*Original Research*

# Coliform-Specific Solar Disinfection of Treated Wastewater

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**Abstract**

Our research investigated the potential use of solar radiation in water disinfection. Contaminated water was exposed to solar radiation under controlled conditions to deactivate and destroy pathogenic microorganisms. The experiment was directed toward examining the effective radiation time required for total coliform inactivation in the wastewater. The experiments were carried out between March and July 2009 with temperature ranges between 30-25ºC and solar radiation intensity of 2073.9-2775.2 Jul/cm$^2$. The impact of three parameters under direct exposure to the sun was studied: depth (10, 20, 30 cm), turbidity (135, 160, 200 NTU), and container color (white and black). Comparison between solar disinfection and chlorination also was conducted. The maximum removal of total coliform was found to be 92.95% at 10 cm depth for sunny conditions, at 110 NTU, and white container. It was found that the optimum contact time in the chlorination experiment was 240 min, which gives a disinfection efficiency of 99.6%. No significant difference in the disinfection efficiency is shown with extra exposure time. These findings of photo-biological inactivation of coliform could be applied in reducing the hazards of water-borne pathogens in an environmentally sound and low-cost system.

**Keywords:** coliform, solar, disinfection, wastewater

## Introduction

Contaminated water with water-borne pathogenic microorganisms, including protozoa, bacteria, and viruses, causes millions of cases of gastrointestinal illness worldwide annually, especially in developing countries due to lack of sanitation. A direct consequence of this situation is that three million people die from water-related diseases each year, the majority of whom are children less than five years old [1].

Disinfection is the process carried out to eliminate or control the microorganisms in water that could affect its quality, causing, among other things, diseases due to microbial activity. Conventional technologies used for reducing pathogen risks through disinfection of unpotable water include ozonation, chlorination, solar heating/pasteurization, artificial UV radiation, and filtration [2-4]. These technologies are capital intensive, require sophisticated equipment, and demand skilled operators [5-7]. Therefore, the need for a low-cost, low-maintenance, and effective disinfection system for the improvement of water quality is high.

The use of solar irradiation for treatment of chemically and biologically contaminated water is not a new phenomenon [8-10]. It is relatively inexpensive and its application for water disinfection avoids the generation of harmful byproducts as in chemically driven technologies [3, 5].

Understanding the effect of solar radiation on the survival of sewage bacteria in treated wastewater has received considerable attention of researchers in recent years. Several studies have shown that sunlight is detrimental to

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bacterial pathogens present in water [11, 12]. The effect of solar radiation and predacious microorganisms on the survival of bacteria of feacal and plant origin was studied by McCambridge and McMeekin [13]. They found that the decline in the numbers of *Escherichia coli* cells in estuarine water samples was significantly greater in the presence of both naturally occurring microbial predators and solar radiation than when each of these factors was acting independently.

Boyle et al. [12] have studied the bactericidal effect of solar water disinfection under real sunlight conditions. They found that the exposure time required for complete inactivation under conditions of strong natural sunlight was as follows: *Camylobacter jejuni*, 20 min; *Salmonella epidermidis*, 45 min; enteropathogenic *Esherichia coli*, 90 min; and *Yerisina enterocolitica*, 150 min.

An extensive study on a high-rate wastewater pond showed that shallow depth and mixing in ecologically engineered high-rate ponds enables greater exposure of wastewater to sunlight than in conventional waste stabilization ponds [14]. The reported efficient disinfection in high-rate ponds reflected the hypothesis of the importance of sunlight as an important factor, sometimes interacting with elevated dissolved oxygen and pH.

This paper aims to experimentally study and assess the effectiveness of natural solar disinfection in deactivating the coliform population of treated wastewater in different climatic conditions. In addition, the effect of physical parameters such as water turbidity and water depth on deactivation of coliform was investigated.

## Materials and Methods

All of our experiments were conducted at the University Research Station in the Jordan valley with annual sunny hours more than 3000. The experiments were carried out between March and July 2009 with an average daily temperature of 25-30ºC. The intensity of solar radiation during this period of the year ranged from 2,300 to 2,500 Jul/cm$^2$. Treated wastewater samples were taken from the pre-chlorination pond at Al-Salt wastewater treatment plant. All samples were analyzed for some major parameters (Table 2), according to the Standard Method for Examination of Water and Wastewater [15].

The effect of sunlight on *E. coli* removal was tested in a batch system. Wastewater samples were placed in open-top circular plastic containers 50 cm in diameter and 40 cm deep. The original color of the containers was white. The containers were painted black with water-insoluble paint when needed. Experiments were conducted under five different conditions (as summarized in Table 1) to cover all possible parameters affecting solar disinfection.

