



A Solar Disinfection Water Treatment System for Rural Areas / Jordan

Yasmeen Smadi¹, Emad Alsood² and Mohammad Aljaradin^{1,2,*}

¹Swedish Center for Science and Education, Malmö, Sweden

²Civil Engineering Department, Tafila Technical University, Tafila, Jordan

*Corresponding Author: mohammad.aljaradin@srwj.se

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Keyword

Solar disinfection, Water disinfection, Dam lakes.

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Abstract:

The present study was conducted to assess the efficiency of solar energy in treating any potential pollution of drinking water in dam lakes caused by human activity in rural areas. The water quality parameters include temperature, pH, conductivity, total suspended solids, total nitrogen, total phosphorus, $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, HCO_3^- , Cl^- , Na^+ , Mg^{2+} , Ca^{2+} , SAR, B, K^+ , SO_4^{2-} , and E-coli were monitored. Samples were collected during the summer and winter (during the filling period). The results showed a rapid decrease in microbial counts upon exposure to solar radiation. More than 98% reductions were achieved after 8 hours for the bacterial communities tested under different conditions. The rate of inactivation, however, varied and was mainly affected by water turbidity and temperature during the experiments. The results indicated that turbidity affected the efficiency of water disinfection, and the efficiency improves with longer exposure duration, implying that in high turbidity and severe weather conditions, exposure time must be increased to compensate for the effects of these factors. The water in the system should be exposed to at least eight hours before leaving to the storage tanks. When scaled up, the proposed method could be a vital tool in solar water disinfection technologies, particularly in isolated and rural locations. Using solar energy to disinfect polluted water will certainly reduce the usage of chlorination and or filtration in water treatment, reducing treatment costs while also protecting the environment.

Keywords: Solar disinfection, Water disinfection, Dam lakes.

نظام معالجة المياه باستخدام الطاقة الشمسية في المناطق الريفية / الاردن

ياسمين الصمادي¹، عماد السعود²، محمد الجرادين^{2,1}

¹ المركز السويدي للعلوم والتعلم

² جامعة الطفيلة التقنية

mohammad.aljaradin@srwj.se

الخلاصة:

يهدف البحث إلى تقييم كفاءة الطاقة الشمسية في معالجة التلوث المحتمل لمياه الشرب في بحيرات السدود بسبب النشاط البشري في المناطق الريفية. لتحقيق ذلك تم فحص ومراقبة جودة المياه من خلال قياس درجة الحرارة، ودرجة الحموضة، والإيصالية، والمواد الصلبة العالقة، والنيتروجين، والفوسفور الكلي، والعديد من الخواص الكيميائية والفيزيائية للمياه بالإضافة للبكتيريا. تم جمع العينات خلال الصيف والشتاء اثناء فترة التعبئة. أظهرت النتائج انخفاضاً سريعاً في عدد البكتيريا عند تعريض المياه للإشعاع الشمسي. تم تحقيق أكثر من 98٪ تناقص في عدد البكتيريا التي تم فحصها ضمن ظروف مختلفة بعد ثمان (8) ساعات. أظهرت النتائج أيضاً تباين في معدلات التعقيم وتأثرت بشكل أساسي بعكارة المياه ودرجة الحرارة. أشارت النتائج إلى أن العكارة أثرت على كفاءة معالجة المياه، وأن الكفاءة تتحسن مع زيادة فترة التعرض للشمس، مما يعني أنه في حالة التعكر الشديد والظروف الجوية القاسية، يجب زيادة وقت التعرض للشمس للتعويض عن تأثيرات هذه العوامل. وأظهرت النتائج أيضاً أنه يجب تعريض مياه الشرب لأشعة الشمس مدة ثمان ساعات على الأقل قبل مغادرتها لخزانات التخزين. يمكن التوسع بالطريقة المقترحة ويمكن أن تكون أداة فعالة في معالجة مياه السدود الملوثة، لا سيما في المواقع المعزولة والريفية. من المؤكد أن استخدام الطاقة الشمسية لمعالجة المياه الملوثة سيققل من استخدام الكلورة و/أو الترشيح في معالجة المياه، مما يقلل من تكاليف المعالجة مع حماية البيئة أيضاً.

الكلمات المفتاحية: التعقيم الشمسي، معالجة المياه، بحيرات السدود.

