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RESEARCH PAPER

Optimization of Solar Disinfection Considering Log Reduction Values (LRV) for Treated Urban Wastewater

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Abstract

Solar disinfection is becoming increasingly popular around the world for eliminating pathogens present in wastewater. The goals of this study were to identify the significant variables and to maximize the log reduction values (LRV) of total coliforms present in treated urban wastewater using solar disinfection. To achieve the goals, a 23 full factorial design of experiments and response surface methodology were used. Solar disinfection was carried out in an open-air batch reactor and in a solar batch reactor. The three variables considered were solar irradiation, volume of sample and exposure time at two markedly different levels: solar irradiation (1100 Wh/m^2 and 1700 Wh/m^2), volume of sample (0.2 L and 2L), and exposure time (0.5 h and 3 h). When compared to other variables, exposure time was the most significant factor in the analysis of variance (ANOVA) study for both the reactor conditions. The regression equation developed for a solar reactor does not adequately explain the variability of the experimental data when compared to the regression equation developed for an open-air reactor. According to the response optimizer, the optimum values of the factors for solar disinfection using a solar reactor to achieve an LRV of 2 for 0.25 L of sample volume are 1700 Wh/m^2 solar irradiation and 2.97 hours of exposure time. With an open-air reactor, 0.2 L of sample must be exposed to 1700 Wh/m^2 of solar irradiation for 3 hours to achieve LRV of 2.

Keywords: ANOVA, Solar reactor, Solar irradiation, Design of Experiments, Total Coliform, Pareto chart

INTRODUCTION

Water is one of Oman's main challenges, with annual double-digit growth in water demand expected in the coming years due to demographic growth and economic diversification. In Oman, drinking water consumption is nearly 200 million cubic meters (MCM) per year, agriculture consumes about 1,600 MCM, and industry consumes 130 MCM. Oman's population increased from less than half a million in 1950 to more than four million in 2015, with a projected increase to seven million by 2055 (Islam, 2020). Potable water demand in the country would skyrocket, reaching 300 MCM of domestic water by then (Yousuf, 2019). However, in order to minimize current and future water shortages, communities must implement wastewater treatment plant (WWTP) technology as a way of ensuring sustainable water use through reuse of treated wastewaters largely from domestic, municipal, and industrial sources (Baawain et al., 2019; de Anda & Shear, 2021). Wastewater reuse could provide a new and reliable source of water for agricultural, industrial processes, and some non-potable home applications. Given the public health and environmental dangers involved with reusing treated wastewater, it is vital to

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guarantee that the physical, chemical, and microbial characteristics of the treated wastewater fulfill local and international criteria depending on the reuse option of interest (Hong et al., 2018; Al-Gheethi et al., 2018; Adegoke et al., 2018).

Guidelines for the quality and reuse of reclaimed water, as well as particular national legislation, limit the concentration of many waterborne pathogens, including fecal coliforms and E. coli (USEPA, 2004; WHO, 2006; MD,1986). The maximum permissible microbial concentrations vary depending on the final use of the treated wastewater; for urban and agricultural applications, they are stricter, while for industrial, recreational, and environmental uses, they are less rigorous. In terms of CFU per 100 mL, the criteria for water recycling established by USEPA (2004) and WHO (2006) are: less than one and less than 1000 respectively. In the Sultanate of Oman, fecal coliform bacteria (per 100 mL) in treated wastewater should be less than 200 and 1000, respectively, for reuse in restricted and unrestricted irrigation (MD,1986). It is apparent that an efficient tertiary treatment of effluents is required, based on the microbiological quality criteria indicated by USEPA (2004),WHO (2006) and MD (1986).

Physicochemical treatment technologies such as chlorine, UVC, and Ozone are now used to disinfect wastewater. Despite being a potential oxidant with a lengthy half-life, chlorine can react with natural organic matter (NOM) to form carcinogenic halogenated disinfection by-products (DBPs) such trihalomethanes (THMs) and haloacetic acids (HAA) (Collivignarelli et al., 2017). UVC is ineffective against highly resistant pathogens, has a non-residual effect, and has high capital, operation, and maintenance costs (Collivignarelli et al., 2017). In order to overcome these constraints, other technologies for the elimination of water pathogens are being researched.

Usage of solar irradiation is not a novel phenomenon in the treatment of chemically and biologically contaminated water (Caslake et al., 2004). It is quite affordable, and its use in water disinfection prevents the production of hazardous by-products that occur with chemical disinfection methods (Barwal & Chaudhary, 2016).

In recent years, researchers have paid close attention to the influence of solar radiation on the survival of sewage bacteria in treated wastewater. Several studies have found that solar radiation is harmful to bacterial pathogens in wastewater (Barwal & Chaudhary, 2016; Gutiérrez-Alfaro et al., 2018). Basem et al., (2012) utilized an open top circular plastic container painted black under actual sunshine circumstances to evaluate the influence of sunlight on E. coli elimination. They observed that increasing the exposure duration from 90 to 270 minutes resulted in a substantial reduction in total coliforms at all depths evaluated in both sunny and gloomy situations. Gutiérrez-Alfaro et al., (2018) deployed SODIS technology in a compound parabolic collector (CPC) photoreactor at the end of a pilot scale urban wastewater treatment plant (WWTP) that included three Upflow Anaerobic Sludge Blanket reactors, six High-Rate Algal Ponds (HRAP), and a Dissolved Air Flotation (DAF). The SODIS unit disinfected E. coli and Enterococcus spp. more successfully than the HRAP or the DAF. The authors found no regrowth of microbes in the dark storage after the SODIS treatment. With the SODIS technology Santos et al., (2020) reduced pathogenic bacteria present in the septic tank effluent to below the limit of detection in 6 h of detention time. Oman has a hot and dry climate in the interior and a hot and humid climate near the shore, with bright sky all year. These climatic conditions are ideal for disinfecting water and wastewater using natural solar radiation. Solar water disinfection technology proved to be very effective in disinfecting falaj water in Oman (Sreedhar Reddy et al., 2019). To the best of our knowledge, there has been no research on solar disinfection of treated urban wastewater in Oman.

