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SOLAR DISINFECTION OF TREATED URBAN WASTEWATER: DEVELOPMENT OF A PREDICTIVE MATHEMATICAL MODEL USING TWO LEVEL FACTORIAL DESIGN

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ABSTRACT

The goal of this work is to apply a factorial experimental design in the disinfection of total coliform bacteria present in treated urban wastewater using solar disinfection processes. Total coliform removal was studied using the factorial design 2^4. The four factors considered were solar energy, Volume of Sample, Exposure time and type of reactor at two markedly different levels: solar energy (1100 and 1700 W.h/m^2), volume of sample (0.2 and2L), exposure time (0.5 and 3 hrs.) and type of reactor (Open air and solar reactor). The experimental results of the solar disinfection process were analyzed statistically using the student's t -test, analysis of variance, F -test, and lack of fit to define the most important process variables affecting total coliform removal. It is observed that the exposure time is the variable with the greatest influence on the response factor (percentage of total coliform removed), although other variables also have a significant influence. Furthermore, a mathematical model (regression equation) has been obtained taking into account the influence of variables of total coliform removal. The model adequately describes the total coliform removal from treated urban wastewater using solar disinfection.

Keywords: urban wastewater, factorial design of experiments, solar disinfection, total coliform.

INTRODUCTION

The sultanate of Oman is an arid country with rapidly developing economy and high population growth rate. Together there is an increase in demand for fresh water. Pumping out ground water to fresh water demand of domestic, industrial and agricultural purposes has resulted decline in the ground water levels and coastal salinization across the country. Prathaper *et al* [1] reported that demand for fresh water in Sultanate is straining country's financial and natural resources. Many reasons are attributable to this condition, but fundamental is the perception that fresh water is used to meet all the demands of water, whether drinking or gardening. To overcome this problem some changes must be done in fresh water usage in order to decrease freshwater consumption in Sultanate.
Reclaimed water or treated wastewater is increasingly regarded as a valuable resource that can be utilized by agricultural, industrial and municipal sectors - rather than as a waste requiring disposal. While it should be viewed as a resource, reclaimed water still needs to be used in a safe and sustainable according to regulations for wastewater reuse and discharge in Oman (MINISTERIAL DECISION 5/86 DATED 17TH MAY, 1986). In Oman currently treated effluents from sewage treatment plants is mainly used for landscape irrigation and watering avenue plantations.

Secondary treated effluent contains pathogenic micro-organisms that pose a potential risk to the health of humans and livestock [2-3]. The organisms of concern in reclaimed water include enteric bacteria, viruses and protozoan [4]. These microorganisms can cause various types of diseases like cholera, typhoid fever, giardiasis, gastroenteritis, infectious hepatitis etc[5]. In a study conducted by Mahad *et al.,* [6] on quality of treated effluents in Oman concluded that E-Coli levels are not meeting Omani standards for wastewater reuse and discharge.

Disinfection is the primary mechanism to destroy/inactivate pathogenic organisms present in the treated wastewater. Conventional technologies used for reducing pathogen risks through disinfection of wastewater include ozonation, chlorination, electrochemical disinfection, radiation, filtration, biological methods, land infiltration, nanotechnology, electroportation, photovoltaic method and combined disinfection methods [7-15]. Chlorination technology is used in all the sewage treatment plants of Oman for disinfecting the secondary effluents. These technologies are capital intensive; require sophisticated equipment, responsible for formation of disinfection by products, and demand skilled operators [4, 16-17]. Therefore, there is need for a low-cost, low-maintenance, and effective disinfection system to make reclaimed water fit for human use.

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 bacterial pathogens present in water [18-20].

Sultanate of Oman's climate is hot and dry in the interior and hot and humid along the coast and sky is clear throughout the year. These climatic conditions are suitable for disinfecting treated wastewater using natural solar radiation. To the best of our knowledge, no studies related to solar disinfection of treated urban wastewater have been conducted in Oman. The aim of this work is to apply a factorial design of experiments in the disinfection of

total coliform present in treated urban wastewater by mean of solar disinfection process. Experimental design methodology is used to evaluate the influence of solar energy, volume of the sample, exposure time and type of the reactor on the inactivation of bacteria. In addition, one common objective of results analysis is to obtain a mathematical model that directly relates the response factor with the most influential variables and which describes the process appropriately.

