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Photocatalytic Ozonation of Deltamethrin: A 3D Response Surface Methodology Approach

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Abstract

Deltamethrin is a persistent, toxic, and synthetic pyrethroid widely used in agriculture. Its environmental persistence leads to significant ecological consequences, necessitating effective removal strategies. While various Advanced Oxidation Processes (AOPs) — such as UV / H_2O_2, ozone-based methods, and photo-Fenton processes-are used to manage deltamethrin concentrations, photocatalytic ozonation has gained prominence. By combining a photocatalyst with ozone, this method achieves a higher degradation rate through the enhanced generation of reactive species. This study focuses on the degradation of deltamethrin via photocatalytic ozonation using a TiO_2/WO_3 composite photocatalyst prepared via the sol-gel method. To optimize the process, the research investigates several key variables, such as: pH, catalyst amount, and initial deltamethrin concentration. The interaction between these variables and their impact on the degradation rate was investigated using 3D Response Surface Methodology (RSM). The results demonstrate that photocatalytic ozonation is a viable method for the degradation of deltamethrin, achieving a 26% degradation rate within one hour of reaction time. Despite the potential of this process, further research should focus on three key areas: developing more efficient heterogeneous catalysts, improving catalyst recyclability, and addressing the technical challenges of scaling photocatalytic ozonation for industrial applications.

Keywords: AOPs, Deltamethrin, Photocatalytic Ozonation, TiO_2/WO_3, 3D Response Surface Methodology

1. Introduction:

There are quite limited clean water resources in the world and industrialization contributes to their deterioration. Heavy metals, organic, inorganic, and trace substances contaminate water [1]. Globally Emerging substance of concern (ESOC) have been found in water supplies. ESCOS is detrimental to environment and human health [2]. Pesticides are substances used to kill or repel unwanted organisms. Currently, Pesticides are one of the primary cause of water contamination. Recent study claims that only 15% pesticides are used to protect crops while other 85% remains in environment and causes problems [3]. Additionally, pesticide compound remain in water bodies for long periods. For example, organochloride pesticide were detectable in surface water after 20 years of its prohibition [4]. Leaching, surface run-off, soil erosion, volatilization, and spray drift are the main pathways through which pesticide enter aquatic ecosystem. In 1970s, USA and Europe banned the use of persistent organic pollutant [5].

Possible ways of pesticide exposure are: workers dealing with pesticide chemicals in pesticide industry, transportation of pesticides, farmers using pesticide in fields, fruit and vegetable vendors. Pesticide in drinking and surface water is major cause of concern due to its toxicity and potential to cause endocrine disruption [6]. Over the last few years, new approach known as

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Advanced Oxidation Process (AOP) has emerged. AOP is a more popular that conventional method of pesticide degradation. Because AOP can handle tough contaminants/pollutants. Specially, conventional methods often struggle to remove pesticides, whereas AOP provide an efficient solution for such contaminants [7].

Commonly used AOPs are TiO_2/UV, TiO_2/UV/O_3, H_2O_2/UV, O_3/UV, H_2O_2/O_3/UV, Vacuum ultra-violet (VUV) [8]. H_2O_2 and O_3 are conventional oxidants used in AOPs with extra stimulant UV/sun light. These oxidants produce hydroxyl radicals that are highly reactive and these radical can oxidizes pesticide [9]. In this study photocatalytic ozononation AOP is used. TiO2/WO3 photocatalyst is used along with ozone. Reason of choosing this AOP is that it requires low energy UV light and reusability of catalyst. Along this TiO_2/WO_3 can be used in sunlight because solar spectrum has 3% UV light [10].

Photocatalytic ozonation is an ecofriendly method for the conversion of toxic pollutants into inorganic mineral salts. Detailed mechanism of photocatalytic degradation of toxic pollutant has been discussed in literature [11] [12] [13] [14]. The mechanism of heterogeneous catalysis can be expressed in following reaction sequences ((1) to (9)).