Response surface design of experiments methodology is a statistical tool and technique used to develop a relationship between variables and response factor (Okolo et al., 2021; Tanyildizi et al., 2005). The optimization process is carried out using statistically planned experiments, which include determining the coefficient of the mathematical model, forecasting the response, and ensuring that the model is adequate (Anouzla et al., 2009). The typical approach of optimizing major variables in the solar disinfection process (one component at a time) is a time-consuming, expensive, and difficult procedure for a multivariable system. Statistical experimental design strategies based on the response surface methodology are commonly employed to overcome this issue (Foo et al., 2020). The aims of this study were to analyze and optimize the effects of solar irradiation, sample volume, and exposure duration on the log reduction values (LRV) of total coliforms and to develop a mathematical model that accurately describes the process and directly links the LRV to the most important variables using factorial design of experiments and surface response methods,

MATERIALS AND METHODS

Treated urban wastewater used in this research was collected from Nizwa sewage treatment plant, Nizwa, Oman. Wastewater was sampled between post-secondary clarifying and chlorination processes. The collected treated urban wastewater was characterized in accordance with the procedures outlined in the standard methods for water and wastewater examination (APHA,2017) and is shown in Table 1. The treated wastewater does not meet Omani agricultural reuse standards for COD, BOD, and total coliform bacteria, as shown in Table 1.

The Colilert-18 test was used to identify total coliforms and E. coli in treated urban wastewater samples before and after solar disinfection. It employs a patented Defined Substrate Technology (DST) nutrient indicator ONPG and MUG to detect coliforms and E. coli. Coliforms metabolize ONPG and turn it from colorless to yellow using their -galactosidase enzyme. Minimum and maximum detection limit of this method is 1 coliform per 100 mL and 2419.6 coliform per 100 ml respectively. This methodology is appropriate to drinking water without dilution, whereas for wastewater, sample must be diluted. In the present study, wastewater sample was diluted ten times.

To monitor solar radiation and air temperature during the experiment, a Campbell Scientific, USA made pyranometer sensor (model CMP 10-L) with sensitivity of 7 to 14 V/W/m^2 and a HygroVUE10 Digital Temperature and Relative Humidity Sensor with M12 Connector were placed near the experiment site.

Solar disinfection experiments were conducted in the daytime (9:00 am to 3:00 pm) at the University of Nizwa initial campus during the middle of January, April, July, and October 2020 to cover all of Nizwa's climatic seasons. The University of Nizwa is located at 22° 54' 38.1"N; 57° 40' 20.1"E. Samples were exposed to natural solar radiation in a 2-litre capacity rectangular shallow (10 cm height) borosilicate glass basin. In addition to being exposed to solar radiation in the open air, glass basin with sample was also placed in a rectangular solar batch reactor made of aluminium reflectors and insulators. Total coliform removal in terms of Log reduction values (LRV) was checked on samples subjected to solar radiation at regular time intervals.

Table 1. Characteristics of the treated urban wastewater

Parameter	Value	Agriculture reuse standards in Oman [MD,1986]
Temperature °C	18	--
pH	7.4	6-9
Turbidity, NTU	30	---
COD, mg/l	244	200
Total Suspended Solids, mg/l	140	15
BOD, mg/L	166	20
Total Coliform Bacteria (MPN/100 ml)	24000-25000	1000

This study employed a full 2^3 factorial experimental design (three factors at two levels each). Eight experiments (in replicate) were conducted for each type of reactor. LRV was used to evaluate solar disinfection efficiency. The factors chosen were solar irradiation, sample volume and exposure time. The surface response experimental design was used to determine and optimize the effect of solar irradiation, sample volume, and exposure time on the LRV. Solar irradiation ranged from 1100 to 1700 Wh/m^2 (coded factors: −1, 1), volume of the sample ranged from 0.2 to 2 L(coded factors: −1, 1) and exposure time varied in the range of 0.5–3 hours (coded factors: −1, 1). The experimental matrix and the results of LRV are shown in Table 2 and Table 3 for an open-air reactor and solar reactor respectively. Minitab 19 statistical package was used to perform factorial design of experiments and variable optimization using surface response methodology.

RESULTS AND DISCUSSION

Fig. 1 and 2 shows the pattern of seasonal variation of 1- h average of peak solar radiation intensity and air temperature at University of Nizwa, Oman. The horizontal solid trend line in Fig.1 represents the solar radiation intensity threshold for solar disinfection, i.e. 500 W/m^2.

When compared to the radiation intensity threshold, the threshold was not met on average during the morning hours (6:00 AM-10:00 AM) and after 4:00 PM in the month of January. In the months of April and October, the threshold was met on average between 9:00 AM and 3:00 PM. During the month of July, the average peak solar radiation is greater than the threshold from 7:00 AM to 4:00 PM. Solar disinfection is advised in areas where the 5-hour average radiation intensity is greater than 500 W/m^2 (Moosa et al., 2020). At a water temperature of 30°C and a turbidity of 30 NTU, this radiation intensity threshold is related with a 3 log reduction unit of bacterial pathogens.

The highest and lowest air temperatures were recorded in July and January, as shown in Fig.2.

