

Drinking Water Disinfection by Solar Radiation

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Abstract A primary concern of developing countries throughout the world is that of obtaining safe drinking water. Waterborne diseases are still common in developing countries since drinking water sources are contaminated and the conventional rural water treatment plants are often inefficient to produce safe drinking water. This situation in developing countries is a major problem in terms of preventing public health. It is estimated that diarrhea accounted for 99% of the 69 million deaths among children before the age of five. Inadequate operation and maintenance after installations caused by a lack of trained operators, by a treacherous supply of chemicals and spare parts, and by financial problems lead to produce unhealthy drinking water. Since major urban water supplies are also not always capable of maintaining a regular supply of qualitatively good water, the distributed water is often considered unsafe for direct consumption. Treatment of water at the household level (etc. boiling) or purchasing of mineral water for consumption is more real than an exception in urban areas of developing countries. Recently, another small-scale approach using the lethal effect of sunlight has gained importance to sanitary contaminated water. Solar disinfection (SODIS) is one of the simplest methods for providing acceptable quality drinking water and consists of filling transparent containers (plastic bags, plastic bottles or glass bottles) with water and exposing the containers to sunlight for approximately 6 hours. Because of the low cost and easy usage, solar disinfection is commonly used in developing countries in Asia, Africa and South America. The aim of this literature review is to give information about solar disinfection mechanism, to compare the efficiency of solar disinfection on different microorganisms based on the past studies, and to discuss the several applications of solar disinfection in the world.

Keywords Drinking Water, Microorganism, Rural Area, Solar Disinfection

1. Introduction

Supplying safe drinking water is one of the most important issues in terms of sustainability of life. However, water

resources are increasingly threatened with increasing population density, overuse and wastage [1]. According to the World Health Organization (WHO), 884 million people lack from the access to improved water supplies. In the context of the envisaged energy crisis in the future, problems with the provision of healthy drinking water are expected to worsen, or it is expected that the water problems will increase the energy problems due to the close relation between water and energy [2]. In this case, it is important to ensure that drinking water is supplied in sufficient quantity and quality, continuously and economically for developing countries [3, 4].

There is a significant amount of microbial pathogens in sewage systems. Viruses as well as bacteria and many protozoans occur in the sewage system. Although many pathogens can be removed by treatment systems, most of them are discharged in the effluent and reached to surface waters [5]. Wastewater and contaminated water used for irrigating, drinking, and recreational purposes have been widely related to the transmission of infectious viral diseases among human populations [6-9].

Waterborne diseases are still common as water resources are contaminated with pathogens; and conventional rural treatment processes are often inadequate to produce safe drinking water in developing countries. The inadequacy of water resources forces microbiologically unsafe water usage which causes the transmission of epidemics including cholera, typhoid, hepatitis [1, 10, 11]. In developing countries, 50% of the population is exposed to polluted water resources, resulting in 4 billion diarrhea cases each year due to inadequate supplies of water for personal care and insufficient treatment. Therefore, 2.2 million people, the majority of whom are under the age of 5, lose their lives every year [1, 11].

Although the interventions in the distribution network have been shown to reduce diarrhea, current research has demonstrated that point of use applications within the household can be more effective. However, these applications must have certain criteria such as low cost, easy use and sustainability. In addition to boiling, chlorination and filtration, sunlight disinfection has gained popularity as a household water disinfection method in recent years [10].

Solar disinfection (SODIS) is an efficient, low technology

and cost-effective method for inactivation of pathogenic microorganisms in low-income communities where clean drinking water providing is limited or absent. [12]. The use of sunlight for supplying healthy water is not a new phenomenon. It has been demonstrated that solar disinfection inactivates microorganism by direct exposure is volume independent economic process and avoids production of hazardous by-products of chemically driven technologies [13].

Solar radiation removes a broad range of microorganisms such as viruses, bacteria and protozoa [14]. Contaminated drinking water in the transparent carriers such as plastic bottles, bags and glass bottles are placed in direct sunlight for at least 6 hours prior to consumption [14-16]. Destruction of microorganisms during solar disinfection is achieved by the synergistic effects of mild heat and UV radiation, leading to pasteurization and UV disinfection [17]. In addition, pathogens are removed by indirectly with the photosensitizer which absorbed UV light and produced reactive oxygen species by reacting with oxygen in water [18].

The efficacy of solar disinfection is affected by several factors including presence of organic and inorganic compounds and dissolved oxygen in water, solar light intensity, temperature, type of container and nature of microorganisms [1, 19].