$$TiO_2 + h\nu \rightarrow h^+ + e^- \quad (1)$$

$$H_2O \rightarrow H^+ + OH^- \quad (2)$$

$$O_2 + e^- \rightarrow O_2^- \quad (3)$$

$$O_2 + H^+ \rightarrow HOO^\bullet \quad (4)$$

$$2HOO^\bullet \rightarrow O_2 + H_2O_2 \quad (5)$$

$$H_2O_2 \rightarrow 2OH^\bullet \quad (6)$$

$$OH^- + h^+ \rightarrow OH^\bullet \quad (7)$$

$$OH^\bullet + RH \rightarrow R^\bullet \quad (8)$$

$$R^\bullet \rightarrow \text{Intermediate} \rightarrow CO_2 + H_2O \quad (9)$$

When photocatalyst is exposed to photon having greater or equal energy than bandgap, an electron from valance bong (VB) is moved to conduction bond (CB) and generate a hole in VB as shown in equation (1). Photogenerated electrons perform reduction reactions and while holes perform oxidizing reactions. Water is dissociated into H^+ and OH^- in parallel as shown in equation (2). Oxygen molecules accept H^+ and e^- generated in equation (1),(2) and form superoxide (O_2^-) and peroxide ($HOO^\bullet$) radicals as shown in equation (3),(4). Peroxide radicals are converted into hydrogen peroxide as shown in equation (5) and further into hydroxyl radical as shown in equation (6). Holes can oxidize pesticide molecule/OH^- / H_2O into OH• radicals. Holes generated in equation (1) react with hydroxyl ions and convert them into OH• as shown in equation (7). OH• from equation (6),(7) react with pesticide molecules (RH) and form their respective radicals (R•) as shown in equation (8). These pesticide molecule radicals ultimately mineralize into CO_2, H_2O and other products possible as shown in equation (9) [15].

Additionally, ozone gas is used to provide a synergic effect. The generation of OH• is greatly increased when photocatalysis and ozonation are combined. Firstly, ozone acts as electron scavenger. It captures photo-generated electrons from conduction bond of photocatalyst and prevent the recombination of electron-hole pairs that is the major disadvantage of using photocatalyst alone. Secondly, ozone reacts with electrons, holes, and pollutant molecules in water and starts the chain reaction that leads massive generation of hydroxyl radicals. This synergy dramatically increases both the degradation speed and overall degradation rate [16].

To achieve optimum conditions for deltamethrin degradation, we used Response Surface Methodology (RSM) with the Box-Behnken Design (BBD) approach. Furthermore, we used RSM to investigate the relationship between different parameters and how they affect the rate of degradation. [17]. This helped us to understand the factors affecting photocatalytic ozonation activity.

2. Methodology:

2.1. Materials and Chemicals:

All chemicals were analytical grade reagents and were used without further purification. Titanium butoxide ((Ti(OBu4) MACKLIN, 99.0%)) is used as a titanium source and Sodium tungstate ((Na_2WO_3) SIGMA-ALDRICH 99.0%) is used as a doped material for photocatalyst (TiO_2/WO_3) preparation. Deionized water was purchased from the local market. Sodium Hydroxide (NaOH), Potassium iodide (KI), and anhydrous alcohol (C_2H_6O) were used.

2.2. Synthesis of TiO2/WO3:

Sol-gel method is adapted for the preparation of TiO_2/WO_3. Ti(OBu4), Na_2WO_3, and anhydrous alcohol were the initial materials. Ti(OBu4) is used as a titanium

source and Na_2WO_3 is used as a doped material. To create a mixture, 10 mL of Ti(OBu4) were dissolved in 10 mL of anhydrous alcohol and then ultrasonically dispersed. The mixture was stirred for an hour at room temperature. 5 mL of deionized water were gradually poured into it. The required amount (15 weight %) of WO_3 in the TiO_2/WO_3 nanocomposites was added to the mixture by dripping in Na_2WO_3 solution. pH of the suspension was maintained at 10 and aged for 12 h at room temperature. The initial pH of the solution was maintained within the range of 5-7 through the addition of NaOH. The resulting mixture was aged for 12 hours at room temperature, followed by filtration and sequential washing with deionized water and anhydrous alcohol. Finally, the product was dried at 80 °C for 12 hours to obtain the precursor. TiO_2/WO_3 nanocomposites were created by calcining the precursor at 400 °C for 4 hours [18].

2.3. Physiochemical Characterization of photocatalyst TiO_2/WO_3:

Physiochemical Characterization of the photocatalyst is crucial for understanding the properties of catalyst and for optimizing its performance. Various analytical techniques are used to achieve a comprehensive understanding of the chemical and physical properties of catalyst. These techniques provide valuable insights of catalyst morphology, topography, crystal structure, and surface chemistry [19]. Techniques used in this study are XRD, SEM, EDX analysis and FTIR.

