



Enhanced degradation of textile wastewater by activated carbon–assisted Fenton oxidation: economic analysis and ANN-based optimization

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Abstract

This study aims to improve the removal organic contaminants from biologically pre-treated textile wastewater using activated carbon (AC)–assisted Fenton oxidation. The optimum conditions for Fenton process were found to be pH 3.0, 2 mM Fe²⁺ and 10 mM H₂O₂. Reed activated carbon (RAC), produced from *Phragmites australis*, and commercial activated carbon (CAC) were used to enhance Fenton process under optimized conditions. Different doses and reaction times of RAC and CAC were tested to improve chemical oxygen demand (COD) and colour removal. The results showed that COD removal was 64% within the first 10 min, in the Fenton process. When RAC and CAC were added (2 g/L), COD removal increased to 83% and 88%, respectively. Colour removal was nearly complete at 436, 525, and 620 nm for both AC types. The total operational costs for textile wastewater treatment were calculated as 0.660 USD/m³ for Fenton process, 4.160 USD/m³ for CAC-assisted Fenton process, and 2.950 USD/m³ for RAC-assisted Fenton process. Additionally, artificial neural networks (ANNs) results demonstrated the success of the RAC and CAC-assisted Fenton systems, with determination coefficients (R^2) of 0.9503 and 0.9440, respectively. In this context, high R^2 values indicate that the model predicts the results of the RAC and CAC-assisted Fenton systems well and demonstrates the high efficiency of these systems.

Keywords Activated carbon · Artificial neural network · Fenton oxidation · Textile wastewater

1 Introduction

As industrialization progresses rapidly, environmental issues are becoming more severe, resulting in the presence of multiple pollutants in aquatic environments, altering the physical and chemical properties of water, causing substantial damage to ecosystems and threatening aquatic life [1, 2]. The textile production process is one of the most water-consuming sectors and wet processes used in the textile industry consume large amounts of water. Wastewater generated in the desizing, bleaching, dyeing, printing and washing processes can be multicoloured and resistant to biodegradation [3]. Physicochemical and biological processes are commonly applied to treat textile wastewater. Coagulation-flocculation

is a widely used physicochemical method, but it merely transfers pollutants from the water phase to the solid phase [4]. Biological methods degrade dyes through metabolic pathways or adsorption by living or dead biomass, such as bacteria, fungi, yeasts, algae, and plants. These processes are generally low-cost, eco-friendly, and applicable to a wide range of dyes [5]. However, biological treatments are ineffective in decontaminating textile wastewater due to the presence of non-biodegradable pollutants and toxic substances inhibiting biodegradation, such as azo dyes, phenols, and polychlorinated biphenyls (PCBs). Therefore, combined treatment methods are needed to improve the treated water quality and recycle wastewater [6].

Advanced oxidation processes (AOPs) involve the formation of highly reactive oxygen species, particularly hydroxyl radicals (•OH), which can fully or partially oxidize most organic pollutants [7–11]. The •OH is extremely reactive, has a high standard oxidation potential ($E^0 = 2.81$ V), and reacts non-selectively with most molecules [4, 10, 12, 13]. Treating pollutants through oxidation offers several advantages, including efficient degradation of persistent organic

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contaminants, formation of environmentally harmless products, and integration with renewable energy systems [14, 15]. AOPs have become critical technologies for the degradation of recalcitrant organic pollutants [13]. The oxidation method, especially when combined with adsorbents/catalysts, improves the breakdown of organic pollutants, resulting in a higher pollutant removal efficiency [15]. Additionally, AOPs can be combined with biological treatment processes either as pre-treatment or post-treatment steps in order to improve treatment efficiency. AOP pre-treatment is particularly beneficial for wastewaters with low biodegradability, as it converts recalcitrant pollutants into more easily degradable compounds, facilitating subsequent microbial degradation. Furthermore, AOPs can also be used as a post-treatment step to remove persistent contaminants and polish wastewater after biodegradation. The main advantage of this combination is that no additional chemicals or electrical energy are required for biodegradable organics [6].

Fenton oxidation is one of the most widely applied AOPs due to its simplicity, fast reaction rate, high efficiency, and non-toxicity [16, 17]. The general mechanism for the production of $\bullet\text{OH}$ in the Fenton process involves a series of cyclic reactions, where Fe^{2+} or Fe^{3+} ions act as catalysts to decompose H_2O_2 [18–21]. $\bullet\text{OH}$ is produced by the decomposition of H_2O_2 in the presence of various catalysts, both homogeneous (e.g. Fenton's reagent) and heterogeneous (e.g. supported metals, metal oxides, graphite, activated carbon) [22]. Fenton-based treatments are very effective in removing a wide range of contaminants, although their performance depends largely on the composition of the water matrix [23]. In the Fenton process, many factors such as initial pH, H_2O_2 dose, and catalyst dose affect the formation of active species and the degradation of pollutants [24].

Integrating Fenton oxidation and adsorption improves the removal of organic contaminants and overall treatment efficiency. Several mechanisms have been proposed to explain the increase in treatment performance by combining Fenton and adsorption processes. The adsorbents can effectively remove organic pollutants resistant to oxidation, resulting in increased overall efficiency of the treatment process. The reaction intermediates formed during AOPs, which may resist further oxidation, is facilitated by adsorbents, leading to greater mineralization. The catalytic role of carbonaceous and transition metal-based materials promotes the formation of reactive oxygen species (ROS) and accelerates the decomposition of resistant pollutants [25, 26]. The generated ROS can increase the adsorption capacity of the adsorbents by producing additional adsorption sites and regenerate the adsorbents by degrading the adsorbed pollutants [30]. Additionally, carbon-based materials act as catalysts and improve the efficiency of the Fenton process by enabling electron transfer from H_2O_2 to Fe^{3+} , facilitating the $\text{Fe}^{3+}/\text{Fe}^{2+}$ cycle and accelerating the formation of $\bullet\text{OH}$ [25].

Activated carbon is one of the most effective catalytic supports in wastewater treatment due to its large specific surface area, high chemical inertness, high chemical inertness, and good thermal stability [25]. Recent studies have shown that surface modifications, especially N,S codoping, significantly enhance the catalytic performance of activated carbons [27]. Integration of surface-modified activated carbons with advanced oxidation processes provides an effective approach for the removal of non-biodegradable pollutants by enhancing the removal of persistent organic pollutants [28].

Agricultural biomass-derived activated carbon, produced from agricultural waste products such as crop residues, husks, straws, and fruit and vegetable waste, offers a renewable and eco-friendly solution for the disposal of these materials while also demonstrating significant potential in environmental applications [29–33]. Reed (*Phragmites australis*) is one of the most widely distributed plant species in the world, growing mostly in swamps and marshes. It is considered a promising source for biofuel production through pyrolysis due to its rapid growth characteristics, high biomass yield, resistance to extreme ecological conditions, and low nutrient and water requirements. In addition, reed is used as a low-cost adsorbent for various water pollutants. It has a large number of hydroxyl groups on its surface, which facilitate surface modification, making it an ideal precursor for activated carbon and biochar production [34]. *Phragmites australis* has a great potential for the production of high-quality activated carbons (ACs) with its unique chemical composition. Several studies reported that ACs produced from *Phragmites australis* exhibited excellent performance for the treatment of dyes and heavy metals and has a potential in addressing water pollution challenges [35–42].

This study aimed to enhance the removal of organic contaminants from biologically pre-treated textile wastewater and improve water quality by activated carbon-assisted Fenton oxidation. Reed activated carbon (RAC) was produced using reed plant (*Phragmites australis*), a cost-effective raw material, and its performance was compared with commercial activated carbon (CAC). The optimal pH, Fe^{2+} , and H_2O_2 doses were determined for the Fenton process; then, the treatment efficiency of AC-assisted Fenton oxidation was evaluated using different doses and reaction times for both RAC and CAC. Chemical oxygen demand (COD) and colour parameters were monitored to evaluate the effectiveness of the processes in removing dyes and organic pollutants. Additionally, economic analysis was conducted to evaluate the suitability of oxidation systems for applications. The experimental results were modeled using artificial neural network (ANN) tailored to improve prediction accuracy for the RAC and CAC-assisted Fenton systems.