Table 2. Design matrix for an open-air reactor

Assay	Solar Irradiation (Wh/m^2)	Volume (L)	Exposure Time (Hr)	LRV
1	1100	0.2	0.5	0.18
2	1700	0.2	0.5	0.48
3	1100	2.0	0.5	0.017
4	1700	2.0	0.5	0.207
5	1100	0.2	3.0	0.886
6	1700	0.2	3.0	2.00
7	1100	2.0	3.0	0.16
8	1700	2.0	3.0	1.096
9	1100	0.2	0.5	0.20
10	1700	0.2	0.5	0.443
11	1100	2.0	0.5	0.026
12	1700	2.0	0.5	0.1938
13	1100	0.2	3.0	0.795
14	1700	0.2	3.0	2.000
15	1100	2.0	3.0	0.148
16	1700	2.0	3.0	1.000

Table 3. Design matrix for solar reactor

Assay	Solar Irradiation (Wh/m^2)	Volume (L)	Exposure Time (Hr)	LRV
1	1100	0.2	0.5	0.34679
2	1700	0.2	0.5	0.92082
3	1100	2.0	0.5	0.05552
4	1700	2.0	0.5	0.44370
5	1100	0.2	3.0	2.00000
6	1700	0.2	3.0	2.00000
7	1100	2.0	3.0	0.44370
8	1700	2.0	3.0	2.00000
9	1100	0.2	0.5	0.37675
10	1700	0.2	0.5	0.82391
11	1100	2.0	0.5	0.07572
12	1700	2.0	0.5	0.46852
13	1100	0.2	3.0	2.00000
14	1700	0.2	3.0	2.00000
15	1100	2.0	3.0	0.39794
16	1700	2.0	3.0	2.00000

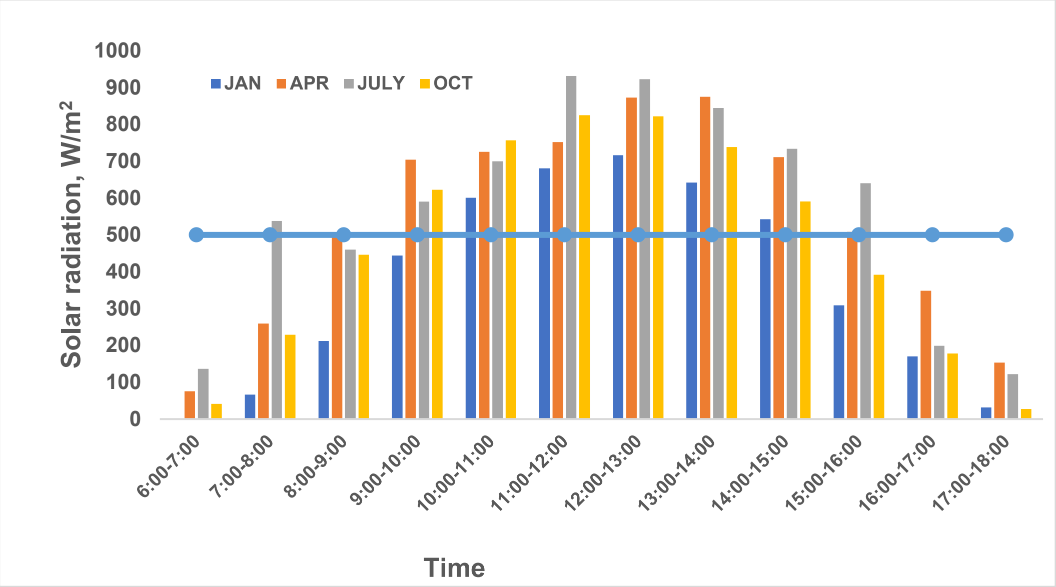

Fig. 1. Seasonal variation of solar radiation intensity

Between 9:00 a.m. and 6:00 p.m. in July, average 1 hour air temperature exceeds 40 degrees Celsius. Between 6:00 a.m. and 6:00 p.m. in April and October, the air temperature ranged from 25 to 35 degrees Celsius. An increase in the air temperature will cause water temperatures to increase as well. The influence of solar radiation is significantly greater than the effect of water temperature, and that the effects of temperature and solar radiation are not only additive but synergistic (Qiang et al., 2013). Water temperatures ranging from 20 °C to 40 °C have little

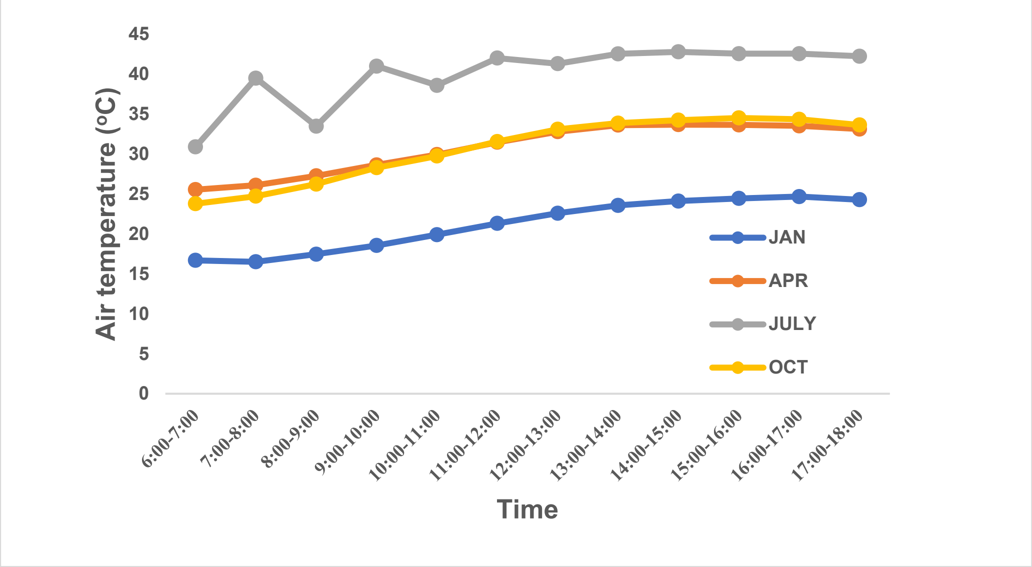

Fig. 2. Seasonal variation of air temperature

Table 4. ANOVA for LRV of total Coliforms using solar reactor

Source	DF	Adj. S.S	Adj. M.S	F Value	P Value
Model	6	9.12623	1.52104	18.79	0.000
Linear	3	8.29123	2.76374	34.14	0.000
Irradiation	1	1.53793	1.53793	19.00	0.002
Volume	1	1.31284	1.31284	16.22	0.003
Exposure Time	1	5.44046	5.44046	67.20	0.000
2-Way Interaction	3	0.83501	0.27834	3.44	0.065
Irradiation*Volume	1	0.53223	0.53223	6.57	0.030
Irradiation*Exposure Time	1	0.11495	0.11495	1.42	0.264
Volume*Exposure Time	1	0.18783	0.18783	2.32	0.162
Error	9	0.72860	0.08096		
Lack-of-Fit	1	0.72189	0.72189	861.48	0.000
Pure Error	8	0.00670	0.00084		
Total	15	9.85483			

influence on the inactivation of bacteria by UVA and visible light radiation (Ayoub & Malaeb, 2019). At temperatures above 50 ^{0}C, the fluences required for E. coli inactivation were found to be more than 30% lower than at lower temperatures (Ayoub & Malaeb, 2019).