2.4 Experimental Setup:

A batch reactor made up of Pyrex glass double face flasks with an effective volume of 500 mL. The schematic reactor setup is shown in Figure 1.

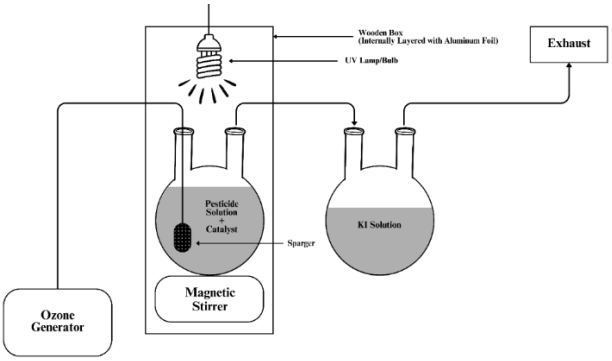


Figure 1: A schematic diagram of experimental setup for photocatalytic ozonation of deltamethrin

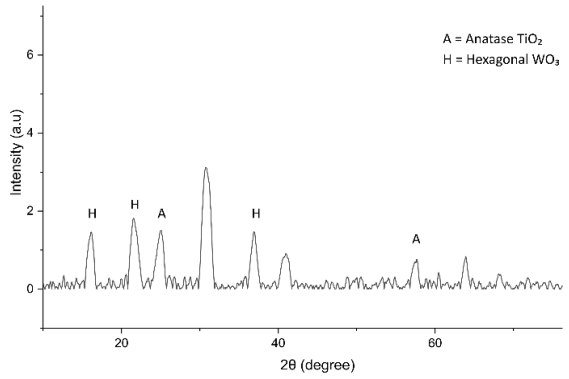
Design Expert software is used for Design of Experiments (DOE). Design of Experiments (DOE) is a statistical methodology for determining how factors or variables influence a response or outcome. Solutions were formulated according to the concentrations suggested by Design Expert software. Total volume of pesticide solution is 500 mL. By using ozonator (Voltage: 220/240VAC 50/60 Hz, Power: 35W, Ozone Output: 150 ml/h, Air flow rate: 150 ml/h) ozone gas was bubbled in pesticide solution in the presence UV light and catalyst. For UV light source (10W Fluorescent Lamp 253nm) UV lamp is used. Ozone exit from pesticide solution is bubbled through KI solution because ozone is harmful gas. All experiments were performed at room temperature. After running this setup, samples were taken at 3,6,9,15,20,25,30,40,50,60 minutes. These samples were filtered using a 0.45 µm syringe filter because catalyst particles can go with samples.

3. Results and Discussion:

3.1 Characterizations of TiO_2/WO_3:

XRD pattern and FTIR spectra of the Photocatlyst are illustrated in figure 1(a)-1(b) respectively. The structural and chemical characterization of materials relies on precisely controlled measurement conditions across XRD, FTIR, and SEM to ensure data integrity. For XRD, a **Cu - Kα** radiation source is typically operated at 40 kV and 40 mA, scanning a finely ground powder over a 2θ range of 5° to 80° with a step size of 0.02° to accurately resolve diffraction peaks. In FTIR analysis, the mid-infrared region from 4500 to 400 cm^{-1} is scanned, usually averaging 32 to 64 scans at a resolution of 4 cm^{-1} to improve the signal-to-noise ratio, while necessitating a background subtraction to eliminate atmospheric CO2 and water vapor. Finally, SEM imaging is conducted under a high vacuum (10^{-5} Torr) using an acceleration voltage of 10-20 kV and a working distance of 10 mm, often requiring non-conductive samples to be sputter-coated with gold or carbon to prevent surface charging and ensure high-resolution topographical mapping. In XRD analysis, TiO_2 anatase phase and the hexagonal phase of WO_3 both appear in the TiO_2/WO_3 photocatalyst. A keyway to assess the relative abundance of various crystal phases in a sample is the intensity of XRD peaks. Greater concentrations of that specific crystallographic phase are indicated by higher peak intensities [20]. FTIR is a powerful analytical technique for identifying and characterizing chemical

bonds in a sample using their vibrational frequencies. The spectrum contains several broad absorption bands, particularly in the low wavenumber region (below 1500 cm^{-1}). These bands are indicative of metal-oxygen vibrations, suggesting the presence of TO_2 and WO_3 at 700 cm^{-1} [21].



