Hindawi
International Journal of Photoenergy
Volume 2021, Article ID 9981068, 9 pages
https://doi.org/10.1155/2021/9981068

Research Article

RSM-Based Optimization of the Parameters Affecting TiO_2-Mediated UV Photocatalysis of Vehicular Emissions in Enclosed Parking Garages

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Received 1 April 2021; Revised 8 June 2021; Accepted 17 June 2021; Published 6 July 2021

Academic Editor: Weijie Yang

In the preceding times, the number of enclosed parking garages has increased significantly in developing nations. The toxic emissions from vehicular exhausts are expected to drastically compromise the environmental conditions of the parking garages. Subsequently, exposure of humans to these accumulated pollutants is also expected to degrade their health. Therefore, in the present investigation, efforts were made to estimate the applicability of TiO_2-mediated UV photocatalysis in degrading the concentration of vehicular emissions, viz., NO_x and SO_2, in the enclosed parking garages (EPGs). In this regard, an artificial EPGs' environment was created and experiments were designed using the Box-Behnken design in combination with response surface methodology. The process parameters chosen for maximizing the degradation of the pollutants were a concentration of TiO_2 emulsion (20 to 120 ml/m^2), UV irradiance (1 to 5 mW/cm^2), and relative humidity (10 to 50%). Optimization of the laboratory experiments revealed that at optimal conditions of the process parameters, i.e., a concentration of TiO_2emulsion = 77.50 ml/m^2, intensity of UV irradiance = 3 mW/cm^2, and relative humidity = 43.2%, maximum degradation of the NO_x and SO_2, i.e., 61.24% and 55.05%, respectively, was achieved. Further, it was revealed that relative humidity may prove to be the limiting factor while using the TiO_2-mediated UV photocatalysis in humid areas. Findings of this study may prove beneficial in urban planning as it may assist scientific auditory and local authorities in identifying the applicability of TiO_2-based photocatalysis in mitigating the impacts of vehicular emissions.

1. Introduction

Anthropogenic activities involving the combustion of fossil fuels contribute significantly to the air pollution content of the world [1]. Among the various emission sources, industrial emissions and vehicular emissions are the most prominent ones [2]. With the recent advancements in technology, the obsolescence rate of the vehicles has tremendously increased owing to lower prices of the vehicular technology in the developing countries. In this way, a substantial increase in the vehicular density of the developing countries such as India, Kuwait, and Prishtina has also been reported [3–6]. Further, the number of vehicles owned by a single citizen of these nations has also increased. The sudden surge in the number of vehicles on the roads of these nations has put forward an issue of management of vehicular density among the urban planners. Also, due to the lack of parking space, in urban residential areas, the vehicles are generally parked on the road sides, leading to traffic congestion and accidents. To overcome these issues, in recent years, the citizens of these nations have initiated adopting the provisions of the enclosed parking garages (EPGs) in their residencies [7].

In order to cut the cost involved in construction and operation, these EPGs are generally designed with natural ventilation. However, studies have reported that the vehicular emissions generated in the EPGs are not efficiently dispersed using natural ventilation [8, 9]. In this way, several toxic pollutants, viz., PM, NO_x, SO_2, CO, CO_2, poly-aromatic hydrocarbons (PAHs), and volatile organic carbons (VOCs), are accumulated inside the EPGs [9–12]. These pollutants were reported to have several deteriorating health impacts on human beings [13, 14]. Therefore, the working staff in the EPGs, such as security guards and cleaner, is exposed to these pollutants and consequent health impacts can be speculated. Thus, these EPGs may act as hot spots of the air pollutants which may compromise the human health [15–17]. Therefore, it is imperative to identify an innovative and cost-effective approach to reduce the vehicular pollution inside the EPGs [18].

