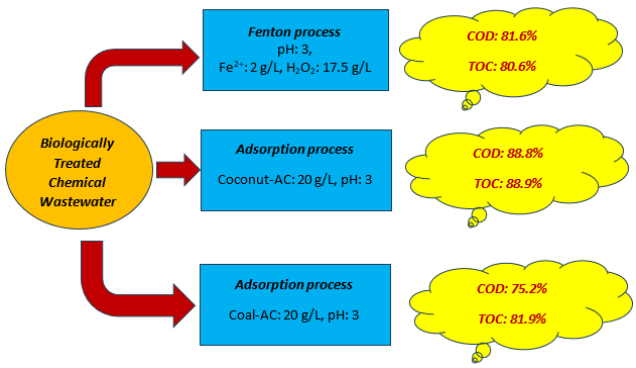
Global NEST Journal, Vol 27, No X, pp 1-9

Advanced treatment of biologically treated chemical industry wastewater producing organic peroxides using Fenton and adsorption processes

Ali Rıza Dinçer[1], Deniz İzlen Çifçi[1], Demet Darcan[2] and İbrahim Feda Aral[3]*
[1]Tekirdağ Namık Kemal University, Corlu Engineering Faculty, Department of Environmental Engineering, Çorlu, Tekirdağ, Turkey, A.R. Dinçer
[2]Akpa Chemical, Muratlı-Tekirdağ
[3] Tekirdağ Namık Kemal University, Corlu Engineering Faculty, Department of Civil Engineering, Çorlu, Tekirdağ, Turkey
Received: 24/09/2025, Accepted: 25/10/2025, Available online: 03/11/2025
*to whom all correspondence should be addressed: e-mail: iaral@nku.edu.tr
https://doi.org/10.30955/gnj.08034

Graphical abstract



Abstract

In this study, the advanced treatment of biologically treated chemical industrial wastewater from organic peroxide production was investigated using Fenton and adsorption processes. In the Fenton oxidation process, wastewater treatment was performed at different Fe^{2+} and H_2O_2 concentrations, pH values, and oxidation times to determine the optimal treatment conditions and treatment kinetics. In the adsorption process, wastewater treatment was conducted using coconut-based activated carbon (Coconut-AC) and coal-based activated carbon (Coal-AC) at different pH values, activated carbon doses, and adsorption times to determine the best treatment conditions, adsorption kinetics, and isotherms. In Fenton oxidation, COD (4680 mg/L), TOC (1022 mg/L), and organic peroxide removal were 81.6%, 80.6%, and 77.3%, with 1 h oxidation at pH 3, 2 g/L Fe^{2+}, and 17.5 g/L H_2O_2, respectively. In the adsorption process, better wastewater removal was achieved with Coconut-AC than with Coal-AC. At pH 3, with a 20 g/L activated carbon dose, 88.8% COD, 88.9% TOC, and 86.4% organic peroxide removal were obtained with Coconut-AC after 24 h of adsorption, while 75.2% COD, 81.9% TOC, and 54.5% organic peroxide removal were observed with Coal-AC. Although the SO_4^{2-} concentration in the wastewater increased with Fenton oxidation, 30.8% SO_4^{2-} removal was observed with Coconut-AC and 10.6% with Coal-AC. The cost was 15.77 $/m^3$ in Fenton oxidation under optimal conditions, compared to 15.87 $/m^3$ in the adsorption processes with Coconut-AC and Coal-AC. As a result, the adsorption process with Coconut-AC achieved higher wastewater treatment efficiency than Fenton oxidation, while the cost per m^3 of wastewater remained nearly the same. Moreover, SO_4 removal was effectively achieved in the adsorption process

Keywords: Adsorption, COD removal, cost analysis, Fenton oxidation, organic matter removal, TOC removal, organic peroxide, wastewater treatment

1. Introduction

Organic peroxides are widely used as crosslinkers, catalysts, or initiators in the chemical industry, drug synthesis, and polymerization reactions (Yan *et al.* 2024a; Zhu *et al.* 2024). Organic peroxides have a large market due to their use in the production of many materials, such as rubber, plastic, resin, and polymers. The demand for organic peroxides is increasing, because the number and capacity of facilities producing organic peroxides are also growing (Yan *et al.* 2024a; Liu *et al.* 2021). However, due to the large amount of water used in their production, the volume of wastewater generated is also quite high (Yan *et al.* 2024b). As water recycling has become one of the main focuses of sustainable development, the reuse of wastewater generated in industries is becoming widespread (Maruthai *et al.* 2025). Wastewater from the production of organic peroxides has low biodegradability and is toxic due to the presence of pollutants that are resistant to degradation (Yan *et al.* 2024b). Additionally, these wastewaters have high sulfate and organic peroxide concentrations, making them very difficult to treat with conventional wastewater treatment systems (Yan *et al.*

2024b; Dinçer *et al.* 2021). Therefore, additional treatment with advanced processes is required.

Advanced oxidation processes enable the removal of persistent and difficult to treat organic pollutants by producing the non-selective and highly reactive oxidizing agent •OH (hydroxyl) radical (Gómez *et al.* 2023). Fenton oxidation, one of the advanced oxidation processes, has been shown to be effective in treating many complex industrial wastewaters (Gómez *et al.* 2023; Gholami *et al.* 2022). In the Fenton oxidation of leather dyeing industrial wastewater with 0.981 mM Fe^{2+} and 5.38 mM H_2O_2 at pH 3.15, 82% COD, 92% TOC, and 97% color removal were achieved (Gómez *et al.* 2023). In the Fenton oxidation of pulp and paper wastewater with 15 mM Fe^{2+} and 15 mM H_2O_2 at pH 3, 78% COD removal was achieved (Gholami *et al.* 2022). Additionally, 85% COD removal was achieved in the treatment of coking wastewater with Fenton oxidation, and 77% TOC removal was achieved in the treatment of swine wastewater with Fenton oxidation (Verma *et al.* 2020; Toor *et al.* 2021).

The adsorption process has become a preferred tertiary treatment for industrial wastewater due to its high removal capacity for persistent organic compounds (Feng *et al.* 2020; Jorge *et al.* 2022; Kushwaha *et al.* 2010). The effectiveness of this process, which involves the retention of pollutants in wastewater on the surface of the adsorbent material by physical or chemical mechanisms, varies depending on factors such as the properties of the adsorbent, the properties of the pollutants and the current operating conditions (Selvanarayanan *et al.* 2024). COD removal was 98% in cork wastewater treatment combined flocculation and adsorption process (Ge *et al.* 2018). In the treatment of winery wastewater combined coagulation-flocculation, Fenton oxidation, and adsorption process (with bentonite), 81% COD and 72% TOC removal were obtained (Jorge *et al.* 2022). In the coagulation and adsorption of mixed (textile and chemical industry) industrial wastewater with coconut-based activated carbon, 97.5% COD and 95.5% TOC removal was achieved (Enfiyeci and Çifçi 2025). In the treatment of dairy wastewater pretreated by coagulation or electro-coagulation using the adsorption process, around 80% TOC removal was achieved at the adsorption stage (Al-Qodah *et al.* 2024; 2025).