All experiments were conducted at exposure times of 0, 90, 180, and 270 min, with each experiment repeated five times. The effect of solar radiation on chemically disinfected wastewater samples using sodium hypochlorite was also tested. For each set of experimental runs, control wastewater samples received the same treatment (except for solar irradiation) as they were stored inside a weakly illuminated room. On-site water temperatures as well as ambient temperature were recorded over the course of each run. Water samples were collected at each designated exposure time and analyzed for total coliform using a multiple tube fermentation technique according to the Standard Methods for Examination of Water and Wastewater [15].

Table 1. Operating conditions for different experimental runs.

| Run | Description |
|---|---|
| 1 | Sunny weather: Experiments were carried out on cloud-free days. The experiments were repeated for water depths of 10, 20, 30 cm. The color of the containers was white. |
| 2 | Cloudy weather: Experiments were carried out on cloudy days. Other parameters were similar to those in run 1. |
| 3 | Turbid wastewater: Experiments were carried out at different turbidity levels of wastewater. Bentonite was added to achieve the required turbidity levels of 135, 160, and 200 NTU. All runs were carried out at water depth of 10 cm in white containers. |
| 4 | Container color: Experiments in sunny days were conducted using both white and black containers at water depth of 10 cm. |
| 5 | Combined solar and chlorination disinfection: Experiments were carried out using combined chlorination and solar radiation. Sodium hypochlorite was used at a concentration of 15 mg/L. All runs were carried out at water depth of 10 cm using white containers. |

The lethal effect of UV radiation on the reduction of coliform count was calculated based on a first-order kinetic [1]:

$$D = 2.303 / K_D \qquad \text{Eq. 1}$$

...where $D$ is the time necessary for the disappearance of 90% of the initial bacterial population and $K_D$ is the slope of a linear regression line of the plot relating coliform count to exposure time; the lower the $D$ value, the higher the disinfection efficiency.

## Results

Pre-chlorination-treated wastewater samples from the Wadi Shuaib wastewater treatment plant were used to test the effectiveness of solar radiation in inactivating present coliforms under controlled conditions. The effects of various parameters under direct sun exposure were studied. The principal parameters of experimentation included: water depth, water turbidity, container color. The characteristics of treated wastewater samples are shown in Table 2.

The effect of solar radiation on coliform at different exposure times under sunny and cloudy conditions was tested (Runs 1 and 2). The results are shown in Figs. 1 and 2. It is clearly seen that increasing exposure time from 90 to 270 minutes resulted in a significant decrease in the number of total coliform for both sunny and cloudy conditions

Table 2. Characteristics of treated wastewater samples.

| Parameter | Result |
|---|---|
| Biochemical oxygen demand $BOD_5$ | 40 mg/L |
| Chemical oxygen demand COD | 91.2 mg/L |
| Total dissolved solids TDS | 880 mg/L |
| Total suspended solids TSS | 130 mg/L |
| Dissolved oxygen DO | 6.6 mg/L |
| Turbidity | 120 NTU |
| pH | 7.29 |
| Salinity | 0.4 |
| Conductivity | 1290 µs/cm |
| Alkalinity | 336 mg/L |
| Chloride | 189 mg/L |

at all depths tested. However, the maximum impact of solar disinfection was at water depth of 10 cm in both cases. The solar radiation effect in killing coliform under sunny conditions was higher than those under a cloudy sky.

Wastewater samples with relatively increasing turbidities (NTU values 135, 160, and 200) were used to study the impact of turbidity on the rate of bacterial deactivation by direct solar radiation at a constant depth of 10 cm (Run 3). As is obvious, the higher the turbidity of the sample, the longer the exposure time required to reduce the bacterial count (Fig. 3).

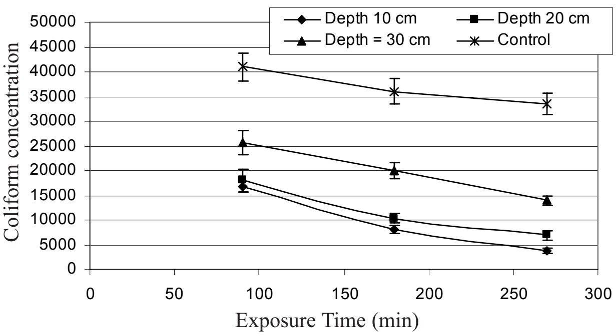


Fig. 1. Effect of solar radiation on coliform removal on sunny days.