Tables 4 and 5 show the analysis of variance (ANOVA) test results for the second-order surface response model for the reactor conditions used in this study.

Because the model's p-value was less than 0.05, there was a statistical relationship between LRV and the selected variables at a 95% confidence level for both reactors. However, in the solar reactor the interaction between irradiation and exposure time and volume and exposure time are statistically insignificant as their p value is greater than 0.005.

Using main effects plots (Fig .3 and 4) and Pareto diagrams (Fig.5 and 6), the results obtained in this research were statistically analysed to know the influence of the variable on the LRV.

Table 5. ANOVA for LRV of total Coliforms using an open-air reactor

Source	DF	Adj. S.S	Adj. M.S	F Value	P Value
Model	6	6.1647	1.0274	506.2	0.00
Linear	3	5.1300	1.7100	842.4	0.00
Irradiation	1	1.5538	1.5538	765.5	0.00
Volume	1	1.0725	1.0725	528.4	0.00
Exposure Time	1	2.5036	2.5036	1233.	0.000
2-Way Interaction	3	1.0346	0.3448	169.9	0.000
Irradiation*Volume	1	0.0316	0.0316	15.57	0.003
Irradiation*Exposure Time	1	0.6445	0.6445	317.5	0.000
Volume*Exposure Time	1	0.3584	0.3584	176.6	0.000
Error	9	0.01827	0.00203		
Lack-of-Fit	1	0.00827	0.00827	6.62	0.033
Pure Error	8	0.01000	0.00125		
Total	15	6.18297			

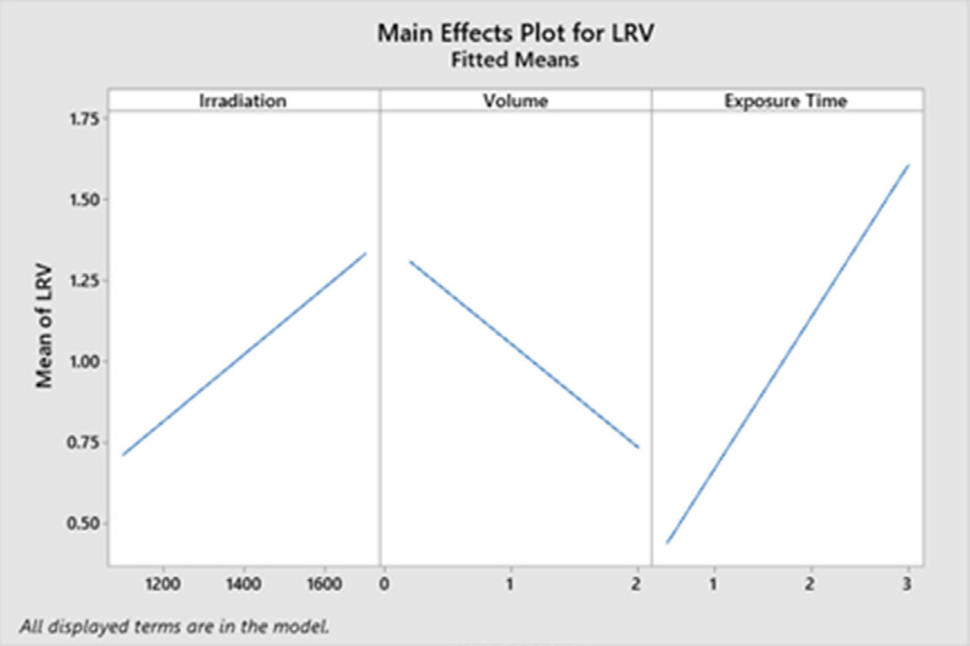

Fig. 3. Main effects plot for solar disinfection using solar reactor

The main effects plot in Figures 1 and 2 depicts the effect of each variable on the LRV. This form of illustration depicts the effect of modifying one of the influential factors chosen for solar disinfection on the response component. As can be observed, irradiation has a substantially favourable influence on the LRV of total coliform in both types of reactors studied. Aside from that, extending the exposure period in both reactors improves LRV. In both circumstances, increasing the volume has a detrimental influence on the LRV of total coliforms. The slope of the figure indicates the variable's influence on the response factor.

The variables and interactions that can be considered important in solar disinfection processes are shown in the Pareto chart for open reactor (Fig.5): exposure time, irradiation,