When the literature is examined, it is evident that there are very few studies on the treatment of wastewater generated by industries producing organic peroxides (Yan *et al.* 2024a; 2024b; Dinçer *et al.* 2021). The treatment of organic peroxide wastewater using the ozone oxidation process with a CeO_2-C catalyst has been investigated, yielding 28.1% COD removal, while oxidation with iron-carbon microelectrolysis resulted in 35.7% COD removal (Yan *et al.* 2024a; 2024b). In our previous study on organic peroxide wastewater, 83.3% COD and 71.1% TOC removal were achieved using nanofiltration after Fenton oxidation (Dinçer *et al.* 2021). The chemical industry generates quite complex wastewater due to the diversity of chemicals produced. Studies on the treatment of chemical wastewater from which organic peroxides are produced are also quite limited. This study, unlike the aforementioned study, examined the Fenton oxidation and adsorption treatment processes applied to wastewater subjected to biological treatment at an organic peroxide production facility. Thus, the treatment performance of chemical wastewater from which organic peroxides are produced using both processes was evaluated and compared.

The aim of this study is to research the advanced treatability of biologically treated chemical industry wastewater producing organic peroxides using Fenton and adsorption processes. The study examines the effects of Fe^{2+} and H_2O_2 concentrations, pH, and oxidation time in Fenton oxidation, and determines the kinetics of the process. In the adsorption process, adsorption was performed using coconut-based and coal-based activated carbons, and the effects of pH, adsorbent dose, and adsorption time were investigated. Adsorption isotherms and kinetics were also determined. Finally, a cost analysis was conducted for both processes and compared. The novelty of this study lies in the fact that the wastewater used was sourced from the chemical industry where organic peroxides are produced, and there is a lack of sufficient research on the treatment of such wastewater.

2. Material and Method

2.1. Biologically treated chemical industrial wastewater characterization

The chemical industry wastewater, which contains various chemicals with organically bound peroxides, is located in the Muratlı/Tekirdağ region. Wastewater produced in the chemical industry is first treated with aerobic biological treatment after coagulation, and then it is sent to the Muratlı Organized Industrial Zone wastewater treatment plant after final sedimentation. This study investigates the advanced treatment of biologically treated chemical industry wastewater. The properties of the biologically treated wastewater are presented in **Table 1**. The COD and TOC concentrations of the wastewater are 4680 and 1022 mg/L, and it contains 0.22% H_2O_2 and 10,640 mg/L SO_4^{2-}, respectively.

Table 1. Characterization of biological treated chemical industry wastewater producing organic peroxide

Parameter	Unit	Value
pH	-	7.41
Conductivity	mS/cm	11.91±0.17
Turbidity	NTU	30.3±0.5
COD	mg/L	4680±17
TOC	mg/L	1022±12
H_2O_2	%	0.22±0.01
SO_4^{2-}	mg/L	10640±249

2.2. Fenton oxidation experiments

Fenton oxidation studies were carried out by placing 200 mL of wastewater in a 600 mL beaker and mixing at 45 rpm for 1 h using Jar Test. After adding Fe^{2+} (as $FeSO_4.7H_2O$, CAS: 7782-63-0) to 200 mL of biologically treated chemical wastewater, the pH was adjusted to 3 with a pH meter using H_2SO_4 (CAS: 7664-93-6). H_2O_2 (30%,

CAS: 7722-84-1) was added to the wastewater and oxidation was carried out for 1 h. At the end of oxidation, the pH value of the wastewater was adjusted to the range of 7.5-8.0 with 6 N NaOH (CAS: 1310-73-2) using a pH meter, and precipitation was allowed to occur for 30 min. Samples were taken from the clear upper wastewater and the necessary analyses were carried out.

In Fenton studies, by performing wastewater treatment at 8 different H_2O_2 concentrations up to 22.5 g/L at 2.0 g/L Fe^{2+} concentration to determine the required H_2O_2 concentration for wastewater treatment. Then, by performing wastewater treatment at 8 different Fe^{2+} concentrations up to 2.25 g/L at 17.5 g/L H_2O_2 concentration to determine the required Fe^{2+} concentration for wastewater treatment. In addition, by performing wastewater treatment at 5 different pH values between pH 2 and 4 at 2 g/L Fe^{2+} and 17.5 g/L H_2O_2, the optimum pH value for wastewater treatment was determined. Finally, oxidation kinetics were calculated by wastewater treatment at different oxidation times up to 2.0 h at 2 g/L Fe^{2+} and 17.5 g/L H_2O_2 concentration at pH 3.

2.3. Adsorption experiments

Coconut based activated carbon (Coconut-AC) and coal based activated carbon (Coal-AC) were used in the adsorption studies. The properties of these activated carbons were detailed in a previous study (Enfiyeci and Çifçi 2025). Adsorption studies were conducted by placing 100 mL of wastewater in a 250 mL conical flask and shaking at 150 rpm. After adding activated carbon to the wastewater, the pH was adjusted using a pH meter with H_2SO_4 and NaOH. After adsorption was performed on the wastewater shaker at 150 rpm, the activated carbon was separated by centrifugation (4000 rpm for 5 min). In the adsorption studies, adsorption was carried out at pH values of 3, 5, 7, 9, and 11, using a dose of 25 g/L of Coconut-AC or Coal-AC, and the pH value that provided the best wastewater treatment was determined. Then, the activated carbon dose that provided the best wastewater treatment was determined by adsorbing at different activated carbon doses (5, 10, 15, 20, 25, 30, and 35 g/L) at pH 3. Finally, adsorption kinetics and the adsorption isotherm were determined.

2.4. Analysis methods

COD analyses were carried out according to the closed reflux-titrimetric method given in the standard method on APHA5220C. TOC, organic peroxide and SO_4^{2-} analyses were carried out in AKPA Chemical R&D laboratory.