1. INTRODUCTION:

Jordan is regarded as one of the most water-stressed country in the world [1]. Jordan, a country of 9.5 million people [2]. Increased population and declining water shortages have resulted in a drop in renewable water resources per capita., from 1,857 m³/ capita/year in 1967 to 145 m³ /capita/ year in 2013 [1,3,4 and 5]. Those living in rural communities are the most affected, as they face severe water shortages and are unable to meet basic water needs. Jordan's annual per capita freshwater consumption is 170 m³ per year, which is below the internationally recognized threshold of water stress of 1,700 m³ per year and below 1,000 m³ per year threshold typically considered as water scarcity according to the World Bank. Population growth,

economic development, and climate change are predicted to increase variability and bring more extreme weather events, putting further pressure on water resources in Jordan.

Jordan depends mostly on groundwater; overexploitation of groundwater has declined aquifer levels and increased water salinity [6]. Jordan's water must be utilized where its social and economic value is highest to address this unprecedented water scarcity. Water availability is also affected by pollution. Intensive agricultural activities, industrial output, and untreated wastewater are the main causes of water quality issues. Jordan must manage and reuse nearly all its water. The importance of water purification is that drinking water exposed to microbial contamination due to agricultural and untreated wastewater must be addressed by using renewable energy like the sun. In recent years, there has been an increase in the need for clean water supply, as well as a need to reduce the cost of the treatment process, so solar disinfection can play a role in reducing the cost of the treatment process.

Solar Water Disinfection is a low-cost, environmentally sustainable drinking water treatment option for people who drink microbiologically contaminated raw water from the tap. Solar water disinfection uses solar energy for the disinfection of pathogenic microorganisms causing water-borne diseases and therewith it improves the quality of drinking water. The importance of water purification is that drinking water is exposed to microbial contamination due to the lack of good treatment of sewage, during transport a lot of epidemics such as cholera and typhoid must be addressed by using renewable energy like the sun. Since Solar water disinfection is simple to use and inexpensive, the method has been widely recognized. Solar radiation can be divided into three ranges of wavelengths: UV radiation, visible light, and infrared radiation. UV-A radiation, for example, has a germicidal impact. The utilization of UV-A radiation and heat together (direct expose to sun) has a synergetic effect that improves the efficiency of the process. The ozone (O₃) layer in the atmosphere absorbs the majority of UV-C and UV-B rays in the 200 to 320 nm range, protecting the planet from radiation coming from space, fortunately, it does not reach the Earth. Only a higher fraction of UV-A radiation in the wavelength range of 320nm – 400nm, referred to as the blacklight, near the visible violet light, reaches the surface of the earth. UV-A radiation directly interacts with the DNA, nucleic acids, and enzymes of the living cells change the molecular structure and leading to cell death see **Figures 1 and 2**.

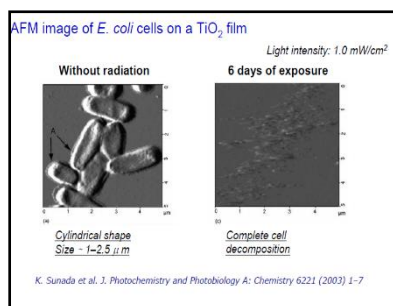


Figure 1: Bacterial decomposition under solar radiation

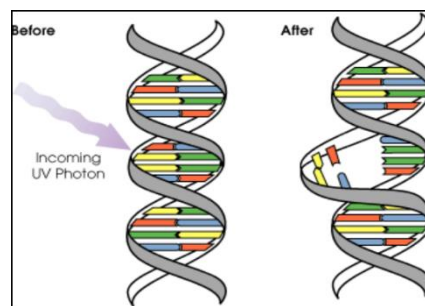


Figure 2: Interacts UV-A radiation directly with the DNA

UV radiation also combines with oxygen dissolved in water, resulting in extremely reactive oxygen forms (oxygen free radicals and hydrogen peroxides). These reactive chemicals also destroy infections by interfering with cell architecture. When compared to other recognized water filtration procedures, this approach has the benefit of total annihilation of organic pollutants, however it is slow in action and difficult to use and maintain. Advanced oxidation techniques for wastewater treatment have been extensively explored, however UV radiation generation by lamps or ozone synthesis is expensive, necessitating the use of catalysis and solar energy in these processes. As a result, research is increasingly focusing on enhanced oxidation processes such as photo-Fenton and heterogeneous catalysis with UV/TiO₂ that can be driven by solar irradiation. Photocatalytic degradation is a type of advanced oxidation process used in the remediation of organic contaminants that are classed as bio-recalcitrant (not biodegradable).

