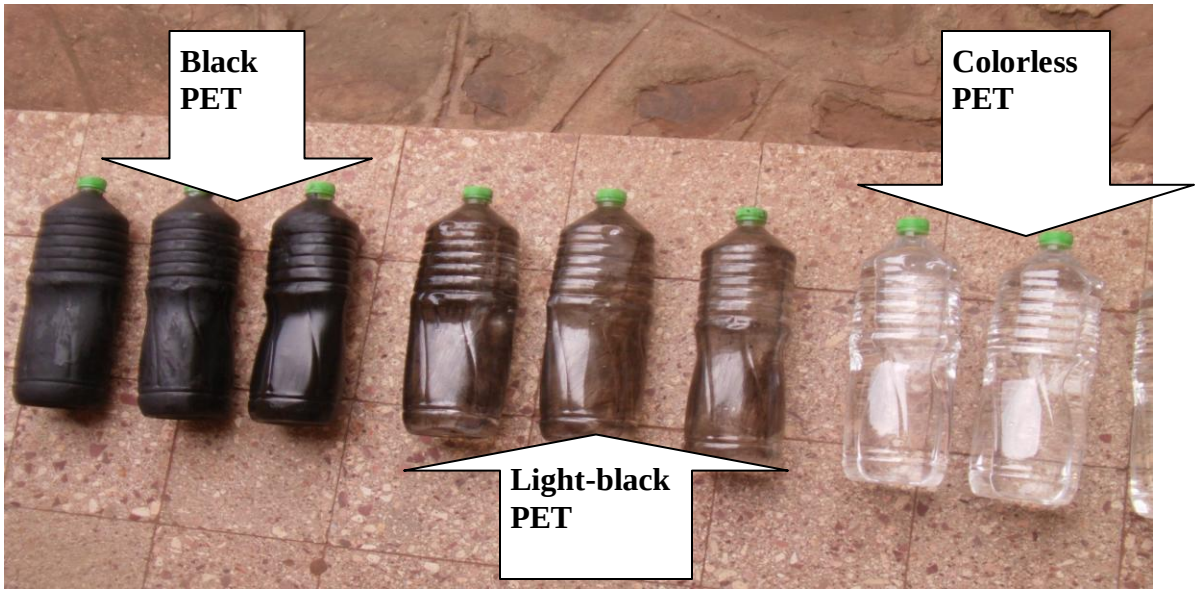

Figure 7. Three different PET colors (black, light-black and colorless) for SODIS, June, 2011, Jimma, Ethiopia.

Effect of solar intensity on SODIS

To determine the effect of solar intensity on SODIS experiment was carried out in three separate days that have different solar irradiance. In the first day a cumulative solar irradiance of 0.602 kWh/m^2 was recorded in which the sky was entirely covered with cloud. In the rest of two days cumulative solar irradiance of 2.77kWh/m^2 (sky with few cloud cover) and 3.99kWh/m^2 (with clear sky) was recorded. Raw water samples in triplicates were filled with PET bottles and administered for the aforementioned days over concrete surface for a period of six hour.

4.4.2. Testing efficiency of SODIS using natural raw water

The application of SODIS for well water disinfection was demonstrated by abstracting well water from *Ginjo Guduru* kebele near Jimma University as it has been described in section 4.3.1. The well water in triplicates were filled into half-surfaced black colored PET bottles and exposed for direct sunlight. Well water samples kept in shade area was used as a control. The well water has turbidity value 13.0NTU and dissolved oxygen concentration of 3.24mg/L. The samples were aerated by aerator prior to sunlight exposure. As a result the DO increased from 3.24mg/L to 4.86mg/L. Subsequently after sunlight exposure, log inactivation of fecal coliform was computed based on the initial and final count of CFU.

4.4.3. Testing the possibility of bacterial re-growth after SODIS

After treating raw water under optimized conditions, possibility of microbial re-growth were determined or tested by storing treated water in the Environmental Health Sciences and Technology laboratory under room temperature for about 4 days. Four days storage time was selected to include the maximum water storage time taken in most of the northern parts of Ethiopia. In some parts of northern Ethiopia water was not fetched in the weekend and if monthly Christianity holyday is there either Friday or Monday water was not fetched due to religious reasons (locally called "*Yesenbet Wuha*"). Afterwards, CFU count was performed within one day interval to quantify the possibility of bacterial re-growth.

4.5. Analytical Methods

All processes carried out in the laboratory aseptically, including the use of 70% ethanol to sterilize workspaces and hands. All glassware, test solutions, and media were sterilized at 121°C for 15 minutes using an autoclave. Pre-sterilized pipette tips and Petri dishes were used (Rojko, 2003).

4.5.1. Physical analysis

Physical parameter of raw water and treated water were measured as of standard procedures (APHA *et al.*, 1998). Table 1 describes physical and chemical parameters and the instruments used for measuring.

Table 1. Physical and chemical parameters and the instruments used for measuring, June, 2011, Jimma, Ethiopia.

S.N^{o}	Parameters	Measuring instrument
1	pH	Wagtech International pH meter
2	Turbidity	Wagtech HANNA instruments micro processor Turbidity meter
3	DO	Multi-parameter probe (HACH)
4	Exposure time	Stopwatch
5	Water temperature	Handheld thermometer
6	Sunlight intensity (irradiance)	Non-contact thermometer and black body

4.5.2. Microbial analysis

Sampling technique for microbial analysis

According to Health Protection Agency of United Kingdom (2006), samples were taken by shaking the exposed bottles so as to distribute fecal coliforms evenly throughout the water sample. During sampling and transportation, samples were protected from direct sunlight and transported in cold box at 2^{o}C -8^{o}C. And the analysis was carried out within on the day of collection within not more than 6 Hr after sample collection.

Fecal coliform Enumeration

In order to evaluate the effectiveness of each exposure regime, it is necessary to determine the amount of microbial inactivation achieved. A standard pour plate method (APHA *et al.*, 1998) was used for fecal coliform enumeration. The colony count found from the enumeration was reported as CFU/mL. Accordingly, samples were diluted with

distilled water to make the growing colonies countable. Plate Count Agar (PCA) was used as a growth media for the microbes. The details of pour plate method is available attached in Annex I.

4.5.3. Measurement of solar radiation intensity

Non-contact thermometer and black body were used to measure solar intensity (Figure 8).

Figure 8. Solar irradiance measurement by non contact thermometer and black body, June, 2011, Jimma, Ethiopia.

The instrument cannot measure solar irradiance or intensity directly; it measures the intensity indirectly based on four important data (sky temperature, surface temperature of black body which is exposed under direct sunlight, surface temperature of black body which is kept in shade area and ambient temperature) using mathematical equation (Cengel, 1998). The mathematical equation used for computation of solar intensity is illustrated as follows.

$$I\varepsilon A_s = Q_{conv} + Q_{rad}$$

$$I\varepsilon A_s = h_{conv} A_s (T_s - T_{amb}) + A_s \delta\varepsilon (T_s^4 - T_{sky}^4)$$

$$h_{conv} = k * Nu / D$$

$$Nu = 0.59 Ra^{0.25}$$

$$Ra = \frac{g * \beta * (T_s - T_{amb}) * D^3 Pr}{v^2}$$

$$\beta = 1/Tf$$

$$Tf = (T_s + T_{amb})/2$$

Where: Q_{conv} = rate of natural convection heat transfer

Q_{rad} = rate of radiation heat transfer

I=solar irradiance, ε = emissivity, A_s = the area of the surface that is in contact with the air

h_{conv} = coefficient of convection heat transfer

T_s=surface temperature, T_{amb}=ambient temperature, δ=Stefan-Boltzmann constant

T_{sky}= sky temperature; k = thermal conductivity; Nu = Nusselt number; D = length of black body facing the air; Ra = Rayleigh number; g =gravitational acceleration; Pr = Prandtl number; β=the coefficient of volume expansion of the air.

T*f*=film temperature that indicated the properties of the air

4.6. Data processing and analysis

Data were processed and analyzed using Microsoft Excel 2003 software and SPSS version 16 statistical package. Descriptive statistics were performed to describe the data in the form of mean and standard deviation. Non-parametric statistical tests (Kruskal Wallis and Mann-Whitney rank sum test) were performed to test mean difference of log inactivation of fecal coliform and rate of inactivation observed among different variables at significance level of (α=0.05).Linear regression analysis was performed on plots of Ln (N/N_0) vs. exposure time) to determine first order inactivation rate constant (k) of fecal coliform and finally the findings were summarized with tables and graphs.

4.7. Data quality control

All processes carried out in the laboratory aseptically, including the use of 70% ethanol to sterilize workspaces and hands. All glassware, test solutions, and media were sterilized at 121°C for 15 minutes using an autoclave. Pre-sterilized pipette tips and Petri dishes were used (Rojko, 2003).

To ensure the quality of the data; appropriate standard procedures were used starting from bottle sterilization and preparation of synthetic water and abstraction of natural raw water till bacterial enumeration at laboratory level. During sampling for bacterial

enumeration appropriate care were taken to avoid formation of shade. Sterilization of sampling bottles for bacterial enumeration was ensured. To ensure reproducibility of the data, triplicates of samples were used for single parameter.

According to Health Protection Agency of United Kingdom (2006), after incubation of plates for bacterial enumeration, colony counting were undertaken within 30 minutes to curb the problem of liability of colonies to change on cooling and standing. To avoid false positivity of pour plate method, 100mL of sterile distilled water were used as a blank control.

4.8. Dissemination of result

The finding of this study will be communicated to all relevant and responsible stakeholders including the scientific community of Jimma University. Efforts will be made to present the finding at different national and international conferences. A great effort will also be made to publish the finding at national or international peer reviewed journals.

4.9. Limitation

Due to resource and time constraint this study has the following limitations. It didn't consider the effect of seasonal, altitudinal and sun angle variation on SODIS efficiency.

4.10. Definition of Terms

Water disinfection: It is the removal, deactivation or killing of pathogenic microorganisms.

SOS response: A bacterial deoxyribonucleic acid (DNA) repair system in which cell division and DNA replication are blocked, and DNA repair, recombination, and mutation genes are induced.

Reactive oxygen: It is unstable molecule of oxygen that tends to react with anything a contact it made. When the contact is made with cells in the body, or the DNA within those cells, the reaction is damaging and can cause the cell to die or the DNA to mutate.

Aseptic technique: It is a set of specific practices and procedures performed under carefully controlled conditions with the goal of minimizing contamination by pathogens.

Optimization: The procedure or procedures used to make a solar disinfection system or process as effective or functional as possible by selecting optimum conditions.

Indicator organisms: These are microbes whose presence in water signals the presence of fecal matter, and potentially, pathogens.