With a motive to reduce vehicular pollution, in ambient air, studies have identified the usage of photocatalytic material, i.e., TiO_2, on the asphalt roads, as significantly efficient [19, 20]. It has been reported that when applied on the surface of the roads, TiO_2 can significantly reduce the concentration of several pollutants, viz., organic carbon, NO_x, SO_2, and volatile organic carbons (VOCs) [21–23]. To reduce the ambient air pollution, many countries, around the world have also adopted the usage of TiO_2 in the construction of pavements, buildings, windows, etcetera [20, 24, 25]. However, studies proving the applicability of photocatalysis in reducing the vehicular pollution, inside the EPGs, are scanty. Moreover, there is still a research gap for identifying the utility of response surface methodology (RSM) in efficiently optimizing the TiO_2-mediated UV photocatalytic treatment of pollutants inside the EPGs.

Therefore, in this study, efforts were made to conduct a laboratory experiment and understand the applicability of TiO_2-mediated photocatalysis in reducing the concentration of NO_x and SO_2. Impacts of concentration of TiO_2 emulsion, UV irradiance, and relative humidity (RH) were estimated in a closed reaction chamber. Further, optimal conditions, for achieving the maximum reduction of NO_x and SO_2, were estimated using Box-Behnken design (BBD) in combination with RSM. The findings, of this study, may prove beneficial in the scientific quest for finding an appropriate solution for air pollution-related problems arising from uncontrolled vehicular emissions in the EPGs.

2. Materials and Methods

2.1. Site Configuration. The brief sketch of the site, where all the experiments were conducted is shown in Figure 1.

As shown in Figure 1, the experiments were conducted inside cemented and empty rooms which had the volume of 812 m^3. These rooms were termed as a reaction chamber in this manuscript. The inner side of the walls and the roof were sprayed with TiO_2 emulsion which was prepared by mixing the required amount of TiO_2 in deionized water. The TiO_2 emulsion was sprayed in crosshatch formation. UV lamps (Mazda/36 W/2500 lm), which acted as a source of UV-A radiation, were installed on all the four walls and the roof. The irradiance inside the reaction chambers was estimated using pyranometers (model: LPPYRA, SolUrja, India), which were placed near the active surfaces of the reaction chamber. The variations in the irradiance were adjusted by removing the required number of UV lamps. In order to investigate the impact of relative humidity on the depollution process, relative humidity, inside the reaction chamber, was estimated using a hygrometer (model: Traceable, Fisher Scientific, USA). Further, variations in the relative humidity were made by using a humidifier and dehumidifier (AC4081/20, Philips, India).

A Bharat Stage-4 and gasoline-driven car was used to generated NO_x and SO_2. The car was kept outside the reaction chamber, and its emissions were introduced in the middle of the reaction chamber using a pipe attached to the car's exhaust pipe. Concentrations of NO_x and SO_2 inside the reaction were estimated using a chemiluminescent NO_x and SO_2 analyzer (Rosemount Analytical; model 951C and 890). On the basis of the standardized permissible limits for indoor environments, the initial concentrations of NO_x and SO_2, for present investigation, were chosen to be 40 $\mu g/m^3$ [26, 27]. Therefore, the car was kept on an idle mode, until concentrations of NO_x and SO_2, inside the reaction, reached the required limits.

2.2. Statistical Analysis. Optimization was performed using Stat-Ease Design Expert (version 8.0.7.1) regression software. In this analysis, the impacts of process parameters on response parameters were assessed. The process parameters chosen in this study were a concentration of TiO_2 emulsion, UV irradiance, and relative humidity of the reaction chamber. Similarly, the response parameters, chosen in present investigations, were the % change in the concentrations of the NO_x and SO_2. Three levels of the process parameters, viz., low, medium, and high, finalized for the optimization process are described in Table 1.

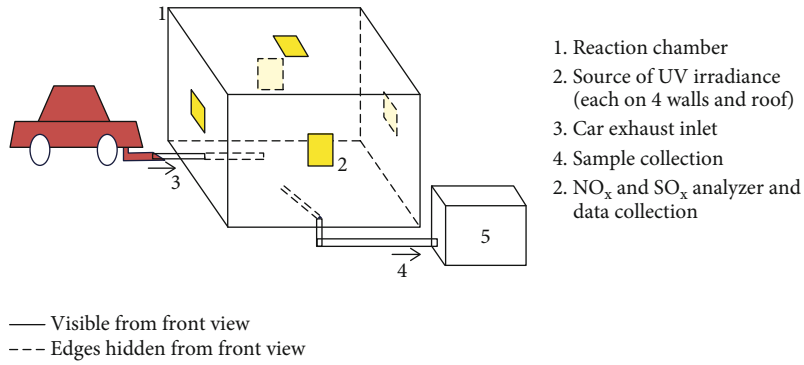

Figure 1: Brief sketch of the experimental site.