It's used in water treatment for organic pollutants that aren't treatable with traditional methods due to their chemical stability and/or biodegradability. The formation and subsequent reaction of hydroxyl radicals ($\bullet\text{OH}$), one of the most powerful oxidizing species, is involved in these processes. For this, a variety of oxidation processes are utilized, including TiO₂/UV, H₂O₂/UV, Photo-Fenton, and ozone (O₃, O₃/UV, O₃/ H₂O₂). Their attack isn't extremely discriminating, which is a good quality for pollution control. The adaptability of AOPs is further strengthened by the fact that numerous $\bullet\text{OH}$ radical manufacturing options exist, allowing them to be tailored to individual treatment needs. Solar photocatalysis is a degradation reaction that converts wastewater pollutants into carbon dioxide, water, and organics. Early in the 1980s, research into the utilization of solar radiation for water disinfection began [7,8]. These studies were conducted to see if the technology can disinfect small amounts of water for use in the manufacturing of oral rehydration solutions, which are used to treat diarrhea. Odeyemi et al., (1988) investigated the germicidal effects of sun radiation on water samples in transparent containers, reporting 100% eradication of three orders of magnitude [3log10] coliforms after

three hours of exposure [9]. Solar heating has also been reported to inactivate fecal germs in drinking water [10]. At the completion of their experiment and a further 12 hours later, no viable *Escherichia coli* germs were identified. Several other studies have been published on the use of UV irradiation as an alternative method for disinfecting partially treated wastewater or contaminated fresh and sea waters [11,12,13 and 14]. Sommer et al. (1996) explored the biosimetric measurement of the influence of reflection on the reduction equivalent fluence in flow-through reactors [15]. Although many researchers have looked at the efficacy of using solar radiation to disinfect water, few have constructed and tested prototype reactors that employ this technology to create a simple and low-cost system that may be deployed in places where contaminated drinking water is a health problem e.g., [14, 15, 16]. The scholars found that under all working circumstances, the prototype reactors in which water is heated and exposed to solar radiation resulted in significant reductions in pollutants.

This article aims to analyze and evaluate the efficiency of solar energy in disinfecting polluted water and, to create a method to remove or decrease the use of chlorination or filtration in water treatment, thus lowering treatment costs and protecting the environment.

1.1 The disinfection of water by UV irradiation

UV irradiation for water disinfection has proven to be a viable alternative to chemical disinfection. Several studies have been carried out to determine the impact of physical parameters such as sunlight and temperature on the rates of microbial indicator and pathogen die-off in estuarine and marine environments [1,15 and 16]. The findings of these study, which were acquired on a laboratory scale, show that turbidity is a factor that determines the percentage of bacteria reduced and consequently the efficacy of UV disinfection of polluted water. When the turbidity exceeds 5 NTU, the efficiency begins to rapidly decline until it hits roughly 93 %. It is required to increase the exposure time in order to get better efficiency percentages. The allowed range for turbidity in Jordanian drinking water, according to national guidelines, is less than or equal to 5 NTU. If the turbidity of the water exceeds Jordanian standards, it is necessary to physically treat it with filtering processes that effectively reduce turbidity before disinfecting it with ultraviolet light.

In estuarine waters, the effects of sun radiation, temperature, salinity, and other variables on the survival of *Salmonella typhimurium*, *Escherichia coli*, *Clostridium perfringens*, and male-specific bacteriophage have been investigated [15, 16]. According to these research, no cultivable *E. coli* organisms were identified in water samples that were heated to temperatures

ranging from 50 to 59.5°C before being exposed to sunlight for 10 to 12 hours. Several studies have been published on the effect of lamp intensity and water transmittance on UV water disinfection. According to this research, UV irradiation between 23 and 27 W/m² throughout the summer was sufficient to sterilize the water. UV irradiation reduces to roughly 4 W/m² during the winter season and in cloudy or rainy conditions, which is still sufficient for water disinfection at low turbidity levels [16,17,18,19,20]. However, while using a UV irradiation system to disinfect water, the flow and water supply to the system were a concern. A submersible pump was necessary, and the pump required electrical power to function. As a result, any remote places where energy is scarce or non-existent will be unable to run the reactor, necessitating the need for new technologies. Another system which incorporation of a flat solar water heater, heat exchanger, and thermal one-way valve is used, the system eliminated the need for a pump to circulate the water. However, this design, on the other hand, suffered flow challenges, notably at high temperatures, mostly in the form of lower flow rates, exposure time and, in some cases, backflow issues.