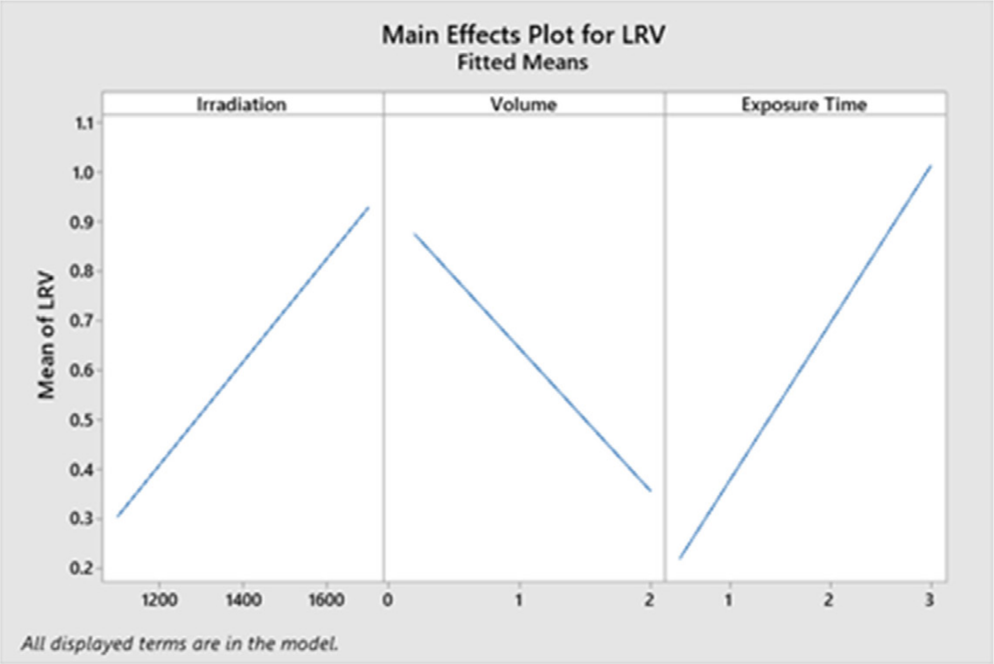

Fig. 4. Main effects plot for solar disinfection using open air reactor

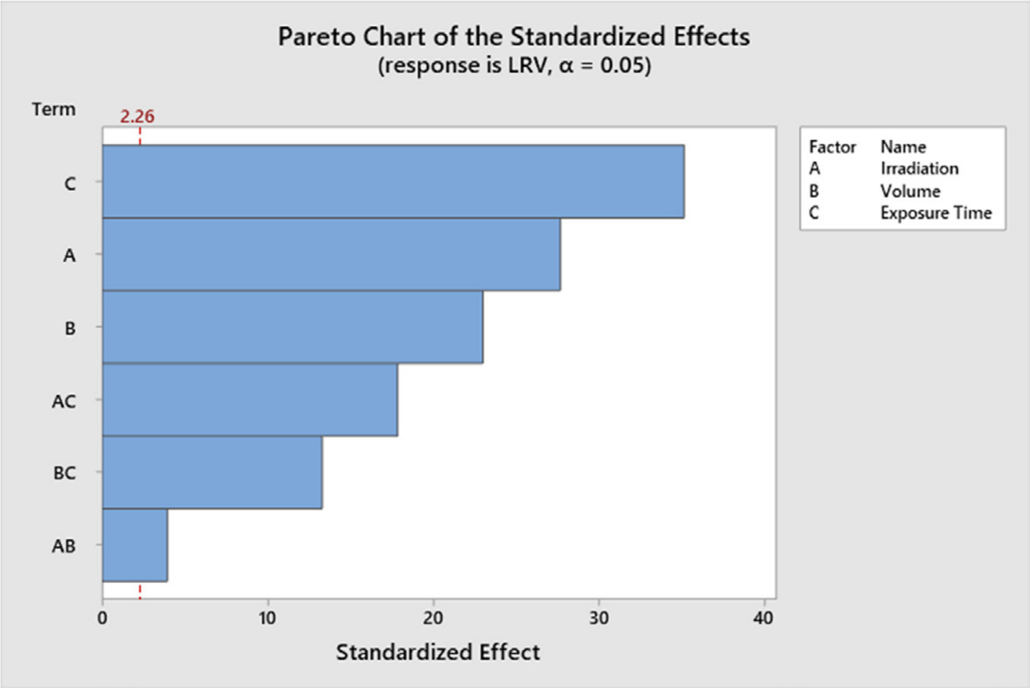

Fig. 5. Pareto chart for Open air Reactor

sample volume, interaction between irradiation and volume (AB), irradiation and exposure time (AC), and volume and exposure time (BC).

Fig. 6 shows that variables irradiation, volume, exposure time and the interaction irradiation and volume (AB) are significant in disinfecting total coliform bacteria in treated urban wastewater using solar reactor. The interaction between irradiation and exposure time (AC)