3. Results and Discussions

3.1. Fenton oxidation process

3.1.1. Effect of H_2O_2 concentrations

In the wastewater treatment study carried out with only a 2 g/L Fe^{2+} concentration (without adding H_2O_2), 9.7% COD and 25.3% TOC removal were achieved (**Figure 1**). While COD and TOC removal increased to 60.0% and 66.3% with a 5 g/L H_2O_2, an increase in COD and TOC removal was observed up to a 17.5 g/L H_2O_2 concentration. The highest COD and TOC removals were obtained at 81.6% and 80.6% at 17.5 g/L H_2O_2, and COD and TOC removal decreased to 79.5% and 71.1% at 20 g/L H_2O_2, respectively. COD removal decreased from 4680 to 1039 mg/L, while TOC removal decreased from 1022 to 260 mg/L at 2 g/L Fe^{2+} and 17.5 g/L H_2O_2. H_2O_2 reacts with HO• and acts as a scavenger of HO• radicals, producing hydroperoxyl radicals (HO_2•) at excessive H_2O_2 concentrations (Machado *et al.* 2023). Although HO• radicals are also reactive against organic pollutants, they have less oxidizing power and slower kinetics than HO• radicals, thus slowing down wastewater treatment (Babuponnusami *et al.* 2014; Machado *et al* 2023). Organic peroxide in the wastewater decreased by 50.0% in the wastewater treatment study with only a 2 g/L Fe^{2+} concentration (without adding H_2O_2), while it increased to 77.3% in Fenton oxidation with a 17.5 g/L H_2O_2. Despite the increase in H_2O_2 concentration in Fenton oxidation, similar organic peroxide removal can be achieved. This is due to the use of H_2O_2 added by Fenton oxidation in the production of hydroxyl radicals (Dinçer and Çifçi 2021). While the SO_4^{2-} concentration in the wastewater was 10,640 mg/L, it increased to 12,564 mg/L in the wastewater treatment study with only a 2 g/L Fe^{2+} concentration (without adding H_2O_2). This is due to the H_2SO_4 used to adjust the pH value to 3 after Fe^{2+} was added to the wastewater. However, no significant change was observed in SO_4^{2-} concentration at different H_2O_2 concentrations in Fenton oxidation.

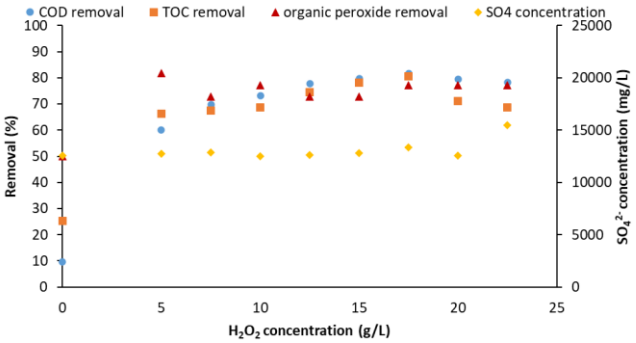


Figure 1. COD, TOC and organic peroxide removal efficiency at different H_2O_2 concentration (Fe^{2+}: 2.0 g/L, t: 60 min, pH: 3)

3.1.2. Effect of Fe^{2+} concentrations

COD removal increased from 54.0% to 79.4% as the Fe^{2+} concentration increased from 0.5 to 1.5 g/L, and reached 81.6% at a 2 g/L Fe^{2+} (**Figure 1**). COD concentrations at 0.5, 1.5, and 2.0 g/L Fe^{2+} concentrations were 2152 963, and 863 mg/L, respectively. As a similiar trend to COD, TOC removal observed as 50.0%, 72.2%, and 80.6% at 0.5, 1.5, and 2 g/L Fe^{2+}concentrations, respectively. A decrease in COD and TOC removal was observed at a 2.25 g/L Fe^{2+} concentration. Since there is not enough H_2O_2 in the presence of excess iron ions, it does not increase the production of hydroxyl radicals. On the contrary, it causes an increase in the amount of iron sludge, the total dissolved solids in the treated wastewater, and the scavenger effect (Babuponnusami *et al.* 2014; Ribeiro *et al.* 2021). While organic peroxide removal increased to 86.4% at a Fe^{2+} concentration of 0.5 g/L, increasing Fe^{2+} concentrations above 0.5 g/L did not provide a significant

change in organic peroxide removal. The SO_4^{2-} concentration increased compared to the inlet wastewater, reaching values of up to 14,140 mg/L. This is due to the increase in the H_2SO_4 concentration used to adjust the pH to 3 with the increase in Fe^{2+} addition.

In the treatment of biologically treated chemical industry wastewater producing organic peroxides by Fenton oxidation, the optimum conditions were found to be pH 3, 2.0 g/L Fe^{2+}, and 17.5 g/L H_2O_2 and the H_2O_2/Fe^{2+} molar ratio was 14.4. Under these conditions, 81.6% COD and 80.6% TOC removal were achieved after 1 h of oxidation. In our previous study with industrial wastewater containing organic peroxide, the H_2O_2/Fe^{2+} molar ratio was found to be 32.8 (Dinçer *et al.* 2021). It is observed that in the case of Fenton oxidation applied after the biological treatment of chemical wastewater containing organic peroxides, the H_2O_2/Fe^{2+} ratio decreases. In the Fenton oxidation of industrial container and drum cleaning wastewater, the H_2O_2/Fe^{2+} molar ratio was found to be 32.9, 19.2, and 13.2 in three wastewater samples, and 91%, 97%, and 95% COD removal achieved (Güneş *et al.* 2018). In the Fenton oxidation of textile wastewater, the optimum H_2O_2/Fe^{2+} ratio was found to be 19.6, and 74% COD removal achieved (GilPavas *et al.* 2017). In the Fenton oxidation of water-based paint wastewater, the H_2O_2/Fe^{2+} ratio was found to be 10.0, and 81% COD removal achieved (Mamadiev *et al.* 2011).

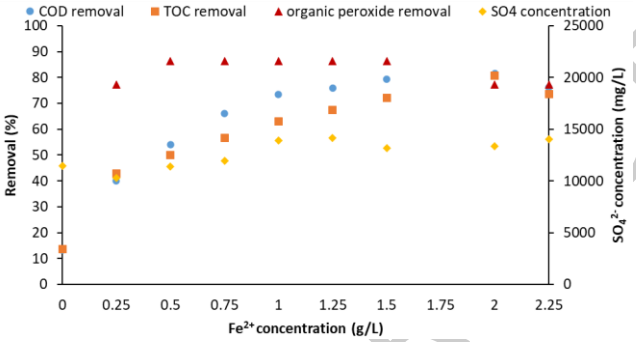


Figure 2. COD, TOC and organic peroxide removal efficiency at different Fe^{2+} concentration (H_2O_2: 17.5 g/L, t: 60 min, pH: 3)

3.1.3. Effect of pH

COD and TOC removals were 69.8% and 67.9% at pH 2 and both of them increased to 81.6% and 80.6%, as the pH value increased to 3, respectively (**Figure 3**). COD and TOC removals decreased above pH 3.5. COD and TOC removals were 69.9% and 69.2% at pH 4. Similar removal was observed at all pH values for organic peroxide removal. However, the SO_4^{2-} concentration increased to 18,238 mg/L at pH 2 and 14,107 mg/L at pH 2.5 due to the use of H_2SO_4 for pH adjustment.

In previous studies, the optimum pH value was determined to be 3 for the treatment of various wastewaters, such as textile, mixed industrial wastewater, pulp and paper wastewater, leather dyeing, and coking wastewater by Fenton oxidation (Enfiyeci and Çifçi 2025; Çalık and Çifçi 2022; Gholami *et al.* 2022; GilPavas *et al.* 2017; Gómez *et al.* 2023; Metin and Çifçi 2023; Verma *et al.* 2020). When the pH value was below 3, stable or unreactive species such as oxonium ions (H_3O^+) and iron complexes such as $[Fe(H_2O)_6]^{2+}$ are formed, which cause slower reactions (Gómez *et al.* 2023; Patil *et al.* 2023; Verma *et al.* 2020). Iron begins to precipitate and •OH consumption occurs during this reaction at high pH values (Gómez *et al.* 2023; Patil *et al.* 2023; Verma *et al.* 2020).

