J. Anthropog Pollut 2025; 9(2): Article 26

Anthropogenic Pollution (AP)

https://doi.org/10.57647/J.AP.2025.0902.26

Research Article

Investigating the Efficiency of Combination of Ozone-Based Advanced Oxidation Process and Nanobubbles in Removing the Chemical Oxygen Demand (COD) from Zar Grain Refinery Industrial Wastewater

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Article History:

Received:
05 September 2025

Revised:
08 October 2025

Accepted:
22 October 2025

Published in Issue:
31 December 2025

Abstract

This study was designed to evaluate the efficiency of a combined Advanced Oxidation Process (AOP) and Ozone Nanobubbles (NB) for treating industrial wastewater from the Zar Grain Refinery. To this end, the optimal concentrations of three oxidizing agents including ozone (O_3), hydrogen peroxide (H_2O_2), and iron chloride ($FeCl_3$) were initially determined using Response Surface Methodology (RSM) and Central Composite Design (CCD). In each experiment, wastewater samples from the Zar Grain Refinery were treated under consistent conditions with varying concentrations of the oxidizing compounds. Then, through multi-objective optimization, an optimal value of O_3, H_2O_2, and $FeCl_3$ was calculated to achieve maximum wastewater treatment efficiency. The results indicated that O_3 had the most significant impact on reducing wastewater COD rates, showing approximately a 75% increase in COD removal efficiency. Regression models revealed that the interactive and non-linear effects of the oxidizing agents on COD reduction were significant. Based on these findings, it can be concluded that the combined AOPs would demonstrate high efficiency in removing COD from Zar Grain Refinery industrial wastewater. Finally, in addition to investigating the efficiency of the AOP process in treating wastewater from other industries, it is recommended that further studies be conducted to optimize other operational parameters influencing the wastewater treatment process, such as reaction time and temperature.

Keywords: Advanced Oxidation Process; Chemical Oxygen Demand; Fenton reaction; Industrial Wastewater treatment; Zar Grain Refinery

Cite this article: Malek Mohammadi, S., Sobhanardakani, S., Yari, A.R., Lorestani, B., Cheraghi, M., (2025). Investigating the Efficiency of Combination of Ozone-Based Advanced Oxidation Process and Nanobubbles in Removing the Chemical Oxygen Demand (COD) from Zar Grain Refinery Industrial Wastewater . *Journal Anthropog Pollut, 9(2), 26*. https://doi.org/10.57647/J.AP.2025.0902.26

1. Introduction

The scarcity of potable water is one of the most challenging issues confronting the world today (Fekri et al., 2021). Despite being one of the most abundant global resources, less than 1% of water is accessible as clean and safe water for human consumption. The problem has been exacerbated with the accelerating pace of industrialization (Grey et al., 2013). Consequently, with the continuous growth in population and industrial development, and the subsequent increases in the discharge of various pollutants into the environment, the need to preserve the environmental and to find novel and efficient wastewater treatment methods is becoming more imperative (Cardoso et al., 2021; Ebrahimzadeh-Rajaei, 2023). Therefore, research into the efficacy of technologies such as nanostructures and Advanced Oxidation Processes (AOPs) for improving wastewater treatment processes holds paramount importance.

In recent years, the escalating increase in industrial productions and activities has led to the presence of persistent, recalcitrant, and complex organic compounds in the wastewater of various industries. Many of these compounds cannot entirely be removed through conventional treatment processes such as coagulation, flocculation, aeration, and adsorption (Ebrahimzadeh-Rajaei, 2022; Nouri-Mashiran et al., 2022). Currently, various physicochemical and biological methods are employed for the removal of organic compounds from industrial wastewater, particularly that from the food industry, depending on the kinds of raw materials consumed and products manufactured (Gooran Ourimi and Nezhadnaderi, 2020; Sadr et al., 2021). In this regard, the efficacy of nanotechnology and advanced oxidation in removing organic compounds from wastewater has been well-established. Furthermore, compared to traditional approaches, these methods have proven more economical in terms of time and cost (Ebrahimzadeh-Rajaei et al., 2013; Aluthgun Hewage et al., 2021).