2 Materials and methods

2.1 Textile wastewater characterization

Real textile wastewater samples were obtained from a textile factory located in Tekirdağ, Türkiye. The wastewater undergoes onsite treatment using a combination of physical and biological processes. Samples were taken from the outlet of the biological treatment process and filtered through a sand filter upon reaching the laboratory. The pH of the wastewater was adjusted to 3.0 with 6N H₂SO₄ and stored in the refrigerator at +4 °C for up to two weeks. Before the experiments, the samples were brought to room temperature (20–25 °C). The pH reduction was carried out to prevent the degradation of organics during storage [43]. Table 1 demonstrates the range of variation and mean values of wastewater parameters for samples collected during the study [44].

Table 1 Characteristics of textile wastewater

Parameter	Unit	Range
pH	-	7.4–8.4
EC	μS/cm	1602–2847
COD	mg/L	91–98
TOC	mg/L	23–32
Colour		
DFZ _{436nm}		4.25–8.21
DFZ _{525nm}	m ⁻¹	3.00–5.09
DFZ _{620nm}		1.84–3.445
Chloride	mg/L	93–633
Sulphate	mg/L	35–418
Sodium	mg/L	265–627
Calcium	mg/L	6–40
Magnesium	mg/L	4–63

2.2 Reagents and chemicals

FeSO₄·7H₂O, H₂O₂ (35%), MnO₂, NaOH, and H₂SO₄ (95–97%) used for Fenton and AC-assisted Fenton experiments were obtained from Merck, while NaOH was sourced from Sigma-Aldrich. The commercial activated carbon (CAC) with CAS number 7440–44–0 was obtained from Merck.

2.3 Material preparation and characterization

2.3.1 Preparation of activated carbon from the reed plant

The dried reed plant (*Phragmites australis*) was ground into small pieces. Afterwards, fragments between 0.425 and 0.600 mm were sieved and separated. A 1:3 weight ratio of reed plant to NaOH was mixed and carbonized at 600 °C for 1 h in a heat-resistant steel reactor. The reactor was removed from the furnace and allowed to cool. The resulting carbon was taken from the reactor and placed on a filter set on a Büchner funnel. It was then washed with distilled water under vacuum until the pH was neutralized. Finally, the carbon was oven-dried at 105 °C for 2 h. The preparation process flow diagram for RAC is shown in Fig. 1.

2.3.2 Characterization of activated carbons

Scanning electron microscopy (SEM) imaging was conducted on an Elementar Unicube microscope to characterize the surface morphology of CAC and RAC. The surface elemental composition of the activated carbons was examined using the Xplore 30 energy-dispersive X-ray spectroscopy (EDX) system.

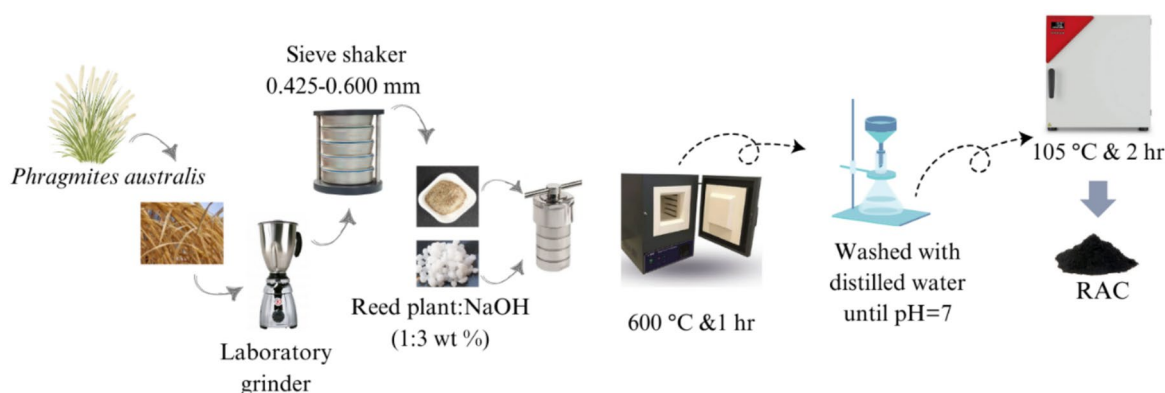


Fig. 1 Flow diagram for RAC preparation

2.4 Experimental procedures

2.4.1 Fenton oxidation and AC-assisted Fenton oxidation

Experiments were performed utilizing a jar testing apparatus, where a 100-mL sample of textile wastewater was placed into beakers with a capacity of 500 mL. The pH of the wastewater was adjusted to the desired level using H_2SO_4 (6N). After adjusting the pH, the necessary amount of $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ solution was added as the iron source (Fe^{2+}), and the reaction was initiated by adding H_2O_2 . The AC-assisted Fenton process followed similar procedures to the classical Fenton process, with the inclusion of activated carbon in the samples. After the completion of the reaction time for all experiments, lime was added to raise the pH and facilitate the precipitation of iron as solid $\text{Fe}(\text{OH})_3$ to terminate the reaction. In order to separate the precipitated solids from the sample, centrifugation was performed at 9000 rpm for 10 min using a Sigma 3-16P brand centrifuge. MnO_2 was then added to the supernatant phase to eliminate any remaining H_2O_2 . Finally, the samples underwent filtration using a 0.45- μm syringe filter, followed by analysis for COD, TOC, and colour. All the experiments were repeated at least twice for each condition and results were averaged. Colour measurements were repeated at least three times in the same samples. For COD measurement, three replicates were prepared and the results were averaged. TOC measurements were also repeated three times and the average of the results were employed.

2.5 Analytical methods

The electrical conductivity and pH were measured using a pH-EC meter (ThermoScientific-Orion Star A215). For COD analysis, a Hach Lange DR-6000 spectrophotometer was employed, utilizing the closed reflux colourimetric method (following APHA Standard Methods 5220 D). The colour of the wastewater before and after treatment was determined using the DFZ method. The standards of European Norms EN ISO 7887 were used as a basis, and the DFZ parameter was measured using a HACH Lange DR 6000 spectrophotometer. The absorbance values measured at three wavelengths (436, 525, and 620 nm) were converted to 'Indices of Transparency' ($\text{DFZ} = \text{Durchsichtsfarbzahl}$). The DFZ calculation (Eq. 1), the colour (Eq. 2), and COD removal percentage (Eq. 3) were calculated using the following equations:

$$\text{DFZ} = 100 \frac{E_\lambda}{d} \quad (1)$$

where E_λ is the absorbance (at a known wavelength) and d is the thickness of the cell in centimetres.

$$\text{Colour Removal (\%)} = \frac{(C_i - C_f)}{C_i} \times 100 \quad (2)$$

$$\text{COD Removal (\%)} = \frac{(\text{COD}_i - \text{COD}_f)}{\text{COD}_i} \times 100 \quad (3)$$

C_i and C_f refer to the initial and final colour of the wastewater, respectively, while COD_i and COD_f represent its initial and final COD.