Table 1: Three levels of the process parameters used during the optimization process.

S. no.	Process parameters	Symbolic representation	Units	Coded values −1 (low)	0 (medium)	+1 (high)
1	Concentration of TiO_2	X_1	ml/m^2	20	70	120
2	UV irradiance	X_2	mW/cm^2	1	3	5
3	Relative humidity	X_3	%	10	30	50

As mentioned in Table 1, the three levels of X_1 were decided on the basis of findings of the previous scientific literature. However, levels of X_2 were chosen considering the average intensity of UV-A light received by landmass of the Earth [28]. Similarly, relative humidity, inside the reaction chamber, was decided as per the required range of the relative humidity in the indoor environments [26].

In statistical investigations, the relationship between the process and response parameters was generated using a multivariate statistical approach, which is faster and more user friendly as compared to the one-variable-at-a-time (OVAT) approach. This statistical approach designed the experiments using the response surface methodology (RSM) involving the Box-Behnken design (BBD). In case of three process parameters and two response parameters, a total of 17 experimental results are required to run this application. After providing the results of 17 experiments, adopted statistical approach derived different types of associations between the response and process parameters, which can generally be described using equation (1) as follows:

$$Y = c_o + c_1X_1 + c_2X_2 + c_3X_3 + c_{12}X_1X_2 + c_{13}X_1X_3 + c_{23}X_2X_3 + c_{11}X_1^2 + c_{22}X_2^2 + c_{33}X_3^2, \quad (1)$$

where Y depicts the response parameter(s), X_1 to X_3 are the process parameters, and c_i is the response function coefficients which are determined using Stat-Ease Design Expert (version 8.0.7.1) regression software. This software was further used to evaluate the accuracy of the generated models using analysis of variance (ANOVA). The various parameters estimated for checking the adequacy were correlation regression coefficients, adjusted regression coefficients, and goodness of fit. After all the statistical analyses, 3D plots of the results were also generated using RSM. Eventually, optimum conditions, of the process parameters, for achieving maximum degradation of NO_x and SO_2, were evaluated.

3. Results and Discussion

3.1. Model Equations and Regression Analysis. Based on the experimental results, two quadratic models were generated which depicted the relation between the response and process parameters. These quadratic models are described in equation (2) as follows:

$$Y_1 = 50 + 4.75X_1 + 13.5X_2 + 6.5X_3 + X_1X_2 + 0.5X_1X_3 + 2X_2X_3 - 20X_1^2 - 5.5X_2^2 - 6.5X_3^2,$$

$$Y_2 = 44 + 5X_1 + 12.25X_2 + 7X_3 - 0.5X_1X_2 + 1.5X_1X_3 + 3X_2X_3 - 19.25X_1^2 - 5.25X_2^2 - 6.75X_3^2, \quad (2)$$

where Y_1 and Y_2 indicate the response parameters, i.e., percentage removal of NO_x and SO_2, respectively; X_1 to X_3 depict the process parameters, i.e., concentration of TiO_2 emulsion, UV irradiance, and relative humidity. Response parameters Y_1 and Y_2 showed negative and positive correlations with certain terms which indicated an antagonistic and synergistic association, respectively. Further, with an objective of assessing the reliability of the models, the results generated using these models were compared with the experimental values. The outcomes of this comparison are shown in Table 2.

Table 2 compares the 17 experimental responses to the predicted responses, with respect to different conditions of the process parameters. In Table 3, it is evident that a significant correlation existed between the experimental

Table 2: Comparison of experimental and predicted responses.