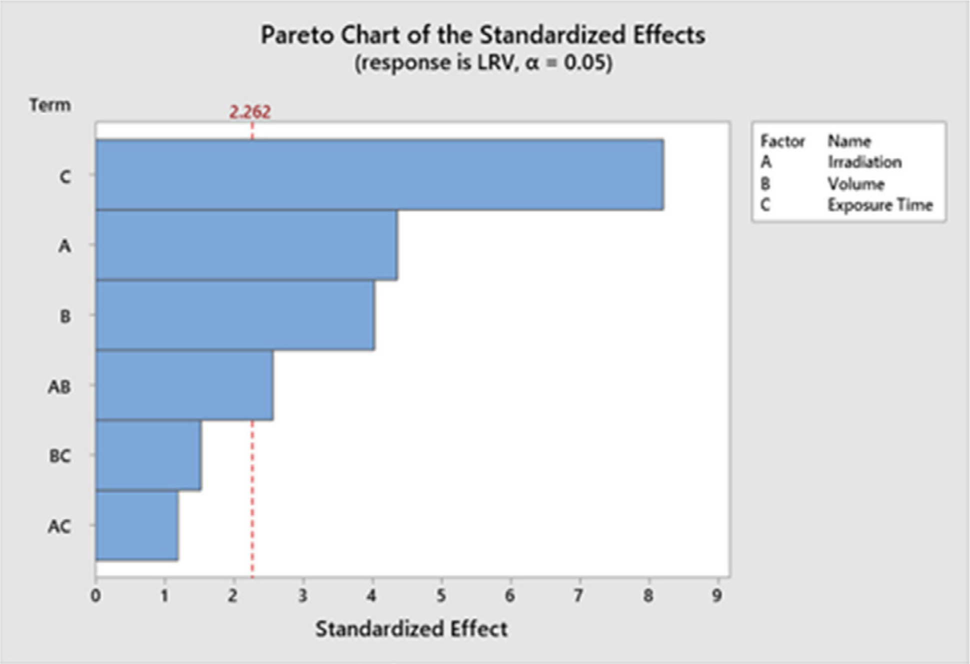

Fig. 6. Pareto chart for solar reactor

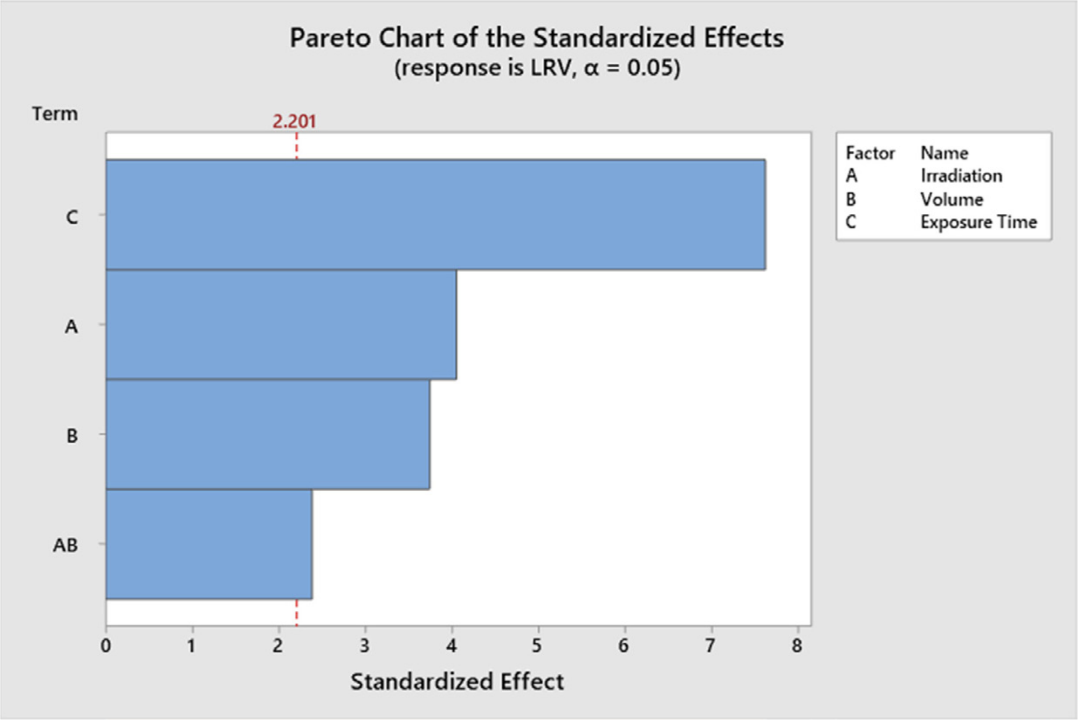

Fig. 7. Pareto chart for solar reactor based on reduced model

and volume and exposure time (BC) are insignificant.

Fig.7 is the pareto chart for solar reactor after discarding interaction between, irradiation and exposure time (AC) and volume and exposure time (BC) which are statistically insignificant. Based on the pareto charts shown in Fig. 6 and Fig .7 the following response surface regression equations in uncoded factors (Equation (1) and Equation (2)) were obtained for each reactor condition.

Solar reactor

LRV = 0.149 + 0.000290 Irradiation - 1.264 Volume + 0.4665 Exposure Time + 0.000675 Irradiation*Volume (1)

Open air reactor

LRV = 0.518 - 0.000105 Irradiation - 1.095 Volume + 0.256 Exposure Time + 0.000675 Irradiation*Volume + 0.000226 Irradiation*Exposure Time - 0.0963 Volume*Exposure Time (2)

Fig. 8 and 9 show a bar chart of the observed and predicted values of LRV for solar and open-air reactors, respectively. As can be seen, the regression equations (1) and (2) able to reproduce the behaviour of solar disinfection process approximately without having to do the experiments. Mansoor Ahmed et al., (2014) made a similar observation in removing Total coliform (TC) and heterotrophic plate count (HPC) using solar water disinfection. The predicted values of TC and HPC using Response models were in good agreement with the observed values.

The quality of fit of the regression equations was determined by computing the determination coefficient (R^2) and the mean average percentage error (MAPE). An R^2 of 0 indicates that the calculation fails to accurately model the data at all, while a value of 1 indicates that the regression predictions perfectly fit the data. The lower the MAPE, the more accurate the forecast. The solar reactor and open-air reactor determination coefficients are 0.8953 and 0.997, respectively. The MAPE of a solar reactor is 7.52, while that of an open-air reactor is 3.28. The regression equation for solar reactor does not adequately explain the variability of the experimental data, as evidenced by R^2 and MAPE, when compared to the regression equation for open air reactor.

Surface response plots based on a quadratic polynomial model were created to clearly visualize the influence of all factors and interactions on LRV(Eq 1and Eq 2). Two variables were changed in the experimental ranges to create the surface response plots, while the other variable