MATERIALS AND METHODS

Treated Urban Wastewater Sample

The treated urban wastewater used in this research was collected from a sewage treatment plant located close to University of Nizwa. 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 [21] and is shown in Table-1. Treated wastewater fails to meet Omani agricultural reuse standards for COD, BOD, and total coliform bacteria (Table-1).

Table-1. Characteristics of the treated urban wastewater.

Parameter	Value	Agriculture reuse standard in Oman [23]
Temperature ^{o}C	18	--
pH	7.4	6-9
Turbidity, NTU	30	---
COD, mg/l	244	200
Total Suspended Solids, mg/l	140	15
TON	17	--
BOD, mg/L	166	20
Total Coliform Bacteria (MPN/100 ml)	24190	1000

Testing for Total Coliforms

Treated wastewater samples before and after the solar disinfection were tested for total coliforms using the Colilert-18 test which uses a proprietary Defined Substrate Technology (DST) nutrient indicators ONPG and MUG to detect coliforms and *E. coli*. Coliforms use their β-galactosidase enzyme to metabolize ONPG and change it from colorless to yellow. The limit of detection is <1 coliform per 100 mL of water.

Solar Radiation and Air Temperature Measurement

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 mounted near the experiment site to measure solar radiation and air temperature during experimentation.

Solar Disinfection

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 were also placed in a rectangular solar reactor made of aluminium reflectors. Total coliform inactivation was checked on samples subjected to solar radiation at regular time intervals.

Factorial Design of Experiments

In this study two-level factorial design (2^4) was used to develop a predictive mathematical model and to infer the significance between the factors and levels. In two level factorial design, each variable assumes two values or levels. Windows Version of MINITAB 19 was used to perform the factorial design of experiments. The variables considered in this study were: Solar energy (W.h/m^2), Volume of Sample (L), Exposure time (Hr), and type of reactor. Percentage of total coliform removed was considered as dependents factor (response). Table-2 shows the four parameters and their respective levels for the two-level factorial experiment. A total of 32 experiments (in replicate) were carried out for two level factorial experimentation.

Table-2. Levels of variables for two level factorial experimentation.

Variable	Low Level, -1	High Level, +1
Solar Energy (Wh/m^2)	1100	1700
Volume(L)	0.2	2
Exposure time (Hrs.)	0.5	3
Type of Reactor	Open air reactor	Solar Reactor

RESULTS AND DISCUSSIONS

Tables-3 shows the design matrix obtained with the MINITAB for two level experimentation. It contains the experimental conditions as well as the results obtained in each experiment in terms of the percentage of total coliform removed.

Table-3. Design matrix for two level factorial experiment.

Assay	Solar Irradiation/Energy (Wh/m^2)	Volume(L)	Time (Hr)	Reactor	Percentage of Total coliform Removed
1	1100	0.2	0.5	Open air Reactor	35
2	1700	0.2	0.5	Open air Reactor	64
3	1100	2	0.5	Open air Reactor	4
4	1700	2	0.5	Open air Reactor	36
5	1100	0.2	3	Open air Reactor	99
6	1700	0.2	3	Open air Reactor	99
7	1100	2	3	Open air Reactor	32
8	1700	2	3	Open air Reactor	90
9	1100	0.2	0.5	Solar Reactor	55
10	1700	0.2	0.5	Solar Reactor	85
11	1100	2	0.5	Solar Reactor	12
12	1700	2	0.5	Solar Reactor	66
13	1100	0.2	3	Solar Reactor	99
14	1700	0.2	3	Solar Reactor	99
15	1100	2	3	Solar Reactor	62
16	1700	2	3	Solar Reactor	99
17	1100	0.2	0.5	Open air Reactor	38
18	1700	0.2	0.5	Open air Reactor	67
19	1100	2	0.5	Open air Reactor	6
20	1700	2	0.5	Open air Reactor	38
21	1100	0.2	3	Open air Reactor	99
22	1700	0.2	3	Open air Reactor	99
23	1100	2	3	Open air Reactor	29
24	1700	2	3	Open air Reactor	92
25	1100	0.2	0.5	Solar Reactor	58
26	1700	0.2	0.5	Solar Reactor	88
27	1100	2	0.5	Solar Reactor	16
28	1700	2	0.5	Solar Reactor	64
29	1100	0.2	3	Solar Reactor	99
30	1700	0.2	3	Solar Reactor	99
31	1100	2	3	Solar Reactor	60
32	1700	2	3	Solar Reactor	99