S. no.	Process parameters TiO_2 X_1 ml/m^2	UV irradiance X_2 mW/cm^2	RH X_3 %	Experimental responses Y_1 %	Y_2 %	Predicted responses Y_1 %	Y_2 %
1	70	5	50	64	60	60	54.25
2	20	3	50	21	14	24.75	18.5
3	70	5	10	42	34	43	34.25
4	70	1	10	16	10	20	15.75
5	120	3	50	34	30	35.25	31.5
6	120	5	30	41	32	43.75	36.25
7	20	3	10	14	9	12.75	7.5
8	120	1	30	15	14	14.75	12.75
9	70	3	30	50	44	50	44
10	120	3	10	25	19	21.25	14.5
11	70	3	30	50	44	50	44
12	70	3	30	50	44	50	44
13	20	5	30	32	26	32.25	27.25
14	70	1	50	30	24	29	23.75
15	20	1	30	10	6	7.25	1.75
16	70	3	30	50	44	50	44
17	70	3	30	50	44	50	44

Table 3: Optimum conditions for TiO_2-based UV photocatalytic degradation of the pollutants.

S. no.	Control parameters	Symbolic representation	Units	Maximum values for responses % degradation of NO_x and SO_2 ($Y_1 = 61.24\%$ & $Y_2 = 55.05\%$) Coded values	Actual values
1	Concentration of TiO_2	X_1	ml/m^2	+0.15	77.5
2	UV irradiance	X_2	mW/cm^2	+1.00	5
3	Relative humidity	X_3	%	+0.66	43.2

and predicted values. These results were further augmented by estimating the correlation (at confidence interval of 95%) between the experimental and predicted responses, as shown in Figure 2.

In Figure 2, it can be implied that the results predicted using the models are significantly correlated with the experimental results. The correlation coefficients for NO_x removal and SO_2 removal were 0.96 and 0.93, respectively, i.e., almost equal to 1. Hence, it can be said that the models can be relied to generate appropriate results. Further, the adequacy and applicability of the models were verified using ANOVA.

3.2. Analysis of Variance (ANOVA). Reliability, of the outcomes predicted via the generated models, was verified using ANOVA-based analysis. Findings of the ANOVA-based analysis, of the experimental and predicted outcomes, at 95% confidence level, are shown in Table 4.

In Table 4, it can be seen that the p values of the models were less than 0.05, and hence, it can be depicted that the models generated in Design Expert software were adequate for predicting the optimal values of the process and response parameters. Also, the p values for the process parameters, i.e., concentration of TiO_2 emulsion, UV irradiance, and relative humidity, were reported to be significant. Regression coefficient, being close to 1, shows that variations observed among experimental and predicted results are insignificant and models are adequate for the present analysis (Kiely 1997; Ehrig and Stegmann 1992) [29, 30]. It can also be illustrated that the generated models can be used to analyze the responses from even more variations in the designed experiments (i.e., more than 17), as the values of correlation coefficients were observed to be very close to adjusted correlation coefficients (R^2_{adj}) [29].

Moreover, the p values can also be used to identify the significant effect of the different terms of the model on response parameters. In the present investigation, the model terms having a p value > 0.05 were considered as having insignificant effect on the response parameters. In this way, it can be observed that only X_1, X_2, X_3, $X_1{}^2$, $X_2{}^2$, and $X_3{}^2$ were having p values > 0.05 and hence have significant effect on the response parameters. The rest of the terms, i.e., X_1