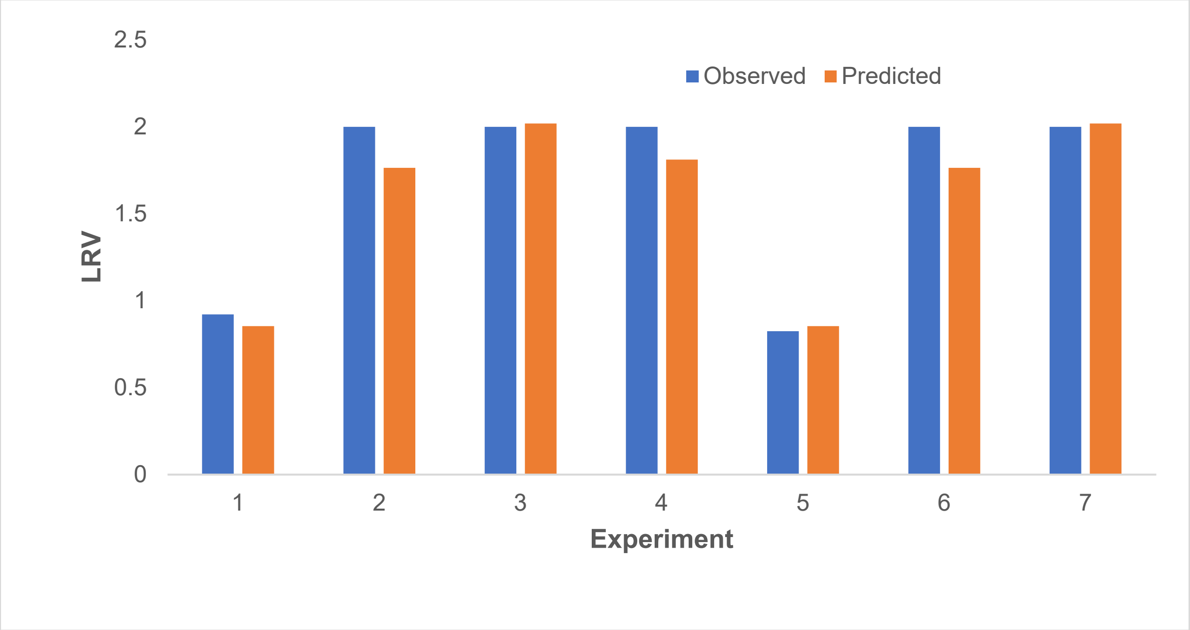

Fig. 8. Observed and predicted LRV for solar reactor

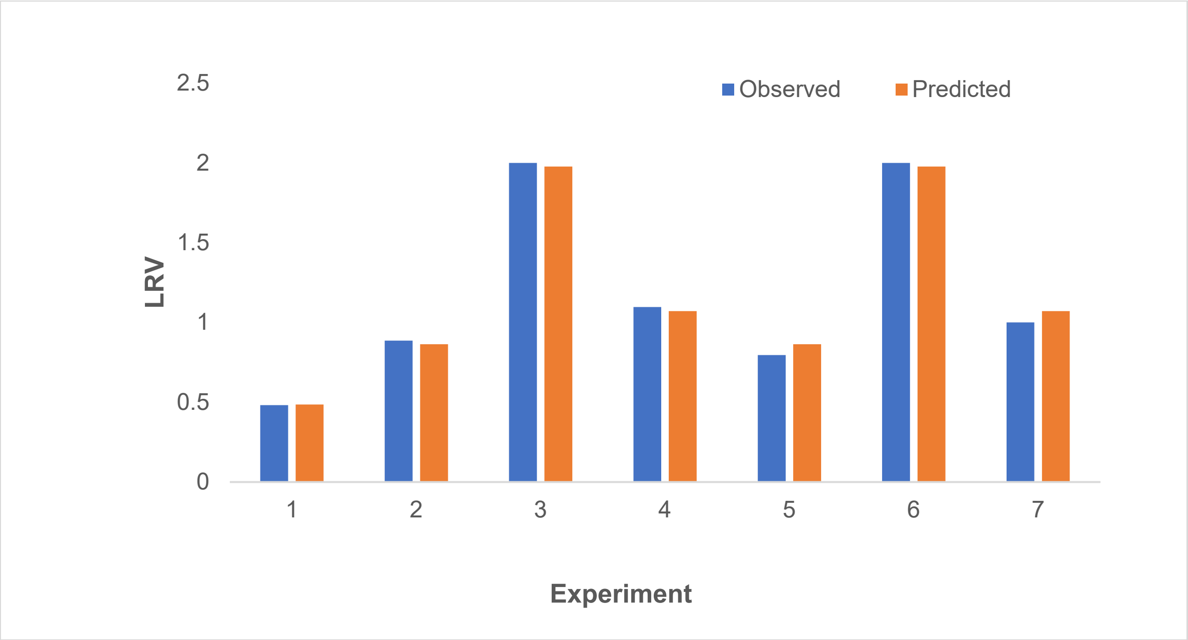

Fig. 9. Observed and predicted LRV for open air reactor

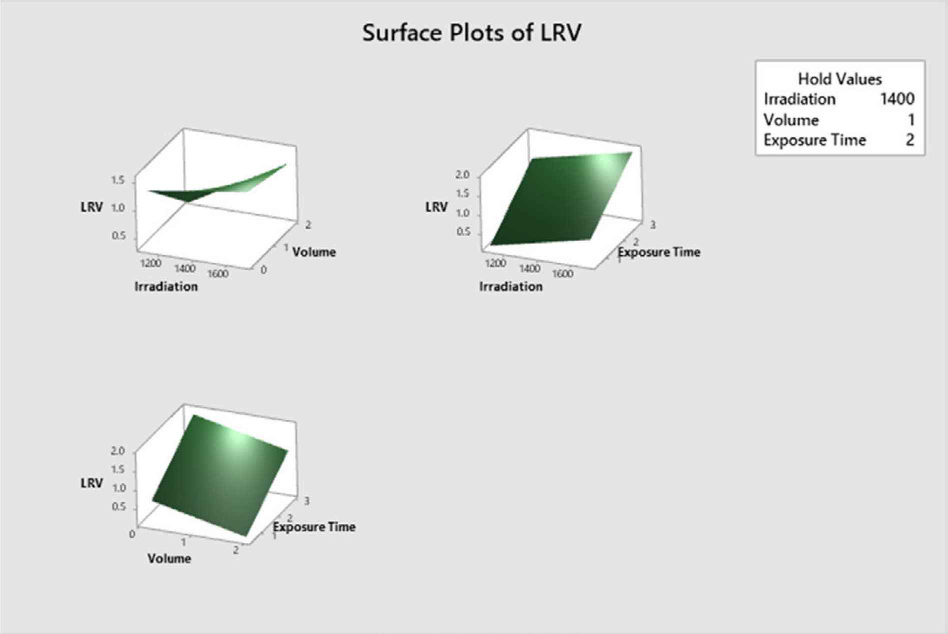

Fig. 10. Surface response plot for open air reactor

was assumed to be constant.