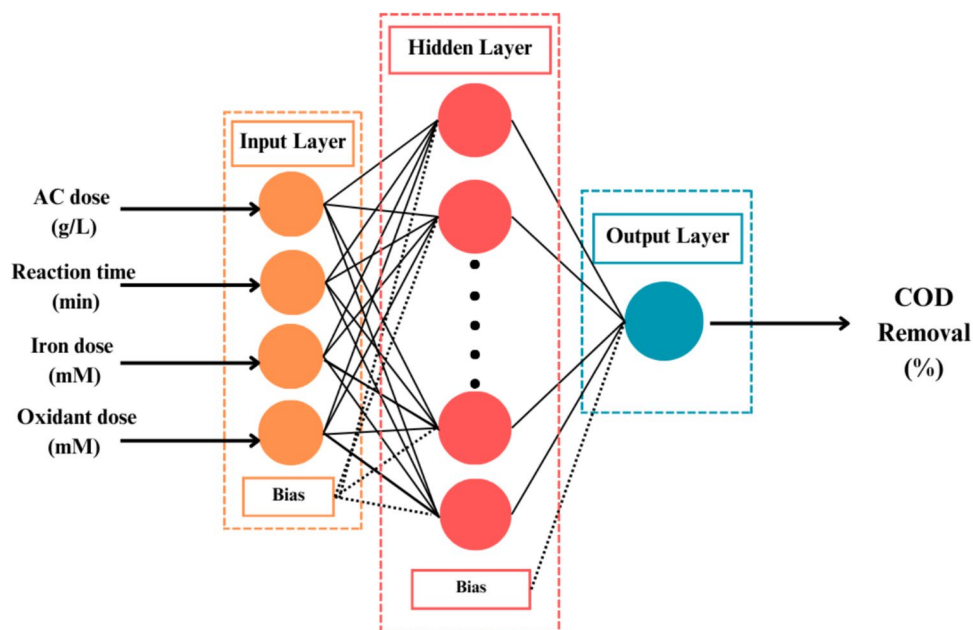
2.6 Artificial neural network modeling

Artificial neural networks (ANNs) have proven highly effective in addressing various environmental engineering challenges [45]. In ANN architectures, individual neurons play a critical role in transmit information between layers via weighted connections. The input layer receives external signals, which are weighted before being propagated to the hidden layers for processing [46]. These layers perform data transformations, applying transfer functions and passing results to subsequent hidden or output layers. This multilayer structure allows ANNs to model and predict complex environmental phenomena effectively [47, 48]. This study aimed to investigate the performance of RAC and CAC-assisted Fenton processes for COD removal from textile wastewater using ANN modeling. MATLAB R 2020b software was used to develop the ANN models. A three-layer ANN architecture with 10 neurons in the hidden layer was implemented, as shown in Fig. 2. The input variables included the activated carbon dose, the reaction time, the iron dose, and the oxidant dose, while the output neuron represented the percentage of COD removal. The Levenberg–Marquardt backpropagation algorithm was used to train the ANN models, utilizing a tangent sigmoid (tansig) activation function in the hidden layers and a linear (purelin) function in the output layers for both RAC and CAC-assisted Fenton processes.

The goodness-of-fit between the ANN-predicted and experimentally observed values was quantified by computing the coefficient of determination (R^2). Model performance evaluation relied on the mean squared error (MSE) metric, aiming to identify the optimal predictive model with the lowest MSE and highest R^2 for each dataset. The calculations for R^2 (Eq. 4) and MSE (Eq. 5) were as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^N (Y_{i,\text{pred}} - Y_{i,\text{exp}})^2}{\sum_{i=1}^N (Y_{i,\text{pred}} - Y_m)^2} \quad (4)$$

Fig. 2 The optimized ANN structure for both RAC and CAC-assisted Fenton systems



$$MSE = \left[\frac{1}{N} \sum_{i=1}^{i=N} (Y_{i,\text{pred}} - Y_{i,\text{exp}})^2 \right]^{1/2} \quad (5)$$

N represents the total number of data points, $Y_{i,\text{pred}}$ represents the i th predicted sample value, $Y_{i,\text{exp}}$ is the i th experimentally observed sample value, and Y_m is the mean of all experimental sample values [49].

3 Results and discussion

3.1 Characterization of activated carbons

3.1.1 SEM, EDX and, BET analyses

The surface morphology of the activated carbons used in the Fenton experiments was observed by scanning electron microscopy (SEM). Data on the surface morphology and elemental composition of the carbons surface was provided by energy-dispersive X-ray spectroscopy (EDX). EDX analyses the elemental composition of a surface by detecting X-ray emissions stimulated by high-energy charged particles or focused X-ray beams applied to the surface. The excitation of an atom's electronic structure produces X-ray emission with a unique energy signature for each element. Therefore, the obtained spectrum can be compared with reference spectra to identify the elements. The elemental analysis, based on SEM and EDX data, reveals that the activated carbons possess a well-developed porous structure. According to the EDX results, RAC contains 83.28% carbon, indicating its high carbon content, while 11.23% oxygen suggests the

presence of surface functional groups. Additionally, it contains 2.65% iron and 0.41% sodium, which may contribute to catalytic activity. In comparison, CAC has a higher carbon content of 97.69%, suggesting a more refined structure with less oxygen. SEM and EDX images of RAC and CAC carbons are provided in Fig. 3a and b, illustrating the differences in surface morphology and elemental composition.

Table 2 presents the textural properties of RAC and CAC. The specific surface area (S_{BET}) of RAC is 1256.170 m²/g, with a large micropore surface area (S_{micro}) of 1006.6 m²/g, and a total pore volume (V_T) of 0.8372 cm³/g. On the other hand, CAC shows lower values, with a S_{BET} of 587.862 m²/g, a S_{micro} of 296.31 m²/g, and a V_T of 0.550 cm³/g. Despite RAC's higher surface area and porosity, CAC demonstrates higher efficiency in experiments for several reasons: CAC's larger pore diameter allows better diffusion and adsorption of larger pollutants, and its surface functional groups and chemical properties can enhance catalytic reactions [50, 51]. Additionally, while RAC's micropores may not always be accessible, CAC's pore structure is more easily reachable, and its reactive surface may remain more stable under operating conditions [50, 52].

Figure 4 a illustrates the relationship between relative pressure and the adsorbed gas volume. As relative pressure increases, the volume of adsorbed gas rises correspondingly. At lower pressures, adsorption occurs rapidly, while at higher pressures, the rate slows down, suggesting that the surface pores are nearing saturation and further adsorption becomes limited. This behaviour is typical of a physical adsorption (physisorption) process. In contrast, Fig. 4b shows a higher adsorption capacity, with a steep increase in adsorption up to a relative pressure of 0.3, indicating a

Fig. 3 SEM and EDX images of **a** CAC and **b** RAC

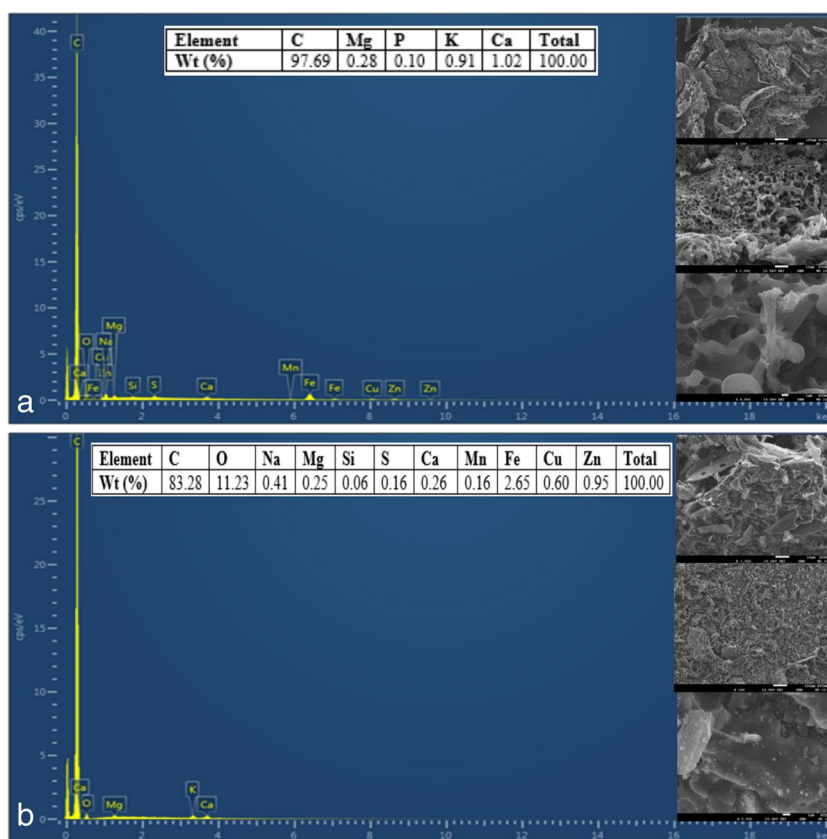


Table 2 Textural characteristics of the RAC and CAC

Material	S_{BET} (m ² /g)	S_{μ} (m ² /g)	S_m (m ² /g)	V_T (cm ³ /g)	V_{μ} (cm ³ /g)	V_m (cm ³ /g)	D_p (nm)
RAC	1256.170	1006.6	249.52	0.8372	0.482	0.3552	2.666
CAC	587.862	296.3	291.551	0.5500	0.143	0.4070	3.745