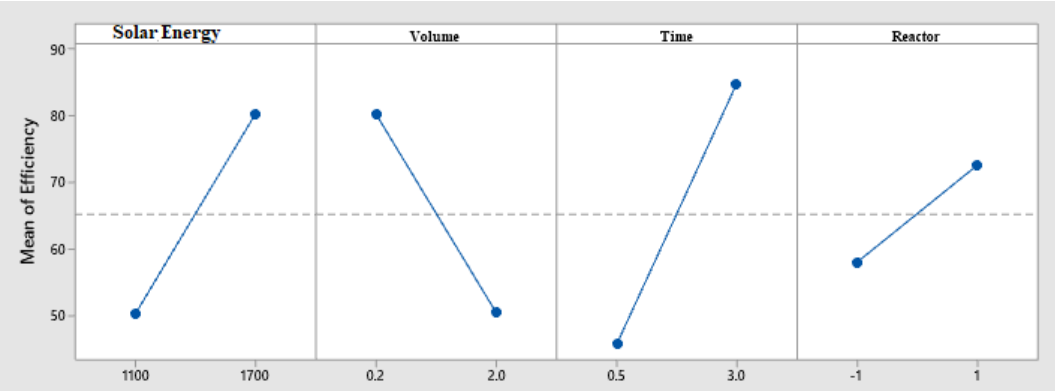

Figure-1. Main effects plots for efficiency based on level two experiments.

Figure-1 represents the effect of each variable and interaction between variables on the response factor percentage total coliform removed (efficiency). It is observed that variables solar irradiation, volume and type reactor has very positive effect on total coliform removal, where as volume of sample has negative effect. After estimating the main effects of the factors, an analysis of variance (ANOVA) was used to determine the significant factors influencing removal efficiency. In Table--4 the sum of squares used to estimate the factors' effects and the F -ratios (F_o) defined as the ratio of the respective mean-square-effect and the mean-square-error. Since $F_{0.05,1,16}$ = 4.49, all effects having F_o higher than 4.49 have statistical significance in two level factorial design. From the P values defined as the smallest level of significance leading to rejection of the null hypothesis it appears that the main effect of each factor and the interaction effects are statistically significant when P< 0.05[22].

Table-4. Analysis of Variance - full model fit for two-level factorial design (2^4).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Irradiation	1	7230.0	7230.0	2856.31	0.000
Volume	1	7110.3	7110.3	2809.00	0.000
Time	1	12129.0	12129.0	4791.72	0.000
Reactor	1	1696.5	1696.5	670.23	0.000
Irradiation*Volume	1	1875.8	1875.8	741.05	0.000
Irradiation*Time	1	236.5	236.5	93.44	0.000
Irradiation*Reactor	1	0.8	0.8	0.31	0.586
Volume*Time	1	11.3	11.3	4.46	0.051
Volume*Reactor	1	148.8	148.8	58.78	0.000
Time*Reactor	1	195.0	195.0	77.05	0.000
Irradiation*Volume*Time	1	693.8	693.8	274.09	0.000
Irradiation*Volume*Reactor	1	2.5	2.5	1.00	0.332
Irradiation*Time*Reactor	1	225.8	225.8	89.20	0.000
Volume*Time*Reactor	1	225.8	225.8	89.20	0.000
Irradiation*Volume*Time*Reactor	1	205.0	205.0	81.00	0.000
Error	16	40.5	2.5		
Total	31	32027.5			