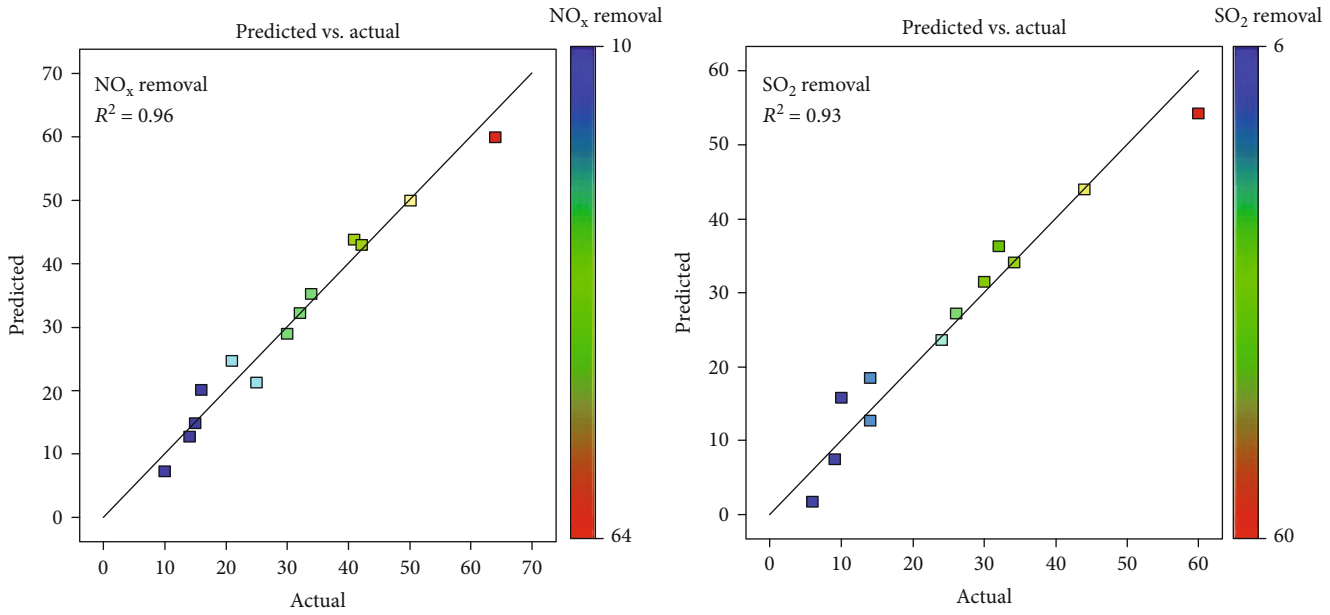

Figure 2: Predicted versus actual plots for decontamination of NO_x and SO_2.

Table 4: ANOVA test for response parameters.

Source	Sum of squares		df	Mean square		F value		p value	
	Y_1	Y_2	Y_1 & Y_2	Y_1	Y_2	Y_1	Y_2	Y_1	Y_2
Model	4128	3843	9	458	427	39.89	19.86	<0.0001	<0.0001
X_1	180.5	200	1	180	200	15.70	9.30	0.0054	0.0005
X_2	1458	1200	1	1458	1200	126.78	55.84	<0.0001	<0.0001
X_3	338	392	1	338	392	29.39	18.23	0.0010	0.0006
X_1X_2	4	1	1	4	1	0.3	0.04	0.5739	0.8354
X_1X_3	1	9	1	1	9	0.08	0.42	0.7760	0.5383
X_2X_3	16	36	1	16	36	1.39	1.67	0.2767	0.2367
X_1^2	1684	1560	1	1684	1560	146.45	72.57	<0.0001	<0.0001
X_2^2	127	116	1	127	116	11.08	5.40	0.0126	0.004
X_3^3	178	191	1	178	191.8	15.47	8.92	0.0057	0.003
Residual	10.5	15	7	11.50	21.5				
Lack of fit	10.5	15	3	26.83	50.17			0.07	0.09
Pure error	0	0	4	0	0				
Total (Corr)	4209	3993	16						

X_2, X_1X_3, and X_2X_3, was eliminated from the model, for further analysis. Moreover, as a p value for lack of fit (LoF) was observed to be >0.05, therefore, it can be depicted that the models generated are suitable for predicting the response parameters. After verifying the accuracy and adequacy of the models, they were further used to generate the response surface plots.

3.3. Response Surface Plots and Optimization. After assessing the adequacy of the models, Design Expert software was further used to plot 3-dimensional surface plots for all the operating parameters. The RSM approach was used to draw these plots and the generated plots are shown in Figure 3.

Analysis of the surface plots, as shown in Figure 3, and derived maximum degradation of the NO_x and SO_2, that assisted in identifying the optimum conditions for TiO_2-based UV photocatalytic degradation of the NO_x and SO_2 which, are shown in Table 3.