S_{BET} BET surface area, S_{μ} micropore surface area, S_m mesopore surface area, V_T total pore volume, V_{μ} micropore volume, V_m mesopore volume, D_p average diameter

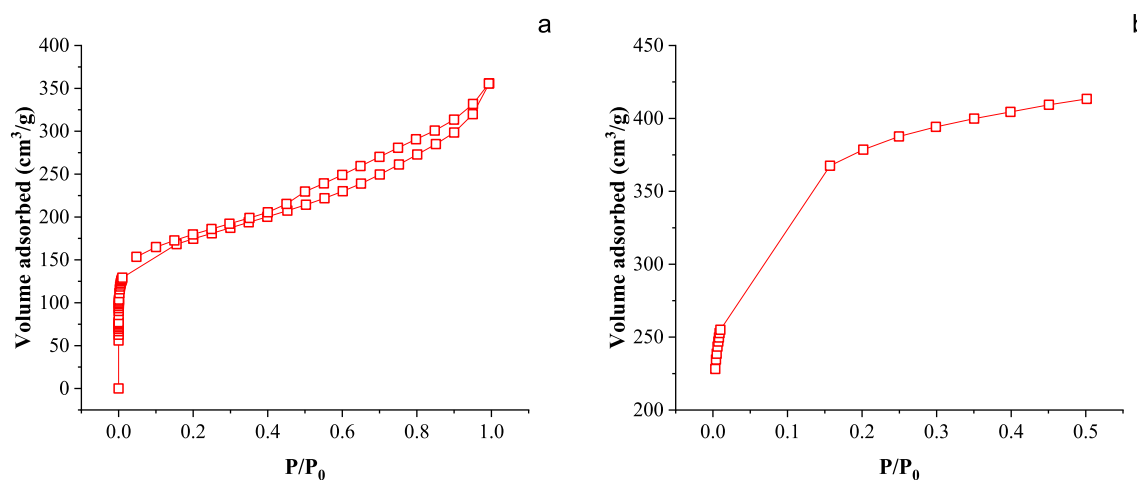
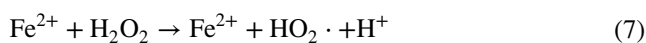
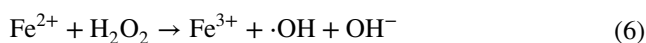


Fig. 4 The N₂ adsorption–desorption isotherms of **a** CAC and **b** RAC

well-developed microporous structure in the activated carbon. This structure facilitates significant adsorption within this pressure range. Beyond this point, the adsorption curve levels off, implying that the surface is approaching saturation and can no longer accommodate additional molecules. According to IUPAC classifications, CAC exhibits the characteristics of a type IV isotherm, which indicates a mesoporous structure, while RAC represents a microporous structure with a type I isotherm [53].

3.2 Performance of Fenton oxidation in textile wastewater degradation

The classical Fenton reaction involves generating highly oxidizing $\bullet\text{OH}$ by activating H_2O_2 with Fe^{2+} under acidic conditions, making it effective for the degradation of persistent organic compounds [54]. The Fenton catalytic reactions are based on the generation of $\bullet\text{OH}$ through the oxidation of Fe^{2+} to Fe^{3+} , as well as the production of $\text{HO}_2\bullet$ through the reduction of Fe^{3+} back to Fe^{2+} (as shown in Eq. 6 and Eq. 7) [55, 56].



3.2.1 Effect of pH

Studies in the literature have shown that the pH value of wastewater generally is a key factor in the catalytic decomposition of pollutants in water [20, 57]. Therefore, the optimum pH value must first be determined in the wastewater to be treated. At low pH values, $\bullet\text{OH}$ is formed faster due

to the reaction between Fe^{2+} and H_2O_2 , while at high pH values, H_2O_2 decomposes into O_2 , leading to a decrease in the degradation of the pollutant [58]. When pH drops below 2.5, H_2O_2 breaks down to form oxanium ion (H_3O_2^+), which neutralizes $\bullet\text{OH}$ and reduces the reactivity of H_2O_2 with iron ion, thus decreasing the dose of the $\bullet\text{OH}$ [59, 60]. In addition, $\text{Fe}(\text{OH})^+$ is formed as the dominant species in acidic pH, and the species formed are more active than the uncomplexed form of Fe^{2+} [60]. To determine the optimal pH for the classical Fenton process, experiments were conducted within the pH range of 2–4, maintaining a consistent Fe^{2+} dose of 2 mM, H_2O_2 dose of 10 mM, and a reaction duration of 30 min. The optimum pH was found to be 3.0, as is mostly the case in the literature [61–63]. As shown in Fig. 5a, the greatest colour removal occurred at a pH of 3.0, achieving 91%, 96%, and 96% colour removal at wavelengths of 436 nm, 525 nm, and 620 nm, respectively. Similarly, Fig. 5b illustrates that the highest COD removal, reaching 73%, was also attained at a pH of 3.0.

3.2.2 Effect of Fe^{2+} dose

Determining the appropriate Fe^{2+} dose is crucial in the Fenton process. Fe^{2+} serves as a catalyst in decomposing H_2O_2 , leading to increased levels of $\bullet\text{OH}$ radicals essential for breaking down persistent organic pollutants. Typically, increasing Fe^{2+} dose enhances efficiency. However, excessive Fe^{2+} addition can intensify $\bullet\text{OH}$ radical scavenging, impeding organic pollutant removal. Excess iron tends to react with the $\bullet\text{OH}$ present in the system, leading to the formation of Fe^{3+} and HO^- and loss of the oxidizing $\bullet\text{OH}$. Therefore, determining the specific Fe^{2+} and H_2O_2 dose required for the wastewater is important for achieving efficient removal. This can escalate system costs and

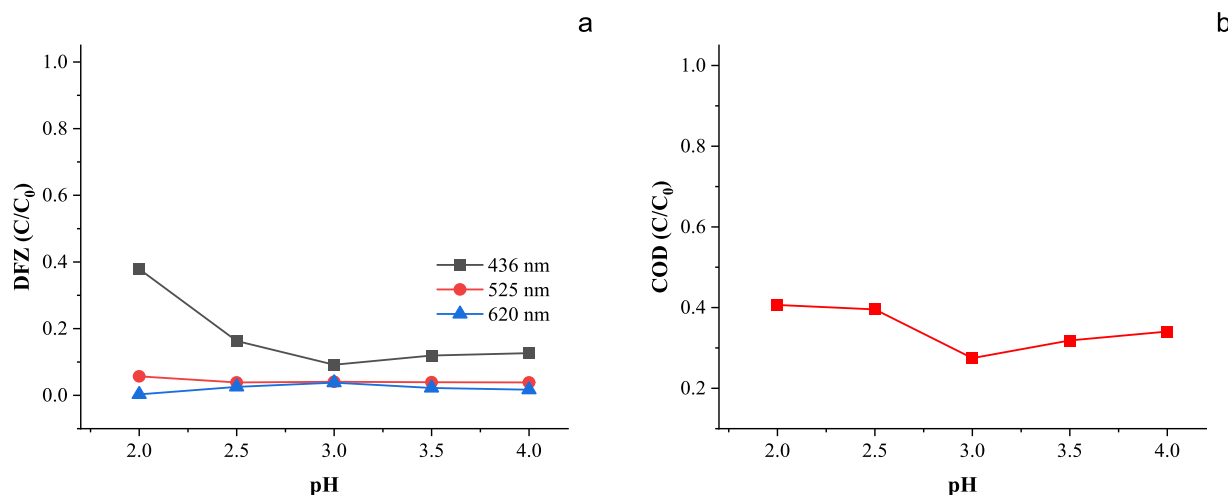


Fig. 5 Effect of pH. **a** Colour degradation index at 436, 525, and 620 nm; **b** COD degradation index ($\text{Fe}^{2+} = 2 \text{ mM}$; $\text{H}_2\text{O}_2 = 10 \text{ mM}$; reaction time = 30 min)

