

SOLAR DISINFECTION OF GRAY WATER

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ABSTRACT

In industrialized countries the potable water demand is approximately between 100-150 liter per capita per day, of which 60 - 70% is transformed to gray water. This demand of water can be reduced by using reclaimed gray water in landscape irrigation. The utilization of Gray water can save more than 37 m³ of potable water per year. In order to benefit from gray water, in 2010 the city of Tucson established the "Gray water Ordinance" that requires new houses to have two pipe networks, one conveying black water and another gray water. Although the houses have this network configuration, gray water is being returned to the sewer system because it can contain pathogens. To prevent the transmission of disease-causing microorganisms, adequate disinfection of the gray water before reuse is important. Guidelines of the United States Environmental Protection Agency specify that fecal coliforms and viable pathogens should be non-detectable in water intended for urban reuse. In this paper, solar disinfection (SODIS) is proposed as an effective treatment method for gray water. A split-split plot experimental design was applied. The treatment was a cover (UV transmitting sheet), and the other two analyzed variables were the time of exposure (3 and 6 hours), and the depth of water (5 and 10 cm). Solar disinfection was found to cause a significant reduction in total coliforms, *Escherichia coli*, and Enterococcus.

Keywords: water treatment; solar radiation; reclaimed water; UV radiation

INTRODUCTION

Reuse of gray water is generally not allowed or restricted to certain uses because it can potentially contain human pathogens. The purpose of this study was to assess the use SODIS to reduce potential enteric bacterial pathogens present in graywater.

SODIS is proposed as an inexpensive and simple method for gray water disinfection. The application and experimentation with SODIS of gray water was done as a batch process. Eight separate individual cells were constructed and covered with two different cover materials, one being transparent to UV light and the other opaque to UV light. The time of sun exposure and the depth of water in the cells were also integrated in the experimental design called split-split-plot design. Three types of fecal indicator bacteria were studied: coliforms, *E. coli* and enterococcus.

LITERATURE REVIEW

Gray water is originated from the drains of hand-washing, showers, bathtubs and clothes washing machines. Wastewater that comes from toilets, dishwashers, laundry sinks or kitchen sinks is called black wastewater [1]. Domestic sewage has a higher pollutant load than the gray water in terms of organic matter and waterborne pathogens [2]. The major contributors of fecal coliforms are bath and shower with average concentrations of 4 x 10⁶ colony forming units per 100 milliliters [3]. If gray water will be reused then it has to be disinfected in order to be in compliance with stringent microbiological standards [4].

Studies have found that the turbidity of the untreated gray water averaged 43 Nephelometric Turbidity Units (NTU), Biodegradable Oxygen Demand (BOD) was 65 mg L⁻¹, Total Suspended Solid (TSS) averaged 35 mg L⁻¹, and the chloride level of 20 mg L⁻¹ [5]. The interval of total coliforms reported for gray

water is from 7.2 to 8.8 log₁₀ per 100 mL. Fecal enterococci range from 1.4 to 3.4 log₁₀ per 100 mL [5, 6]

The gray water characterization is important when the gray water is intended to be reused. Gray water can be used for groundwater recharge; toilet flushing; and irrigation. Gardens, parks, golf courses and crops can be irrigated with gray water [7]. Each of these reuses has microbial standards, which vary with national, state, and local laws.

Numerous methods have been proposed for the elimination of pathogens from wastewater. Such methods include settling tanks, active sludge treatment, infiltration units (sand filter trenches, biofilters and constructed wetlands), membranes, ponds and disinfection [7]. Biological gray water treatment options for reuse of gray water include membrane bioreactor, rotating biological contactor, and constructed wetlands [2].

Activated Sludge processes include an aeration tank and a sedimentation tank. The main purpose of the aeration tank is for microorganisms to oxidize organic compounds. The detention time in the aeration tank varies between 4-8 hours. The second tank allows the sedimentation of microbial flocks. Membrane Filtration is a physical removal of microorganisms. Wetlands consist of shallow excavated basins with an inlet of wastewater and an outlet for receiving the treated water. Treatment is carried out by the biofilms developed on the porous medium [8].

Chlorine is the main method for water disinfection; it is specially used in wastewater and potable water disinfection. The drawbacks of chlorination include the formation of by-products that can cause adverse health effects [9].