(a)

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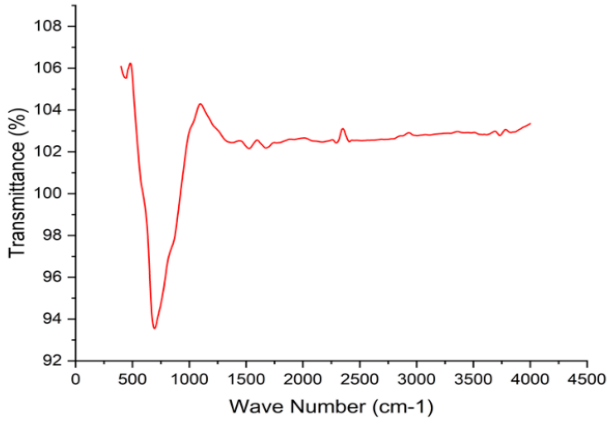

(b)

Figure 2: XRD pattern and FTIR spectra of Photocatlyst

SEM images show a detailed view of the surface structure, including particle size, shape, distribution and potential interactions between components. The image shows a diverse mixture of particles. Some particles appear to be quite large and irregularly shaped, while others are smaller and more spherical. This suggests a possible difference in the size distribution and growth mechanisms of TiO_2 and WO_3. SEM images of Magnitude 500x, 1000x, 2000x, 3000x of catalyst are shown in Figure 3.

EDX Spectrum shows that the sample primarily composed of Oxygen (46.42% of the total number of atoms) with significant amounts of Tungsten and Titanium. The graph demonstrates the X-ray peaks for

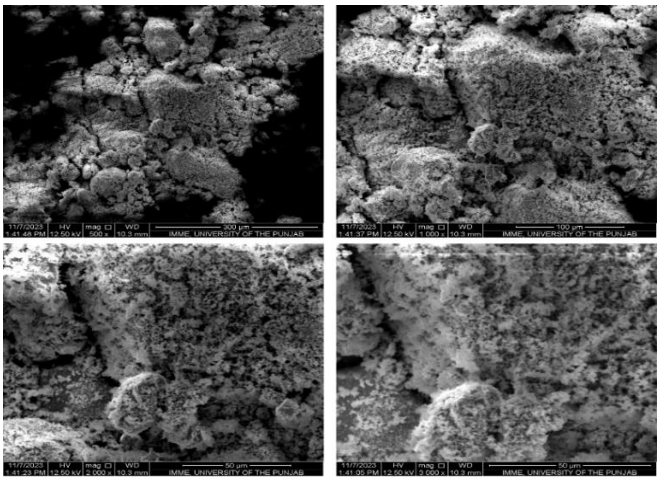

Figure 3: SEM images of photocatalyst

each element. It measures the relative abundance of each element in the catalyst. The element's abundance is proportional to its net intensity [22].

3.2 Photochemical Performance:

3.2.1 A Description about deltamethrin Removal:

We have selected 3 parameters due to their importance of deltamethrin degradation via photocatalytic ozonation. pH (A), Deltamethrin initial concentration (B) and Catalyst dosage (C). Table 1 describe the values of response for the removal of deltamethrin from solution. It is clear from table that all factors effecting the rate of degradation of deltamethrin.

3.2.2 Linear vs Mean Model:

Linear vs Mean model obtained after regression after performing regression analysis is given in equation (10)

$$\text{Removal} = 8.19 + 1.34\,A - 4.19B - 0.84C + 3.06BC + 4.69B^2 + 4.87C^2 \quad (10)$$

To support the sufficiency and importance of each item in the model, an ANOVA is performed. The significance of each term can be determined by the F-values [23]. The ANOVA (Analysis of Variance) table confirms that the mathematical model developed for the photocatalytic ozonation of Deltamethin is statistically valid and reliable. With a Model p-value of 0.0266 (which is less than the standard 0.05 threshold), the model is