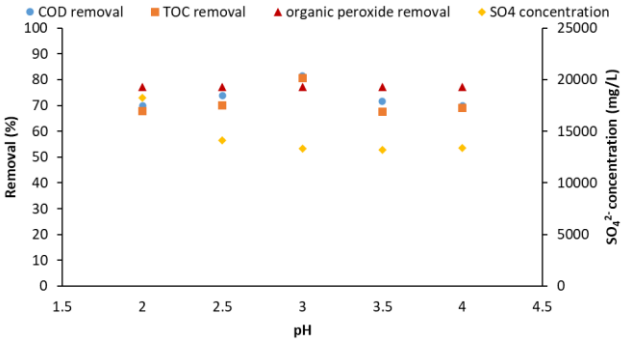


Figure 3. COD, TOC and organic peroxide removal efficiency at different pH value (Fe^{2+} concentration: 2 g/L, H_2O_2: 17.5 g/L, t: 60 min)

3.1.4. Effect of oxidation time

COD, TOC, organic peroxide removal efficiencies obtained at pH 3, 2 g/L Fe^{2+} and 17.5 g/L H_2O_2 concentrations at different oxidation times are given in **Figure 4**. While COD and TOC removal in wastewater continued during 1 h of oxidation, no significant change was observed in wastewater treatment between 1 and 2 h. COD removal was 52.3%, 69.3% and 81.6% and TOC removal was 52.3%, 63.9% and 80.6% at 0.25, 0.5 and 1 h oxidation times, respectively.

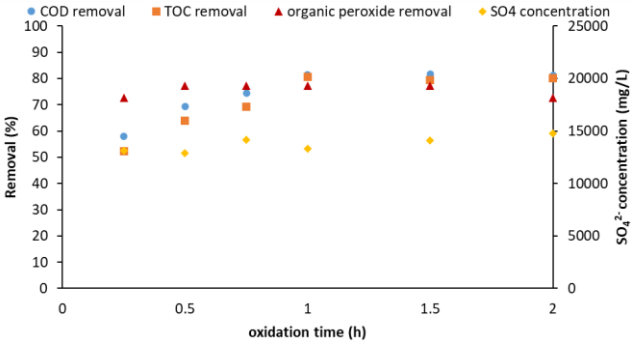


Figure 4. COD, TOC and organic peroxide removal efficiency at different pH value (Fe^{2+} concentration: 2 g/L, H_2O_2: 17.5 g/L, pH: 3)

COD and TOC concentrations and kinetic parameters obtained in the treatment of biologically treated chemical wastewater at pH 3, 2 g/L Fe^{2+} and 17.5 g/L H_2O_2 for different oxidation time were determined and the parameters are given in **Table 2**. 1st order and 2nd order kinetic models were calculated with the formulas given below (Gholami *et al.* 2022).

Table 2. Kinetic parameters obtained from the Fenton oxidation

Parameter	k_1 (h^{-1})	R^2	k_2 ($(mg/L)^{-1}h^{-1}$)	R^2
COD	1.8765	0.9628	0.0009	0.9935
TOC	1.7165	0.9753	0.0037	0.9811

Table 3. Adsorption kinetic model constants using Coconut-AC and Coal-AC

Pollutants		Pseudo 1st order kinetic			Pseudo 2nd order kinetic		
		Coconut-AC					
	q_e (measured) (mg/g)	k_1 (h^{-1})	q_e (calculated) (mg/g)	R^2	k_2 ((g/mg) h^{-1})	q_e (calculated) (mg/g)	R^2
COD	207.71	0.2949	85.37	0.6198	11.52	208.33	0.9991
TOC	45.71	0.3965	11.36	0.4874	132.01	45.87	0.9999
		Coal-AC					
	q_e (measured)	k_1	q_e	R^2	k_2	q_e	R^2
COD	176.00	0.2753	93.05	0.7441	26.41	151.52	0.9992
TOC	42.46	0.6868	15.51	0.5742	102.62	43.29	0.9968

$$\ln\frac{c}{c_0} = -k_1 t \quad (1)$$

$$\frac{1}{c_0} - \frac{1}{c} = -k_2 t \quad (2)$$

Here C_0 represents the initial COD or TOC concentration (mg/L), C represents the COD or TOC concentration at time t. t represents the oxidation time in hours. k_1 (h^{-1}) and k_2 ($(mg/L)^{-1} \cdot h^{-1}$) are the first and second order kinetic constants. As seen in **Table 2**, in the treatment of chemical industry wastewater producing organic peroxides by Fenton oxidation after biological treatment, COD and TOC removal in the Fenton oxidation process is more suitable for the 2nd order kinetic model.

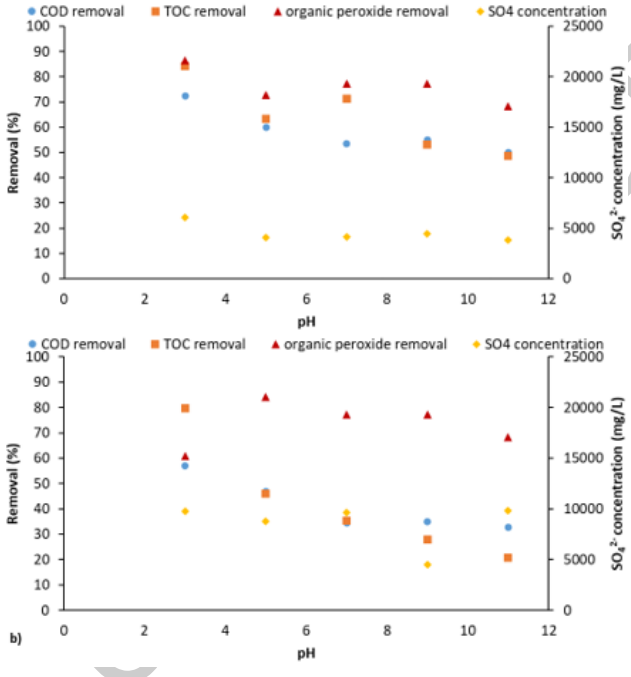


Figure 5. COD, TOC and organic peroxide removal at different pH value a) for Coconut-AC, b) for Coal-AC (Coconut-AC or Coal-AC: 25 g/L, t: 1 h)

3.2. Adsorption process

3.2.1. Effect of pH

The highest removals of COD (72.4%), TOC (84.2%), and organic peroxide (86.4%) were achieved at pH 3, while a decrease in removal efficiencies was observed with increasing pH in adsorption studies using Coconut-AC (**Figure 5**). COD removal was 53.5% and 50.1%, while TOC removal was 71.2% and 48.6% using Coconut-AC at pH 7 and pH 11, respectively. The highest removals of COD (56.9%), TOC (79.8%), and organic peroxide (60.9%) were obtained at pH 3 in adsorption studies using Coal-AC. COD removal was 34.4% and 32.8%, and TOC removal decreased to 35.4% and 20.7% using Coal-AC at pH 7 and pH 11, respectively.