SODIS is used in countries with a lack of safe drinking water. More than five million people around of the world use this method [10]. SODIS relies upon the combined putative abilities of ultraviolet and visible light, as well as elevated temperatures, to inactivate microorganisms [11]. "Exposing viruses to sunlight would decrease the treatment need significantly" [7]. SODIS is recommended in places located between 35° latitude north or south [12].

This process consists of placing water in clear plastic bottles (polyethylene terephthalate and exposing them to direct sunshine [13].

The time required to inactivate *E. coli* is ≥ 6 hours [14].

Some advantages of the SODIS process are a) it is a simple method for water disinfection, b) it is low cost, and c) it does not alter the odor, taste or appearance of the water. Some drawbacks are the scarcity of bottles and the variable effectiveness due to cloudy weather [11].

METHODOLOGY

The location of the experiment was in the Campus Agricultural Center (CAC) of the University of Arizona. The CAC is located in the 110° 56' 48.79" W, 32° 16' 56.39" N. The experiment was run on November 1st, 8th and 15th of 2014. The period was between 9:00 am and 3 pm.

The materials of the experiment include four trays of stainless steel (1 m x 1 m x 0.05 m depth), four trays of stainless steel (1 m x 1 m x 0.10 m depth), four transparent sheets (Plexiglas® by Evonik Industries Ag. 1 m x 1 m x 0.003 m), four black sheets (plastic, 1 m x 1 m x 0.001 m), 3 containers (0.2 m³), plastic wrap, gloves, water, laundry machine, dirty cloths, nine bottles (250 mL), AllTM detergent, Colilert®, and Enterolert®.

Initial disinfection of the trays, covers and containers was necessary prior to each set of replicates. The germicidal used was QD-64 (by QuestVapco® in Brenham, Texas, United States). The active ingredients of this product are Didecyl dimethyl ammonium chloride 1.875% and n-Alkyl dimethyl benzyl ammonium chloride 1.250%. This product remained for 10 minutes on the surface and then rinsed off with tap water. After this process the trays, covers and containers were wrapped to prevent contamination.

Gray water includes the water that comes from the shower, hand-washers, and tub waters but they are difficult to collect. In the present study, the gray water from laundry washing was used. The dirty clothes of two adults and one child was collected over a period of one week were laundered and the gray water collected. Four complete large cycles (wash and rinse) were performed with cold water. The detergent AllTM was selected from the list of the recommendations from the Residential Gray water Guide [1]. The volume of gray water produced was 0.6 m³. The laundry process finished at 13:00 hours then the gray

water was stored in the large containers. The containers were covered with plastic to prevent contamination. The gray water was stored overnight (13:00 pm to 9:00 am). The gray water was stored to air temperature. The air temperature ranged between 7.4°C and 29.8°C during the day and 7.5°C to 27°C at night.

Samples were collected for microbial assay before exposure to the treatment system and from each of the individual treatment cells after exposure to solar irradiation at the different indicated exposure times. Total coliforms and E. coli numbers were determined using quanti-trays using the Colilert® (IDDEX, Portland, ME). Enterolert® (IDDEX, Portland, ME) test was used to determine the presence and amount of enterococcus. To obtain the Most Probable Number (MPN) of bacteria the IDEXX MPN software was used.

The statistical design is called split-split-plot design. The MPN of the three biological indicators were the dependent variable in the statistical model. The independent variables were the cover, the depth and the time of sun exposure. Four trays were covered with the UV transmitting sheet (Plexiglas) and other four trays were covered with a black sheet (Fig. 1). Two water level depths were studied: 5 and 10 cm. The time of sun exposure was 3 and 6 hours.

RESULTS

Table 1 shows the temperature and solar radiation for the dates (replicates) in which the experiment was performed. This data comes from the Arizona Meteorological Network (AZMET). The meteorological station is located 1 km (0.6 miles) northwest of Intersection of Campbell Ave. & Roger Rd in Tucson. This station has an elevation of 713 meters above sea level and the coordinates 32° 16' 49" N and 110° 56' 45" W.