The low amount of dissolved oxygen in liquids is one of the most significant challenges in aerobic treatment of water and wastewater. Owing to the high oxidizing power of the ozone molecules, some recent studies have proposed the use of nano-ozone as an efficient alternative method as a promising technology for removing pollutants that cannot be eliminated from wastewater by conventional methods (Cardoso et al., 2021). In this context, the utilization of Nanobubbles (NBs) can be effective as they have unique and exceptional properties, such as a large gas-liquid interface, long-term stability in the liquid phase, and a high dissolution rate, which leads to an increased dissolution of oxygen in the fluid (Ali et al., 2023). Methods used for producing nanobubbles include such processes as decomposition-based production, gas-water circulation, and the use of palladium electrodes coupled with ultrasonication (Wang et al., 2019). The application of nanobubble technology enables the generation of free radicals without chemical consumption and eliminates the need for complex equipment. By creating a physical barrier, nanobubbles facilitate the entrapment and separation of pollutant layers on their surfaces within wastewater (Inoue et al., 2022; Selihin & Tay, 2022). Nanobubbles facilitate the formation of a physical barrier, causing pollutant layers to be encapsulated by the bubble surface and separated from wastewater. Moreover, ozone not only treats pollutants in wastewater but also eliminates their odor and color, while itself being rapidly removed from the water. Thus, the use of nanobubbles in water and wastewater treatment is expected to increase in the future (Tekile et al., 2016; Temesgen et al., 2017).

Among various techniques, AOPs—including Fenton and Fenton-like oxidation (Ge et al., 2021), photocatalysis (Xiong et al., 2018; Nawaz et al., 2023), electrocatalysis (Yang et al., 2023), ozone oxidation (Fernandes et al., 2019), and ultrasound (Huang et al., 2021; Han et al., 2023; Wang et al., 2023)—are widely regarded as the most effective methods for treating persistent, toxic organic pollutants in wastewater (Gonggong et al., 2024). Generally, AOPs are industrial wastewater treatment approaches designed to remove contaminants that conventional oxidizers like oxygen and chlorine cannot eliminate. These processes rely on the generation of highly reactive free radicals, particularly hydroxyl radicals (OH), which serve as powerful oxidizing agents, and can be activated through hydrogen peroxide (H_2O_2), ultraviolet radiation, catalysts, or photocatalysts

(Saravanan et al., 2022). Because complete degradation of organic matter in wastewater is often costly, AOPs are commonly employed to partially decompose and oxidize organic compounds into less harmful or inert substances, while also aiding in water disinfection (Oturan & Aaron, 2014).

Several studies have investigated the use of advanced oxidation processes and ozone nanobubbles in industrial wastewater treatment (Beltrán et al., 1999; Zhang et al., 2006; Tziotzios et al., 2007; Khoufi et al., 2009; Peng et al., 2016; Fan et al., 2021; Chen et al., 2022; Hutagalung et al., 2023; Farzami et al., 2024; Koundle et al., 2024; Wang et al., 2024). Furthermore, literature reviews have highlighted a synergistic effect in the combined ozonation/Fenton reagent process, as ozonation accelerates hydroxyl radical production by Fenton reagents, enhancing chemical oxygen demand (COD) removal from wastewater (Bijan & Mohsen, 2005; Wang et al., 2008; Van Aken et al., 2013; Sanchis et al., 2018;

Malik et al., 2019; Fernandes et al., 2020; Javeed et al., 2023). Additionally, Hutagalung et al. (2023) used a combined advanced oxidation process (AOP) based on ozone nanobubbles to treat textile industry wastewater. They reported that increased ozone reactivity would significantly improve the quality of the effluents.

Accordingly, although there are still several technical and operational issues that warrant further research, AOPs have attracted considerable attention due to their high efficacy in removing a wide range of pollutants, particularly from industrial effluents. They represent a promising alternative to conventional treatment methods, such as activated carbon adsorption, activated sludge, chemical precipitation, ion exchange, and membrane technologies, which often appear ineffective in removing some emerging complex, non-biodegradable contaminants. As food-industry wastewaters often contain very high COD levels that can inhibit the activity of the microorganisms responsible for biological degradation, and as conventional anaerobic–aerobic treatments typically remove up to about 70% of the initial organic load, it seems that more efficient processes are needed to achieve higher pollutant removal. To our knowledge, there has been limited research on combining the Fenton AOP with ozone nanobubbles for treating food-industry wastewaters. Therefore, this study investigates the efficiency of a combined Fenton process and ozone nanoparticle (nanobubble) treatment to remove COD from wastewater produced by Zar Fructose and Corn Starch Factory (Zar Grain Refinery).