Efficiency: It is the microbial inactivation performance of solar disinfection system. Or it is the ratio of the microbial load after solar disinfection and before disinfection with a certain period of sunlight exposure.

Synthetic raw water: It is raw water prepared by deliberately contaminating distilled water by fecal matter.

Log inactivation: It is the level of microbial inactivation -the degree of destruction of a microbial population (vegetative forms or spores) of known concentration, subject of a process of inactivity.

$T_{99.9}$: It is the time required to achieve 3-log microbial inactivation.

3-log inactivation: It is equivalent to 99.9% microbial inactivation.

Optimized conditions: are variables that are selected for SODIS test based on the best log inactivation found.

CHAPTER FIVE

RESULT

The efficiency of SODIS was evaluated at different conditions and the following results are found as it has been illustrated below in Table 2.

Table 2. Average fecal coliform count in (CFU/mL) (n=3), June, 2011, Jimma, Ethiopia

Parameters		FC count (CFU)/mL under the specified exposure time				
		0 Hr	1.5Hr	3Hr	4.5Hr	6Hr
Turbidity (NTU)	2	1127	577	133	27	0
	13	1180	810	473	313	160
	25	1147	985	667	460	340
	46	1180	1033	987	903	833
	81	1160	1080	1037	997	970
pH	6	777	373	50	4	0
	7	783	404	63	18	0
	8	773	389	57	15	0
	9	783	343	28	0	0
DO (mg/L)	5.24	990	463	232	44	0
	6.52	1000	352	100	0	0
Water depth (cm)	5.5	810	333	0	0	0
	7.5	803	503	81	0	0
	8.5	810	570	181	2	0
	10	810	647	273	22	0
Container type	*Coda*	607	541	487	411	345
	Glass	631	303	169	4	0
	PET	630	341	192	18	0
PET color	Colorless	1233	403	197	18	0
	Light black	1433	820	553	333	233
	Black	1267	1010	883	697	473
Temperature effect	concrete	1147	733	313	55	0
	cardboard	1160	720	310	43	0
	CIS	1140	727	300	49	0
	HSBC- PET	1183	607	109	8	0

Parameters		FC count (CFU)/mL under the specified exposure time				
		0 Hr	1.5Hr	3Hr	4.5Hr	6Hr
Solar intensity (kWh/m^2)	0.602	1023	840	643	510	453
	2.77	1013	423	113	11	0
	3.99	1077	277	24	1	0
Optimization	Test	820	123	2	0	0
	control	830	830	830	823	823
Natural Water	Test	180	49	11	1	0
	Control	177	177	177	176	175

Key, PET = Polyethylene terephthalate

CIS = Corrugated iron sheet

HSBC-PET = Half-surfaced black colored PET bottle

5.1. Effect of raw water turbidity on SODIS efficiency

Within 3 Hr of exposure, higher log inactivation (0.93±0.08) was found on water samples having turbidity value of 2NTU. On the contrary, the least log inactivation (0.05±0.005) was found on water samples having turbidity value of 81NTU (Figure 9). Statistically significant difference on log inactivation of fecal coliform was found among different water turbidity (p=0.009).

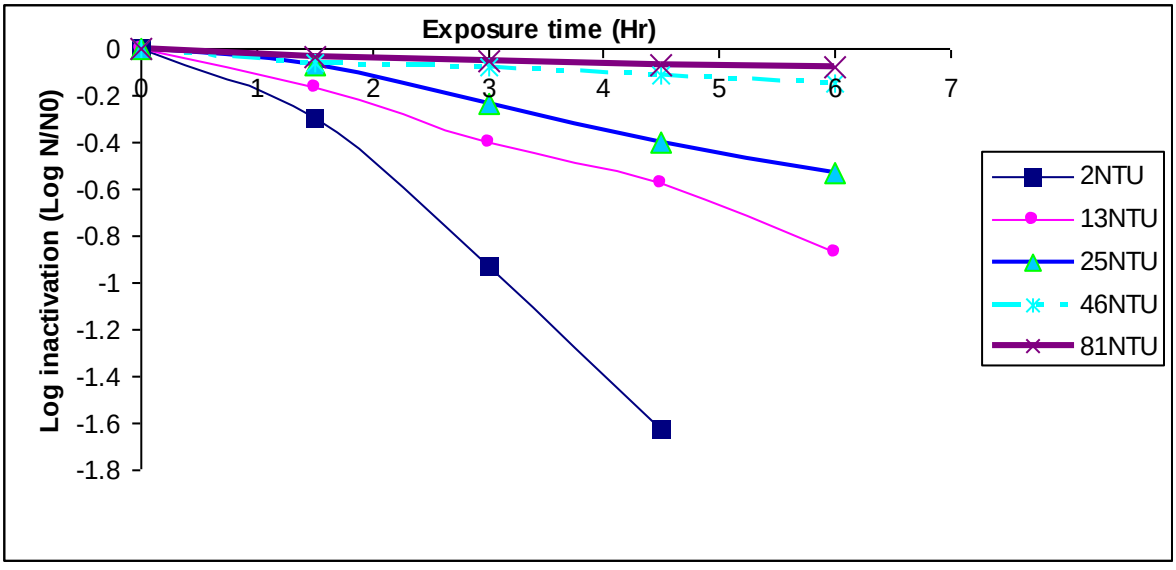

Figure 9. Log inactivation of fecal coliform for different turbidity level of water samples versus exposure time, June, 2011, Jimma, Ethiopia

First order inactivation rate constant (k) revealed that faster rate of fecal coliform inactivation ($0.847Hr^{-1}\pm0.014Hr^{-1}$) was found on water samples having turbidity value of 2NTU. On the contrary, slower rate ($0.03Hr^{-1}\pm0.006Hr^{-1}$) was found on water samples having 81NTU (Table 3). The rate of fecal coliform inactivation was significantly different among water samples with different turbidity (p=0.009).

Table 3. Inactivation rate constant (k) of fecal coliform for different turbidity level of water samples, June, 2011, Jimma, Ethiopia

S.No	Turbidity level of raw water(NTU)	Regression equation	Inactivation rate constant(k) in Hr^{-1}	R^2	P-value
1	2	Ln N/N_0 = -0.847t+0.262	0.847±0.014	0.972	0.014
2	13	Ln N/N_0 = -0.3304t+0.067	0.33±0.014	0.990	<0.0001
3	25	Ln N/N_0 = -0.213t+0.074	0.213±0.006	0.985	0.001
4	46	Ln N/N_0 = -0.055t-0.019	0.055±0.006	0.981	0.001
5	81	Ln N/N_0 = -0.03t-0.015	0.03±0.006	0.968	0.002

Key, N = CFU count at a time t, N_0 = Initial CFU count, t = Exposure time

5.2. Effect of pH on efficiency of SODIS

Figure 10 illustrates log inactivation of fecal coliform on raw water samples having different initial pH value. The figure indicated that higher log inactivation (1.44±0.03) was found on raw water samples having initial pH value of 9. The least log inactivation (1.1±0.035) was found at pH 7. Statistically significant difference on log inactivation of fecal coliform was not found among water samples with different initial pH values (p=0.058).

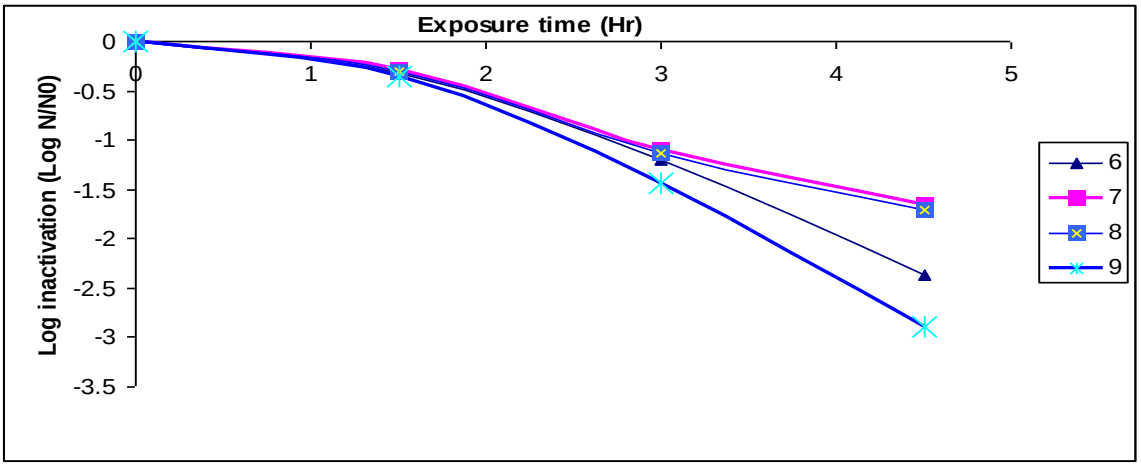

Figure 10. Log inactivation of fecal coliform on water samples having initial pH value of (6, 7, 8 and 9), June, 2011, Jimma, Ethiopia

5.3. Effect of dissolved oxygen concentration on SODIS efficiency

Within 3 Hr of exposure, 1±0.01 and 0.63±0.044 log inactivation was found on water samples having dissolved oxygen concentration (DO) of 6.52mg/L and 5.24mg/L respectively (Figure 11). The observed difference on log inactivation of fecal coliform was not statistically significant (Mann Whitney rank sum test, p=0.05).

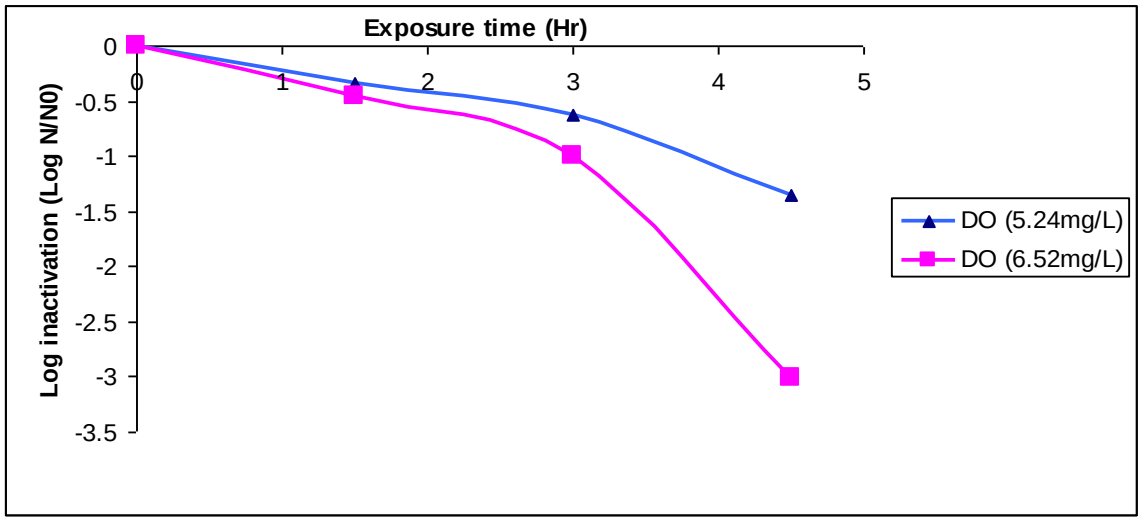

Figure 11. Log inactivation of fecal coliform on water samples having different dissolved oxygen concentration, June, 2011, Jimma, Ethiopia.