Fig. 10 and 11 show the combined effect of irradiation and volume, irradiation and time, and volume and time on efficiency for solar and open-air reactors with 2 hours of exposure time, 1300 irradiation, and 2 litres volume for open air and solar reactor respectively. An increase in irradiation from 1100 to 1700 W/m^2 resulted a significant increase in LRV for the open reactor, from 0.16749 to 2, and for the solar reactor, from 0.44 to 2. The present study's findings are

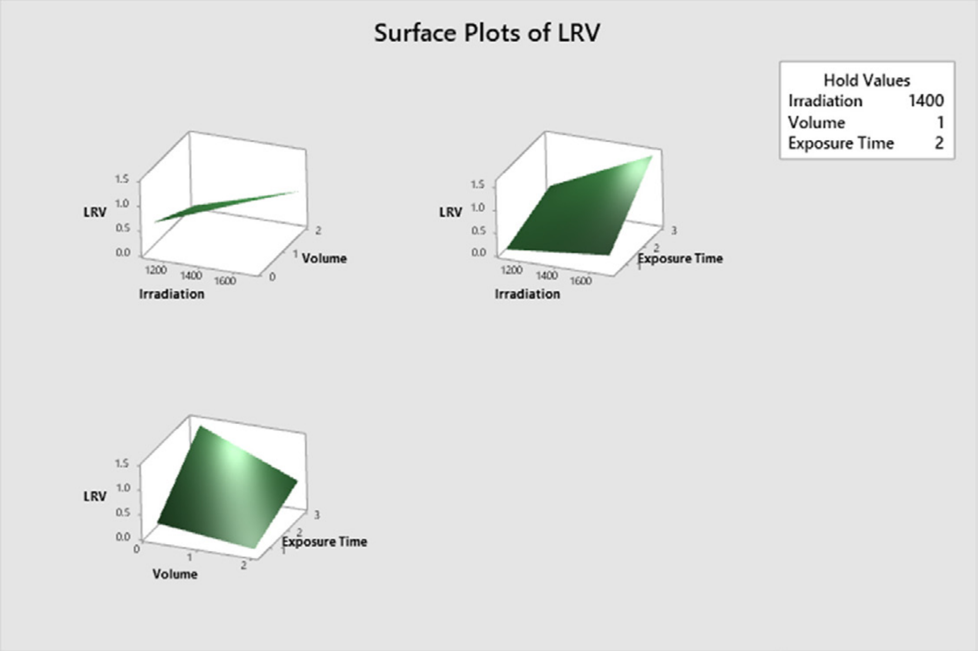

Fig. 11. Surface response plot for Solar Reactor

Table 6. Maximization of LRV

Type of reactor	Solar Irradiation ((Wh/m^2)	Volume of the sample	Exposure time	LRV		95% CI	95% PI
				Predicted	Observed		
Open air Reactor	1700	0.2	3	1.977	2	1.64-2.4	1.3-2.8
Solar Reactor	1700	0.25	2.97	2	2	1.9-2	1.9-2

consistent with SODIS recommendations, which specify that a geographic location is acceptable for SODIS if it gets 3–5 hours of sun radiation over 500 W/m^2 (Moosa et al., 2020).

Increasing the volume of sample has a negative effect on LRV of total coliform bacteria regardless of the type of solar reactor used in this study. Higher sample volumes appear to necessitate more time exposed to higher levels of solar radiation than lower sample volumes. Similar findings were made in the studies conducted by Ubomba-Jaswa et al., (2010) and Nalwanga et al., (2014). In bright and partially sunny circumstances Ubomba-Jaswa et al., (2010) used a 2.5 L borosilicate glass tube reactor to achieve complete inactivation of E. coli K-12 in under 3 hours. However, Nalwanga et al., (2014) achieved full inactivation in a 25 L borosilicate glass tube reactor, which is ten times greater in volume than the reactor used by Ubomba-Jaswa et al., (2010) after 6–7 hours on constantly sunny days.

Table 6 shows the optimum values of solar irradiation, sample volume, and exposure time defined by the response optimizer for both the reactors in order to achieve the highest LRV. Confirmation experiments were carried out with three replications at the predicted optimum conditions to validate the predicted conditions. As shown in Table 6 the maximum LRV was obtained when the experiments were conducted at optimum values of variables. The observed maximal LRV agrees well with the value predicted by the response optimizations with 95 percent confidence interval (CI) and prediction interval (PI), indicating that the statistical optimization strategy used in this study was successful in achieving the maximal LRV.

The optimal conditions shown in Table 6 are site specific. These conditions are primarily determined by local climatic conditions.

CONCLUSION

This study demonstrates that the total coliform present in the treated urban wastewater can be inactivated effectively using solar disinfection process. A full 2^3 response surface experimental design was used with the objective of identifying influenceable variables and to maximize the LRV of total coliforms present in treated urban wastewater using solar disinfection.

According to the pareto chart, the most significant factor in the LRV of total coliforms for both reactor conditions is exposure time. The interaction between solar irradiation and sample volume, solar irradiation and exposure time, and sample volume and exposure time is also significant for open air reactor disinfection. However, for solar disinfection using a solar reactor, the interaction between volume and exposure time, as well as irradiation and exposure time, is insignificant.

The optimum values of the factors for solar disinfection using open air reactor to achieve maximum LRV of 2 are 1700 Wh/m^2 of solar irradiation, 0.25 L of sample volume and 2.97 hours of exposure time. To achieve LRV of 2 using open air rector 0.2 L of sample needs to be exposed to 1700 Wh/m^2 of solar irradiation for 3 hours of duration.

For both the reactor conditions, an empirical model is chosen based on the influential variables and interactions shown in the pareto chart. By validating the experimental data, the goodness of fit of the model for open air reactor and solar reactor was effectively verified. The R^2 of empirical model of solar reactor and open-air reactor are 0.8953 and 0.997, respectively. The MAPE of a solar reactor is 7.52, while that of an open-air reactor is 3.28. It is clear from the determination coefficient and MAPE that the regression equation for solar reactor does not adequately explain the variability of the experimental data compare to that of regression equation for open air reactor.

GRANT SUPPORT DETAILS

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and /or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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