2. Materials and methods

2.1. Introduction to the studied industry

Zar Fructose Company is the first grain refinery in Iran, with an annual processing capacity of four million tons, located in Hashtgerd Industrial Park, Alborz Province, Iran. It includes production units for starch, flour, gluten, industrial bread, liquid sugar, pasta, cakes, cookies, biscuits, sweets, chocolate, baby food, flaked cereals, cornflakes, and animal feed.

2.2. Reagents and instruments

In this study, all chemical materials with high purity (99.99%) were purchased from Merck, Germany. The equipment used included a COD reactor model DRB200, made by HACH, an ozone nanobubble generator, manufactured by Dantek Iran, jar test model SF6 produced by MTOPS Company, a laboratory balance with 0.0001g precision made by AND company, and Whatman No. 42 filter paper.

2.3. Collecting the industrial wastewater and determining its qualitative parameters

The wastewater from Zar Fructose Company originates from various processing stages on grains, including initial washing, soaking, grinding, separating the components, final processing, and packaging of grain products. In this study, 20 to 30 liters of samples were collected from the output of the sedimentation unit, and the samples were transferred to the laboratory using special containers. In the laboratory, the samples were stored in polyethylene containers with a volume of 1500 mL.

To assess the pollution load of the industrial wastewater from Zar Fructose Company, the COD values were measured according to the procedures presented in the Standard Methods for the Examination of Water and Wastewater (APHA, 2005).

2.4. Implementation of advanced oxidation process

To perform the AOP process, the pH of the wastewater sample was first adjusted to approximately neutral using sulfuric acid and normal hydrochloric acid. Then, by adding iron chloride in the range of 5.0 to 25 mg/L and hydrogen peroxide in the range of 5 to 10 mg/L to the wastewater at ambient temperature, the Fenton reagent was formed (Sun et al., 2015).

2.5. Execution of ozone nanobubble process

After Fenton reagent was added and the precipitate and flocs were formed in the wastewater, ozone nanobubbles were injected into the wastewater using an ozone generator capable of producing ozone nanobubbles with dimensions of 200 nm and various flow rates. The input flow rate to the wastewater and the time it took for precipitates or flocs to form in the wastewater were investigated (Ulatowski et al., 2019).

2.6. Filtration

To separate suspended and precipitated materials up to 50 µ in size, the wastewater was passed through a rapid sand metal filter, filled with silica of different particle sizes. Subsequently, colloidal suspended matter, dissolved substances, and remaining macromolecular particles were collected and transferred to the laboratory for further analysis (Benzing & Salant, 2021).

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2.7. Various Stages of Fenton Experiment

To perform the Fenton experiment, 200 mL of a stock solution was first prepared using distilled water at ambient temperature. Then, the pH of the samples was adjusted using dilute solutions of sulfuric acid (0.10 M) and sodium hydroxide (0.30 M). Given that the removal efficiency and Fenton reactions require acidic environments, in this study, acidic ranges of 2 to 4 were evaluated to select the optimal pH levels.

A Jar Test apparatus was used for mixing the solution to facilitate the reaction and ensure its uniformity in the advanced oxidation treatment process. To initiate the reaction, the device was set to 150 rpm, and then prepared Fe(II) solutions containing Fe^{2+} ions, as well as H_2O_2. solution at determined concentrations, were added to the wastewater within a time range of five to 60 min. Then, to form ferric hydroxide precipitates, the pH of the solution was increased to eight, and the alkaline sample was stirred at 150 rpm for about five minutes to complete the formation of Fe(III) hydroxide. Following this, to complete the formation of precipitates, the device speed was set to 50 rpm for 10 min. Subsequently, to allow for complete settling of the precipitates and separation of the two phases, the sample was left for 30 min. Finally, the treated sample was filtered using Whatman filter paper with a pore size of 0.45 µ, and the COD of the samples was then measured (Tuncer & Sönmez, 2023).