First order inactivation rate constant (k) of fecal coliform indicated, the rate was $1.47Hr^{-1}$±$0.001Hr^{-1}$ and $0.67h^{-1}$±$0.03Hr^{-1}$ on water samples having 6.52mg/L and 5.24mg/L DO respectively. The observed difference on the rate of fecal coliform inactivation was not found to be statistically significant (Mann Whitney rank sum test, p=0.05). Even though the difference was not statistically significant, the rate found on 6.52mg/L was increased by a factor of 2.2.

5.4. Effect of Water depth on efficiency of SODIS

As shown in Figure 12, highest log inactivation of fecal coliform (2.91±0.001) was found on water samples having water depth of 5.5 cm. On the contrary, the least log inactivation (0.474±0.044) was obtained on 10 cm water depth after 3 hour of exposure. Kruskal-Wallis test on log inactivation of fecal coliform showed statistically significant difference among water samples with different water depth (p=0.015).

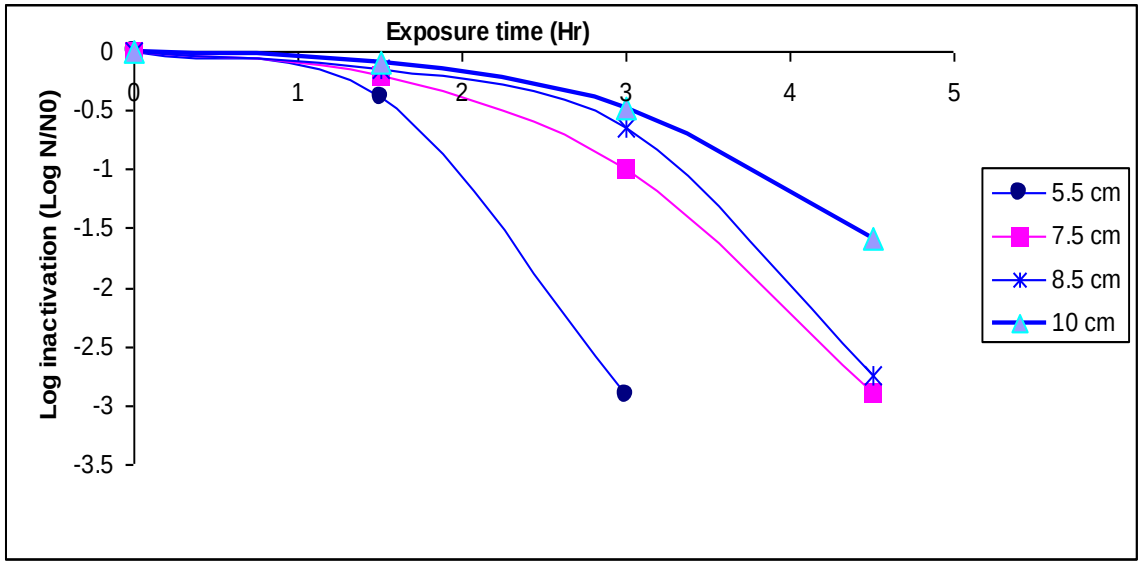

Figure 12. Log inactivation of fecal coliform on water samples having different water depth, June, 2011, Jimma, Ethiopia

5.5. Effect of Container type on SODIS

Figure 13 illustrated that 0.57±0.01, 0.52± 0.03 and 0.1±0.02 log inactivation of fecal coliforms were found using glass bottle, PET bottle and metal container (*coda*), respectively after 3 hour of exposure. Kruskal-Wallis test on log inactivation of fecal coliform among the three containers was found to be significantly different (p=0.027). Mann-Whitney rank sum test on log inactivation of fecal coliform between PET bottle and glass bottles was not found to be statistically significant (p=0.05).

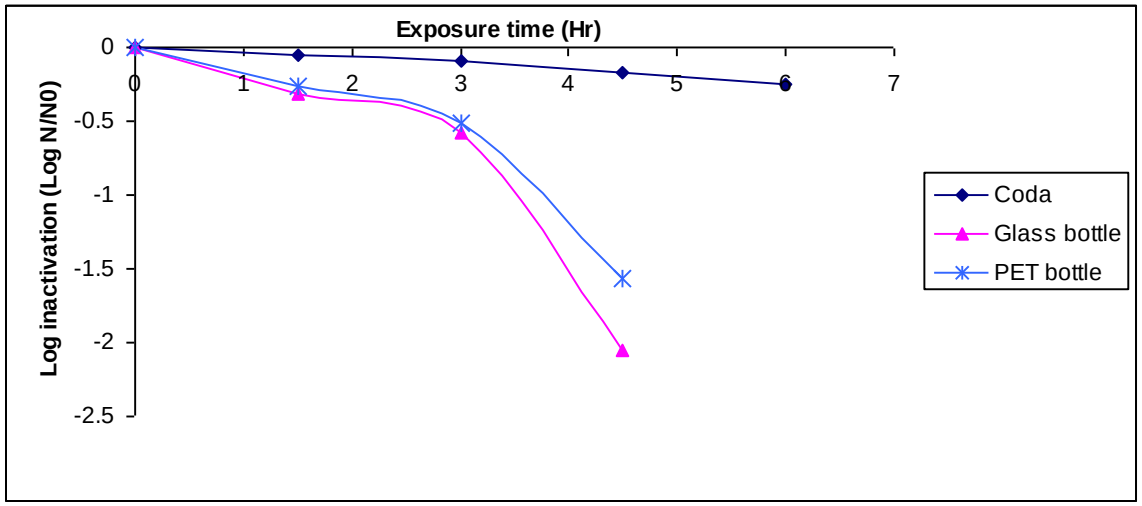

Figure 13. Log inactivation of fecal coliform observed on raw water samples exposed for sunlight three different containers, June, 2011, Jimma, Ethiopia

First order inactivation rate constant (k) revealed that microbial inactivation was found at a rate of $1.01Hr^{-1}\pm0.022Hr^{-1}$, $0.76Hr^{-1}\pm0.07Hr^{-1}$ and $0.094Hr^{-1}\pm0.0044Hr^{-1}$ using glass bottle, PET bottle and metal container (*coda*), respectively. Kruskal Wallis test revealed that there is statistically significant difference on the rate of fecal coliform inactivation among the three containers (p=0.027).

5.6. Effect of PET bottle color on SODIS

During the sunlight exposure, temperature of water was reached $56.23^{o}C\pm0.72^{o}C$ on water samples exposed under black PET bottles. And on water samples exposed under light black and colorless PET bottles, the temperature rose to $48.23^{o}C\pm0.32^{o}C$ and $40.8^{o}C\pm0.05^{o}C$ respectively. There was significant temperature difference between the three PET bottle color (Kruskal-Wallis test, p=0.027).

Within 3 Hr of exposure, highest log inactivation of fecal coliform (0.79±0.03) was found using colorless PET and on the contrary the least log inactivation (0.16±0.03) was found using black PET bottles (Figure 14). Kruskal-Wallis test revealed that there is statistically significant difference on log inactivation of fecal coliform among water samples exposed under different color of PET bottles (p=0.027).

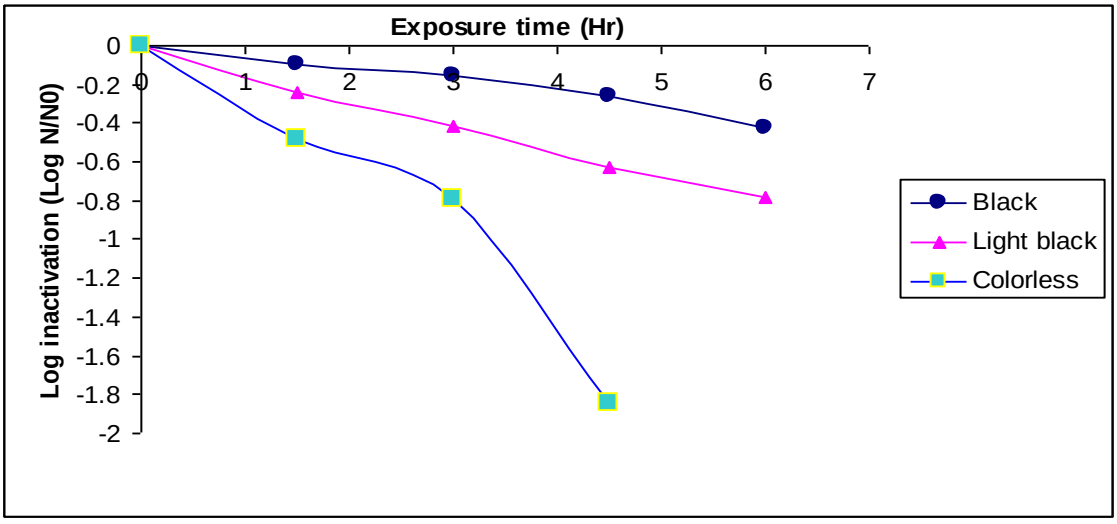

Figure 14. Log inactivation of fecal coliform on water samples exposed for sunlight in PET bottles having three different color, June, 2011, Jimma, Ethiopia

Faster rate of microbial inactivation ($0.90Hr^{-1}\pm0.03Hr^{-1}$) was found on water samples exposed under colorless PET bottles.

On the contrary, the least log inactivation ($0.16Hr^{-1}\pm0.011Hr^{-1}$ and $0.30Hr^{-1}\pm 0.015Hr^{-1}$) was found on water samples exposed under black and light black PET bottles respectively. The observed rate difference among the three colors was statistically significant (p=0.027).

5.7. Temperature effect on SODIS efficiency

Raw water samples having an initial bacterial load of 1180CFU/mL were exposed for direct sunlight at different conditions to achieve different temperature during the exposure. Table 4 illustrates temperature of water samples exposed under different condition in relation to exposure time.