$F_o = MS_{FACTOR} / MS_{ERROR}$; $R^2 = 0.9987$; R^2 adj. =0.9975; R^2 pred. =0.9949

Relative importance of the individual and interaction effects in 2 level factorial design is shown by the Pareto chart of the standardized effects in Figure-2. In order to identify whether the calculated effects were significantly different from zero, Student's *t* -test was performed and horizontal columns in Pareto chart showed these values for each effect. The minimum statistically significant effect magnitude for 95% confidence level is

represented by the vertical line in the chart. For a 95% confidence level the t value was equal to 2.12. Based on F-test and student's t-test the factors Irradiation, volume, time, reactor, Irradiation*Volume, Irradiation*Time, Volume*Reactor, Time*Reactor, Irradiation*Volume*Time, Irradiation*Time*Reactor, Volume*Time*Reactor and Irradiation*Volume*Time*Reactor present the higher statistical significant. Whereas Irradiation*Reactor, Volume*Time and Irradiation*Volume*Reactor are statistically insignificant in two level factorial experimentation.

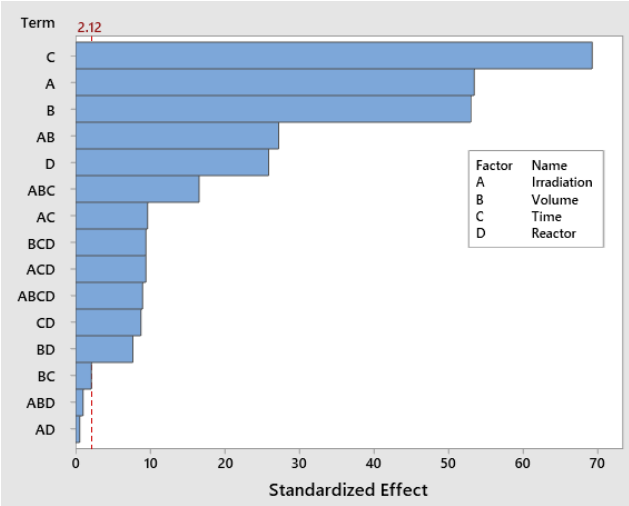

Figure-2. Pareto chart of effects for 2 level experimentation (Full model).

On the basis of the above F and t- tests, factorial design was reanalyzed, eliminating the interaction effects of Irradiation*Reactor, Volume*Time and Irradiation*Volume*Reactor for two level factorial experimentation. Table-5 and Figure-3 shows the analysis of variance and Pareto chart of effects for 2 level experimentation respectively for the reduced model. The lack of fit associated with elimination of the interaction factors Irradiation*Reactor, Volume*Time and Irradiation*Volume*Reactor for two level factorial experimentation produced F_o = 1.92. Since this value is 2.33 times lower than tabulated $F_{0.05,1,16}$ = 4.49, this factor did not have statistical significance.

Table-5. Analysis of Variance - reduced model fit for two-level factorial design (2^4).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Irradiation	1	7230.0	7230.0	2493.40	0.000
Volume	1	7110.3	7110.3	2452.10	0.000
Time	1	12129.0	12129.0	4182.90	0.000
Reactor	1	1696.5	1696.5	585.08	0.000
Irradiation*Volume	1	1875.8	1875.8	646.89	0.000
Irradiation*Time	1	236.5	236.5	81.57	0.000
Volume*Reactor	1	148.8	148.8	51.31	0.000
Time*Reactor	1	195.0	195.0	67.26	0.000
Irradiation*Volume*Time	1	693.8	693.8	239.26	0.000
Irradiation*Time*Reactor	1	225.8	225.8	77.86	0.000
Volume*Time*Reactor	1	225.8	225.8	77.86	0.000
Irradiation*Volume *Time*Reactor	1	205.0	205.0	70.71	0.000
Error	19	55.1	2.9		
Lack-of-Fit	3	14.6	4.9	1.92	0.167
Pure Error	16	40.5	2.5		
Total	31	32027.5			