Since hydroxyl ions are abundant in basic conditions, competition occurs between OH^- and negatively charged organic matter (Enfiyeci and Çifçi 2025; Meng *et al.* 2018). In adsorption studies with activated carbon, the highest removal of cork wastewater was observed at pH 3.5, mineral processing wastewater at pH 2, and mixed (textile and chemical industry) industrial wastewater at pH 3 (Ge *et al.* 2018; Meng *et al.* 2018).

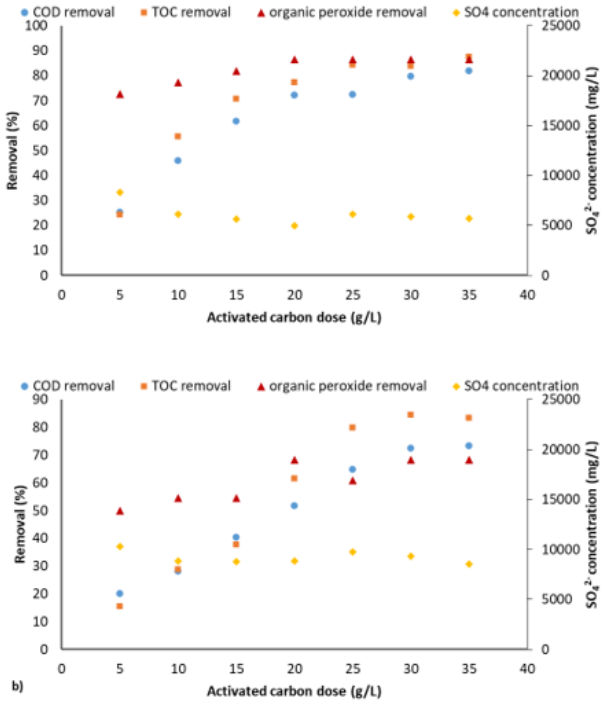


Figure 6. COD, TOC and organic peroxide removal at different activated carbon dose a) Coconut-AC, b) Coal-AC (pH: 3, t: 1 h)

3.2.2. Effect of Coconut-AC or Coal-AC dose

As the Coconut-AC dose increased from 5 to 30 g/L, a decrease in COD and TOC removal was observed, while no significant change was seen at the 35 g/L dose (**Figure 6**). COD removal was 25.3%, 79.8%, and 81.9%, and TOC removal was 24.2%, 83.9%, and 87.3% at 5, 30, and 35 g/L Coconut-AC, respectively. The SO_4^{2-} concentration was 8335 mg/L at 5 g/L Coconut-AC, and it decreased by

21.7%. The SO_4^{2-} concentration was 5901 mg/L, representing a 44.5% decrease at 30 g/L Coconut-AC. Organic peroxide removal increased to 86.4% with increasing Cocounut-AC dose up to 20 g/L, while no significant change was observed in organic peroxide removal after 20 g/L dose.

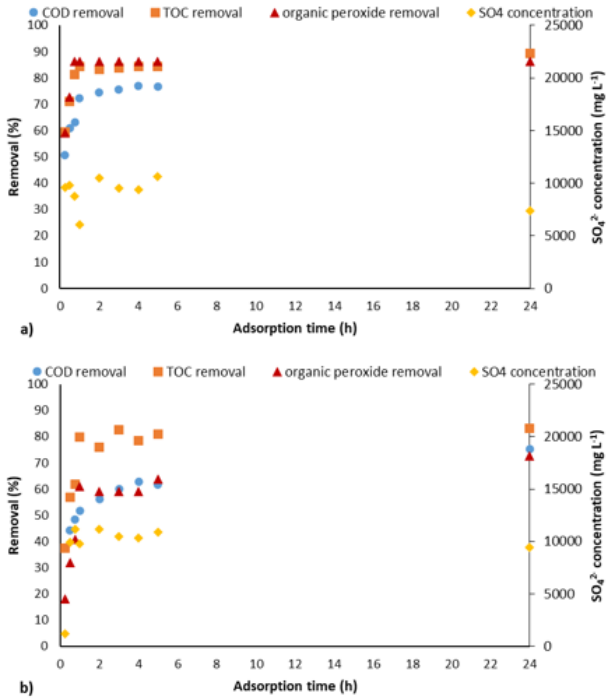


Figure 7. COD, TOC and organic peroxide removal at different adsorption time a) Coconut-AC, b) Coal-AC (pH: 3, Coconut-AC or Coal-AC: 20 g/L)

Similarly, in adsorption studies with Coal-AC, COD and TOC removal increased as the activated carbon dose increased from 5 to 30 g/L, with no significant change in removals observed at 35 g/L. COD and TOC removal were 20.1% and 15.6% at the 5 g/L Coal-AC dose, and 72.5% and 84.4% at the 30 g/L Coal-AC dose, respectively. COD and TOC removal reached 73.5% and 83.3% at the 35 g/L Coal-AC dose, respectively. The SO_4^{2-} concentration was 9335 mg/L, and a decrease of 12.3% was observed. The highest organic peroxide removal, 68.2%, was achieved at the 20 g/L Coal-AC dose, and increasing the Coal-AC dose beyond 20 g/L did not result in any further improvement in organic peroxide removal.

3.2.3. Effect of adsorption time and adsorption kinetic models

COD removal with Coconut-AC was 72.3%, 76.6%, and 88.8% at the end of 1, 5, and 24 h of adsorption, while TOC removal was 84.2%, 84.4%, and 89.4%, respectively (**Figure 7**). COD removal with Coal-AC was 51.8%, 61.7%, and 75.2% at 1, 5, and 24 h of adsorption, while TOC removal was 79.8%, 81.0%, and 83.1%. It was observed that COD and TOC removal in wastewater occurred rapidly within the first hour of adsorption with both activated carbons, after which the treatment rate slowed down.

Using the COD and TOC concentrations obtained at different adsorption times, pseudo 1st order and pseudo 2nd order kinetic models were applied according to the formulas found in the literature (Wang and Guo 2020). It was found that the pseudo 2nd order kinetic model better describes the adsorption process for both activated carbons (**Table 3**). This suggests that the rate-limiting step in the adsorption of biologically treated chemical industry wastewater from organic peroxide production with Coconut-AC and Coal-AC is surface adsorption, including chemical adsorption (El-Naas *et al.* 2010). Additionally, adsorption studies on dairy wastewater, biologically treated papermaking wastewater, and refinery wastewater with activated carbon have also shown a better fit for the pseudo 2nd order kinetic model (El-Naas *et al.* 2010; Feng *et al.* 2020; Kushwaha *et al.* 2010). The q_e values calculated according to the pseudo 2nd order kinetic model were 208.3 mg/g for COD and 45.9 mg/g for TOC with Coconut-AC, and 151.5 mg/g for COD and 43.3 mg/g for TOC with Coal-AC.