2.8. Designing the experiment using response surface method (RSM)

In this study, the Response Surface Method (RSM) based on Central Composite Design (CCD) was used to evaluate the effect of variables on performance and to predict the optimal values of variables and the responses. For this purpose, the range of each factor was coded between -1 to +1 to facilitate regression analysis (Sharma et al., 2017). Accordingly, 34 experiments were performed to optimize the values of the variable parameters including $FeCl_3$, O_3, and H_2O_2. The optimized experiments designed based on CCD are presented in Table 1. A schematic diagram of experimental set-up for the combined ozone-based AOP and NB method is shown in Figure 1 as described also by Hutagalung et al. (2023).

3. Results and discussion

3.1. Results of RSM Analysis

For optimization purposes, the range of variations for $FeCl_3$, O_3, and H_2O_2 parameters were considered at three levels. The response values to these three oxidizing agents in the AOP process, corresponding to the 34 experiments conducted, are presented in Table 1.

Table 1 shows that the minimum, maximum, and mean values of H_2O_2 were 2.5, 17.5, and 10.0 mg/L, respectively; the minimum, maximum, and mean values of $FeCl_3$ were 2.5, 17.5, and 10.0 mg/L, respectively; and the minimum, maximum, and mean values of O_3 were 2.5, 17.5, and 9.85 mg/L, respectively. The resulting values led to changes in wastewater COD contents with minimum, maximum, and mean values of 52, 82, and 62.7 mg/L, respectively.

3.2. Changes in wastewater treatment efficiency

Based on the results of ANOVA for COD (Table 2), among the independent variables, i.e., the concentration of oxidizing agents, only the effect of ozone concentration on COD values was significant (P-value < 0.05). Meanwhile, the interaction effects of $FeCl_3$ and O_3 oxidizers and quadratic effect of ozone on COD values were significant. Furthermore, the adjusted coefficient of determination (Adjusted R_2) value of 0.723 indicated that approximately 72% of the variation in COD values could be explained by the model. On the other hand, the Adequate Precision value of 11.6, which is greater than the desired value of 4.0, represents a suitable signal-to-noise ratio in the model for COD prediction. Additionally, the lack of fit of the model was not significant, indicating a good fit of the model with the experimental data. On the whole, it was decided that the regression model was suitable for predicting and optimizing COD values in the combined AOP process.

The normal probability plot of residuals (a) and the plot of actual COD values versus their predicted values (b) are shown in Figure 2. The normalized probability plot shows how the residuals follow a normal distribution. The plot of predicted response values versus actual values also helps to identify individual or groups of quality-parameter values that the model has predicted. Based on the results, since no significant deviations are observed for COD in either plots (a) or (b), the high accuracy of the calculations can be acknowledged**.** The results of Levene's test and the Breusch–Pagan test for homoscedasticity of the COD variable were non-significant ($p > 0.05$), so the assumption of equal variances was met.

A univariate analysis of variance was used to assess the interactive effects of factors and to evaluate the effectiveness of the combined advanced oxidation process (AOP) with ozone nanoparticles for COD removal. The combined AOP–ozone nanoparticle treatment effectively reduced COD in industrial wastewater from Zar Grain

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Refinery, achieving about a 75%increase in removal efficiency (Figure 3).

The combined effect showed most value at an ozone nanoparticle dose of 10 mg/L (Figure 4). The model's adjusted R-squared was 0.51, indicating that the model explained 51% of the variability in COD levels. The 3D interaction plots (Figure 5) support these results. The interaction between H_2O_2 and O_3 (Figure 5a) produced a steeper decline in COD than the interactions of $FeCl_3$ with O_3 and $FeCl_3$ with H_2O_2 (Figures 5b and 5c), suggesting a stronger synergistic effect for the H_2O_2–O_3 combination

3.3. Optimization results

The results of multi-objective optimization for the parameters H_2O_2, $FeCl_3$, O_3, and COD—conducted with the constraints applied to each parameter using Design–Expert software (version 13.0.5.0)—are presented in Table 3 Results of multi-objective optimization for the H_2O_2, $FeCl_3$, and O_3 parameters. The optimization aimed to identify a set of parameter values and provide solutions to achieve optimal treatment outcomes.