$F_o = MS_{FACTOR} / MS_{ERROR}$; R^2 =0.9983; R^2 adj. = 0.9972; R^2 pred. =0.9951

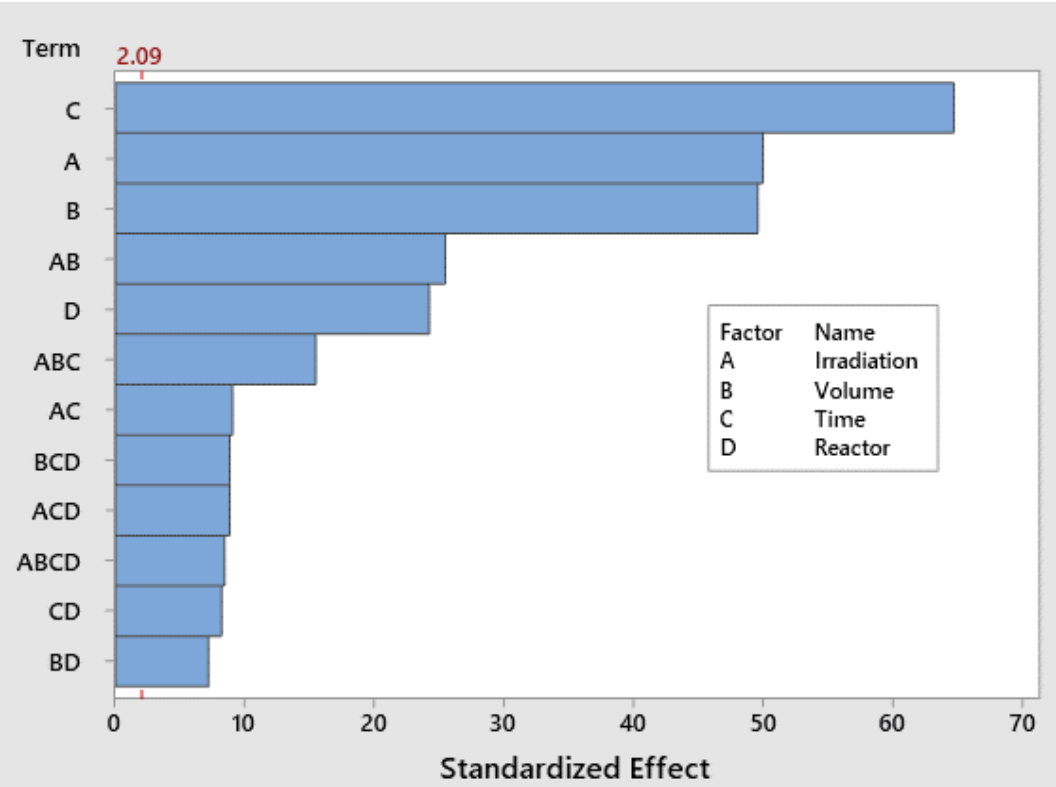

Figure-3. Pareto chart of effects for 2 level experimentation (reduced model).

Equation (1) is the predictive mathematical model (regression equation) in coded units for solar disinfection based on 2 level factorial experimentation.

Efficiency = 65.219 + 15.031 Irradiation - 14.906 Volume
+ 19.469 Time + 7.281 Reactor
+ 7.656 Irradiation*Volume - 2.719 Irradiation*Time
+ 2.156 Volume*Reactor
- 2.469 Time*Reactor
+ 4.656 Irradiation*Volume*Time - 2.656 Irradiation*Time*Reactor
+ 2.656 Volume*Time*Reactor
- 2.531 Irradiation*Volume*Time*Reactor
(1)

Figure-4 compares the experimental percentage of total coliform removal obtained with the solar disinfection process to the theoretical values obtained using the regression equation (eq.1) that describe the solar disinfection process. As can be seen, regression equation developed based on two level factorial experimentation is capable of reproducing the behavior of solar disinfection, and thus inactivation values can be approximated without the need for experiments. Rodriguez-Chueca *et al.*, [4] observed a similar trend by applying a factorial design in the disinfection of E-Coli present in treated urban wastewater using Fenton and photo-Fenton processes.