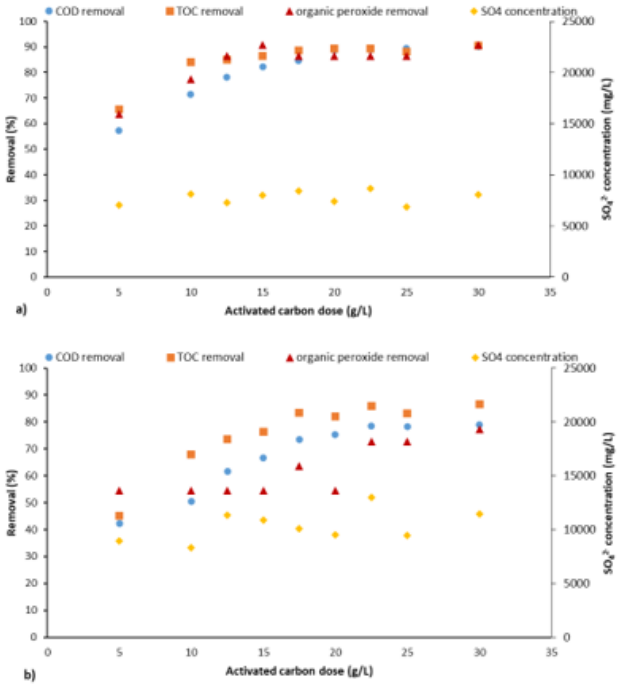


Figure 8. COD, TOC and organic peroxide removal at different activated carbon dose a) Coconut-AC, b) Coal-AC (pH: 3, t: 24 h)

3.2.4. Adsorption isotherm models

Adsorption isotherms are important to determine the equilibrium distribution and interaction between the pollutants and the adsorbent in wastewater (Al-Qodah *et al.* 2023). To establish the Langmuir and Freundlich adsorption isotherm models, adsorption was carried out with different doses of Coconut-AC or Coal-AC for 24 h, and the obtained COD, TOC, and organic peroxide removal efficiencies are shown in **Figure 8**. COD and TOC removal increased up to a 20 g/L activated carbon dose, and no significant change observed at 20 and 30 g/L doses using Coconut-AC. COD removal was 57.2%, 71.6%, 88.8%, and 90.2% and TOC removal was 65.6%, 84.0%, 89.4%, and 90.5% at 5, 10, 20, and 30 g/L Coconut-AC doses, respectively. COD and TOC removal increased up to a 22.5 g/L activated carbon dose using Coal-AC. COD removal was 42.2%, 50.6%, 78.4%, and 79.0 and TOC removal was 45.0%, 67.9%, 85.8%, and 86.7% % at 5, 10, 22.5, and 30 g/L Coal-AC doses. Adsorption isotherms were

constructed using the results from 24 h adsorption at various activated carbon doses.

Langmuir and Freundlich adsorption isotherms were calculated according to the literature (Adedeji *et al.* 2023). When comparing the Langmuir and Freundlich isotherm models, it was found that the adsorption of biologically treated chemical industry wastewater produced with organic peroxide was more suitable for the Freundlich isotherm model with both Coconut-AC and Coal-AC (**Table 4**). This indicates that COD and TOC adsorption occurs on heterogeneous surfaces in both Coconut-AC and Coal-AC adsorption (Adedeji *et al.* 2023).

In the Freundlich isotherm, when 1/n is less than 1, it indicates that the adsorption is favorable (Boubaker and Ridha 2021). It has been observed that the adsorption of paper industry wastewater with activated carbon and the adsorption of biologically treated papermaking wastewater with magnetic activated carbon are also more suitable for the Freundlich isotherm model (Boubaker and Ridha 2021; Feng *et al.* 2020).

Table 4. Adsorption isotherm model constants using Coconut-AC and Coal-AC

Pollutants	**Langmuir isotherm**				**Freundlich isotherm**	
	Coconut-AC					
	q_{max}	K_L	R^2	1/n	KF	R^2
	(mg/g)	(L/mg)			((mg/g)(L/g)n)	
COD	1428.6	0.0003	0.6119	0.775	1.393	0.9561
TOC	1250	0.0003	0.0155	1.102	0.241	0.8523
	Coal-AC					
	q_{max}	K_L	R^2	1/n	K_F	R^2
COD	1250	0.0001	0.2018	0.824	0.495	0.8596
TOC	232.6	0.0012	0.5983	0.750	0.850	0.8950

Table 5. Cost analysis of biologically treated chemical industry wastewater producing organic peroxides using Fenton and adsorption process

COD			**Cost ($/m³)**	**Cost per kg COD removed ($)**
Inlet (mg/L)	**Outlet (mg/L)**	**Removal (%)**		
Fenton (pH: 3, Fe^{2+}: 2 g/L, H_2O_2: 17.5 g/L, t: 1 h)				
4680	863	81.6	15.77	4.13
Adsorption (Coconut-AC) (pH: 3, Coconut-AC: 35 g/L, t: 1 h)				
4680	846	81.9	15.87	4.14
Adsorption (Coconut-AC) (pH: 3, Coconut-AC: 20 g/L, t: 24 h)				
4680	526	88.8	11.90	2.86
Adsorption (Coal-AC) (pH: 3, Coal-AC: 35 g/L, t: 1 h)				
4680	1241	73.5	15.87	4.61
Adsorption (Coal-AC) (pH: 3, Coal-AC: 20 g/L, t: 24 h)				
4680	1160	75.2	11.90	3.38

3.3. Cost analysis

The treatment performances and cost analyses of chemical industry wastewater using Fenton oxidation and adsorption processes are provided in **Table 5**. For the cost analysis, the values given in the literature for the costs of $FeSO_4$ ($0.47 kg^{-1}) and H_2O_2 ($0.64 kg^{-1}) used in Fenton oxidation, as well as activated carbon ($0.45 kg^{-1}) used in the adsorption process (Metin and Çifçi 2023; Mukherjee *et al.* 2022; Sayın *et al.* 2022). The current electricity cost in Turkey is $0.127 per kWh (Enfiyeci and Çifçi 2025).

In Fenton oxidation, COD decreased from 4680 to 863 mg/L at pH 3, with 2 g/L Fe^{2+} and 17.5 g/L H_2O_2 concentrations, resulting in an 81.6% COD removal. The treatment cost was $15.77 m^{-3}, with the cost per kg of COD removed calculated at $4.13.