Table 4. Temperature of water samples observed on water samples exposed for sunlight on three different surfaces and under half-surfaced black colored PET bottles, June, 2011, Jimma, Ethiopia

Exposure time	Water temperature(^{o}C)				Ambient air temperature(^{o}C)
	PET bottles exposed under concrete surface	PET bottles exposed under card board	PET bottles exposed under CIS	Half-surfaced black colored PET bottle	
0	24.9±0.1	24.9±0.1	24.87±0.11	24.97±0.06	25.8
1.5	32.1±0.46	33.07±0.21	32.53±0.42	37.53±0.15	26.2
3	35.53±0.32	38.37±0.25	38.3±0.2	45.37±0.06	28.1
4.5	38.1±0.26	41.8±0.36	45.57±0.15	51.1±0.17	28.6
6	37.16±0.21	40.27±0.31	41.37±0.15	48.57±0.06	26.4

Table 4 indicated that highest water temperature ($51.1^{o}C\pm0.17^{o}C$) was found on water samples exposed under half-surfaced black colored PET bottle. On the contrary, the least water temperature ($38.1^{o}C\pm0.26^{o}C$) was observed on water samples exposed on concrete surface. There was statistically significant difference on water temperature (Kruskal-Wallis test, p=0.015).

Within 3 Hr of exposure, highest log inactivation of fecal coliform (1.04±0.042) was found on water samples exposed under half-surfaced black colored PET bottle. On water samples exposed for sunlight on CIS, cardboard and concrete surface, 0.57±0.038, 0.58±0.038 and 0.56±0.011 log inactivation were found, respectively (Figure 15). After 3

hour of exposure statistically significant difference on log inactivation of fecal coliform was not found (p=0.082).

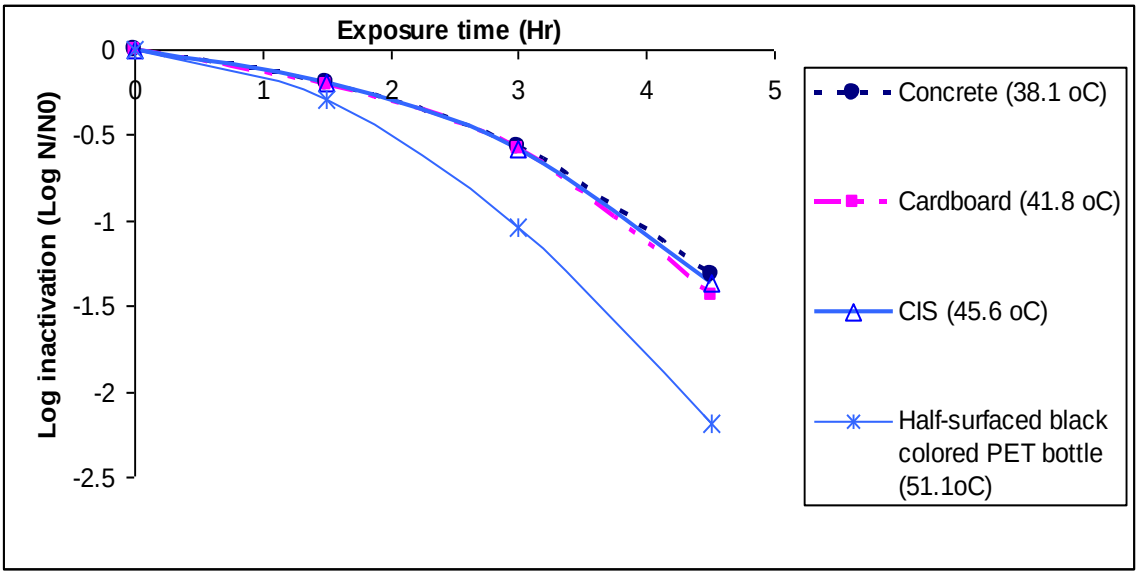

Figure 15. Log inactivation of fecal coliform on water samples exposed for sunlight on three different surfaces and under half-surfaced black colored PET bottles , June, 2011, Jimma, Ethiopia

Faster rate of fecal coliform inactivation ($1.12Hr^{-1}\pm0.08Hr^{-1}$) was found on water samples exposed under half-surfaced black colored PET bottle. On the contrary, slower rates ($0.66Hr^{-1}\pm0.033Hr^{-1}$, $0.69Hr^{-1}\pm0.007Hr^{-}1$ and $0.72Hr^{-1}\pm0.02Hr^{-1}$) was found on water samples exposed to sunlight on concrete, CIS and cardboard surfaces, respectively. The rate was found to be significantly different among water samples exposed under different temperature (p=0.027). Exposing bottles in three different places (concrete, cardboard and CIS) didn't show any significant difference on the rate of fecal coliform inactivation (p=0.079).

5.8. Effect of solar intensity on SODIS

Water samples having an initial bacterial load of 860CFU/mL were exposed on three days that received a cumulative solar irradiance of $2.77kWh/m^2$, $3.99kWh/m^2$ and $0.6026kWh/m^2$ each (Figure 16).

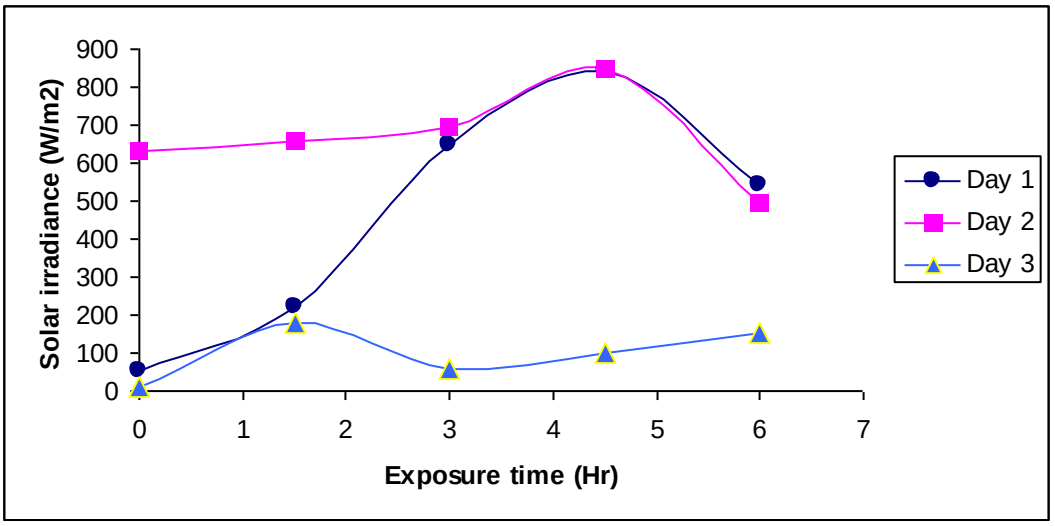

Figure 16. Trends of solar irradiance observed in three exposure days, June, 2011, Jimma, Ethiopia.

Within 3 Hr of exposure, highest log inactivation of fecal coliform (1.65±0.05 log) was found on water samples exposed for sunlight having a cumulative solar irradiance of 3.99kWh/m^2. On the contrary, the least log inactivation (0.2±0.01 log) was found on water samples exposed for sunlight having a cumulative solar irradiance of 0.6026kWh/m^2 (Figure 17). The mean log inactivation of fecal coliform found on the three different days was significantly different (Kruskal-Wallis test, p=0.027).

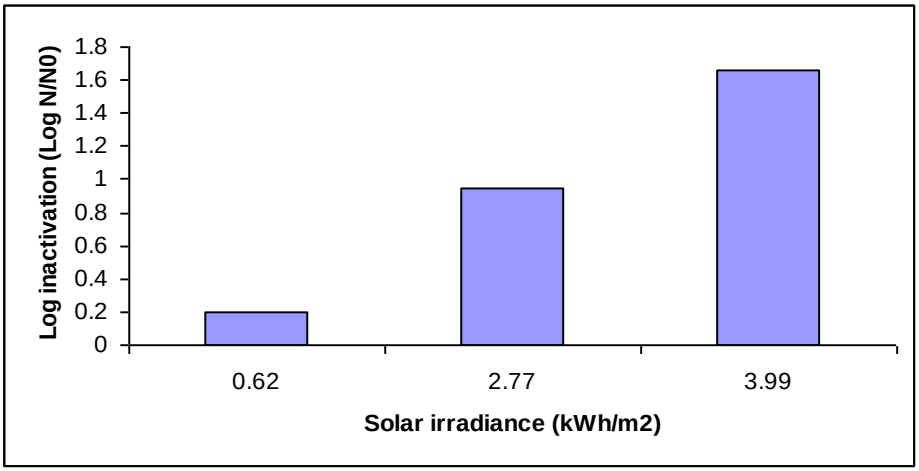

Figure 17. Log inactivation of fecal coliform on water samples exposed under different cumulative solar irradiance, (3 hour exposure time), June, 2011, Jimma, Ethiopia

Faster rate of microbial inactivation (1.56Hr^{-1}±0.01Hr^{-1}) was found on water samples exposed for sunlight having cumulative solar irradiance of 3.99kWh/m^2. On water samples exposed for sunlight having cumulative solar irradiance of 2.77kWh/m^2 and 0.6026kWh/m^2, the rate was 0.993Hr^{-1}±0.25Hr^{-1} and 0.142Hr^{-1}±0.005Hr^{-1} respectively.

Kruskal-Wallis test showed that there is statistically significant difference on the rate of fecal coliform inactivation among water samples exposed at different solar irradiance (p=0.027).

5.9. Optimization

The result of optimization has indicated, 2.554±0.093 log inactivation was found after 3 Hr of exposure on the test water under optimized condition (at turbidity of 2NTU, pH 7, DO of 6.52mg/L, half-surfaced black colored PET bottle, and water depth of 10 cm). On the contrary, no microbial inactivation was found on the control water samples (Figure 18). Mann-Whitney rank sum test on log inactivation of fecal coliform showed that there is statistically significant difference between the test and the control water samples (p=0.037).