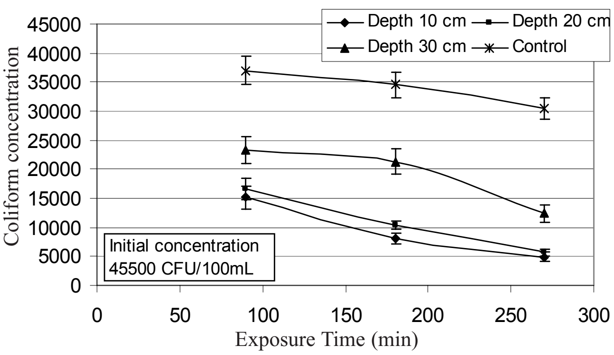


Fig. 2. Effect of solar radiation on coliform removal on cloudy days.

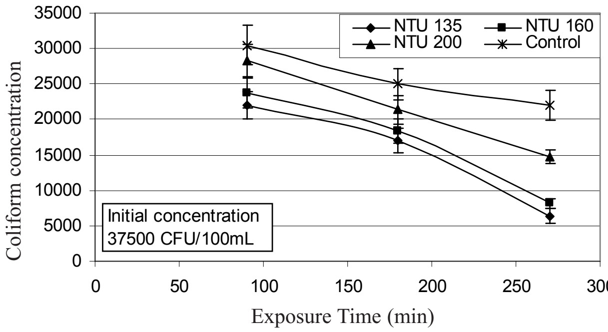


Fig. 3. Effect of water turbidity on reduction of coliform.

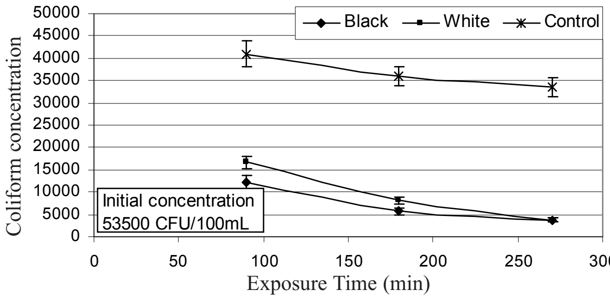


Fig. 4. Effect of container color on reduction of coliform.

To demonstrate the effect of container color on coliform reduction, black and white containers were tested (Run 4). The results, are shown in Fig. 4, show that higher reduction of coliform was achieved in black containers than in white containers. At 90 and 270 minutes the disinfection efficiencies in white containers were found to be 68.8% and 84.7%, respectively, while in black containers they were found to be 81.3% and 87.6%, respectively.

The effect of chlorination (sodium hypochlorite) with and without solar radiation on coliform inactivation at water depth of 10 cm was also studied (Run 5). These results are shown in Fig. 5, which shows that chemical disinfection has a high capacity for reducing microorganisms. A further decrease in coliform count was observed when chemical disinfection and solar radiation were combined, showing their synergist effect.

The calculated $D$ values for the entire experimental runs are tabulated in Table 3. These values were determined based on linearization of Equation (1). It can be seen that solar dis-

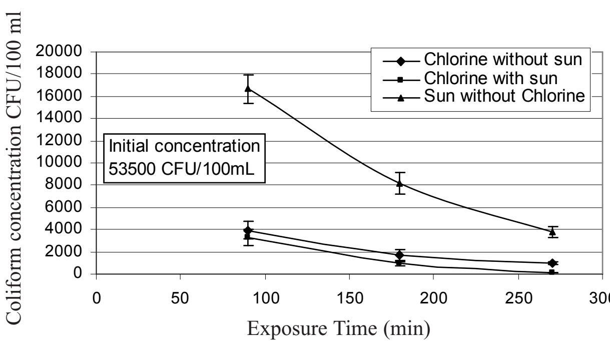


Fig. 5. Synergic effect of chemical and solar radiation on coliform concentration.

Table 3. Calculated D values for all experimental runs.

| Run | | D value, minutes | |
|---|---|---|---|
| | | $D_1$ : Initial phase | $D_2$ : Second phase |
| | | Exposure time 0-90 min | Exposure time 90-270 min |
| 1 | Control | 0.0166 | 0.0552 |
| | 10 | 0.00562 | 0.0321 |
| | 20 | 0.00583 | 0.0373 |
| | 30 | 0.00744 | 0.0354 |
| 2 | Control | 0.0244 | 0.0637 |
| | 10 | 0.0683 | 0.0402 |
| | 20 | 0.00718 | 0.0378 |
| | 30 | 0.00934 | 0.0378 |
| 3 | Control | 0.0296 | 0.0487 |
| | 135 | 0.0134 | 0.0265 |
| | 160 | 0.015 | 0.0266 |
| | 200 | 0.02258 | 0.0304 |
| 4 | Control | 0.01656 | 0.0552 |
| | White | 0.0048 | 0.0321 |
| | Black | 0.0050 | 0.0491 |
| 5 | Sun without hypochlorite | 0.00562 | 0.0321 |
| | Hypochlorite without sun | 0.00418 | 0.1367 |
| | Sun with hypochlorite | 0.00412 | 0.1302 |