In Table 3, it can be implied that under optimized conditions, i.e., concentration of TiO_2emulsion = 77.5 ml/m^2, UV irradiance = 3 mW/cm^2, and RH = 43.20%, the % degradation of NO_x and SO_2 was reported to be 61.24% and 55.05%, respectively. Hence, the experiments designed in this

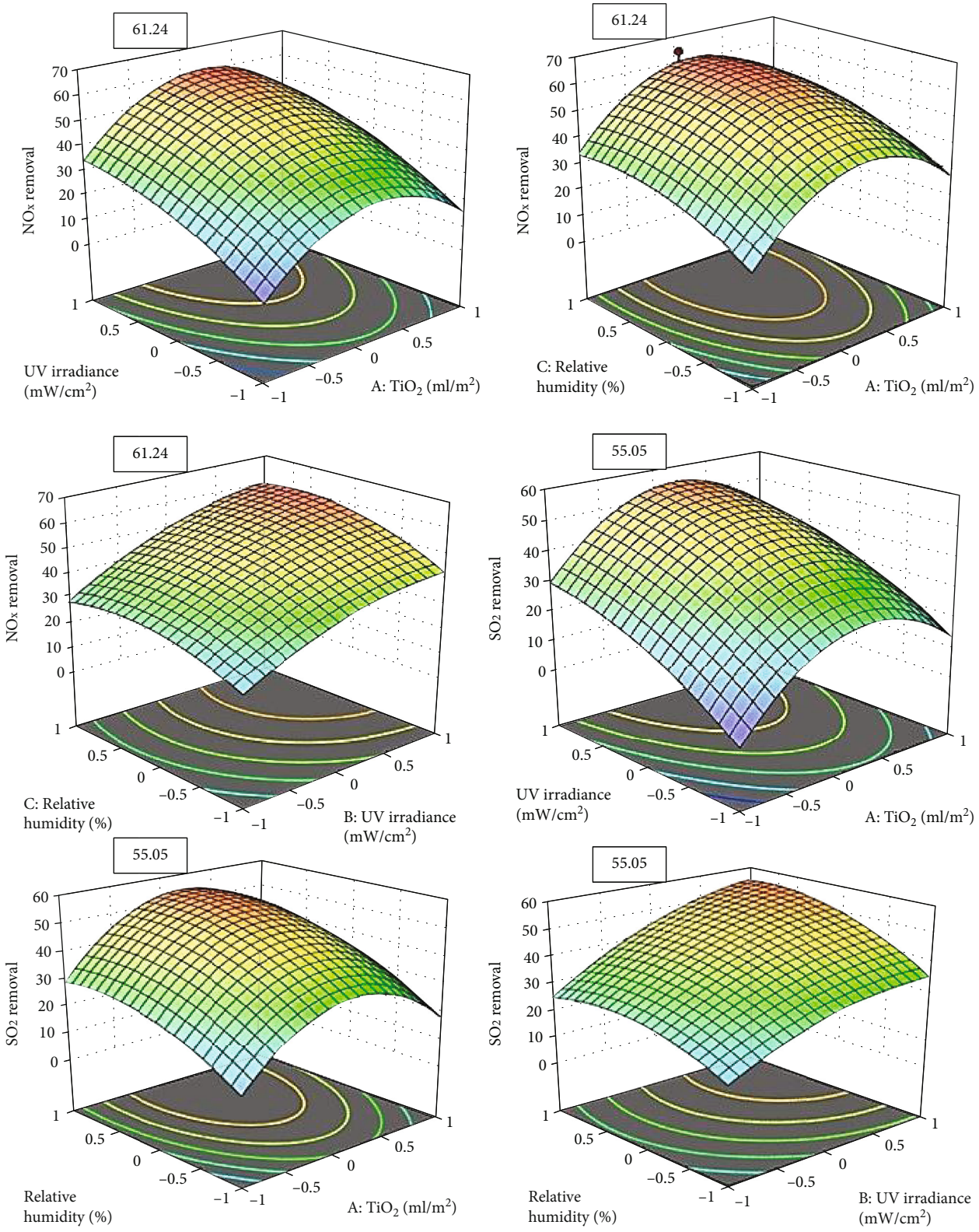

Figure 3: Response surface plots.

investigation using the Design Expert software were found to be suitable in deciding the optimal conditions of the process parameters under which significant degradation of the air pollutants could be achieved.