1.2 Solar Energy Desalination Potentials in Jordan

Jordan has a high solar radiation percentage. Jordan is positioned within the solar belt, 320 days of sunshine a year, where the intensity of shining solar radiation is 5-7 kWh/m² and 1000 GWh annually. This is due to its elevated altitude and dry environment. Solar energy in Jordan started to give attention locally and internationally for investments, encouraged by the government by tax subsidies and low interest loan rates and adapting build-operate-transfer (BOT) strategy. As an example, Ma'an development zone constructed the first solar energy plant to produce 52.5 MW that counted about 1% of the country's energy. Feasibility studies in Jordan show that concentrating solar power (CSP) technology may be employed in numerous industries, including chemical (distillation), metallurgy (dissolving nitrate), textiles (dyeing), and medicines (sterilization). According to its economic relevance, one of the most potential chemical industries for the use of concentrated solar heat in Jordan is the processing of potash, phosphate, and bromine, as well as the manufacture of fertilizers. Jordan's overall energy usage in thermal industrial processes requiring more than 150°C is projected to be 300,000,000 kWh (about 1 x 10¹² Btu). Ram Pharma for Pharmaceutical Industries took advantage of the clear potential to use solar heating in industrial processes in Jordan, establishing a system for using solar heat in industrial processes with a capacity of 223 kilowatts in 2015; it produces saturated steam, which is used in drying, sterilization, and fermentation processes. The facility, which is based on Fernel technology produced by the German business Industrial Solar, generates steam

at a temperature of 160 degrees Celsius, allowing the company to cut diesel usage in the factory by 42%. The Baynounah Solar Energy Project, located east of Jordan's capital, Amman, is one of the most important current projects in Jordan. It is the largest solar energy project in Jordan. The plant went into commercial operation in 2020, producing enough electricity to power around 160,000 houses each year while also helping to reduce carbon dioxide emissions by 360,000 tons per year. The project was created in collaboration with the Jordan's ministry of energy and Abu Dhabi future energy company "Masdar". This project, which will cost 240 million US dollars, will contribute to the generation of 563.3 Gigatonnes of electricity per year, which is equivalent to 3% of consumption annual energy in Jordan. Desalination with solar energy is a very feasible technique in the Middle East. Sunlight is the most abundant and renewable energy source on the planet; thus, it has a lot of advantages. Although the thermal desalination method produces potable water using a combination of evaporation and solar energy, it consumes a lot of energy. Jordan's Ministry of Water and Irrigation has started the first phase of the national carrier project to desalinate Red Sea water. The project's capital value is anticipated to be between 1.5 and 2 billion US dollars, with a capacity of 350 million m³/year in the first and second phases under the BOT system [21].

2. MATERIAL AND METHODS

2.1 Experiment setup:

The experiment setup is shown in **figure 3** consisted mainly of a disinfection reactor, storage tanks, a submersible pump, and a light-activated switching unit. The water must be exposed to ultraviolet solar radiation. The water was collected from the lake of the dam in 10 litter polyethylene gallons. The water is filtered before transferring to the main tank (source). The water is exposed to the sun through the flow inside a tube glass with a diameter of 10 mm and 3 meters long. The flow rate for waster circulation inside the tube was achieved by a controlled submersible pump and adjusted to obtain the right residence time. The exposure duration varies from 6 to 48 h depending on the intensity of sunlight and sensitivity of the pathogens. The system germicidal impact is based on a combination of solar light thermal heating and UV radiation which shown to be effective for eliminating microbial pathogens.

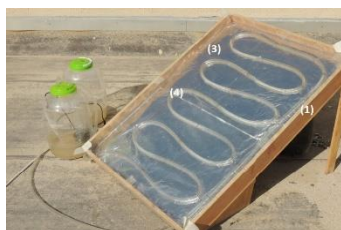


Figure 3: The experiment setup

The flow rate was adjusted so that the time it took the water to pass the reactor was sufficient to inactivate the bacteria. Similar to photocatalytic decontamination of organics in water, the presence of organic and inorganic matter in the water during disinfection has a significant impact on both the kinetics and the final disinfection result. In photocatalysis, the inhibitory effect of various electrolytes is well documented, with phosphates having the most damaging influence on the efficiency of the process. The disinfection process has been found to be slowed by the presence of inorganic and organic matter. Bacterial cells are subjected to reduced osmotic pressure when using water containing ions, large quantities of ions may have a limiting influence on the process. In addition, HCO_3 causes photo absorption, limiting the quantity of light that reaches microorganisms in water. Other anions, such as phosphates, chloride, and sulphates, have been demonstrated to be absorbed by bacteria, but they do not cause sun inactivation unless they are combined with a photocatalyst, such as titanium dioxide.