Since it is very important to provide healthy drinking water economically in developing countries, the household water treatment method is a matter to be considered. Several modifications such as thermal enhancement, heterogeneous photocatalysis, chemical addition, flow reactors, solar mirrors have been developed to enhance the effectiveness of solar disinfection on pathogens especially viruses and protozoa which are very resistant to disinfection because of several limitations of traditional solar disinfection [20]. These systems are crucial in reducing the incidence of gastrointestinal infection in communities where supplying clean drinking water is limited or absent.

The aim of this literature review is to give information about solar disinfection mechanism, to compare the efficiency of solar disinfection on different microorganisms based on the previous studies, and to discuss the several applications of solar disinfection on the worldwide [21-23].

2. Fundamental Aspects of Solar Disinfection

Solar disinfection is affected by several variables such as solar radiation wavelengths, water temperature, turbidity, and container type [1].

2.1. Solar Radiation Wavelengths

The inactivation effect of sunlight on microorganisms has been known for 4000 years [16]. The spectrum of solar energy that reaches the Earth's surface is very broad

covering radiation wavelengths of generally 300 nm and upwards [15, 24, 25]. Studies have shown that the components of sunlight such as UV-A (wavelengths, 320 to 400 nm), UV-B, and UV-C radiation are able to inactivate microorganisms [26-27]. UV-C radiation has the greatest efficiency on inactivation because of its absorption by DNA. UV-C (at 254 nm) leads to changes in nucleic acids and other structures such as enzymes and immunogenic antigens of microorganisms. However, UV-C component of solar radiation does not reach the earth [15]. Since wavelengths below 290 nm do not reach the earth, it has been concluded that the most bactericidal wavelengths are between 315 to 400 nm [15, 17, 24, 25, 28, 29]

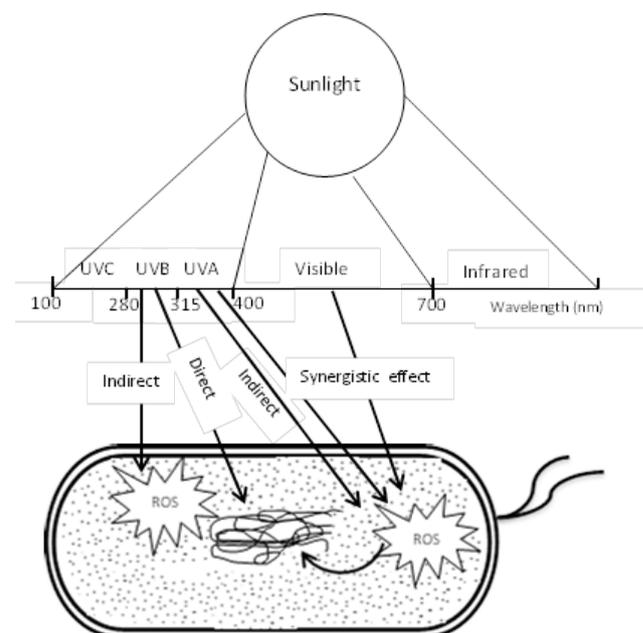


Figure 1. Effects of solar light on microorganisms (Adapted by Silverman et al. [30])

UV-B light (290-320 nm) affects considerably organisms in water since its germicidal effect is 100-1000 times more efficient than UV-A. It damages cellular components (chromophores, enzymes, vitamins), genetic materials and proteins of organism, while UV-A leads oxidation of pyrimidines, purines and CPD (Cyclo butane pyrimidine dimers), strand breaks [31]. Synergistic effects of UV-A and violet light are responsible for inactivation of microorganisms by UV-A light (320-400 nm) which is principle wavelength region. Besides other cell damage, reactive oxygen species (ROS) can lead to lipid peroxidation, pyrimidine dimer formation and even DNA lesions. When ROS interacts with DNA, single strand breaks occur as well as nucleic base modifications which may be lethal and mutagenic for microorganisms. Apart from DNA; UV-A light affects compounds which are vital for a metabolic cycle and cell homeostasis. The irradiation of intracellular chromophores with UV-A light in the presence of oxygen results absorption through chromophores contributes the generation of ROS [32].