3.4. Impacts of TiO_2. In Figure 3 and Table 4, it is evident that the concentration of TiO_2 emulsion has a significant influence (p value > 0.05) on the decontamination of NO_x and SO_2 in the reaction chamber. In the reaction chamber, TiO_2

particles get excited after getting in contact with the photon-embedded light, emitted from the UV lamp. Excited TiO_2 particles generate free electrons and holes that further react with the water molecules and eventually initiate the decontamination process. These charged particles, in the reaction mixture, assist in enhancing the degradation process of NO_x and SO_2. The free electrons react with oxygen molecules and generate oxidizing radicals. On the other hand, holes lead to oxidation of gaseous molecules by producing hydroxyl radicals from water molecules. The overall reactions taking place during photocatalysis-induced decontamination of NO_x and SO_2 are described in equation (3) as follows:

$$\begin{aligned}
TiO_2 &\xrightarrow{h\nu} h^+ + e^-,\\
h^+ + H_2O &\longrightarrow OH^\bullet + H^+,\\
e^- + H^+ + O_2 &\longrightarrow HO_2^\bullet,\\
NO + HO_2^\bullet &\longrightarrow NO_2 + OH^\bullet,\\
NO_2 + NO + H_2O &\longrightarrow 2HONO,\\
NO_2 + OH^\bullet &\longrightarrow NO_3^- + H^+,\\
SO_2 + OH^\bullet &\longrightarrow HSO_3,\\
HSO_3 + OH^\bullet &\longrightarrow H_2SO_4.
\end{aligned} \tag{3}$$

In equation (3), it can be seen that during the TiO_2-mediated UV photocatalysis, hydroxyl radicals react with NO_x and SO_2 and finally degraded them into nitrates and sulphates, respectively. Subsequently, it can also be seen in Figure 3 that with the increase in concentration of the TiO_2 solution, the degradation of NO_x and SO_2 also increased. It can be attributed to the accelerated generation of hydroxyl radicals. However, such a scenario was observed till the concentration of TiO_2 solution was 77.50 ml/m^2, after which a continuous slight decrease was reported. One of the various promising explanations of such a trend could be the decreased exposure of TiO_2 particles to UV light caused by obstruction in the passage of light due to agglomeration of TiO_2 particles.

It has also been reported that overdosing of the TiO_2 particles lead to intershifting of charge among the ground state and activated particles [31, 32]. In this way, lesser electrons and holes are available for generating the hydroxyl radicals [33, 34]. Moreover, with a larger concentration of the TiO_2 solution, the solvent may seep the particles deeper into the walls, where they could not get exposed to the UV light. Similar observations had also been reported in studies conducted using TiO_2-mediated photocatalysis to degrade contaminants such as toluene (Morteza [35]) and benzene [36]. In a similar study, Hussein et al. [24] estimated the photocatalytic efficiency of TiO_2 particles by spraying its 3% solution (w/v) on the concrete surface. It was revealed that surface coating of concrete led to 98.85% reduction of nitric oxide. In another study, it was estimated that surface coating of concrete with 5% TiO_2 reduced approximately 60% of NO_x (Guo et al. [37].

3.5. Impact of UV Irradiance. Response surface plots, as shown in Figure 3 and Table 4, clearly indicate that a significantly positive (p value > 0.05) and quadratic association exits between the UV-A irradiance and the decontamination of gaseous pollutants. In the present investigation, the % decontamination of the NO_x and SO_2 gases was observed to increase with the increase in UV irradiance and maximum % decontamination of the NO_x and SO_2 gases was reported at 5 mW/cm^2 of UV irradiance. A promising explanation to this could be that on increasing the intensity of UV-A light, at a surface of catalyst-covered walls, the rate of generation, of free electrons and holes from the TiO_2 particles, escalated. These excited particles further increase the generation of hydroxyl radicals that finally oxidized the NO_x and SO_2 molecules. In a similar study done by Hüsken et al. [38], increase in the decontamination of NO_x was reported till the UV irradiance was increased up to 13 W/m^2. The findings of Ballari et al. [39] also support such an association between UV irradiance and gaseous decontamination argument. However, disagreement exists while deciding the linear or quadratic relation between the decontamination of the pollutants and intensity of the UV-A irradiance [40–42]. These studies explained that linearity exists when electron holes are stabled on reacting with pollutants at the photocatalytic surface rather than recombining with the electrons. However, in case of quadratic relation, opposite phenomenon existed and holes are filled largely by recombination. In the present investigation, the impact of UV irradiance on the photocatalysis is depicted to follow the latter phenomenon.