Based on the findings, the software yielded 10 solutions showing the optimal value for each parameter and the corresponding *desirability* rate (an index measuring solution quality). Thus, solution No. 1, with a desirability index of 0.950, was selected as the best solution, the 3D plots of which are shown in Figures 6a–c.

As shown in Figure 6, the optimal values for O_3, H_2O_2, and $FeCl_3$ are 15, 5, and 5, respectively, at a desirability level of 0.95. Therefore, it is concluded that the combined AOP process, under optimized conditions, can substantially improve the treatment efficiency of industrial wastewater generated by Zar Grain Refinery and thereby minimize the environmental pollution associated with this industrwastewater generated by Zar Grain Refinery and thereby minimize the environmental pollution associated with this industry.

The selection of a wastewater treatment method is influenced by such factors as wastewater composition, regulatory and administrative constraints, process cost, treatment efficacy, and the intended end use of the treated water. Conventional treatment methods, such as flotation, emulsification, chemical coagulation, gravity separation, flocculation, sedimentation, and biological treatment, face limitations including long settling times, large land requirements, and sludge management issues. Given the scarcity of safe water, developing cost-effective and efficient wastewater treatment technologies has become a priority (Hassan et al., 2022). In this context, advanced oxidation processes (AOPs) have been proposed as alternatives to traditional treatment methods. AOPs rely on the in-situ generation of strong oxidants to oxidize organic compounds in wastewater (Miklos et al., 2018, El-Gawad et al., 2023). These processes utilize advanced physicochemical mechanisms by releasing reactive species (free radicals). These reactive agents possess high redox potentials for oxidizing and degrading a wide range of pollutants, from endocrine-disrupting compounds to a broad spectrum of water contaminants, and under optimal conditions, can achieve up to 100% degradation efficiencies for many compounds (Titchou et al., 2021; Vieira et al., 2021).

While conventional biological treatment methods face major challenges in removing pharmaceutical compounds and microplastics as emerging contaminants, AOPs address this issue via radical-mediated chain reactions that sequentially break down complex molecules into simpler inorganic compounds (Yan et al., 2023). However, despite their proven effectiveness, the application of AOPs has its own limitations. Many AOPs require high energy input, making large-scale implementation economically and environmentally challenging. Furthermore, the formation of potentially toxic intermediate byproducts during oxidation can raise new concerns and necessitate additional treatments. Additionally, AOP efficiencies reported in laboratory-scale studies often decline in real-world applications due to complex wastewater matrices, catalyst deactivation, and similar factors (Saravanan et al., 2022; Mukherjee et al., 2023; Satyam & Patra, 2025). Owing to ozone's strong oxidizing power, Ozonation is one of the most important and efficient advanced oxidation processes which can provide a promising approach for removing contaminants that conventional methods cannot eliminate. Nanobubbles also possess unique properties such as large gas–liquid interfacial area, long-term stability in the liquid phase, and high dissolution rates, which increase the dissolution of oxygen gas in the liquid. When formed under favorable conditions, nanobubbles can remain stable for several hours or even months. Producing nanobubbles does not require complex equipment, and the process can generate free radicals without chemical additives (Fan et al., 2020,Fan et al., 2021; Hutagalung et al., 2023). Therefore, the method is both cost-effective and environmentally friendly. Accordingly, this study was conducted to evaluate the efficiency of the ozone nanobubble advanced oxidation process (AOP) for removing COD from industrial wastewater produced by the Zar Grain Refinery.

Analysis of variance and regression coefficients showed that ozone as the oxidant had the largest effect on reducing COD, as the response parameter, accounting for 75% of the impact. This result can be attributed to ozone's high oxidation capability for decomposing various organic and inorganic pollutants in wastewater. This finding is consistent with Javeed et al. (2023), who

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reported a COD removal efficiency of 95.9% using advanced oxidation processes with ozonation for pulp and paper industry wastewater. Similarly, Hutagalung et al. (2023) reported an 81.1% COD removal efficiency using combined AOP and ozone nanobubble methods for textile industry wastewater. Other studies also corroborate these results (Daneshvar et al., 2004; Kruithof et al., 2007).