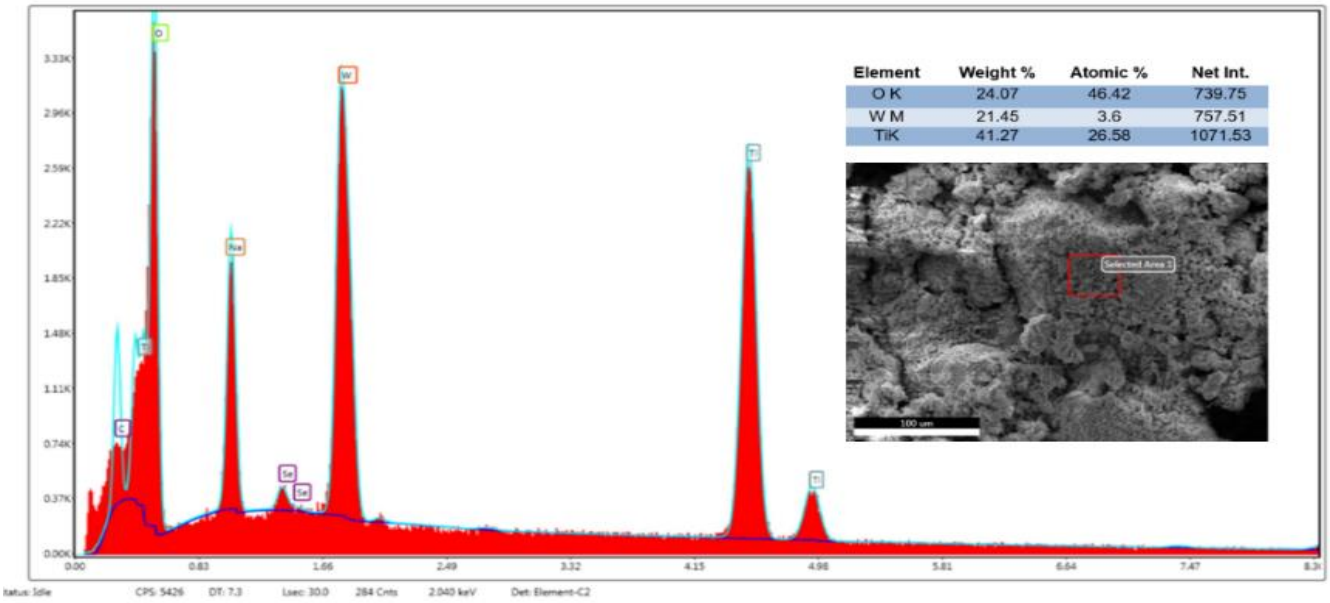

Figure 4: Energy Dispersive X-Ray Spectrum (EDX) of TiO2/WO3

Table 1: Design of Experiment (DOE) for input parameters and response (removal)

Std	Run	pH	Initial Conc (PPM)	Catalyst dosage	Removal %
15	1	5.5	30	0.125	16.2471
3	2	4	40	0.2	17.3731
1	3	7	40	0.05	17.6035
4	4	4	20	0.05	26.0118
9	5	5.5	30	0.018934	15.5273
7	6	5.5	15.8579	0.125	23.7378
2	7	7	20	0.2	18.8779
11	8	5.5	30	0.125	16.2471
13	9	5.5	30	0.125	16.2471
12	10	5.5	30	0.125	16.2471
14	11	5.5	30	0.125	16.2471
5	12	3.37868	30	0.125	5.875
8	13	5.5	44.1421	0.125	7
10	14	5.5	30	0.231066	15.9306
6	15	7.62132	30	0.125	9.669

considered significant, meaning there is a high probability that the observed results are due to the experimental factors rather than random chance. Most importantly, the Lack of Fit p-value of 0.5332 is "not significant," which is actually a positive result in Response Surface Methodology (RSM); it indicates that the model fits the experimental data well and successfully captures the relationship between the variables.

When looking at the individual factors, the Initial Concentration (B) is the most influential linear variable, showing a significant impact on the degradation process ($p = 0.0249$). However, the most striking results are the quadratic terms, B^2 and C^2, which both have very low p-values (0.0165 and 0.0138, respectively). This significance in the squared terms indicates a non-linear relationship, suggesting that the efficiency of the ozonation follows a curve. In practical terms, this means there is an optimal "sweet spot" for both the initial concentration and the catalyst dosage; increasing these factors beyond a certain point will likely lead to diminishing returns or a decrease in degradation efficiency.

In summary, while factors like pH (A) and Catalyst dosage (C) did not show a dominant linear effect in this specific range, their overall contribution to the model's curvature is essential. The high F-value and the non-significant lack of fit provide strong statistical evidence that the 3D response surfaces generated from this data can be used to predict the best conditions for removing Deltamethin from water.