In the adsorption using Coconut-AC, 81.9% COD removal was achieved after 1 h of adsorption at pH 3 and a 35 g/L Coconut-AC dose. The treatment cost was $15.87 m^{-3}, with the cost per kg of COD removed being $4.14. When 20 g/L Coconut-AC was used at pH 3 for 24 h of adsorption, COD removal increased to 88.8%, and the cost decreased to $11.90 m^{-3}, with the cost per kg of COD removed dropping to $2.86.

The lowest COD removal and highest cost were observed in the adsorption using Coal-AC. In the adsorption with Coal-AC, 73.5% of COD removal was achieved after 1 h of adsorption at pH 3 with a 35 g/L Coal-AC dose, resulting in a treatment cost of $15.87 m^{-3}, with the cost per kg of COD removed being $4.61. COD removal reached 75.2% at pH 3, 20 g/L Coal-AC dose and 24 h of adsorption, and the cost decreased to $11.90 m^{-3}, with the cost per kg of COD removed at $3.38.

4. Conclusions

In this study, the treatment of biologically treated chemical industry wastewater producing organic peroxides was investigated using Fenton oxidation and adsorption processes. The optimal conditions for Fenton oxidation was obtained at pH 3, with 2 g/L Fe^{2+} and 17.5

g/L H_2O_2 for 1 h of treatment and COD, TOC, and organic peroxide removals were obtained as 81.6%, 80.6%, and 77.3%, respectively. The COD and TOC removal by Fenton oxidation was found to be more suitable for pseudo 2nd order kinetics.

In the adsorption process, 88.8% COD, 88.9% TOC, and 86.4% organic peroxide removal were achieved at pH 3 and 20 g/L activated carbon dose after 24 h using Coconut-AC. In these conditions, 75.2% COD, 81.9% TOC, and 54.5% organic peroxide removal were observed using Coal-AC. The adsorption kinetics for both Coconut-AC and Coal-AC more suitable for the pseudo 2nd order kinetic model, while the adsorption isotherms were more fitting for the Freundlich model.

The cost was \$15.77 m^{-3} in Fenton oxidation under optimal conditions, compared to \$15.87 m^{-3} for the adsorption process with either Coconut-AC or Coal-AC. The cost per kg of COD removed was calculated as \$4.13 in Fenton oxidation, while it was \$2.86 using Coconut-AC and \$3.38 using Coal-AC.

In conclusion, although the cost per m^3 of wastewater treated was similar for all methods, the adsorption process using Coconut-AC provided superior treatment performance compared to Fenton oxidation and Coal-AC. Moreover, the lowest cost per kg of COD removed was achieved with Coconut-AC, and SO_4^{2-} removal was also observed during its adsorption process. The SO_4^2 concentration (10640 mg/L) in wastewater generated in the chemical industry, where organic peroxides are produced, is high. Therefore, it is important to ensure SO_4^{2-} removal in addition to organic matter removal. While SO_4^{2-} removal cannot be achieved in the Fenton oxidation process, the use of coconut-AC in the adsorption process would be advantageous in this process. Future studies should focus on optimizing the regeneration and reuse of activated carbons to increase economic and environmental sustainability. Additionally, combining Fenton oxidation with adsorption in a hybrid treatment system could be investigated to further improve organic and sulfate removal efficiencies.

Acknowledgements

This study was supported by AKPA chemistry. Adress: İstiklal-Kurtpınar OSM Atatürk Street No: 23/159700, Muratlı-Tekirdağ, Turkey.

Data Availability

Data are available upon request.

Conflict of Interest

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.

References

Adedeji O.M., Jahan K. (2023). Removal of pollutants from aqueous product of Co-hydrothermal liquefaction: Adsorption and isotherm studies. *Chemosphere*, **321**, 138165. https://doi.org/10.1016/j.chemosphere.2023.138165

Al-Qodah Z., Dweiri R., Khader M., Al-Sabbagh S., Al-Shannag M., Qasrawi S., Al-Halawani M. (2023). Processing and characterization of magnetic composites of activated carbon, fly ash, and beach sand as adsorbents for Cr(VI) removal. *Case Stud Chem Environ Eng*, **7**, 100333. https://doi.org/10.1016/j.cscee.2023.100333

Al-Qodah Z., Al-Shannag M., Hudaib B., Bani-Salameh W. (2024). Enhancement of dairy wastewater treatment efficiency in batch chemical-assisted solar-powered electrocoagulation-adsorption system. *Case Stud Chem Environ Eng*, **9**, 100760. https://doi.org/10.1016/j.cscee.2024.100760

Al-Qodah Z., Al-Shannag M., Hudaib B., Bani-Salameh W., Shawaqfeh A.T., Assirey E. (2025). Synergy and enhanced performance of combined continuous treatment process of pre-chemical coagulation (CC), solar-powered electrocoagulation (SAEC), and post-adsorption for dairy wastewater. *Case Stud Chem Environ Eng*, **11**, 101183. https://doi.org/10.1016/j.cscee.2025.101183

Babuponnusami A., Muthukumar K. (2014). A review on Fenton and improvements to the Fenton process for wastewater treatment. *J Environ Chem Eng*, **2**, 557-572. http://dx.doi.org/10.1016/j.jece.2013.10.011

Boubaker F., Ridha B.B. (2021). Esparto paper industry wastewater treatment by adsorption onto powdered activated carbon. *Inter J Environ Anal Chem*, **101**(15), 2817-2834. https://doi.org/10.1080/03067319.2020.1711897

Çalık Ç., Çifçi D.İ. (2022). Comparison of kinetics and costs of Fenton and photo-Fenton processes used for the treatment of a textile industry wastewater. *J Environ Manag*, **304**, 114234. https://doi.org/10.1016/j.jenvman.2021.114234

Dinçer A.R., Çifçi D.İ., Darcan Cinkaya D., Dülger E., Karaca F. (2021). Treatment of organic peroxide containing wastewater and water recovery by fenton-adsorption and fenton-nanofiltration processes. *J Environ Manag*, **299**, 113557. https://doi.org/10.1016/j.jenvman.2021.113557

Enfiyeci A., Çifçi D.İ. (2025). Comparison of coagulation–Fenton oxidation and coagulation–adsorption processes in textile and chemical industry mixed wastewater. *J Chem Technol Biotechnol*, **100**, 466-476. https://doi.org/10.1002/jctb.7789

Ge X., Wu Z., Cravotto G., Manzoli M., Cintas P., Wu Z. (2018). Cork wastewater purification in a cooperative flocculation/adsorption process with microwave-regenerated activated carbon. *J Hazard Mater*, **360**, 412-419. https://doi.org/10.1016/j.jhazmat.2018.08.022

Gholami M., Shomali A., Souraki B.A., Pendashteh A. (2022). Advanced numerical kinetic model for predicting COD removal and optimisation of pulp and paper wastewater treatment by Fenton process. *Inter J Environ Anal Chem*, **102**(12), 2729-2752. https://doi.org/10.1080/03067319.2020.1759565

GilPavas E., Dobrosz-Gómez I., Gómez-García M.Á. (2017). Coagulation-flocculation sequential with Fenton or Photo-Fenton processes as an alternative for the industrial textile wastewater treatment. *J Environ Manag*, **191**, 189-197. http://dx.doi.org/10.1016/j.jenvman.2017.01.015