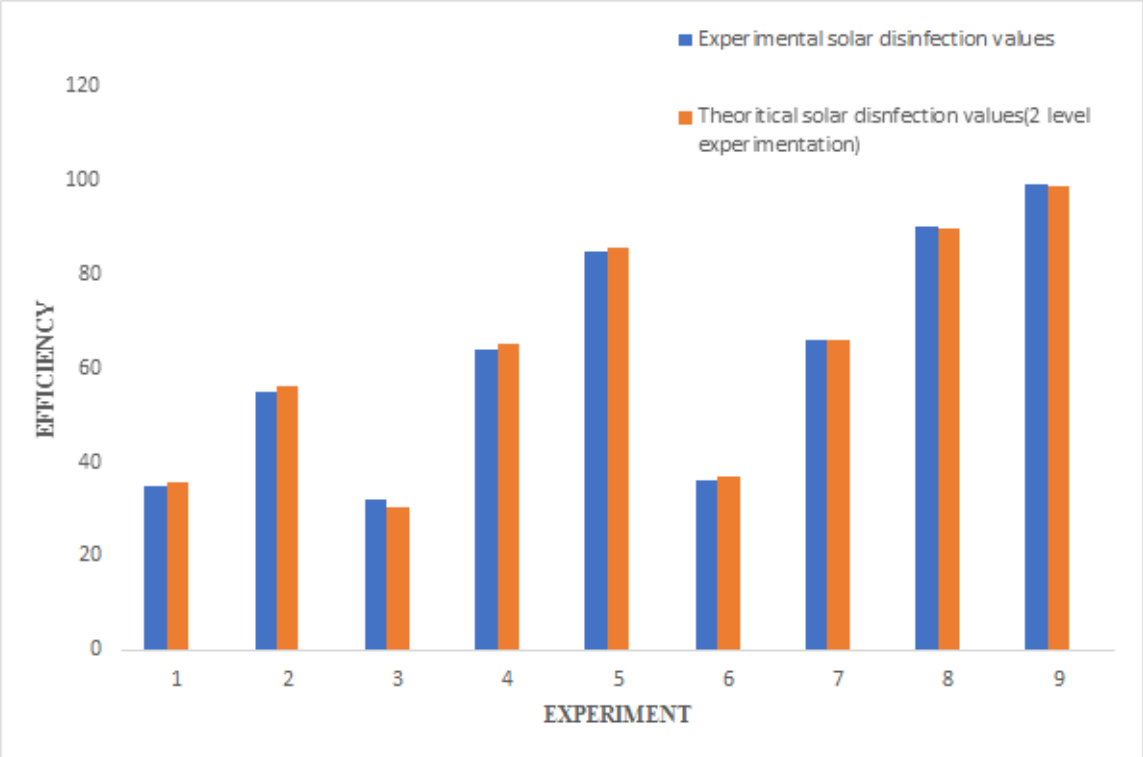

Figure-4. Comparison between experimental and theoretical solar disinfection efficiency values obtained with mathematical model

CONCLUSIONS

The factorial experiment design method, without a doubt, is a good technique for studying the influence of major process parameters on response factors by considerably reducing the number of experiments and hence saving time, energy, and money. The use of a factorial design enabled the identification of the most important parameters for the removal of total coliform bacteria present in urban treated wastewater using solar disinfection. The most significant effect for total coliform removal, according to the Pareto graphic, was attributed to exposure time. Volume and irradiation/solar energy also have a significant influence on total coliform removal efficiency.

The predictive mathematical model chosen based on the Pareto chart's influential variables and interactions shown to be capable of predicting the behavior of solar disinfection treatment process.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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