Samples for analysis were collected from the dam in polyethylene bottles (250 ml) for chemical analysis and in sterilized glass bottles for microbiological analysis and transported to the laboratory. In addition, pH and EC, the temperature was conducted in the site. The water was analyzed according to the Standard Methods for Examination of Water and Wastewater methods. Escherichia coli MPN/100 ml analyzed using Multiple Tube Fermentation; The Total Coli forms MPN/100 ml analyzed using the Multiple Tube Fermentation; The BOD_5 mg/l; COD Closed Reflux Titration Method; NH_4 mg/L Ammonia Selective Electrode BOD_5 mg/L 5-day BOD; NO_3 - mg/l Ion Chromatographic system Ca Titration method, Mg Titration method, Cl Ion Chromatographic system Ec $\mu\text{S}/\text{cm}$ – EC electrode.

2.2 Case study

Samples were collected from Tannur dam. Tannur dam, located 150km south of Amman in Jordan, part of the Southern Ghors project for water supply and irrigation in the Jordan valley. The dam was built in 2001 at a cost 23 MJD, with RCC Type and overflow stepped spillway with height of 60 meters high, 250 meters long, and holding capacity 18 MCM of runoff from Wadi Hasa, one of the major Dead Sea wadis. The dam was built for irrigation purposes, the annual yield is around 8 MCM. The dam location is about 400 meters above sea level, whereas the Dead Sea is about 30 kilometers downstream at 370 meters. The dam sits in a narrow V-shaped valley, with abutment walls rising to 100m above wadi bed level at a 30° angle. The geological foundation for half of the dam's height is made up of interbedded limestone and marl, some of which is extensively fractured and contains thin gypsum seams and clay layers. The foundation is a better-quality limestone with a reasonably high permeability above mid

dam height. The bedding dips around 20 degrees downstream. Because of the influence of the Dead Sea and El Hasa faults on the dam site, design ground accelerations have been set at 0.2g for the design basis earthquake (DBE) and 0.5g for the maximum credible earthquake (MCE). The natural water table at the location rises slowly from riverbed level on each abutment because to the dry climate. The Wadi Hasa valley, on the other hand, is over 500 meters deep, ensuring a steady flow of water. Nonetheless, it is expected that a significant volume of water will be absorbed into each abutment during reservoir filling and then restored to reservoir storage during drawdown.



Figure 4: The Tannur DAM lake

The presence of many uncontrolled agricultural practices adjacent to the dam lake area, as well as the population presence resulting from the development of a random and unstudied residential area, are the causes of water pollution in the dam lake, which has a negative impact on the quality of the dam's water and poses a threat to the main reason for which the dam was built; to collect rainwater and the flow of neighboring valleys for the purposes of agriculture, drinking, groundwater recharge and providing a water source for main industry in the area.

3. RESULT AND DISCUSSIONS

The project was carried out to assess the efficiency of solar energy in disinfecting contaminated drinking water (Tannur dam). Different water parameters were examined between 2013 and 2020, with the average shown in **Table 1** and compared to different Jordanian standards for drinking and irrigation. The solar disinfection unit was tested with both Dam water and tap water from Tafila area, 20km from the dam site. In less than 20 Hour the unit eradicated more than (99%) of bacteria contained in highly contaminated water samples. The disinfection results indicate a reduction in 2.47 log of total coliforms, 3 log reduction of fecal coliforms, 2.67 log reduction of streptococci, 3.17 log reduction of staphylococci, 0.08 log reduction of yeasts, 0.19 log reduction of molds, and a reduction of 1.17 log of sulfite-spores. The results showed a rapid decrease in microbial counts upon exposure to solar radiation. More than 98% reductions were achieved after 9hours for the bacterial communities tested under different

conditions. The rate of inactivation, however, varied and was mainly affected by water temperature during the experiments. The results indicated that temperature affected the efficiency of water disinfection, and the reactor can be a valuable tool in solar water disinfection technology, especially, for remote and rural areas. When scaled up, the proposed method could be a vital tool in solar water disinfection technologies.

Table 1: The Tannur Dam water analysis compared to drinking and irrigation water standards, December 2020.