infection has two modes of coliform deactivation. The first one represents the highest reduction rate, D1 (exposure time from 0-90 min), followed by the slower reduction rate, D2 (exposure time from 90-270 min). It could be seen that the lowest D1 values obtained in runs 1 and 2 were 0.00562 and 0.0683 min, respectively, thus showing high coliform deactivation under sunny conditions. A similar trend of a killing effect at the next exposure phase (D2) was obtained, but at a slower rate. In Run 3, D1 values for turbidities 135, 160, and 200 NTU were found to be 0.0134, 0.015, and 0.0258, respectively, indicating high solar effect at lower turbidity. As previously mentioned, black containers revealed higher disinfection rates than white containers as seen by the associated D values (0.0048 vs 0.0050). However, the lowest D1 value of all runs were found to be 0.00412 min for Run 5 (chemical disinfection with solar radiation).

## Discussion

Contaminated water causes an estimated 6 to 60 billion cases of gastrointestinal illness annually. Most of these cases occur in rural areas of developing nations where the water supply is polluted with a variety of microorganisms, including viruses, fecal coliform and protozoa, and where adequate sanitation is unavailable [16].

Due to water the scarcity problem in Jordan, treated wastewater can be identified as a new water resource. Solar water disinfection can be used as an effective treatment method, especially in arid and semiarid countries, like Jordan, that have an abundant daily supply of sunlight. This study investigated the feasibility of using sun energy to destroy pathogens under different operating parameters.

The results show eradication of coliform from highly contaminated wastewater using solar radiation. The bacterial killing rate is highest during the first 90 minutes (D1 in Table 3), followed by further reduction of total coliform at all depths (10, 20 and 30 cm). The reduction rate of coliform was found to decrease by increasing water depth.

Our findings are in agreement with the results of Acra et al. [17], where they reported that the bacterial inactivation rate in a contaminated water sample is proportional to the intensity of sunlight and atmospheric temperature and inversely proportional to water depth. Sunlight can penetrate into water. Its intensity decreases with the depth of penetration due to scattering caused by suspended particles present in the water [17, 18].

Running an experiment for similar samples on a cloudy day, coliform disappearance rate was reduced at all depths in comparison with those in sunny days. This is attributed to the screening effect of the clouds that reduces the intensity of radiation. The same situation was confirmed by comparing sunny and cloudy conditions with the control. It is imperative to mention that during the time period of this run, no tangible change in air temperature between sunny and cloudy days was noticed, so that ambient temperature effect on coliform reduction is not evaluated.

The effect of increasing turbidity on decreasing solar disinfection rate is evident at higher turbidities. At higher water turbidities, longer exposure time to solar radiation was required to obtain a satisfactorily coliform reduction. These findings corroborate similar results that have shown enhanced bacterial elimination under similar light intensity by lowering turbidity [17, 19, 20].

Experiments on the effect of solar radiation on coliform confined in black and white containers demonstrated that the Black color increases efficiency of solar disinfection. This is attributed to the absorption of radiation by black color, resulting in efficacy of heating in coliform reduction while white color reflects the radiation in the water sample body.

This study proved a synergistic effect between chlorination and solar radiation, where a combination of these methods increases the rate of coliform inactivation and thus reduces exposure time. This can be clearly seen by comparing the obtained D values for each run, where the lowest *D* values (D1 = 0.00412 and D2 = 0.1302) were found at combined solar and chemical disinfection comparing to those for single solar (D1 = 0.00562 and D2 = 0.0321) or chemical disinfection (D1 = 0.00418 and D2 = 0.1367).

The obtained D1 and D2 values at all runs show that the majority of coliform was eliminated during the initial exposure phase, leaving the remaining cells to be terminated at a slower rate in the second exposure phase, reflecting the specific mode of action for solar radiation on coliform.

Chlorination is a conventional technology used for disinfection. It is a capital-intensive process that requires sophisticated equipment and demands skilled operators [5-7]. Its implementation could be environmentally unsound or hygienically unsafe. According to some previous studies, hypochlorite solution might pose a safety hazard [17]. Hence, using combined solar treatment along with conventional processes could reduce chlorine consumption, which in itself is of value.

In conclusion, solar disinfection has successfully been used to eliminate coliform in wastewater under various operating conditions. It could be used as a low-cost technology in sunny areas for disinfection of wastewater, especially in areas where most of the treated wastewater is used for irrigation.

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