The results also showed that the other oxidants, that is, H_2O_2 and $FeCl_3$, affected the treatment process through interactive and nonlinear influences. This finding is consistent with studies reporting a synergistic effect of combining multiple oxidants to improve treatment efficiency (Wang et al., 2019; Fernandes et al., 2020).

Possible reasons for differences in treatment performance between this study and those reported in similar research include variations in the composition and concentration of pollutants in the wastewater as the industrial effluent from Zar Grain Refinery contains specific organic and inorganic compounds that may respond differently to oxidants. Other contributing factors may include AOP operational conditions such as residence time, reaction temperature, and oxidant ratios.

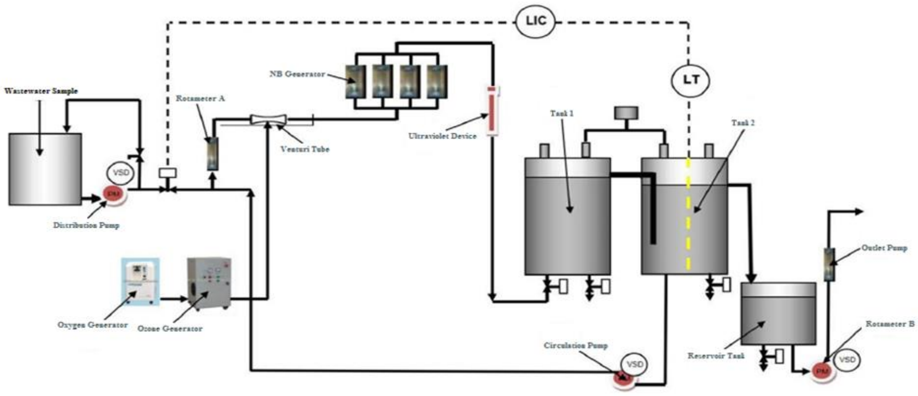

Figure 1. Diagram of the combined ozone-based AOP and NB method

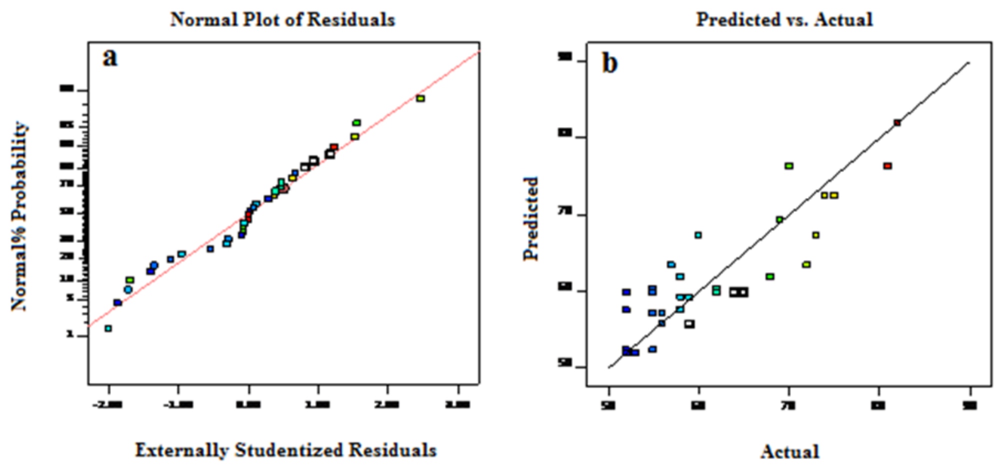

Figure 2. Normal probability plot of residuals, b) Actual values versus predicted values plot for COD

4. Conclusion

This study was conducted to evaluate the efficiency of a combined advanced oxidation process using ozone nanobubbles together with three oxidants-ozone, hydrogen peroxide, and ferric chloride- for treating industrial wastewater from the Zar Grain Refinery. To optimize the concentrations of these oxidants, response surface methodology (RSM) and a central composite design were employed. ANOVA and regression analyses indicated that O_3 had the greatest effect on reducing the response parameter (COD). H_2O_2 and $FeCl_3$ also influenced the treatment via interactive and nonlinear effects, although their impacts were smaller than that of ozone. The multi-objective optimization of the experimental data using Design-Expert also showed that, among the 10 solutions provided, Solution No. 1, including H_2O_2= 5 mg/L, $FeCl_3$ = 5 mg/L, and O_3 = 15 mg/L, had the highest desirability (0.95) and could be selected as the best option for treating the industrial wastewater of the Zar Grain Refinery. Overall, it can be concluded that the combined AOP using ozone nanobubbles, hydrogen peroxide, and ferric chloride is an efficient and effective method for treating this industrial wastewater. By generating reactive oxygen radicals such as hydroxyl radicals, the process can remove a range of organic and inorganic pollutants from industrial effluents. Therefore, applying the AOP under the optimized conditions found in this study can significantly improve treatment efficiency and minimize the environmental pollution caused by this industry.