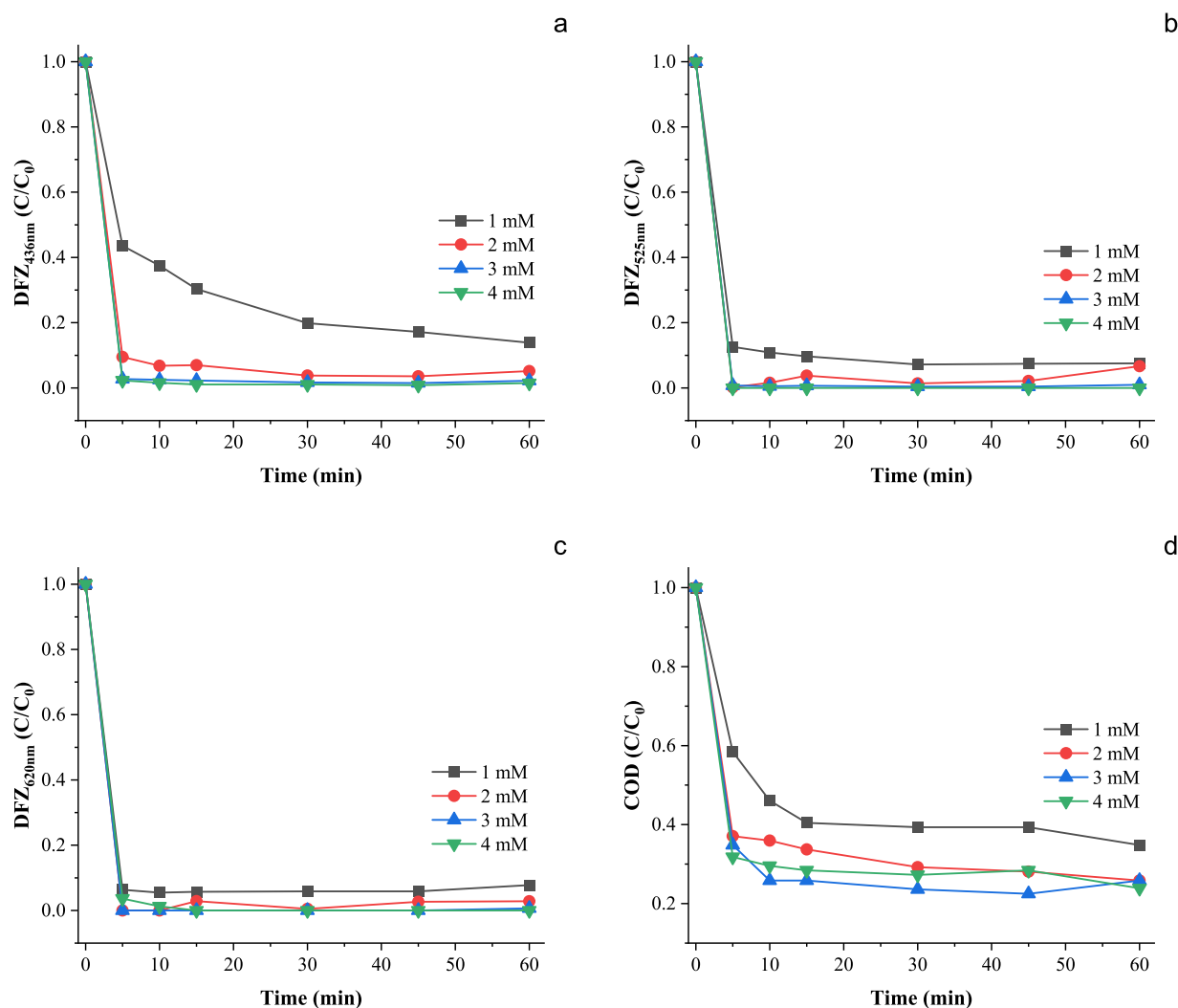


Fig. 6 Effect of Fe^{2+} dose. **a** Colour degradation index at 436 nm; **b** colour degradation index at 525 nm; **c** colour degradation index at 620 nm; **d** COD degradation index (pH = 3.0; H_2O_2 = 10 mM)

lead to secondary sludge issues [22, 64]. In order to obtain the appropriate Fe^{2+} dose, experiments were carried out at varying Fe^{2+} doses between 1 and 4 mM at pH of 3.0 and H_2O_2 dose of 10 mM. As shown in Fig. 6a–d, lower colour and COD reduction were attained at 1 mM Fe^{2+} dose. Colour removal efficiencies were found to be 86%, 92%, and 92% at wavelengths of 436, 525, and 620 nm, and COD removal efficiency was found to be 66% at 1 mM Fe^{2+} dose and 60 min of reaction time. Colour and COD removal increased as the Fe^{2+} dose rose from 1 to 2 mM, stabilizing thereafter with further increases in iron dose. Due to the disadvantages of increasing the Fe^{2+} dose, 2 mM was determined as the optimum dose. At the end of the 60 min reaction time, the removal efficiencies of colour at the 2 mM Fe^{2+} dose were found to be 95%, 93%, and 100% at wavelengths of 436, 525, and 620 nm, respectively. COD removal efficiency was achieved as 74% after 60 min of reaction time.

The relationship between Fe^{2+} dose and sludge formation in the Fenton process was also investigated. Experiments conducted with 2, 3, and 4 mM Fe^{2+} and 10 mM H_2O_2 revealed that as the Fe^{2+} dose increases, the amount of sludge produced rises. The suspended solids (SS) concentration was measured as 589 mg/L at 2 mM Fe^{2+} , while 708 mg/L was observed at 4 mM Fe^{2+} . This indicates that higher iron doses result in more sludge formation, which poses challenges for sludge disposal and increases the risk of secondary pollution. Therefore, optimizing Fe^{2+} dose is essential to balance effective contaminant removal and manageable sludge production in the Fenton process.

3.2.3 Effect of H_2O_2 dose

H_2O_2 dose is an important operating parameter affecting Fenton process. The degradation efficiency of organic

pollutants increases with increasing H_2O_2 dose owing to the greater production of $\bullet\text{OH}$, resulting from the higher dose of H_2O_2 [57]. However, high H_2O_2 doses lead to a decrease in degradation efficiency. This can be explained by the production of less reactive species such as $\text{HO}_2\bullet$ owing to the radical scavenging effect in Fenton-based processes and the automatic decomposition of H_2O_2 into O_2 and H_2O [57, 60, 65]. In addition, excessive H_2O_2 reacts with the formed $\bullet\text{OH}$ to produce the $\text{HO}_2\bullet$, which has a lower oxidation potential. Additionally, $\bullet\text{OH}$ radicals react with each other to form H_2O_2 again. Therefore, it is crucial to determine the appropriate H_2O_2 dose in conjunction with Fe^{2+} and adapt it specifically to the wastewater. Therefore, the optimal H_2O_2 dose needs to be determined to ensure maximum removal of organic pollutants. Experiments were conducted under stable conditions, maintaining a constant pH of 3.0 and 2 mM Fe^{2+} dose, and varying H_2O_2 doses ranging from 5 to 15 mM. A significant decrease was observed in absorbances at 436,

525, and 620 nm for all H_2O_2 doses, as seen in Fig. 7a–c. Colour removal efficiency at 436, 525, and 620 nm was found to be higher than 95% for all H_2O_2 dose. As seen in Fig. 7d, COD removal increased slightly with increasing H_2O_2 dose. H_2O_2 dose (10 mM) was determined as the optimum dose to avoid excessive H_2O_2 consumption. COD removal efficiency was found to be 74% for 10 mM H_2O_2 dose at a reaction time of 10 min.