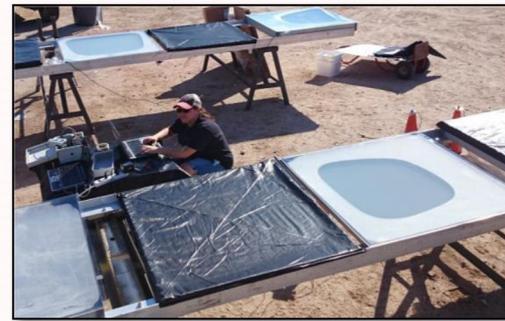


Fig.1 Experiment set up

Table 1 Temperature (°C) and solar radiation (MJ m⁻²) observed in the experimental site

Hour	Nov. 1		Nov. 8		Nov. 15	
	°C	MJ m ⁻²	°C	MJ m ⁻²	°C	MJ m ⁻²
9:00	20.0	1.0	14.4	1.0	15.2	0.9
10:00	24.1	1.1	17.9	1.6	17.7	1.4
11:00	25.0	1.3	21.7	2.0	19.4	1.8
12:00	26.6	1.9	25.5	2.2	20.5	2.0
13:00	27.8	1.9	27.6	2.2	21.3	2.1
14:00	29.2	2.1	28.3	2.0	22.4	1.9
15:00	29.3	1.7	28.7	1.7	22.9	1.5

Table 2 presents the increment of temperature per cell during the experiment. At the beginning of the experiment, the gray water average temperatures ranged between 19.5°C and 23.8°C. At the end of the experiment, the gray water average temperatures ranged between 31.0°C and 40.8°C.

Table 2 Average increase of temperature (°C) of the gray water after SODIS¹ per cell

Hours of exposure	3		6	
	5	10	5	10
Depth (cm)	5	10	5	10
Treatment	°C			
UV-trans. cover	+13.2	+13.0	+21.3	+18.2
Black plastic cover	+13	+9.1	+20.0	+14.4

The gray water turbidity was measured. The average turbidity in the initial samples was 46.4 NTU. After the SODIS treatment, the average turbidity per cell are shown in Table 3.

Table 3 Average gray water turbidity in NTU after SODIS treatment²

Hours of exposure	3		6	
	5	10	5	10
Depth (cm)	5	10	5	10
Treatment	NTU			
UV-trans. cover	46.5	51.0	44.8	44.4

¹ Average of the measurements from Nov. 1st, 8th and 15th.

² Average of the measurements from Nov. 1st, 8th and 15th.

Black plastic cover	45.6	45.6	45.6	45.6
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The initial average MPN of total coliforms for the three repetitions was 1.14 E+05. The after the SODIS treatment the final concentration of total coliforms are shown in Table 4. Tables 5 present the disinfection percentage for total coliforms.

Table 4 Most Probable Number of total coliforms after SODIS³

Hours of exposure	3		6	
	5	10	5	10
Depth (cm)	5	10	5	10
Treatment	MPN of Total Coliforms per 100 mL			
UV-trans. cover	16.0	257.22	<1.03	307.6
	435.2	64880	137.4	1553.1
	1.0	178.9	88.4	85.7
Black plastic cover	1119.9	686.7	488.4	410.6
	>2419.63	>2419.63	2419.64	86640.0
	248.1	461.1	1553.1	387.3

To calculate the percentage of disinfection, the difference between the initial MPN and the final MPN was divided by the initial MPN, and multiplied by 100. Table 5 present the disinfection percentage for total coliforms.

Table 5 Percentage reduction of total coliforms by SODIS treatment⁴

Hours of exposure	3		6	
	5	10	5	10
Depth (cm)	5	10	5	10
Treatment	% reduction			
UV-trans. cover	99.87	80.90	99.93	99.43
Black plastic cover	98.89	28.92	98.70	74.43

From the statistical analysis (significance level $\alpha = 0.05$) there is significant difference between the UV-transmitting and black plastic covers (p-value = 0.0012 from an F test). The 5 cm and 10 cm depths have a significant difference (p-value = 0.0035). The dates (repetitions) have also significant difference (p-value = 0.0006).

The initial average MPN of E. coli was 5.65 E+02. After the SODIS treatment the final concentration of E. coli are shown in Table 6. In Table 7 the percentage of disinfection for E. coli were calculated with the formula described for total coliforms.