Given the financial constraints of this study, it is recommended that future studies evaluate AOP performance on wastewaters from other industries and optimize additional operational parameters (e.g., reaction time and temperature). Future research should also investigate and, where possible, propose solutions to AOP limitations, such as the need for pretreatment to remove suspended solids and the potential formation of toxic intermediate byproducts.

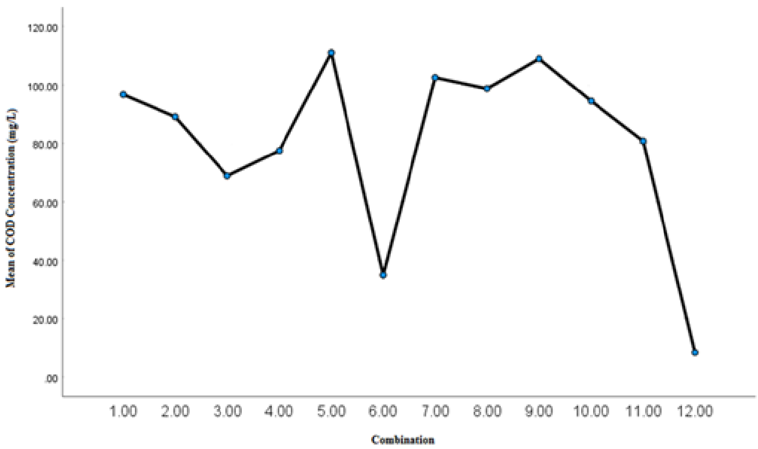

Figure 3. Mean values of COD variable in factorial combinations

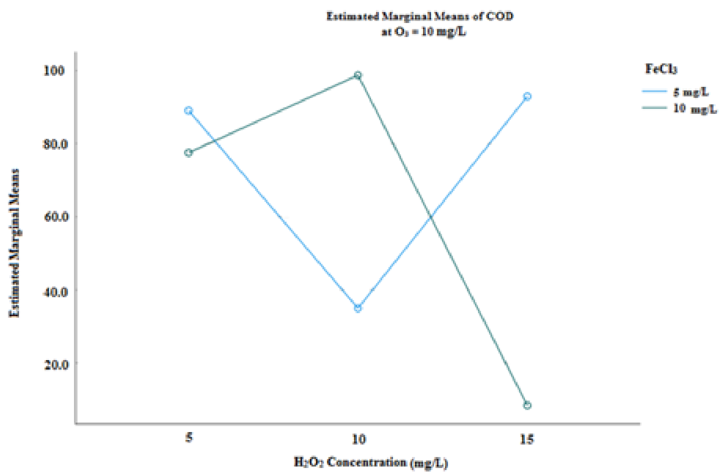

Figure 4. Interactive effects of AOP methods and ozone nanoparticles on COD removal

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Table 1. Designed experiments based on CCD and results of RSM

Experiment	Factor A (H_2O_2)	Factor B ($FeCl_3$)	Factor C (O_3)	Response
1	5.0	5.0	15	55
2	5.0	5.0	5.0	74
3	10	10	10	62
4	5.0	5.0	5.0	75
5	10	10	2.5	82
6	15	5.0	15	52
7	17.5	10	10	59
8	10	10	17.5	58
9	10	10	10	64
10	5.0	5.0	15	52
11	5.0	15	15	72
12	10	10	17.5	59
13	15	5.0	15	53
14	5.0	15	5.0	69
15	10	17.5	10	68
16	15	15	5.0	73
17	10	2.5	10	62
18	15	15	15	56
19	5.0	15	15	57
20	10	2.5	10	55
21	15	5.0	5.0	70
22	10	10	10	62
23	15	5.0	5.0	81
24	10	10	2.5	82
25	10	10	10	65
26	15	15	10	55
27	10	10	10	52
28	10	17.5	10	58
29	10	10	10	55
30	17.5	10	10	56
31	2.5	10	10	58
32	15	15	5.0	60
33	5.0	15	5.0	69
34	2.5	10	10	52