2.2. Heating

Heating is accomplished by sunlight during solar exposure [28, 33, 34]. Previous researches showed that most of the microorganisms are inactivated when they exposed to temperatures of over about 70°C for a certain period of time. Water temperatures within the bottles heated with solar energy in a solar hot box are raised to 65°C or higher degrees [23, 35]. Thus, the synergistic effect of optical and thermal inactivation processes leads higher reductions of *E. coli*, *Salmonella enterica* serotypes *typhi*, *paratyphi* and *enteritidis*, *Shigella flexneri*, *Pseudomonas aeruginosa*, *Enterococcus faecalis* and *Vibrio cholerae*. Thermal inactivation has not been reported for water temperatures < 40°C. Fecal indicators are inactivated in heated water up to 62°C and above, while spore-forming bacteria are never completely inactivated at these temperatures [36]. *E. coli* can be reduced by 3 logs with pasteurization at 65°C within 3 hours. The same reductions can be achieved in a combination of solar disinfection and pasteurization within 2 hours at 56°C [37].

Resistant organisms such as protozoal oocyst cannot be inactivated by heating during sunlight exposure; however, their infection potential can be reduced effectively. Infectivity studies on oocysts showed that *Cryptosporidium parvum* oocyst in turbid water exposed for 4, 8 and 12 hours to solar light caused significant decrease in the intensity of infection on mice at the end of all exposure times depending on thermal inactivation [38].

2.3. Impurities

Turbidity is a significant factor in the solar disinfection since hinder of light to transmit through water. It has been concluded that higher turbidity samples exposed to sunlight had less inactivation of *E. coli* compared to samples with little or no turbidity. This may be occurred due to the protective effect of particulate matter [22, 23, 39]. Suspended solids need to be reduced to a maximum of 5 µm in order to achieve effective inactivation. Sunlight has no lethal effect on the colored waters since wavelengths have been absorbed in a certain rates within water [28].

2.4. Containers

The solar disinfection process is carried out in transparent containers such as glass bottle, plastic bottle and bag which transmit sunlight [40]. Shape and color of the container may have significant impacts on the effectiveness of disinfection. Depending on the movement of the sun in the sky, the intensity of light that enters the bottle may change, and affects the efficiency of the disinfection. Thus, using round, conical bottles, not square or irregular shaped containers is suggested [28]. It is also noted that colorless containers allow the most transmittance of ultra-violet wavelengths in comparison to orange, yellow, red and green containers. The shallow water depth in the bag as opposed to the bottle,

allows for better penetration of the wavelengths because the depth of water is less in bag than PET bottle [41, 42]. Plastic—bottles which are made of Poly Ethylene Terephthalate (PET) are considered the best choice since they do not have as much UV stabilizer as compared to PVC bottles, which are made of Poly Vinyl Chloride (PVC). Bottles that are scratched will not work as well as clear clean plastic. Glass bottles can be used for SODIS however they are not nearly as efficient as PET bottles. Window glass is not recommended as it does not transmit enough UV radiation into water. The increase in the amount of water in high volumes (22 L - 25 L) can affect the disinfection efficiency, while the increase in the amount of water in the low volume water (0.5 -1.5 L) does not cause any change in the disinfection efficiency [22, 43]. Further research is needed to detect effects of volume variations on solar disinfection.

3. Inactivation of Microorganisms

Numerous researches have been conducted to determine the effectiveness of the SODIS on microorganisms. It has been demonstrated that the lethal effect of sunlight is due to the strong synergistic effect of optical and thermal processes at temperatures exceeding 45°C. Using solar radiation is effective disinfection method which is constantly being developed [24]. In addition to direct inactivation of solar radiation sunlight is absorbed by endogenous (e.g. cytochromes) and exogenous (e.g. humic substances) photosensitizers that produced highly reactive oxygen molecules such as hydrogen peroxide (H₂O₂), singlet oxygen and superoxides which destroy bacteria [44-46].

Both gram positive and gram negative bacteria including *Campylobacter jejuni*, *Enterococcus* sp., *Enteropathogenic E. coli*, *Mycobacterium avium*, *Mycobacterium intracellulare*, *P. aeruginosa*, *Salmonella typhi*, *S. typhimurium*, *Shigella dysenteriae* Type I, *Shigella flexneri*, *Streptococcus faecalis*, *Staphylococcus epidermidis*, *Vibrio cholerae*, *Yersinia enterocolitica* are inactivated at different levels by 6 h solar disinfection. However, 16 h of natural sunlight required for 1.3 log reduction of *Bacillus subtilis* endospores [10, 15, 28, 39, 47-50].