3.3 Performance of AC-assisted Fenton oxidation in textile wastewater degradation

In the classical Fenton reaction, although the rapid formation of Fe^{3+} occurs by the oxidation of Fe^{2+} in the first stage, the reduction of Fe^{3+} with H_2O_2 and $\text{HO}_2\bullet$ in the second stage is extremely slow, significantly affecting the oxidation efficiency. Activated carbon can be used as an effective mediator to accelerate the regeneration of Fe^{2+} from Fe^{3+} and the

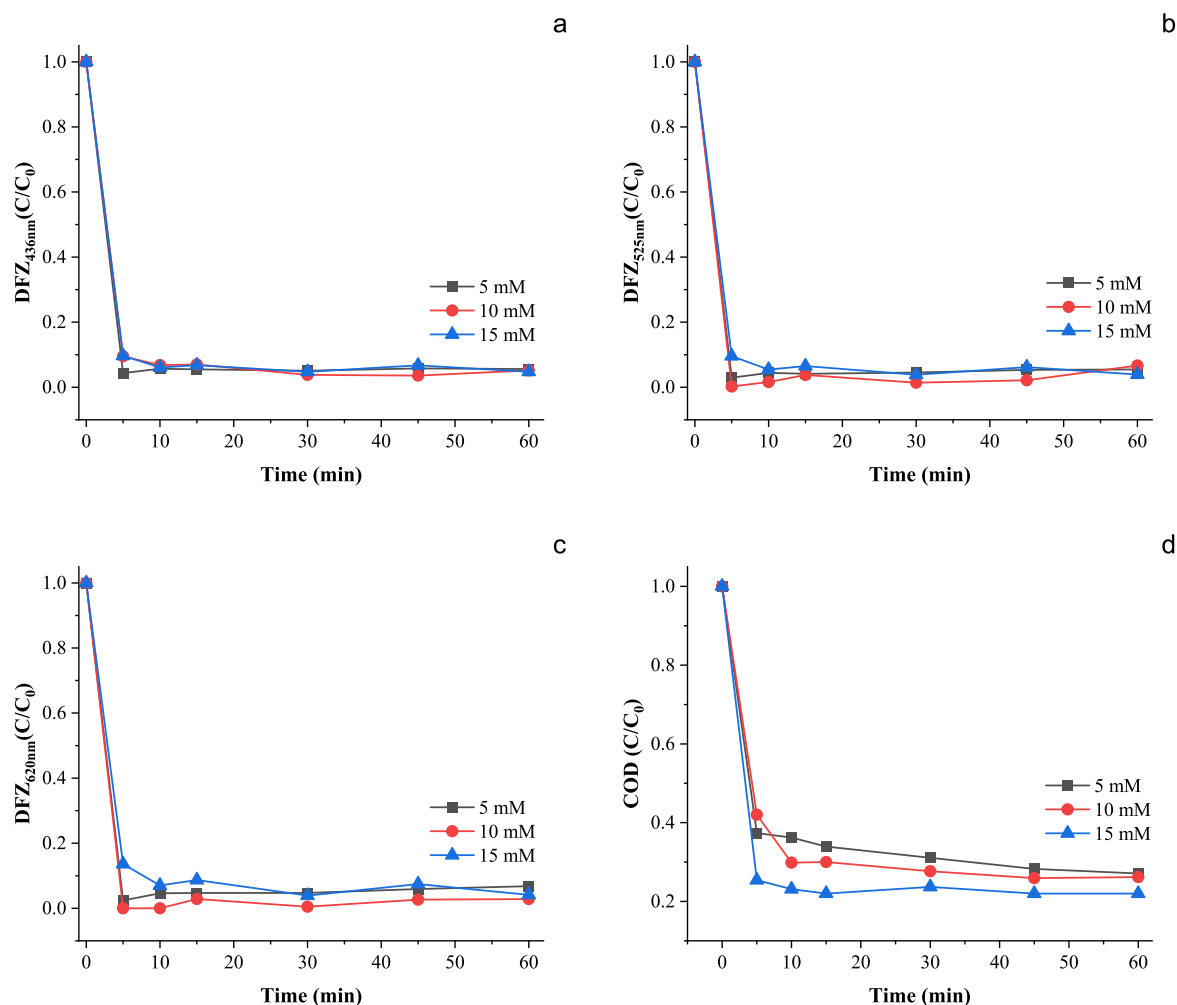


Fig. 7 Effect of H_2O_2 dose. **a** Colour degradation index at 436 nm; **b** colour degradation index at 525 nm; **c** colour degradation index at 620 nm; **d** COD degradation index (pH = 3.0; Fe^{2+} = 2 mM)

production $\bullet\text{OH}$ and enhance overall oxidation efficiency [66]. Furthermore, activated carbon can efficiently adsorb some oxidation-resistant organic substances and oxidation intermediates in wastewater and enhance the removal of pollutants. AC also acts as a catalyst to enhance the formation of reactive oxygen species (ROS), which decompose adsorbed pollutants and improve the adsorption capacity and regeneration of the adsorbent [67].

3.3.1 Effect of reaction time

In the AC-assisted Fenton experiments, the effect of reaction time was investigated. The experiments were performed at the optimum conditions determined in the classical Fenton process (pH 3.0, 2 mM Fe^{2+} and 10 mM H_2O_2) by adding 2 g/L of CAC and RAC. As seen in Fig. 8a–d, for both activated carbons added to the Fenton

system, colour and COD values decrease significantly in 10 min. COD removal efficiencies in the first 10 min were found to be 77% and 84% for RAC and CAC-assisted Fenton processes, respectively. AC can enhance the efficiency of the system by accelerating the reduction of Fe^{3+} with H_2O_2 , a slow step in Fenton and Fenton-like systems, and initiating a Fenton reaction chain by forming Fe^{2+} . In the RAC-assisted Fenton process, COD removal efficiency reached 83% at a reaction time of 120 min. In the CAC-assisted Fenton process, efficiency reached 86%, but no significant increase was observed as the reaction time increased. Based on these results, no significant increase in COD removal was observed after the 10th min. Regarding colour removal efficiencies, for CAC-assisted Fenton process, they were determined to be 100%, 100%, and 100% at 436, 525, and 620 nm, respectively. For the RAC-assisted Fenton process, the colour removal efficiencies were found to be 99%, 99%, and 98% at 436, 525, and 620 nm.