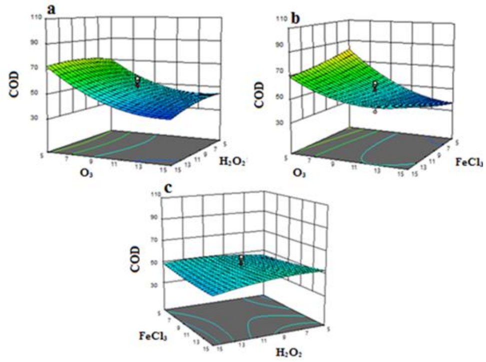

Figure 5. 3D response plot of COD to combined AOP and ozone nanoparticles process: a) Interactive effect of H_2O_2 with O_3, b) Interactive effect of $FeCl_3$with O_3, and c) Interactive effect of $FeCl_3$ with H_2O_2

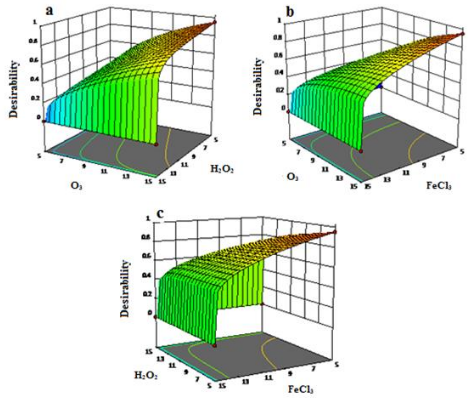

Figure 6. 3D plots of optimal desirability values for oxidants: (a) interactive effect of H_2O_2 with O_3, (b) interactive effect of $FeCl_3$ with O_3, and (c) interactive effect of $FeCl_3$ with H_2O_2

Table 2. Results of Analysis of Variance for COD

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2182.10	9	242.46	10.56	0.0001	significant
A-H_2O_2	9.61	1	9.61	0.4186	0.5238	
B-$FeCl_3$	6.25	1	6.25	0.2723	0.6066	
C-O_3	1436.41	1	1436.41	62.57	0.0001	
AB	33.06	1	33.06	1.44	0.2418	
AC	18.06	1	18.06	0.7868	0.3839	
BC	203.06	1	203.06	8.85	0.0066	
A^2	35.31	1	35.31	1.54	0.2269	
B^2	5.46	1	5.46	0.2379	0.6302	
C^2	392.61	1	392.61	17.10	0.0004	
Residual	550.96	24	22.96			
Lack of Fit	51.96	5	10.39	0.3957	0.8456	not significant
Pure Error	499.00	19	26.26			
Cor Total	2733.06	33				
Std. Dev.	4.79	R^2	0.7984			
Mean	62.71	Adjusted R^2	0.7228			
C.V.%	7.64	Predicted R^2	0.5886			
		Adeq. Precision	11.5884			

Table 3. Results of multi-objective optimization for the H_2O_2, $FeCl_3$, and O_3 parameters

Solution number	COD	Desirability
1	52.3	0.950
2	52.4	0.949
3	52.4	0.949
4	52.3	0.949
5	52.4	0.949
6	52.4	0.949
7	52.4	0.949
8	52.4	0.948
9	52.4	0.947
10	52.5	0.946

Authors Contribution

Saeed Malek Mohammadi: Formal analysis, investigation, software, validation, writing
Soheil Sobhanardakani: Conceptualization, formal analysis, investigation, methodology, software, supervision, validation, writing
Ahmadreza Yari: Formal analysis, investigation, methodology, software, supervision, validation
Bahareh Lorestani: Investigation, supervision
Mehrdad Cheraghi: Investigation, supervision.

Availability of data and materials:

The authors declare that they don't need research data support with this submission. Also, the authors are sure that all data and materials as well as software application or custom code support their published claims and comply with field standards.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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