Solar disinfection is effective in inactivating some encysted parasitic Protozoa (*Cryptosporidium*, *Giardia* and *Entamoeba*) causing waterborne diseases. [14, 51, 52]. Most of these pathogenic protozoa can be destroyed in water samples that are continuously exposed to sunlight for 7 hours and kept at 50-60°C in 2 liter one side blackened bottles [52, 53]. *Cryptosporidium parvum* oocyst viability can be reduced by 86.3% and 97.7% during 8 h and 12 h strong solar exposure [14, 54]. It should be noted that the cumulative dose as well as the way of dosing (continuously, intermittently, average radiation, as direct or diffuse UV) significantly affects the observed behavior of inactivation [55, 56].

MS2, rotavirus, adenovirus, and poliovirus are effectively inactivated by UV-B ($\lambda=280-320$ nm) when water exposed to the full sunlight spectrum [57-60]. It leads modifications in the genome by producing photoproducts such as thymine dimers or bond breakage of the nucleic acid which will inhibit the reproduction of the viruses [61-62]. Both indirect endogenous and indirect exogenous effect of UV-A radiation is less efficient in inactivating viruses, because they rarely have such chromophores which act as sensitizers for the formation of reactive oxygen species (Calado 2013).

4 logs of MS2 was achieved in Swiss tap water in 6 hours at 22°C and a fluence rate of 1.34 kJ/cm² less than 1 log of inactivation was obtained in Swiss tap water for phiX174 adenoviruses. High temperatures during SODIS enhanced inactivation efficacy, 6 logs in 6 hours could be expected at 45°C and with a fluence rate of 1.34kJ/cm² [63].

It has been proven that solar disinfection is very effective in spores of phytopathogenic fungi, which are responsible for diseases of great incidence in agriculture and hospital distribution systems [64, 65]. It is possible to inactivate about 1000 colonies per millilitre of spores of five types of the *Fusarium* species (*F. equiseti*, *F. verticillioides*, *F. solani*, *F. oxysporum*, and *F. antophilum*) with different level in bottle reactor during 1-6 h exposure to natural solar radiation in perfectly sunny day [66].

4. Field Applications

Solar disinfection is very well suited for rural communities of low income in developing countries, which do not have access to standard water purification systems, do not boil or chlorinate the water, and are only interested in treating the water required for their daily consumption. [67-68].

It is estimated that 5 million people treat their water by using SODIS method in homes, schools, health centers, and other institutions (depending on structural, political, and geographic circumstances) in 55 countries in Asia, Africa, and Latin America (Figure 2). According to statistics the risk of diarrhoea in the Tamil Nadu region of South East India was reduced by 40% by using solar disinfection [10].

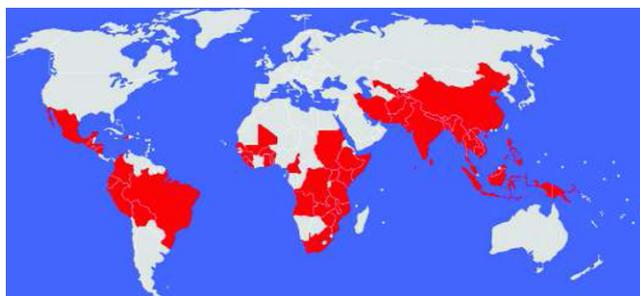


Figure 2. A map of the World indicating the 55 countries (Mc Guigan et al. [10])

The efficiency of solar disinfection for the inactivation of Total Coliforms (TC) and *Escherichia coli* (EC) in drinking

water was tested with three types of bottles which were transparent, partially painted black (one half of the bottle, along the longitudinal axis), and totally black in rural communities of the Guachochi Municipality, in the Tarahumara Sierra, State of Chihuahua, Mexico. The results of study showed that the available water has to be disinfected before consumption. Furthermore, all microorganisms in this geographic region were completely inactivated by the use of solar radiation. Complete disinfection takes place by simply placing water bottles under the sunlight during whole day [67].

The results of experiment conducted by Narain et al. [69] in Roorkee which is located at 29.850 latitude and 77.880 longitudes at an elevation of 255 m above the sea level in India showed that there was a significant reduction in Total coliform (79.2%), Turbidity (66.67%), TDS (41.03%) and EC (40.67%) after exposing the sample for 8 hours (one day) on sunlight (Figure 3).



Figure 3. Solar disinfection application in India (Narain et. al. [69])

It was stated by Mahvi [70] approximately 3 logs reduction in fecal coliforms are possible by using bottles at the temperature of 39.6°C. Replacing bottle with more transparent one, it would be possible to decrease the required contact time from 8 h to 6 h for 3 logs reduction [70].