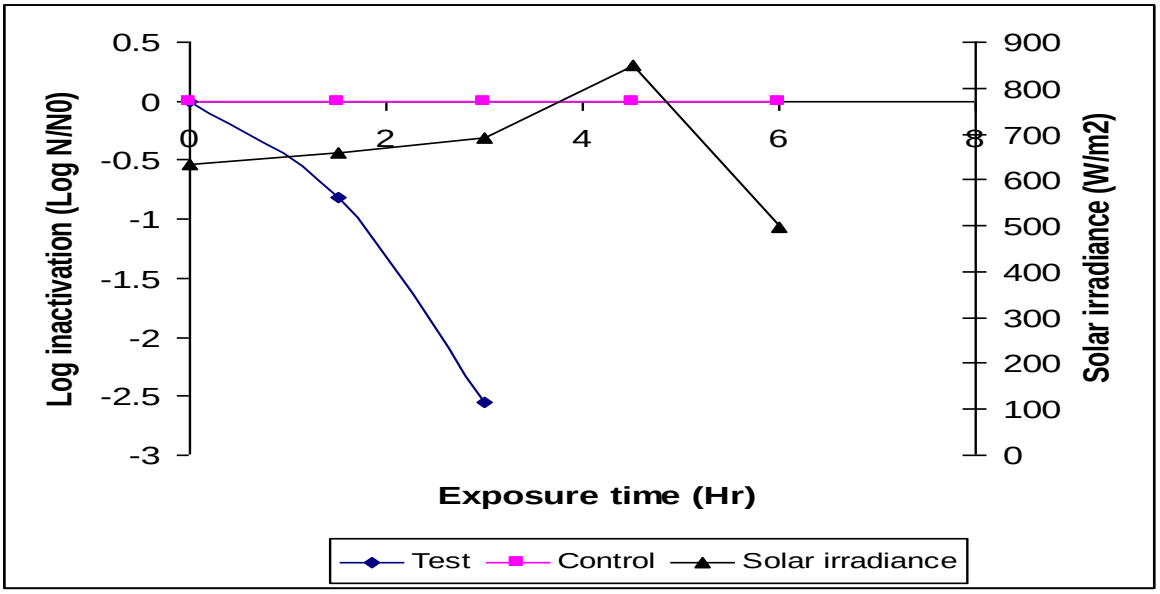

Figure 18. Log inactivation of fecal coliform on water samples exposed for sunlight under optimized conditions, June, 2011, Jimma, Ethiopia

The rate of fecal coliform inactivation was found to be $1.96Hr^{-1}$±$0.071Hr^{-1}$(Figure 19). $T_{99.9}$ was computed and showed that 3-log inactivation was achieved after 3.7Hr±0.12Hr exposure. After 4.5 Hr of exposure no CFU count was detected as it has been indicated in Table 2. Furthermore, possibility of microbial re-growth was tested and the result showed that inactivated coliform bacteria fail to re-grow at ordinary room conditions.

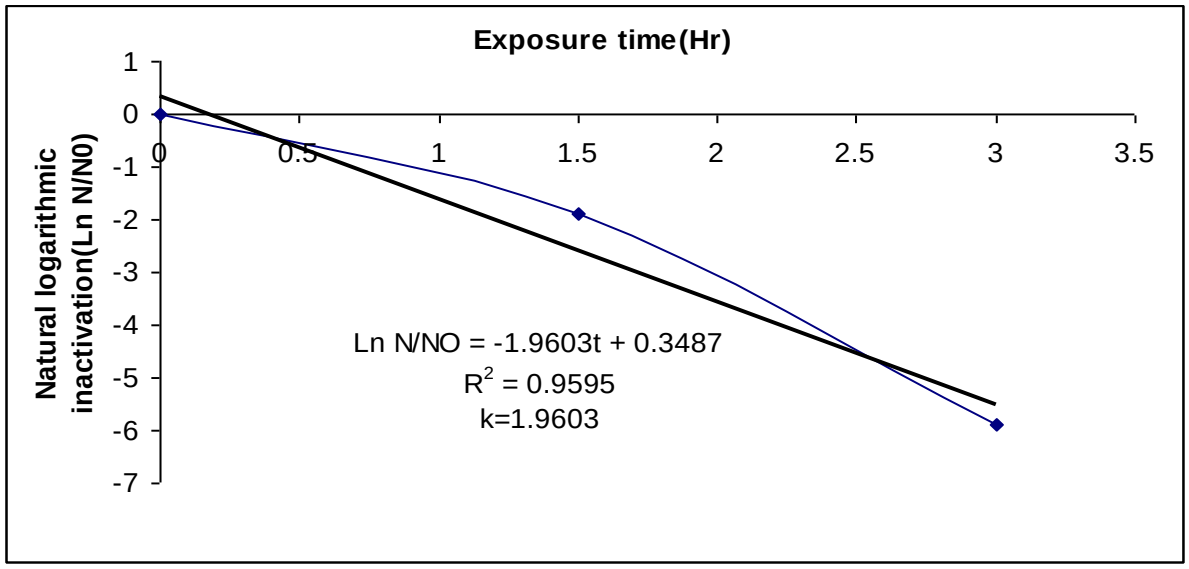

Figure 19. Inactivation rate constant (k) of fecal coliform contaminating synthetic raw water kept under half-surfaced black colored PET bottle, June, 2011, Jimma, Ethiopia

5.10. Testing SODIS on natural water

Within 3 hour of exposure, 1.22±0.074 log inactivation of fecal coliform was observed on test water samples. But on control water samples, no fecal coliform inactivation was observed (Figure 20). Significant difference on log inactivation of fecal coliform was found between test and control water samples (p=0.046).

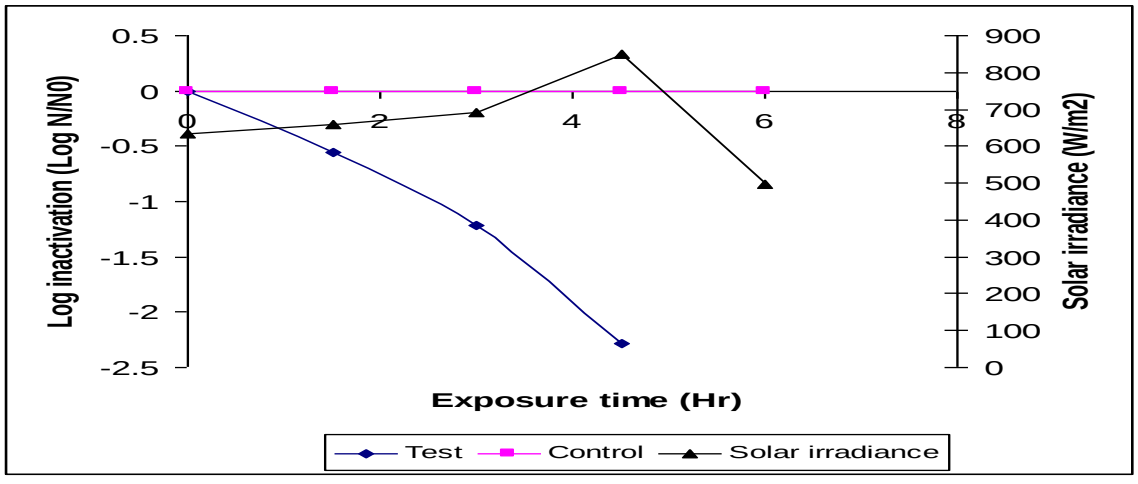

Figure 20. Log inactivation of fecal coliform on natural raw water (well water) samples, June, 2011, Jimma, Ethiopia

The rate of fecal coliform inactivation was found to be $1.22Hr^{-1}$±$0.004Hr^{-1}$(Figure 21). 3-log inactivation was found with an exposure time of 5.88Hr±0.012Hr and after 6 Hr exposure no CFU count was detected as it has been indicated in Table 2. Possibility of

microbial re-growth was tested and the test revealed that inactivated microbes fail to re-grow at ordinary room conditions, confirming that the inactivation was irreversible.

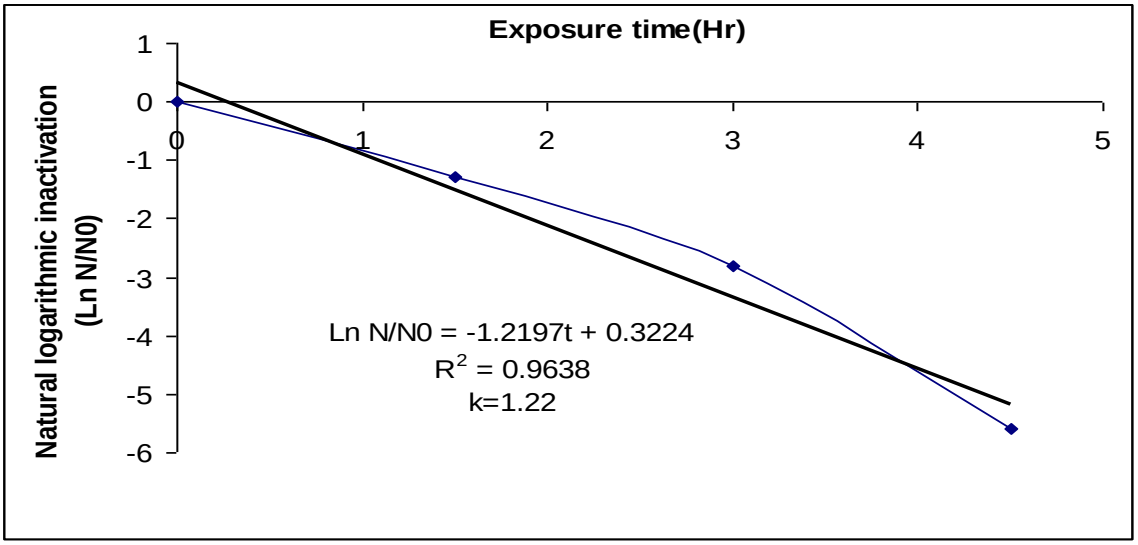

Figure 21. Inactivation rate constant (k) of fecal coliform contaminating natural (well) raw water kept under half-surfaced black colored PET bottle, June, 2011, Jimma, Ethiopia

CHAPTER SIX

DISCUSSION

Effectiveness of SODIS was evaluated under different conditions using fecal coliform as a test organism. The present study has shown that higher log inactivation was found on clear raw water (<5NTU). On the contrary, significant microbial inactivation was not observed on raw water having turbidity value of greater than 20 NTU. This might be due to shielding of organisms by particles (Kehoe *et al*., 2001, McGuigan et al., 1999 and Sommer *et al*., 1997) and due to reduction of the amount of UV radiation that penetrates the water (Meierhofer and Landolt, 2009). This finding is in agreement with the finding of Wagelin *et al*. (1994). They reported that turbidity level of raw water greater than 25NTU significantly reduces the efficiency of solar disinfection. This finding is also supported by Ambelu (2001), Kehoe *et al*. (2001) and Oates (2001) who described that in the elimination of FC by sunlight, turbidity has shown significant impact on the FC reduction. Therefore, if the turbidity of water is greater than 20NTU, the water needs to be pretreated before being exposed. Bigger particles and solids can be eliminated by storing the raw water for one day and letting the particles settle to the bottom (Ambelu and Faris, 1999). Solid matter can be separated by filtration, using a sand layer or a cloth. Turbidity can also be reduced by flocculation /sedimentation using aluminium sulphate or crushed *Moringa oleifera* seed (Bina *et al*., 2007). Furthermore, this study illustrated higher water temperature was observed on turbid water samples. This might be due to absorption of heat by suspended particles (Waterwatch Australia Steering Committee, 2002).