Table 6 Most Probable Number of E. coli after SODIS treatment⁵

Hours of exposure (h)	3		6	
	5	10	5	10
Depth (cm)	5	10	5	10
Treatment	MPN of E. coli per 100 mL			
UV-trans. cover	99.87	80.90	99.93	99.43
Black plastic cover	98.89	28.92	98.70	74.43

Table 7 Percentage of disinfection of E. coli⁶

Hours of exposure	3		6	
	5	10	5	10
Depth (cm)	5	10	5	10
Treatment	% reduction			
UV-trans. cover	99.82	94.69	99.82	93.91
Black plastic cover	93.33	92.89	97.66	78.53

Similar to the results of total coliforms, the statistical analysis of E. coli shows that there is significant difference between the UV-transmitting and black plastic covers (p-value = 0.0021). The 5 cm and 10 cm depths have significant difference (p-value = 0.0011). The dates (repetitions) have also significant difference (p-value < 0.0001).

Enterococcus had an average 2.42 E+02 MPN before the SODIS treatment. The MPN after the SODIS are presented in Table 8. The Enter-ococcus percentage of disinfection is resumed in Table 9. As opposed to the first two indicators, for enterococcus only the covers (p-value = 0.0452) and the depths (p-value = 0.0112) showed significant effects.

Table 8 Most Probable Number of Enterococcus after SODIS treatment⁷

Hours of exposure	3		6	
	5	10	5	10
Depth (cm)	5	10	5	10
Treatment	MPN of Enterococcus per 100 mL			
UV-trans. cover	1.0	2419.68	1.0	178.9
	31.3	>2419.6	83.3	721.5
	1.0	6	>2419.6	>2419.6
		1986.3	6	6
Black plastic cover	>2419.6	>2419.6	1.0	172.2
	6	6	1732.9	>2419.6
	>2419.6	>2419.6	2419.68	6
	6	6		

³ Average of the measurements from Nov. 1st, 8th and 15th.

⁴ Statistical analysis was performed without using less and greater than symbols.

⁵ IDEXX MPN calculates it without greater than symbol

⁶ Replicates from Nov. 1st, 8th and 15th.

⁷ Statistical analysis was performed without using less and greater than symbols.

Hours of exposure	3		6	
	>2419.6 6	>2419.6 6		>2419.6 6

Table 9 Percentage of disinfection of Enterococcus

Hours of exposure	3		6	
Depth (cm)	5	10	5	10
Treatment	% reduction			
UV-trans. cover	99.54	5.97	65.61	54.26
Black plastic cover	0.00	0.00	42.78	30.96

DISCUSSION

The UV-transmitting Plexiglas resulted in a greater reduction of the fecal-indicator-bacteria than the black plastic cover for total coliforms, *E. coli* and enterococcus. The reduction is due to two factors. First, the UV-transmitting Plexiglas transmits a greater amount of radiation i.e. both UV light and infrared. And the second factor is that the UV-transmitting cover produces the greenhouse effect. With this effect, the radiant energy is captured in the cells and increases the temperature of the gray water.

Our results reaffirm that the UV radiation and the thermal radiation contribute to the disinfection process in agreement with Fisher (2011). In future studies, we will study the thermal effect in more detail and the actual UV wavelength that is received in the gray water cells.

The 5 cm depth had better disinfection performance than 10 cm depth. This can be explained because the solar radiation could be transmitted through to the bottom of the trays. In future works the turbidity will be included as a variable and related with the depth.

The experiment was run on three different dates (considered as replicates) but the results indicate a significant difference between dates. This is explained because of the difference in the meteorological conditions. On November 8, in contrast with November 1 and 15 with a clear sky, there was an overcast from 9:00 am to approximately 12:00 pm.

For future research, we need to register all the meteorological phenomena, but also consider their random nature in practical applications of SODIS.

CONCLUSIONS

SODIS can inactivate more than 80% of total coliforms and *E. coli*. In order to comply with the guidelines of the United States Environmental Protection Agency, which specify that fecal coliforms and viable pathogens should be non-detectable in reused water, the SODIS process used in this research need to be further optimized.

Enterococcus showed less reduction than the *E. coli*. We conclude that this indicator is more resistant to SODIS.

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