In studies conducted in Spain and Bolivia, the time required for complete inactivation of *Campylobacter jejuni*, *Yersinia enterocolitica*, enteropathogenic *Escherichia coli*, *Staphylococcus epidermidis*, and endospores of *Bacillus subtilis* was determined as follows: *C. jejuni*, 20 min; *S. epidermidis*, 45 min; enteropathogenic *E. coli*, 90 min; *Y. enterocolitica*, 150 min. endospores of *Bacillus subtilis* approximately 2 days. SODIS was shown to be effective against the vegetative cells of a number of emerging waterborne pathogens; however, bacterial species which are spore forming may survive this intervention process under that conditions [40].

Samples of turbid water from open dug wells and clear water from shallow wells obtained on a weekly basis from Ndagwe sub-county in the central part of Uganda (latitude

0°20' 15" N, longitude 32° 33' 51" E and altitude 1,300 m) were exposed to natural solar light in order to demonstrate that if glass bottles are as effective as PET bottles in terms of microbial inactivation. Results of this study showed that SODIS efficacy in glass bottle under tropical field conditions was comparable to PET plastic bottle [71]. This means users in these regions can choose containers depending on availability and preference of the user. The results of another study which conducted to assess the efficacy of the borosilicate glass tube reactor fitted with a compound parabolic collector (BGTR-CPC) over an extended period of 17 months under local weather conditions in Uganda which is a tropical country with two rainy and two dry seasons in the year showed that satisfactory bacterial inactivation (log reduction values >6 units or inactivation to below the limit of detection <1 CFU/100 ml) was achieved during 6 h exposure [68].

In Kenya, water resource containing 10^5 E.coli / 100ml of *E.coli* was effectively disinfected by using continuous flow reactor combined with CPC [72].

The SODIS method carried out under field conditions in the Tabernas Desert (Almeria, Southern Spain: latitude, 37° 05' 54" N; longitude, 2° 21' 32" W; altitude, 500 m) with 1.5 L PET bottles containing turbid waters contaminated with *C. parvum* oocysts significantly reduced the potential viability of *C. parvum* oocysts. However, longer exposure times appear to be required than those required for the bacterial pathogens [73].

In another study, 8 areas in Bolivia were visited by researchers, and 644 families were interviewed on the basis of a structured questionnaire in order to predict current use of SODIS [74]. In the long run, it was concluded that bottles must be supplied regularly or adequately by an organization that will continue unlimited operations in the region concerned, or that a local plan must be initiated for the purchase of used PET bottles and transportation of the bottles to the cities.

The intention to use of SODIS in the future and actual use were investigated in two cities of Nicaragua by Alther et al. [75]. Families in La Paz Centro and Waslala were interviewed, half of which were using SODIS and half of which were not. According to the results of interview, the intention to use and actual use were mainly related to an overall positive attitude, intention to use was related to the use of SODIS by other people, and actual use is was related to knowledge about SODIS. In addition, SODIS users also stated that the frequency of diarrhea cases was significantly lower than SODIS nonusers. These results clearly indicate that increasing the number of promotional activities by selecting a promoter that can provide confidence as a new technology will increase the use of this method, and will decrease the rate of diarrhea.

Clinical field trials had been conducted to determine the efficiency of SODIS on reduction of diarrhea cases in Kenya [76, 77], India [78], Iran [70], and Cambodia [79].

It can be clearly seen from previous studies that

widespread of SODIS usage appears to be one of the most effective solutions in preventing waterborne diseases in the area where safe water supply is limited.

5. Limitations in Solar Disinfection

The application of solar disinfection is very simple, but there are several limitations in solar disinfection. Since solar disinfection is a process based on sunlight, it is only suitable for areas that receive 300 days a year, and between latitudes 35°N and 35°S having the optimum exposure of sunlight [28,33]. The other limitation is lack of materials required for the process immediately. Clear, cylindrical bottles are most effective containers allowing solar radiation to obtain healthy drinking water. However, it may be difficult to supply large scale use in remote communities where plastic containers are not sold. In addition, such devices for enhancement (foil, solar panels, copper piping, and thermostat valves) were required for pasteurization of drinking water [36]. It is not possible to find these materials easily in less developed areas. On the other hand, the information about solar water heater is not common, so this method of water heating for large-scale usage is impractical in developing countries. In addition, the shelf-life of the disinfected water is very short. It should be consumed within 24 hours before reactivation of bacteria. Small-scale individual usage of plastic bottles for SODIS is a promising treatment method that can be implemented with minimal resources and little training. Based on these considerations, it can be concluded that the SODIS technique can only useful as a point-of-use intervention, rather than for large-scale water disinfection. Thus, there is a real need to develop simple and inexpensive alternatives to SODIS that are able to provide larger volumes of healthy clean drinking water [80, 81].