Statistically significant difference on the rate of microbial inactivation was not found on water samples having different pH value in the range of 6 to 9. Literatures illustrated that low pH and high pH may increase inactivation rate by presenting a significant additional stress to the cell, for example by requiring it to expend energy for maintenance of pH homeostasis, thus accelerating the depletion of ATP and/or reducing equivalents. This metabolic stress might then reduce the rate at which energy-consuming proteins in the cell can scavenge ROS and/or repair damaged DNA, facilitating more rapid photo inactivation (Michael *et al.*, 2008). But within the pH range of 6 to 9 the stress exerted on

the cells might not be significant. Hartel *et al*, (2000) strengthened this idea by describing that survival of pathogens is not adversely affected within the pH range of 5.8 to 8.4. Hence, the stated elaboration can be a possible justification why significant difference on the rate of fecal coliform inactivation was not found within the pH range of 6 to 9. The finding is in agreement with finding of Rincon and Pulgarin (2004), who found that initial pH values between 4 and 9 did not affect E. coli inactivation rates. But it is differing from the finding of Michael *et al*. (2008) in which bacterial inactivation was increasing by factors of 2 and 8 at pH 4.0 and 3.0, respectively compared to at pH 7. The discrepancy might be due to the difference of initial pH of raw water and the light source. Their result indicated that higher inactivation rate was found at pH 4.0 and 3.0, but in this study the pH range is above 5.5. Taken together, the differences in light source, pH values tested, and experimental conditions may account for much of the disparity between this work and theirs. To conclude, this study showed that significant difference on microbial inactivation was not found within the recommended pH range of raw water (5.5 to 9) for drinking water abstraction (European Communities Council Directive, 1991).

The present study indicated that statistically significant difference on the rate of bacterial inactivation was not observed on water samples having 5.24mg/L and 6.52mg/L dissolved oxygen. Though the difference was not statistically significant, the rate was increased by a factor of 2.2 on the latter water samples. The observed higher rate might be due to formation of reactive forms of oxygen (oxygen free radicals and hydrogen peroxides) in the water and these reactive molecules react with cell structures and kill pathogens and finally the inactivation rate enhanced (Kehoe *et al*., 2001, Reed, 1997). This result is supported by Reed (1997) who indicated that bacterial inactivation rate of aerobic water was increased by a factor of 3.8 than anaerobic water. To enhance the rate of bacterial inactivation, aerating raw water prior to solar exposure is very important. Most of ground water sources are lacking enough dissolved oxygen (Hem, 1985). Hence, aerating such kind of raw water sources prior to sunlight exposure can enhance the rate of microbial inactivation. Mechanical shaking can be one of the techniques that increase the

concentration of dissolved oxygen and this can be applied at household level (Mahafooz, 2009, Kehoe *et al*., 2001 and Reed, 1997).

This study has also shown that higher bacterial log inactivation was found on water samples having shallow depth (5.5 cm) while slower inactivation was observed on water samples with deep longer depth (10 cm). This could be due to the reduction of intensity of UV radiation with increasing water depth (Hannah, 2008). The finding is in agreement with previous studies done by Wagelin *et al*. (1994). They indicated that UV-radiation is reduced by increasing water depth. At a water depth of 10 cm and moderate turbidity level of 26 NTU, UV-A radiation is reduced to 50%. Ambelu (2001) has reported similar results. His finding has indicated exposing water having initial bacterial load of 1100MPN/100mL with 7 cm depth for 2 and 3 hours reduced the FC to 220 and 70 MPN/100mL and depth with 15cm were reduced to 460 and 288 MPN/100mL respectively. To compact the influence of water depth on the efficiency of solar disinfection, an alternative container design would be considered. As an alternative, bags made out of a transparent and a black PET-sheet have been produced (SODIS-bags) with a larger area for sunlight exposure and water depth of less than 6 cm. This increases the exposed area/ water volume ratio and it might enhance the inactivation process (SANDEC/ EAWAG, 2002).

The present study indicated that faster microbial inactivation on water samples exposed under glass bottle and PET bottle and on the contrary slower rate was observed under metal containers (*coda*). This finding demonstrated that PET bottle is a best alternative container for SODIS application. The possible justifications for this conclusion are comparable microbial inactivation was found with glass bottles. And due to the worldwide availability of PET bottles in varying sizes (Mahafooz, 2009), so the abundance of plastic bottles increases the likelihood of employing the solar disinfection process. The other important justification might be the traces of the plasticizers DEHA and DEHP leaching from PET bottles upon SODIS (solar water disinfection) treatment has a negligible cancer risk (2.8×10^{-7}) and are below the respective limits for drinking water fixed by the WHO, as it is investigated by Schmid and his colleagues (2008). In fact

detailed study should be undertaken on toxicity and carcinogenicity of chemicals released from PET bottles prior to wide application of PET bottles as household solar disinfection purpose. And the other possible explanation is due to less attractiveness of glass bottles. Because, unlike PET bottles, it is known with their high costs, easily breakable, not simple for handling and their rare availability in the developing areas of the world.

Color of PET bottle has shown significant effect on the rate of fecal coliform inactivation. The rate observed on colorless PET was increased by a factor of 5.6 from black PET bottles. This indicated UV-A radiation is a major cause for bacterial inactivation. The contribution of heat observed within six hour of exposure time was 0.42±0.03 log inactivation. This implies that the thermal effect found from sunlight alone cannot achieve significant microbial inactivation. This finding is in agreement with the finding of Rojko (2003). He dictated that there was less than 0.5-log inactivation of *E. coli* in each experiment for any given temperature. Painting the entire surface of PET bottle with black color didn't show any significant microbial inactivation.

Using half-surfaced black colored PET bottle has shown significant bacterial inactivation in comparison to raw water samples exposed on the surface of cardboard, concrete and CIS. It has increased the rate by a factor of 1.68. This observed higher inactivation rate can be explained by the observed $51.1^{o}C \pm 0.17^{o}C$ temperature of water. At this range of temperature synergistic effect between thermal inactivation and optical inactivation was expected (Wagelin, 1994, McGuigan, 1998). Furthermore, this study showed that exposing water on concrete, cardboard and CIS surfaces didn't show statistically significant difference on the rate of microbial inactivation. This might be due to the observed water temperature range ($38^{o}C$ to $45^{o}C$); thermal effect is very minimal or not pronounced (McGuigan, 1998). This finding is in agreement with the finding of Wagelin(1994), who dictated survival curves of E.coli remains basically unchanged at a temperature range of 20-40^{o}c. It also supported by Rojko (2003) and McGuigan(1998) who have indicate that temperatures up to 46°C have no significant effect on the disinfection of *E. coli* bacteria. Varying place of bottle exposure cannot have any significant difference on the rate of microbial inactivation.

This finding has shown that under optimized conditions for water disinfection, complete inactivation was found within exposure time of less than four hour. Within exposure time of 3.7Hr±0.12Hr, 3-log or 99.9% inactivation was found. Within this (<4 Hr) exposure time complete inactivation can be found at different parts of Ethiopia like, Nazret, Mekele, Dire Dawa, etc, which are receiving an average of 6.00, 5.54 and 5.96kWh/m^2 solar irradiance respectively (Boxwell, 2011). The exposure time required for complete inactivation was in a good agreement with some literatures. And discrepancy was observed with some other literatures. Boyle and his colleagues (2008) dictated complete inactivation (i.e., reductions greater than 4 orders of magnitude and final population below the limit of detection, which is 17 CFU/mL) was achieved within 3 Hr of exposure. Joyce et al. in1996 reported that complete disinfection of highly contaminated water (10^6 CFU/mL) in 2-liter transparent plastic bottles (a batch system) was achieved in 7 Hr by heating the water to approximately 55°C. A 3-log reduction in *E. coli* concentration by solar irradiation of contaminated water in a batch system in about 5 Hr has been reported by Wagelin in 1994. The solar reactor tested in the study done by Laurie in 2004 successfully eradicated more than 4 log10 U (99.99%) of total coliforms within 30 min in midday summer sunlight. The discrepancy observed between this study and previous study might be due to altitudinal variation, sun angle variation, variation of experimental design (some literatures have used solar reactor, but in this study used PET bottles was used), source of radiation (some are used artificial lamp, but in this study natural sunlight was used as a source of radiation), seasonal variation, etc.

This study demonstrated that SODIS is effective for treatment of bacteriologically contaminated well water. Complete fecal coliform inactivation was found on well water that has turbidity level of 13NTU after 6 Hr exposure. But within similar exposure time complete inactivation was not found on synthetic raw water samples that have same turbidity level. The discrepancy might be due to the presence of natural organic matter (NOM), which is an important constituent of natural waters, is known to act as photosensitiser for a variety of chemical reactions that are produced by energy transfer, singlet oxygen and radical species, such as methylene blue or rose Bengal, are very effective in mediating the killing of microorganisms (Wagelin, 1994). Solar disinfection

can be a good alternative technology for the treatment of well water sources that are mostly hidden from sunlight and are prone to contamination due to unsanitary condition of the vicinity of the well and poor cleanliness of materials used for water withdrawal. Furthermore, this study showed that microbial re-growth was not observed after 4 days storage in dark place, confirming that the inactivation process was irreversible. The finding is in agreement with similar study done by Berney *et al*. (2006) (5 days post treatment). Irreversible inactivation would have an importance in relation to the need to store drinking water.

Generally, applying SODIS technology could have enormous importance for deprived communities who have a scarcity of safe water supply. Rural communities, who are relying on boiling as a disinfectant, required one kilogram of wood per one liter of water (Acra *et al*, 1984 and Ellis, 1991). By applying SODIS technology one household can conserve 3650 kg of wood per year. Imagine what a huge amount of wood can be conserved if SODIS technology is applied at a large scale. Currently, in different parts of Ethiopia, Aquatabs are utilized as a disinfectant. One tablet of Aquatabs, which is sold with 50 cents of Ethiopian currency, can treat 20 liter of raw water. Besides getting rid of the complications formed due to procedural errors when they are applying Aquatabs, one household can save 730 Ethiopian birr per year by applying SODIS technology.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATION

7.1. Conclusion

The study has showed the possibility of disinfecting bacteriologically contaminated water with low cost technology. This technology can be easily adapted to Ethiopian communities where plenty of sunshine is available and who are deprived of safe water supply. The finding has demonstrated that complete fecal coliform inactivation can be achieved within an exposure time less than 4 Hr under optimized conditions. Utilizing half-surfaced black colored container and aerating raw water prior to sunlight exposure has shown a significant increment on the rate of fecal coliform inactivation. Bacterial re-growth was not found after SODIS treatment, confirming the inactivation process is irreversible.

7.2. Recommendation

Based on the finding, the following recommendations were forwarded for relevant stakeholders.