Also, while evaluating the impact of UV irradiance on efficiency of photocatalysis, it was observed that maximum % decontamination was observed at 5 mW/cm^2. However, it can be depicted that further increase in the UV irradiance could have increased the decontamination. Therefore, it is suggested that further research is required to conclude the optimum value of UV irradiance by increasing its range.

3.6. Impact of Relative Humidity. Relative humidity inside the reaction chamber was also observed to impact the TiO_2-based UV photocatalytic degradation of NO_x and SO_2. As shown in Figure 3, the maximum degradation of NO_x and SO_2 was achieved when RH of the reaction chamber was 43.2%. Also, as mentioned in Table 4, the decontamination process of the pollutants showed a significantly positive (p value > 0.05) and quadratic relation with the relative humidity of the reaction chamber. It was observed that with the increase in RH, till 43.2%, the degradation of the pollutants also increased.

Discussion on the interaction of water molecules and holes generated in TiO_2 particles made it evident that RH is a crucial factor for deciding the degradation efficiency of TiO_2-mediated UV photocatalysis. In an enclosed reaction chamber like EPGs, generation of hydroxyl radicals is majorly limited by the content of reaction chamber's RH. Due to hydrophilic nature of the surface of TiO_2 particles, the water molecules initially form a monolayer on the TiO_2

particles [43]. This interaction between the TiO_2 particles and water molecules initiates the photocatalytic degradation of the NO_x and SO_2 molecules. However, with the increase in RH, the number of layers of water molecules also increases on the TiO_2 particles [44]. Consequently, the interaction of TiO_2 particles with the gaseous molecules decreases and adsorption stops.

Moreover, this phenomenon also assisted in higher generation of free radicals further leading to radical scavenging. In case of radical scavenging, free radicals, instead of causing decontamination, are indulged in generating water molecules, as described in equation (4) as follows:

$$\begin{aligned} H_2O_2 + {}^*OH &\longrightarrow HO_2^* + H_2O, \\ HO_2^* + {}^*OH &\longrightarrow H_2O + O_2. \end{aligned} \tag{4}$$

In this way, the increase in RH of the reaction chamber, after a certain amount, leads to hinder the photocatalysis of the gaseous molecules. Therefore, in present investigation, the maximum degradation of the gaseous pollutants was observed at RH = 43.2%. Increasing the RH beyond this content could have increased the competition between the water and gaseous molecules for getting attached to the active sites of the TiO_2 particles. Therefore, it can also be implied that in humid areas, the RH could prove to be a limiting factor for TiO_2-mediated UV photocatalysis of air pollutants. Sleiman et al. [45] and Rismanchian et al. [46], also observed the photocatalytic degradation of Toluene in the 20% to 80% of RH and reported that maximum degradation was achieved at RH = 40%.

4. Conclusions

The findings of the present investigation proved that TiO_2-mediated UV photocatalysis can be used as a promising technology for the decontamination of NO_x and SO_2 in the enclosed parking garages. A comprehensive approach of RSM-BBD showed that at optimized conditions of the process parameters, i.e., concentration of TiO_2emulsion = 77.5 ml/m^2, UV irradiance = 3 mW/cm^2, and relative humidity = 43.20%, concentrations of NO_x and SO_2 can be degraded up to 61.24% and 55.05%, respectively. In this way, accumulation of pollutants in the EPGs and associated human health impacts can be prevented.

Data Availability

Data will be made available on demand.

Conflicts of Interest

The authors would like to declare that they do not have any conflict of interest.

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