Table 2: ANOVA table for degradation of deltamethrin during three-parameter optimization

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	507.32	6	84.55	4.55	0.0266	significant
A-pH	7.20	1	7.20	0.3872	0.5511	
B-Initial Conc	140.98	1	140.98	7.58	0.0249	
C-Catalyst dosage	5.77	1	5.77	0.3104	0.5927	
BC	18.82	1	18.82	1.01	0.3438	
B^2	169.96	1	169.96	9.14	0.0165	
C^2	183.26	1	183.26	9.86	0.0138	
Residual	148.71	8	18.59			
Lack of Fit	71.06	4	17.77	0.9152	0.5332	not significant
Pure Error	77.64	4	19.41			
Cor Total	656.03	14				

Insignificant terms rarely have any influence on adequacy of model to desired response. Therefore, the updated model as shown in the equation (11) after irrelevant elements have been removed.

$$\text{Removal} = 88.37 + 0.89\,\text{pH} - 3.74\,\text{Initial Conc} - 350.49\,\text{Catalyst dosage} + 4.088\,\text{Initial Conc}^{*}\,\text{Catalyst dosage} + 0.04\,\text{Initial Conc}^{2} + 865.92\,\text{Catalyst dosage}^{2} \quad (11)$$

3.2.3 3D Surface Curves and Contours:

3D response surfaces offer a direct explanation of the effect of interaction variable on desired response. They provide an in-depth overview of the relationship between two independent variables (factors) and a response variable [24].

Figure 6 represents the relationship between independent process variables pH (A), Initial Concentration (B), and Catalyst Dosage (C) and the dependent response, which is the removal efficiency of Deltamethin. In plot (a), the interaction between pH and initial concentration is depicted. The gradual slope suggests that while both factors influence the outcome, the removal efficiency is particularly sensitive to pH fluctuations. This is likely due to the amphoteric nature of the photocatalyst; the surface charge of the catalyst changes based on the solution's pH, affecting its electrostatic attraction to the Deltamethin molecules. When the pH aligns with the catalyst's optimal adsorption range, the generation of reactive oxygen species (ROS), such as hydroxyl radicals (•OH), is maximized, leading to the higher removal rates seen at the edges of the surface.

Plots (b) and (c) highlight the critical role of Catalyst Dosage (C). In plot (b), the interaction with initial concentration shows a distinct "valley" curvature, indicating that as the catalyst mass increases from 0.05 to 0.2 g, there is a significant increase in available active sites for the photocatalytic ozonation process. However, the contours also suggest a diminishing return at higher concentrations, often attributed to the "shielding effect" where excess catalyst particles increase the turbidity of the solution, thereby inhibiting light penetration and reducing the overall photonic efficiency of the system. The elliptical nature of the contours, especially visible in plot (b), signifies a statistically significant interaction between the variables. If the contours were perfectly circular, it would imply that the factors act independently of one another. The convergence of these ellipses toward the upper-right quadrants of the coordinates provides precise "operational window" required to achieve maximum Deltamethin mineralization while minimizing chemical and energy expenditure.