- Visible turbidity greater than 20NTU should be removed before the SODIS process can be applied, because turbidity will interfere with the disinfection efficiency.
- Since the treated water do not have any residual effect, communities should develop good hygienic and water handling practice to minimize secondary contamination.
- Just at the end of treatment the water is hot, so it needs cooling prior to consumption.
- Health education should be given on good hygienic and safe water handling practices.
- Further study is recommended on the effect of seasonal, altitudinal and sun angle variation on inactivation rate of microbes and the toxicity chemicals that might released from PET bottles during sunlight exposure.

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ANNEXES

Annex 1. Procedure of microbial Analysis by pour plate method

The concentration of viable fecal coliform was enumerated using the pour plate method according to Method 9215B of Standard Methods (APHA *et al.*, 1998). In this method, pre-sterilized 100 mm plates (in which 100 μL to 10 mL can be plated) were used. The procedures are as follows:

- 1mL of sample was pipetted into the center of the Petri dish and 10 to 12 mL of plate count agar was pipetted directly on top of the sample to ensure evenly distribution of sample throughout the agar.
- The dish was mixed using a figure-eight motion, and then allowed to solidify for 5 to 8 minutes.
- In addition, for each sample, one blank control (1mL of distilled water) was plated.
- Then, the dishes were capped, inverted, and incubated at 44.5^{o}c for 24 to 48 hours.
- Afterwards, the colonies were counted with colony counter.

Annex 2. Temperature and sunshine profile of Jimma town

Temperature profile of Jimma town

The figure below indicates the temperature profile of Jimma town from 2005 to 2009; the annual average maximum temperature is in the range of 27.69^{o}c in 2009 to 28.17 ^{0}C in 2008. Since the temperature is fluctuated in a day, yearly minimum temperature was found to be in the range of 11.27^{o}c in 2005 to 12.7^{o}c in 2006. Seasonal variation of the temperature was also taken in to account in National meteorological agency, Jimma sub-branch office , as the data indicates higher maximum temperature has been registered in January, February; march, October, November and December. In May, June, July, august and September lowest monthly average maximum temperature has been seen. However, when we look at the minimum average monthly temperature profile of jimma town, it is higher as of May, June, July, august and September. Likewise lowest minimum average monthly temperature have been seen in January, February, March, October, November and December. The five year monthly average temperature profile of Jimma town is attached in appendix III. The raw temperature data is secured from National meteorological agency, Jimma sub-branch office and analyzed and presented by using Microsoft excels 2003 software.

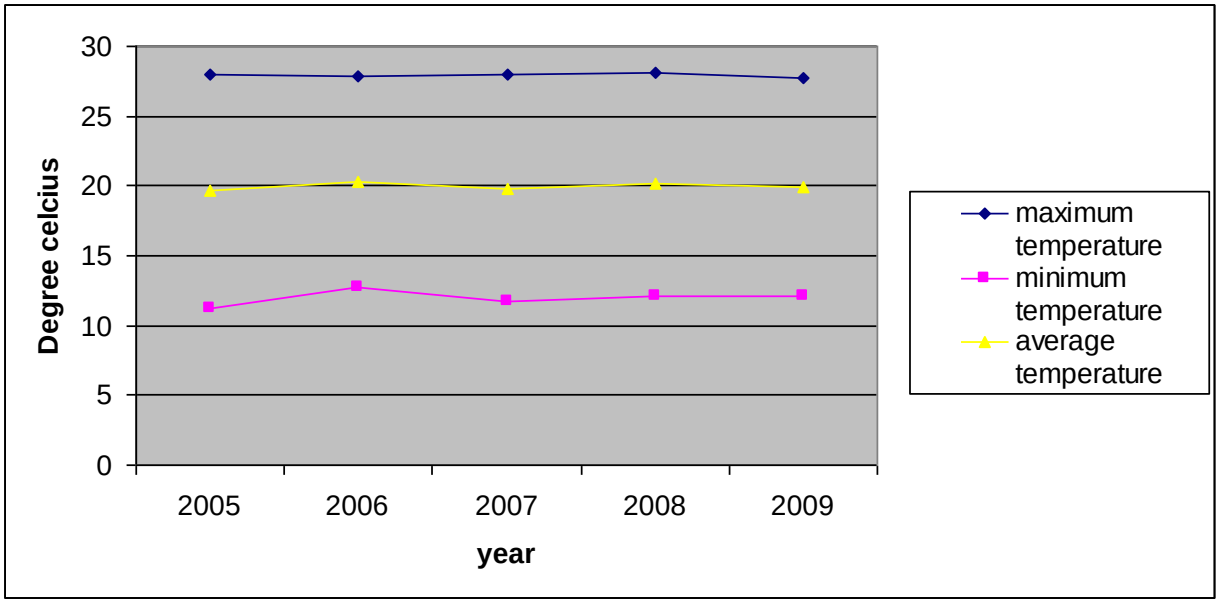

Figure 22. Annual average temperature profile of Jimma town from 2005 to 2009
(Personal communication, Kumela, December 13, 2010)

Sunshine duration and solar irradiance profile of Jimma town

As it is indicated in the figure below, the five year sunshine duration profile of Jimma town is in the range of 6.51hour in 2006 to 6.97 hour in 2005. The sunshine duration of the town is found to be varied from season to season; longest sunshine duration is observed in January, February; march, April, October, November and December. In these months, the sunshine duration reaches 7.5 to 9.03 hour. But the shortest sunshine duration has been seen in June, July, august, September; the duration is reduced till 3 hour in these months.

Generally, as the temperature profile of Jimma town and sunshine duration data shows, in dry months, like; January, February; march, April, warmer temperature and long sunshine duration registered. Therefore, this particular study will be undertaken in sunny months, from February to May, in which the sunshine duration is greater than 6 hour. In addition, the study will evaluate if solar disinfection could be possible and optimize the disinfection for the shortest sunshine duration (3 hours).

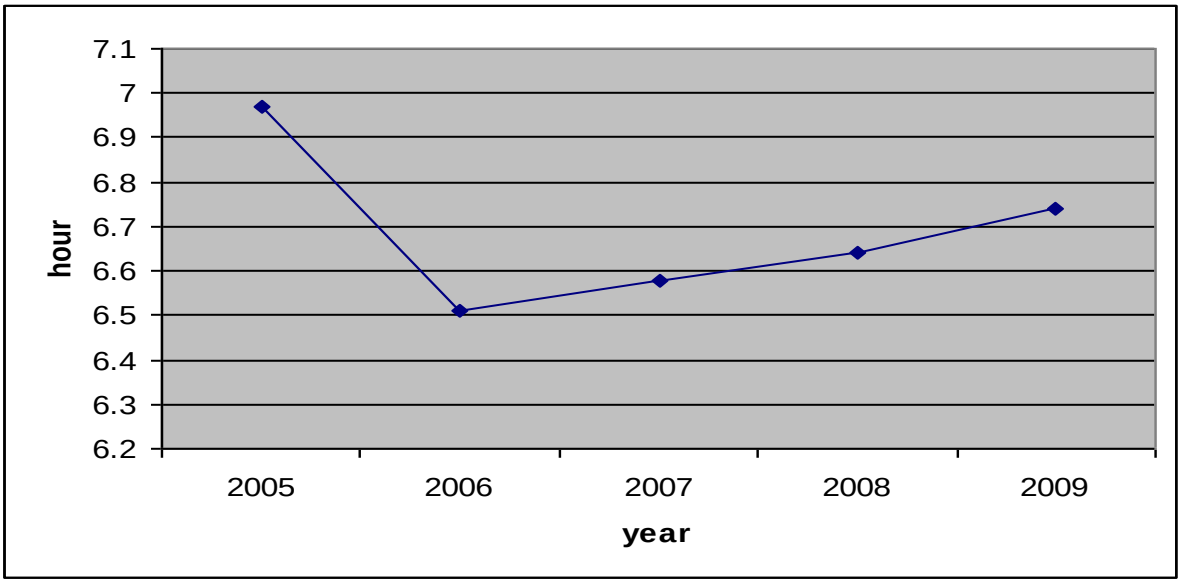

Figure 23. Annual average sunshine duration of Jimma town from 2005 to 2009
(Personal communication, Kumela, December 13, 2010)

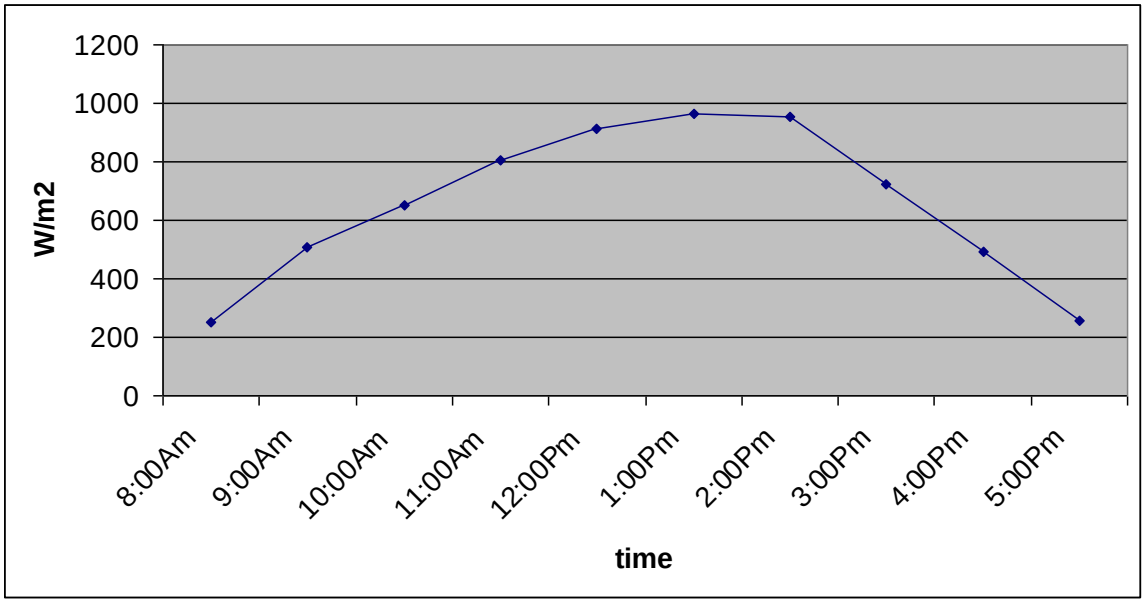

Figure 24. Solar irradiance profile of Jimma town (Yohannes, personal communication on February 23.2011). The data was measured in September 2010.