Gómez C.A., Gómez-García M.-Á., Dobrosz-Gómez I. (2023). Analysis of the capacity of the Fenton process for the treatment of polluted wastewater from the leather dyeing

industry. *Sci World J*, 2023, 4724606. https://doi.org/10.1155/2023/4724606

Güneş E., Çifçi D.İ., Çelik S.Ö. (2018). Comparison of Fenton process and adsorption method for treatment of industrial container and drum cleaning industry wastewater. *Environ Technol*, **39**(7), 824-830. https://doi.org/10.1080/09593330.2017.1311948

El-Naas M.H., Al-Zuhair S., Alhaija M.A. (2010). Reduction of COD in refinery wastewater through adsorption on date-pit activated carbon. *J Hazard Mater*, **173**, 750-757. https://doi.org/10.1016/j.jhazmat.2009.09.002

Feng Z., Chena H., Li H., Yuan R., Wang F., Chen Z., Zhoua B. (2020). Preparation, characterization, and application of magnetic activated carbon for treatment of biologically treated papermaking wastewater. *Sci Total Environ*, **713**, 136423. https://doi.org/10.1016/j.scitotenv.2019.136423

Jorge N., Teixeira A.R., Marchão L., Lucas M.S., Peres J.A. (2022). Application of combined coagulation–flocculation–decantation/photo-Fenton/adsorption process for winery wastewater treatment. *Eng Proc*, **19**, 22. https://doi.org/10.3390/ECP2022-12653

Kushwaha J.P., Srivastava V.C., Mall I.D. (2010). Treatment of dairy wastewater by commercial activated carbon and bagasse fly ash: Parametric, kinetic and equilibrium modelling, disposal studies. *Bioresour Technol*, **101**, 3474-3483. https://doi.org/10.1016/j.biortech.2010.01.002

Liu S.H., Wang Y.R., Cao C.R., Cheng Y.-C. (2021). Systematic process hazard assessment of three kinds of solid organic peroxides with kinetic analysis and heat transfer equilibrium. *J Therm Anal Calorim*, **145**, 451-466. https://doi.org/10.1007/s10973-020-09732-6

Machado F., Teixeira A.C.S.C., Ruotolo L.A.M. (2023). Critical review of Fenton and photo-Fenton wastewater treatment processes over the last two decades. *Inter J Environ Sci Technol*, **20**, 13995-14032. https://doi.org/10.1007/s13762-023-05015-3

Maruthai S., Rajendran S., Selvanarayanan R., Gowri S. (2025). Wastewater recycling integration with IoT sensor vision for real-time monitoring and transforming polluted ponds into clean ponds using HG-RNN. *Global NEST Journal*, **27**(4), 06758. https://doi.org/10.30955/gnj.06758

Mamadiev M., Yilmaz G. (2011). Treatment and recycling facilities of highly polluted water-based paint wastewater. *Desalin Water Treat*, **26**(1-3), 66-71. https://doi.org/10.5004/dwt.2011.2111

Meng X., Wu J., Kang J., Gao J., Liu R., Gao Y., Wang R., Fan R., Khoso S.A., Sun W., Hu Y. (2018). Comparison of the reduction of chemical oxygen demand in wastewater from mineral processing using the coagulation–flocculation, adsorption and Fenton processes. *Miner Eng*, **128**, 275-283. https://doi.org/10.1016/j.mineng.2018.09.009

Metin S., Çifçi D.İ. (2023). Chemical industry wastewater treatment by coagulation combined with Fenton and photo-Fenton processes. *J Chem Technol Biotechnol*, **98**(5), 1158-1165. https://doi.org/10.1002/jctb.7321

Mukherjee A., Okolie J.A., Niu C., Dalai A.K. (2022). Techno-Economic analysis of activated carbon production from spent coffee grounds: Comparative evaluation of different production routes. *Energy Convers Manag: X*, **14**, 100218. https://doi.org/10.1016/j.ecmx.2022.100218

Patil Y., Lakshmi Priya B.S., Sonawane S.H., Shyam P. (2023). Comparative performance of Fenton and cavitation assisted Fenton techniques for effective treatment of greywater. *J Environ Chem Eng*, **11**, 110667. https://doi.org/10.1016/j.jece.2023.110667

Ribeiro J.P., Nunes M.I. (2021). Recent trends and developments in Fenton processes for industrial wastewater treatment - A critical review. *Environ Res*, **197**, 110957. https://doi.org/10.1016/j.envres.2021.110957

Sayın F.E., Karatas O., Özbay İ., Gengec E., Khataee A. (2022). Treatment of real printing and packaging wastewater by combination of coagulation with Fenton and photo-Fenton processes. *Chemosphere*, **306**, 135539. https://doi.org/10.1016/j.chemosphere.2022.135539

Selvanarayanan R., Rajendran S., Pappa C. K. and Thomas B. (2024). Wastewater recycling to enhance environmental quality using fuzzy embedded with rnn-iot for sustainable coffee farming. *Global NEST Journal*, **26**(8), 06346. https://doi.org/10.30955/gnj.006346

Toor U.A., Duong T.T., Ko S.-Y., Hussain F., Oh S.-E. (2021). Optimization of Fenton process for removing TOC and color from swine wastewater using response surface method (RSM). *J Environ Manag*, **279**, 111625. https://doi.org/10.1016/j.jenvman.2020.111625

Torrades F., García-Montaño J. (2014). Using central composite experimental design to optimize the degradation of real dye wastewater by Fenton and photo-Fenton reactions. *Dyes Pigm*, **100**, 184-189. http://dx.doi.org/10.1016/j.dyepig.2013.09.004

Verma V., Chaudhari P.K. (2020). Optimization of multiple parameters for treatment of coking wastewater using Fenton oxidation. *Arabian J Chem*, **13**, 5084-5095. https://doi.org/10.1016/j.arabjc.2020.02.008

Wang J., Guo X. (2020). Adsorption kinetic models: Physical meanings, applications, and solving methods. *J Hazard Mater*, **390**, 122156. https://doi.org/10.1016/j.jhazmat.2020.122156

Yan Z., Ma H., Yang M. (2024a). Preparation and performance of catalyst for organic peroxide wastewater treatment. *Heliyon*, **10**(21), e39147. https://doi.org/10.1016/j.heliyon.2024.e39147

Yan Z., Xie S., Yang M. (2024b) Effect and mechanism of iron-carbon micro-electrolysis pretreatment of organic peroxide production wastewater. *Environ Sci Pollut Res*, **31**, 11886-11897. https://doi.org/10.1007/s11356-023-31057-8

Zhu N., Yao H., Zhang X., Bao H. (2024). Metal-catalyzed asymmetric reactions enabled by organic peroxides. *Chem Soc Rev*, **53**, 2326-2349. https://doi.org/10.1039/D3CS00735A