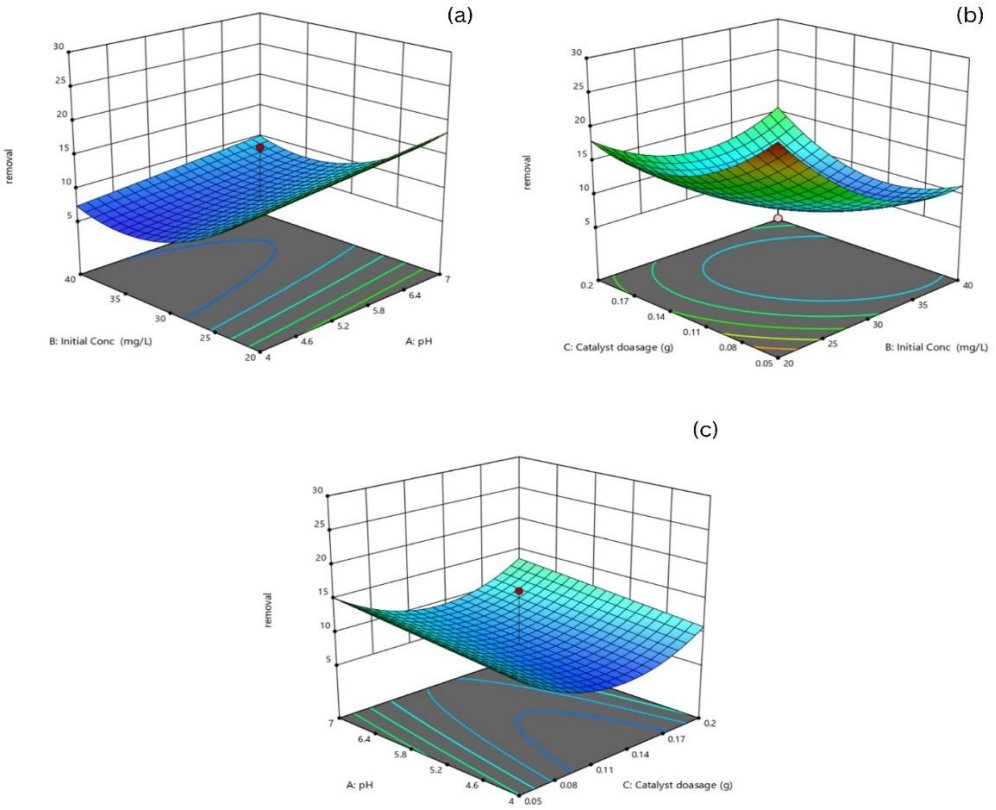

Figure 5: 3D Surface Curves and Contours between independent process variables pH (A), Initial Concentration (B), and Catalyst Dosage (C) and the dependent response

Conclusion:

Deltamethrin is a highly toxic and persistent synthetic pyrethroid pesticide that poses a significant health threat to human and aquatic life. Addressing this challenge, Photocatalytic Ozonation of deltamethrin has been successfully investigated in a batch reactor. Using Design Expert and RSM, it has been observed that degradation is highly dependent on variables including pH, catalyst dosage and initial concentration. This study finds a maximum 26% degradation of deltamethrin. All results indicate that the photocatalytic ozonation process is very effective in degradation of deltamethrin. Intermediates and by products formed in photocatalytic ozonation are less toxic to the environment. This research was conducted in lab and further investigation is needed how photocatalytic process can be scale up for industrial application and its performance under different conditions. Furthermore, these findings highlight photocatalytic ozonation as a promising and easily scalable process that bypass issues like catalyst reusability and stability. It is further suggested that photocatalytic ozonation is required to improve in performance and expected to scale-up for real-life environmental scenarios as a future aspect.

References:

[1] P.K. Surolia and R.V. Jasra, "Degradation and mineralization of aqueous nitrobenzene using ETS-4 photocatalysis," Desalination and Water Treatment, vol. 57, no. 34, pp. 15989–15998, 2016/07/01/ 2016, doi: https://doi.org/10.1080/19443994.2015.1079801.

[2] R.A. Hamza, O.T. Iorhemen, and J. H. Tay, "Occurrence, impacts and removal of emerging substances of concern from wastewater," Environmental Technology & Innovation, vol. 5, pp. 161–175, 2016/04/01/ 2016, doi: https://doi.org/10.1016/j.eti.2016.02.003.

[3] I. Katsikantami et al., "Estimation of daily intake and risk assessment of organophosphorus pesticides based on biomonitoring data–the internal exposure approach," Food and chemical toxicology, vol. 123, pp. 57–71, 2019.

[4] E.J. Mrema, A. V. Ngowi, S. S. Kishinhi, and S. H. Mamuya, "Pesticide exposure and health problems among female horticulture workers in Tanzania," Environmental health insights, vol. 11, p. 1178630217715237, 2017.

[5] S.K. Golfinopoulos, A.D. Nikolaou, M.N. Kostopoulou, N. K. Xilourgidis, M.C. Vagi, and D. T. Lekkas, "Organochlorine pesticides in the surface waters of Northern Greece," Chemosphere, vol. 50, no. 4, pp. 507–516, 2003/01/01/ 2003, doi: https://doi.org/10.1016/S0045-6535(02)00480-0.

[6] M. Syafrudin et al., "Pesticides in Drinking Water—A Review," International Journal of Environmental Research and Public Health, vol. 18, no. 2, p. 468, 2021. [Online]. Available: https://www.mdpi.com/1660-4601/18/2/468.

[7] Y. Deng and R. Zhao, "Advanced oxidation processes (AOPs) in wastewater treatment," Current pollution reports, vol. 1, no. 3, pp. 167–176, 2015.

[8] M.A. Quiroz, C.A. Martínez-Huitle, and E.R. Bandala, Advanced oxidation processes (AOPs) for removal of pesticides from aqueous media. IntechOpen London, UK, 2011.