Select Country: Ethiopia

Select Town/City: Jimma
Measured in kWh/m^2/day onto a horizontal surface:

Jan	Feb	Mar	Apr	May	Jun
5.38	5.76	5.8	5.56	5.3	4.78

Jul	Aug	Sep	Oct	Nov	Dec
4.33	4.57	5.14	5.33	5.35	5.36

Figure 25. Average solar irradiance of Jimma town
Source (Michael Boxwell, 2011)

Annex 3. Statistical test outputs

a. Turbidity

Kruskal Wallis output of mean difference of log inactivation among varied turbidity values of water samples (3 hour of exposure time)

Ranks

	turbidity	N	Mean Rank
Log inactivation	1.78NTU	3	14.00
	13.13NTU	3	11.00
	25.43NTU	3	8.00
	45.67NTU	3	5.00
	80.6NYU	3	2.00
	Total	15	

Test Statistics[a,b]

	Log inactivation
Chi-Square	13.500
df	4
Asymp. Sig.	.009

a. Kruskal Wallis Test

b. Grouping Variable: turbidity

Kruskal Wallis output of mean difference of inactivation rate constant of fecal coliform among varied turbidity values of water samples

Ranks

	Turbidity	N	Mean Rank
inactivation rate constant	1.78NTU	3	14.00
	13.133NTU	3	11.00
	25.43NTU	3	8.00
	45.67NTU	3	5.00
	80.6NTU	3	2.00
	Total	15	

Test Statistics[a,b]

	inactivation rate constant
Chi-Square	13.500
df	4
Asymp. Sig.	.009

a. Kruskal Wallis Test

b. Grouping Variable: Turbidity

b. pH

Kruskal Wallis output of mean difference of log inactivation of fecal coliform among varied pH values of water samples (3 hour of exposure time)

Kruskal-Wallis Test

Ranks

	pH	N	Mean Rank
Log inactivation	ph=6.113	3	6.33
	ph=7	3	3.17
	ph=7.96	3	5.50
	ph=8.93	3	11.00
	Total	12	

Test Statistics[a,b]

	Log inactivation
Chi-Square	7.501
df	3
Asymp. Sig.	.058

a. Kruskal Wallis Test

b. Grouping Variable: pH

c. Dissolved oxygen

Output of Mann-Whitney test on mean difference of log inactivation of fecal coliform between water samples having different dissolved oxygen concentration (3 hour exposure time)

Mann-Whitney Test

Ranks

	Dissolvedoxygen	N	Mean Rank	Sum of Ranks
Log inactivation	5.24mg/L	3	2.00	6.00
	6.52mg/L	3	5.00	15.00
	Total	6		

Test Statistics[b]

	Log inactivation
Mann-Whitney U	.000
Wilcoxon W	6.000
Z	-1.964
Asymp. Sig. (2-tailed)	.050
Exact Sig. [2*(1-tailed Sig.)]	.100[a]

Output of Mann-Whitney test on mean difference of inactivation rate constant (k) between water samples having different dissolved oxygen concentration

Mann-Whitney Test

Ranks

	dissolvedoxygen	N	Mean Rank	Sum of Ranks
inactivation rate constant	DO=6.52mg/L	3	2.00	6.00
	DO=5.24mg/L	3	5.00	15.00
	Total	6		

Test Statistics[b]

	inactivation rate constant
Mann-Whitney U	.000
Wilcoxon W	6.000
Z	-1.964
Asymp. Sig. (2-tailed)	.050
Exact Sig. [2*(1-tailed Sig.)]	.100[a]

d. Water depth

Kruskal Wallis output of mean difference of log inactivation among varied depth of water samples (3 hour of exposure time)

Kruskal-Wallis Test

Ranks

	depth	N	Mean Rank
Log	5.5 cm	3	11.00
	7.5 cm	3	8.00
	8.5 cm	3	5.00
	10 cm	3	2.00
	Total	12	

Test Statistics[a,b]

	Log
Chi-Square	10.532
df	3
Asymp. Sig.	.015

a. Kruskal Wallis Test

b. Grouping Variable: depth

e. Container type

Output of Kruskal-Wallis Test on mean difference log inactivation of fecal coliform on water samples exposed under varied container (3 hour exposure time)

Kruskal-Wallis Test

Ranks

	container	N	Mean Rank
log inactivation on container type within 3 hour	Metal(coda)	3	2.00
	glass	3	8.00
	PET	3	5.00
	Total	9	

Test Statistics[a,b]

	log inactivation on container type within 3 hour
Chi-Square	7.200
df	2
Asymp. Sig.	.027

a. Kruskal Wallis Test

b. Grouping Variable: container

Output of Mann-Whitney Test on mean difference of log inactivation of fecal coliform on water samples exposed under Glass bottles and PET bottles (3 hour of exposure time)

Mann-Whitney Test

Ranks

	container	N	Mean Rank	Sum of Ranks
log inactivation on container type within 3 hour	glass	3	5.00	15.00
	PET	3	2.00	6.00
	Total	6		

Test Statistics[b]

	log inactivation on container type within 3 hour
Mann-Whitney U	.000
Wilcoxon W	6.000
Z	-1.964
Asymp. Sig. (2-tailed)	.050
Exact Sig. [2*(1-tailed Sig.)]	.100[a]

Output of Kruskal-Wallis Test on mean difference of inactivation rate constant of fecal coliform on water samples exposed under varied container

Kruskal-Wallis Test

Ranks

	container	N	Mean Rank
inactivation rate constant	Metal(Koda)	3	2.00
	glass	3	8.00
	PET	3	5.00
	Total	9	

Test Statistics[a,b]

	inactivation rate constant
Chi-Square	7.200
df	2
Asymp. Sig.	.027

a. Kruskal Wallis Test

b. Grouping Variable: container

f. Color of container

Output of Kruskal-Wallis Test on mean difference log inactivation of fecal coliform on water samples exposed under varied color of PET bottle (3 hour exposure time)

Kruskal-Wallis Test

Ranks

	COLOR	N	Mean Rank
log inactivation among varied color of PET bottle after 3 hour of exposure time	black	3	2.00
	light black	3	5.00
	white transparent	3	8.00
	Total	9	

Test Statistics[a,b]

	log inactivation among varied color of PET bottle after 3 hour of exposure time
Chi-Square	7.200
df	2
Asymp. Sig.	.027

a. Kruskal Wallis Test

b. Grouping Variable: COLOR

Output of Kruskal-Wallis Test on mean difference inactivation rate constant (k) of fecal coliform on water samples exposed under varied color of PET bottle

Kruskal-Wallis Test

Ranks

	color	N	Mean Rank
inactivation rate constant	black	3	2.00
	light black	3	5.00
	white transparent	3	8.00
	Total	9	

Test Statistics[a,b]

	inactivation rate constant
Chi-Square	7.200
df	2
Asymp. Sig.	.027

a. Kruskal Wallis Test

b. Grouping Variable: color

g. Temperature effect

Output of Kruskal-Wallis Test on mean difference log inactivation of fecal coliform on water samples exposed under varied surfaces and under half-surfaced black colored PET bottle (3 hour exposure time)

Kruskal-Wallis Test

Ranks

	Temperature	N	Mean Rank
Log inactivation	concrete surface(38.1 degree celcius)	3	4.00
	card board(41.8 degree celcius)	3	5.00
	CIS(45.57 degree celcius)	3	6.00
	half-surfaced black colored PET(51.1 degree celcius)	3	11.00
	Total	12	

Test Statistics[a,b]

	Log inactivation
Chi-Square	6.692
df	3
Asymp. Sig.	.082

a. Kruskal Wallis Test

b. Grouping Variable: Temperature

Output of Kruskal-Wallis Test on mean difference inactivation rate constant (k) of fecal coliform on water samples exposed under varied surfaces and under half-surfaced black colored PET bottle

Kruskal-Wallis Test

Ranks

	temperature	N	Mean Rank
inactivation rate constant	concrete surafec(38.1 degree celcius)	3	2.67
	card board surface(41.8 degree celcius)	3	7.67
	CIS(45.57 degree celcius)	3	4.67
	half-surfaced black colored PET(51.1 degree celcius)	3	11.00
	Total	12	

Test Statistics[a,b]

	inactivation rate constant
Chi-Square	9.154
df	3
Asymp. Sig.	.027

a. Kruskal Wallis Test

b. Grouping Variable: temperature

Output of Kruskal-Wallis Test on mean difference inactivation rate constant (k) of fecal coliform on water samples exposed under varied surfaces

Kruskal-Wallis Test

Ranks

	temperature	N	Mean Rank
inactivation rate constant	concrete surafec(38.1 degree celcius)	3	2.67
	card board surface(41.8 degree celcius)	3	7.67
	CIS(45.57 degree celcius)	3	4.67
	Total	9	

Test Statistics[a,b]

	inactivation rate constant
Chi-Square	5.067
df	2
Asymp. Sig.	.079

a. Kruskal Wallis Test

b. Grouping Variable: temperature

h. Solar intensity

Output of Kruskal-Wallis Test on mean difference of log inactivation of fecal coliform on water samples exposed under varied solar irradiance

Kruskal-Wallis Test

Ranks

	Intensity	N	Mean Rank
Log inactivation	0.602kWh/m2	3	5.00
	2.77kWh/m2	3	8.00
	3.99kWh/m2	3	2.00
	Total	9	

Test Statistics[a,b]

	Log inactivation
Chi-Square	7.200
df	2
Asymp. Sig.	.027

a. Kruskal Wallis Test

b. Grouping Variable: Intensity

Output of Kruskal-Wallis Test on mean difference of inactivation rate constant (k) of fecal coliform on water samples exposed under varied solar irradiance

Kruskal-Wallis Test

Ranks

	Intensity	N	Mean Rank
inactivation rate constant	2.77kWh/m2	3	5.00
	3.99kWh/m2	3	8.00
	0.602kWh/m2	3	2.00
	Total	9	

Test Statistics[a,b]

	inactivation rate constant
Chi-Square	7.200
df	2
Asymp. Sig.	.027

a. Kruskal Wallis Test

b. Grouping Variable: Intensity

i. Optimization

Output of Mann-Whitney Test on mean difference of log inactivation of fecal coliform between test and control water samples

Mann-Whitney Test

Ranks

	code	N	Mean Rank	Sum of Ranks
Log inactivation	Test	3	5.00	15.00
	Control	3	2.00	6.00
	Total	6		

Test Statistics[b]

	Log inactivation
Mann-Whitney U	.000
Wilcoxon W	6.000
Z	-2.087
Asymp. Sig. (2-tailed)	.037
Exact Sig. [2*(1-tailed Sig.)]	.100[a]

j. Testing SODIS on natural water

Output of Mann-Whitney Test on mean difference of log inactivation of fecal coliform between test and control water samples

Mann-Whitney Test

Ranks

	watersamples	N	Mean Rank	Sum of Ranks
Log inactivation	Test	3	5.00	15.00
	Control	3	2.00	6.00
	Total	6		

Test Statistics[b]

	Log inactivation
Mann-Whitney U	.000
Wilcoxon W	6.000
Z	-1.993
Asymp. Sig. (2-tailed)	.046
Exact Sig. [2*(1-tailed Sig.)]	.100[a]