Parameter	Tested value Average (2013, 2020)	Jordanian irrigation water standards 2014/1766	Jordanian drinking water standards 2015/286
pH (SU)	8.54	6.0 -9.0	6.5-8.5
EC (μ S/cm)	1320	1700-3000	NA
TSS (mg/l)	170	50-100	NA
T-P (mg/l)	1.06	6-20	NA
-N (mg/l) NH_4	1.52	NA	< 0.2 as NH_4
-N (mg/l) NO_3	1.200	5-30	50 as NO_3 ***
T-N (mg/l)	3.13	NA	NA
HCO_3 (mg/l)	326	90-520	
Cl (mg/l)	171	142-355	500
Na (mg/l)	110	69-207	200
Mg (mg/l)	48	NA	NA
Ca (mg/l)	96	NA	NA
**SAR (Unit less)	2.29	**	NA
B (mg/l)	0.33	0.7-3.0	2.4
K (mg/l)	14	NA	NA
SO_4 (mg/l)	212	<960	500
<i>E-coli</i> (MPN/100ml)	3.3E+02	***	<1.1

1900 μ S/cm; 12-20 / ECw between 1300-2900 μ S/cm and 20-40 / ECw between 2900-5000 μ S/cm. (Ecw :Electrical Conductivity for irrigation water)

***E coli threshold varies depending on the set health-based target.

The results also suggested that water after treatment can be appropriate for irrigation reasons, with additional studies recommended to stand on the SAR and EC parameter values taken from different locations to decide what sort of crops can be irrigated and the level of usability. However, under the current situation, it is not advised to be used for either drinking or irrigation.

4. RECOMMENDATIONS

Securing water supplies suitable for human consumption has become an increasingly difficult undertaking in many parts of the world and in Jordan. Many human diseases are water-borne and can cause a variety of illnesses varying from slight discomfort to death. Diseases such as cholera, typhoid fever and shigellosis for example are well-known water-borne diseases, which can cause a staggering number of deaths annually. Treatment is required to lower the quantity of hazardous microbes; but, in many cases, the cost and energy required to

carry out this task may be too expensive or simply unavailable. In such cases, the availability of low-cost technique may be the solution. The utilization of natural ultraviolet light (UV), which is part of natural solar radiation, is one of the approaches that can meet the low condition.

However, the approach has some limitations, including the fact that the solar source is affected by weather and climatic conditions, and the treatment procedure is not suitable for large volumes of water. Further research into the effects of turbidity and temperature on the efficiency of UV radiation in the UV-range in the inactivation of polluted drinking water is advised. It is worth emphasizing that future research should include the use of different test organisms in the evaluation of disinfection plant effectiveness, such as bacterial spores and bacteriophages. This is due to the fact that, while the more UV sensitive indicator bacteria are no longer discernible, other UV resistant pollutants may still be present in the water.

Furthermore, future research should focus on the PET employed in reactor's long-term UV transmittance stability. Various types of water can be investigated using the suggested method, including well water, and river and lake water, more research is needed to figure out the exact mechanism of temperature-accelerated bacterial inactivation, enhance the architecture of the solar water disinfection reactor, and test its performance against more resistant pathogens including bacterial spores and viruses. Using solar energy to disinfect polluted water will certainly reduce the usage of chlorination or filtration in water treatment, reducing treatment costs while also protecting the environment. Solar disinfection, on the other hand, has a substantial disadvantage when compared to other techniques of residential water treatment and storage. Because this method does not rely on a material that has been commercially developed for the purpose of water disinfection, no major manufacturing company usually invests in advertising efforts to promote the product or the technique.

The presence of many uncontrolled agricultural practices adjacent to the dam lake area, as well as the population presence resulting from the development of a random and unstudied residential area, are the causes of water pollution in the dam lake, which has a negative impact on the quality of the dam's water and poses a threat to the main reason for which the dam was built; to collect rainwater and the flow of neighboring valleys for the purposes of agriculture, drinking, groundwater recharge and providing a water source for main industry in the area. The results also suggested that water after treatment can be appropriate for irrigation reasons, with additional studies recommended to stand on the SAR and EC parameter values taken from different locations to decide what sort of crops can be irrigated and the level of usability.

However, under the current situation, it is not advised to be used for either drinking or irrigation. When scaled up, the proposed method could be a vital tool in solar water disinfection technologies, particularly in isolated and rural locations. Further work is still needed before it can be concluded that solar radiation can be an effective, cost-free, technique for drinking water disinfection.

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