[9] P.B. Patil, "Studies in degradation/removal of pollutants/organics using cavitation," 2022.

[10] Y. Sang, H. Liu, and A. Umar, "Photocatalysis from UV/Vis to near-infrared light: towards full solar-light spectrum activity," ChemCatChem, vol. 7, no. 4, pp. 559–573, 2015.

[11] U.I. Gaya and A.H. Abdullah, "Heterogeneous photocatalytic degradation of organic contaminants over titanium dioxide: a review of fundamentals, progress and problems," Journal of photochemistry and photobiology C: Photochemistry reviews, vol. 9, no. 1, pp. 1–12, 2008.

[12] D. Bahnemann et al., "Aquatic and surface photochemistry," Lewis, Boca Raton, vol. 261, 1994.

[13] J.M. Herrmann et al., "Photocatalytic degradation of pesticide pirimiphos-methyl: Determination of the reaction pathway and identification of intermediate products by various analytical methods," Catalysis Today, vol. 54, no. 2-3, pp. 353–367, 1999.

[14] V. Maurino, C. Minero, E. Pelizzetti, and M. Vincenti, "Photocatalytic transformation of sulfonylurea herbicides over irradiated titanium dioxide particles," Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol. 151, no. 1-2, pp. 329–338, 1999.

[15] D. Vaya and P. K. Surolia, "Semiconductor based photocatalytic degradation of pesticides: An overview," Environmental Technology & Innovation, vol. 20, p. 101128, 2020/11/01/ 2020, doi: https://doi.org/10.1016/j.eti.2020.101128.

[16] T. Yang et al., "Enhanced photocatalytic ozonation degradation of organic pollutants by ZnO modified TiO2 nanocomposites," Applied Catalysis B: Environmental, vol. 221, pp. 223–234, 2018/02/01/ 2018, doi: https://doi.org/10.1016/j.apcatb.2017.09.025.

[17] S. Hmamouchi, A. El Yacoubi, M. El Hezzat, B. Sallek, and B. C. El Idrissi, "Optimization of photocatalytic parameters for MB degradation by g-C3N4 nanoparticles using Response Surface Methodology (RSM)," Diamond and Related Materials, vol. 136, p. 109986, 2023/06/01/ 2023, doi: https://doi.org/10.1016/j.diamond.2023.109986.

[18] H. Yang, R. Shi, K. Zhang, Y. Hu, A. Tang, and X. Li, "Synthesis of WO3/TiO2 nanocomposites via sol–gel method," Journal of Alloys and Compounds, vol. 398, no. 1-2, pp. 200–202, 2005.

[19] M.F.G. Pereira, M.M. Nascimento, P.H.N. Cardoso, C.Y.B. Oliveira, G.F. Tavares, and E.S. Araújo, "Preparation, Microstructural Characterization and Photocatalysis Tests of V5+-Doped TiO2/WO3 Nanocomposites Supported on Electrospun Membranes," Inorganics, vol. 10, no. 9, p. 143, 2022. [Online]. Available: https://www.mdpi.com/2304-6740/10/9/143.

[20] E. Kowsari, F. Morad, N. Seifvand, B. Bazri, and M. Karimi, "Synthesis of reduced graphene oxide functionalized with methyl red dye and its role in enhancing photoactivity in TiO2–IL/WO3 composite for toluene degradation," Research on

Chemical Intermediates, vol. 46, no. 2, pp. 1217–1234, 2020.

[21] E. Safaei, S. Mohebbi, and M. Irani, "Selective aerobic photocatalytic oxidation of benzyl alcohol over spherical structured WO3/TiO2 nanocomposite under visible light irradiation," Journal of Sol-Gel Science and Technology, vol. 87, no. 1, pp. 170–182, 2018.

[22] L. M. González Rodríguez et al., "Synthesis, characterization and photocatalytic activity evaluation of WO3, TiO2 and WO3/TiO2 supported on zeolite faujasite," International Journal of Chemical Reactor Engineering, vol. 18, no. 10-11, p. 20200095, 2020.

[23] M. S. McIntosh, "Can analysis of variance be more significant?," Agronomy journal, vol. 107, no. 2, pp. 706–717, 2015.

[24] K. A. Stevens, "The visual interpretation of surface contours," Artificial Intelligence, vol. 17, no. 1, pp. 47–73, 1981/08/01/ 1981, doi: https://doi.org/10.1016/0004-3702(81)90020-5.