6. Enhancement for Solar Disinfection of Water

The efficiency of SODIS process is dependent on the solar irradiance which varies with the latitude, time of day, atmospheric conditions, and several environmental factors including initial water quality for example organic loading, turbidity, level, nature of the bacterial contamination. In addition, the resistance of microorganisms leads to variation in treatment times of solar disinfection [1]. These factors have led to the necessity of developing the solar disinfection method.

Because of strong synergy between optical and thermal inactivation at exceeding temperatures of 45°C, many studies have been conducted to enhance the efficiency of solar disinfection. Periodic agitation, using foil to increase reflection rate, adding non-transmissive backing to the container, circulation of water on a black surface in a closed

enclosure that passes UVA radiation, using a solar collector connected to a double glass enclosure, and painting the half of the bottle's black to increase the achievable temperatures are main examples of these enhancement applications [22,35,39,67,71,82].

Other alternatives which are used to improve disinfection efficiency are design of SODIS bags where the solar dose per volume is increased, use of UVA dosimetric sensors (polyoxometalate, semiconductor photocatalyst and photodegradable dye) which indicate to the user when the desired dose has been received design of customised SODIS treatment systems which maximise the solar dose using compound parabolic collectors (CPC) and include UVA feedback sensors for automated control, and the use of semiconductor photocatalysis. By using reactors combined with CPC, 5 log *E.coli* inactivation is obtained in open air, while non-CPC requires more than 1 hour contact time [83].

Photocatalytic materials such as TiO₂, ZnO etc. are also used to increase the efficiency of solar disinfection. During photocatalytic disinfection the hydroxyl radical suggested to be the primary species that is responsible for microorganism inactivation. Other reactive species (ROS) such as H₂O₂, O⁻₂ can cause fatal damage to microorganisms by disruption of the cell membrane or by attacking DNA and RNA. Other effects of photocatalysts include damage to the respiratory system within the cells and loss of fluidity and increase ion permeability in the cell membrane [55, 84-86].

The exposure time required to achieve desired reductions is shorten by using solar photocatalytic materials with containers. The PET bottles with solar photocatalytic (SPC) inserts reduces the exposure time by approximately 25% compared to standard PET bottles, while solar photocatalytic (SPC) coated glass bottle reduces approximately 80% to achieve inactivation compared to the uncoated bottle [1]. Using borosilicate glass bottles 20% effective than PET bottles because of their good solar light transmittance. Similarly, using smaller volume bottles exhibited superior performance to larger volume bottles [10]. Glass rings, glass rods and porcelain beads with P25 powder also has been shown as an effective application on disinfection [87].

It is understood from results of previous studies, these methods help to improve or enhance the traditional solar disinfection process [22,35,39,67,82] since over 6 log *E.coli* inactivation can be achieved by using these ways [39,71].

7. Conclusion and Suggestions

Water and energy consumption has increased much faster and disproportionately than the human population in recent years, which causes the degradation of the environment and natural sources. Difficulty in access to safe drinking water and water stress in the ecosystem presents danger in many parts of the world. The need to access safe drinking water from poor quality water sources leads people to find low cost and sustainable methods. It is important that the

method to be used is sustainable and environmentally friendly. It is not possible to use the latest new technologies all over the world. While suggesting technologies, it is necessary to pay attention to many issues such as regional leads, economic conditions, water characteristics, natural resources, location characteristics and experiences. Solar energy, which has the highest potential and sustainability among all renewable energy sources, can be used in particular areas. It has been proven that sunlight is effective in the inactivation of pathogenic microorganism strains that are responsible for almost all waterborne diseases. Different raw water sources contain natural organic matter in different amounts depending on the surrounding basin and geological conditions. The presence of natural organic substances can negatively affect pathogen inactivation by sunlight. In addition, some pathogenic microorganisms may resist inactivation by sunlight. Semiconductor photocatalytic methods used with solar energy can be used as a good alternative to pathogen removal as well as mineralization of natural organic materials to prevent all these negative effects. Water treatment and efficient inactivation can be obtained by effective design of solar energy collection technology.

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