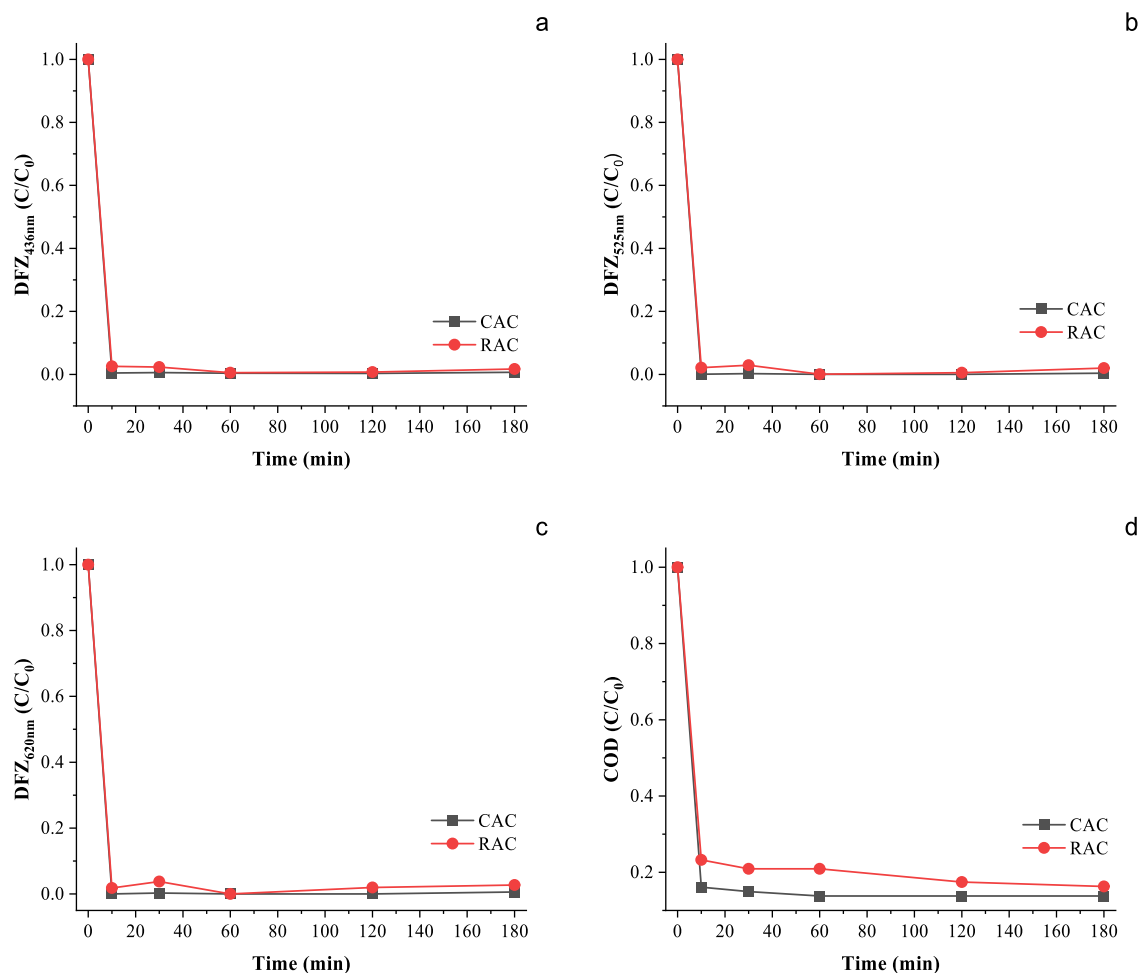


Fig. 8 Effect of time in AC-assisted Fenton process. **a** Colour degradation index at 436 nm; **b** colour degradation index at 525 nm; **c** colour degradation index at 620 nm; **d** COD degradation index (Fe^{2+} = 2 mM, H_2O_2 = 10 mM, pH = 3.0, RAC = CAC = 2 g/L)

3.3.2 Effect of activated carbon dose

To determine the optimum dose for both carbons, AC-assisted Fenton oxidations were carried out using CAC and RAC doses within the range of 0.5–5 g/L at a reaction time of 10 min and the optimum conditions determined for Fenton process (pH 3.0, 2 mM Fe^{2+} , and 10 mM H_2O_2). As seen in Fig. 9a–c, colour was removed completely at the lowest dose of 0.5 g/L for both activated carbons. Meanwhile, COD removal increased with increasing carbon dose. As seen in Fig. 10d, COD removal efficiencies for RAC and CAC-assisted Fenton processes were found to be 68% and 78% at carbon dose of 0.5 g/L, rising to 83% and 88% at 2 g/L, and reaching 92% and 94% at 4 g/L. The colour removal efficiencies were determined to be 98%, 99%, and 99% for

CAC-assisted Fenton process and 97%, 97%, and 97% for RAC-assisted Fenton process at 436, 525, and 620 nm, at carbon dose of 0.5 g/L.

3.3.3 Comparison of AC adsorption, Fenton oxidation, and AC-assisted Fenton oxidation

In order to evaluate the effect of AC on the Fenton oxidation system, different reaction systems such as CAC only, RAC only, $\text{Fe}^{2+}/\text{H}_2\text{O}_2$, CAC/ $\text{Fe}^{2+}/\text{H}_2\text{O}_2$, and RAC/ $\text{Fe}^{2+}/\text{H}_2\text{O}_2$ were compared in terms of COD and TOC removal efficiency. Initially, adsorption study was carried out with RAC and CAC to investigate the efficiency of adsorption process. In the adsorption study, conducted at a carbon dose of 2 g/L and a reaction time of 60 min, the removal

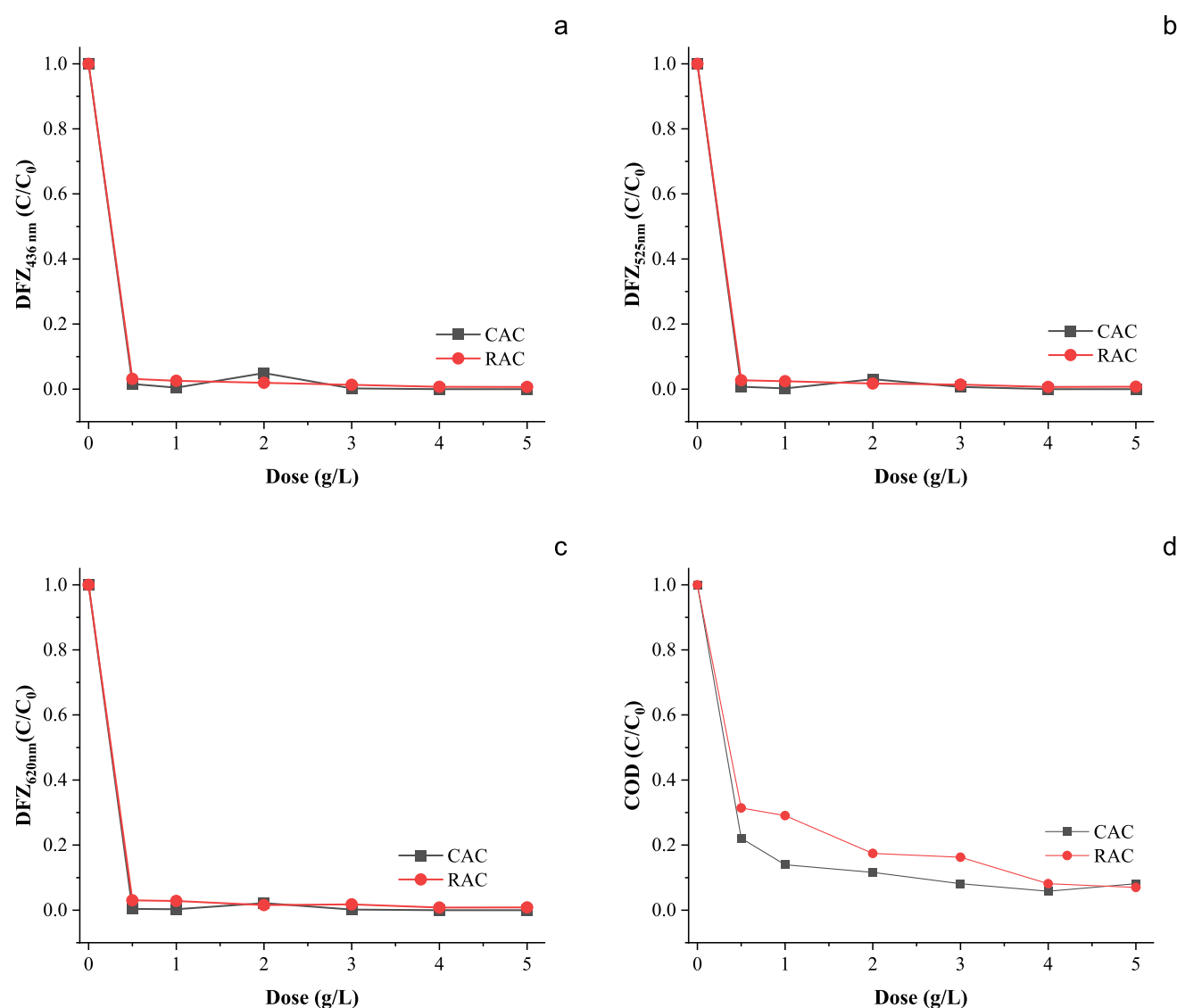


Fig. 9 Effect of dose in AC-assisted Fenton process. **a** Colour degradation index at 436 nm; **b** colour degradation index at 525 nm; **c** colour degradation index at 620 nm; **d** COD degradation index (Fe^{2+} = 2 mM, H_2O_2 = 10 mM, pH = 3.0, reaction time = 10 min)

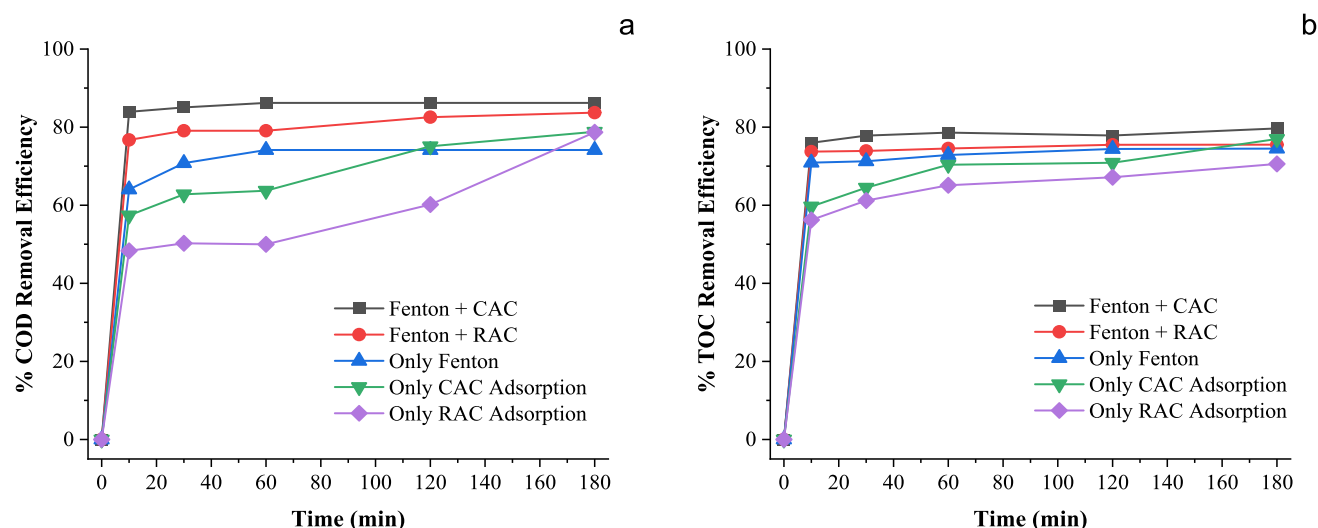


Fig. 10 Comparison of time-dependent removal efficiencies of adsorption, Fenton, and AC-assisted Fenton processes. **a** COD removal; **b** TOC removal ($\text{Fe}^{2+} = 2 \text{ mM}$, $\text{H}_2\text{O}_2 = 10 \text{ mM}$, $\text{CAC} = \text{RAC} = 2 \text{ g/L}$)

efficiency achieved for RAC was 50% for COD and 65% for TOC, while for CAC, the removal efficiencies were 64% for COD and 70% for TOC. In the Fenton process ($\text{Fe}^{2+}/\text{H}_2\text{O}_2$), removal efficiencies of COD and TOC were achieved at 74% and 68%, respectively, after 60 min of reaction time, using a Fe^{2+} dose of 2 mM and an H_2O_2 dose of 10 mM. COD removal increased significantly with the addition of RAC and CAC. In AC-assisted Fenton system ($\text{RAC}/\text{Fe}^{2+}/\text{H}_2\text{O}_2$ and $\text{CAC}/\text{Fe}^{2+}/\text{H}_2\text{O}_2$), COD and TOC removal efficiencies were 79% and 75% for RAC and were 87% and 80% for CAC at 60 min reaction time, 2 mM Fe^{2+} , 10 mM H_2O_2 , and 2 g/L carbon dose. As seen in Fig. 10a, COD removal decreased in order of $\text{Fe}^{2+}/\text{H}_2\text{O}_2/\text{CAC} > \text{Fe}^{2+}/\text{H}_2\text{O}_2/\text{RAC} > \text{Fe}^{2+}/\text{H}_2\text{O}_2 > \text{CAC} > \text{RAC}$. As seen in Fig. 10b, TOC removal decreased in order of $\text{Fe}^{2+}/\text{H}_2\text{O}_2/\text{CAC} > \text{Fe}^{2+}/\text{H}_2\text{O}_2/\text{RAC} > \text{CAC} > \text{RAC} > \text{Fe}^{2+}/\text{H}_2\text{O}_2$. As a result, while the COD removal efficiency achieved with the classical Fenton process under the optimum conditions (pH: 3.0, 2 mM Fe^{2+} , 10 mM H_2O_2 , and reaction time: 10 min) was 59.2%, it increased to 82.6% with the addition of 2 g/L RAC and to 88.4% with the addition of 2 g/L CAC in the AC-assisted Fenton system.

Table 3 summarizes studies on classical and AC-assisted Fenton and Fenton-like processes. Yang et al. [68] reported that the addition of functionalized multi-walled carbon nanotubes (FCNT-H) to classical Fenton-like processes significantly increased the degradation of the model pollutant atrazine (> 90%) within 30 min. Seo et al. [69] investigated the production of reactive oxidants in $\text{Fe}^{3+}/\text{H}_2\text{O}_2$ systems, both in the presence and absence of carbon materials (PAC and CNT), and revealed that the presence of carbon materials increased the production of reactive oxidants kinetically and accelerated the decomposition of H_2O_2 . They noted that the

addition of carbon materials increased oxidant production but reduced the efficiency of H_2O_2 usage, with this effect becoming more pronounced as solution pH and carbon dose increased. Peng et al. [70] reported that the $\text{Fe}^{3+}/\text{H}_2\text{O}_2$ system can effectively eliminate triclosan (TCS) within 30 min in the presence of graphene oxide (GO), achieving a 90% removal efficiency. They found that $\bullet\text{OH}$ were responsible for TCS degradation, with GO's structure remaining mostly unchanged after the reaction. Their ecotoxicity assessment indicated that the $\text{Fe}^{3+}/\text{H}_2\text{O}_2/\text{GO}$ system could lower the ecological toxicity of pollutants like TCS, showing potential as a cost-effective, eco-friendly wastewater treatment technology. Yan et al. [71] studied the decomposition of Acid Red G (ARG) using a $\text{Fe}^{3+}/\text{H}_2\text{O}_2$ system enhanced with activated carbon (AC) derived from coconut shell, wood, and coal. They observed that AC improved degradation in the $\text{Fe}^{3+}/\text{H}_2\text{O}_2$ process. Similarly, Zhao et al. [16] examined a heterogeneous Fenton process using pyrite as a catalyst for ciprofloxacin (CIP) degradation and found that adding carbon materials like AC, biochar, and CNT improved $\bullet\text{OH}$ production, enhancing CIP degradation. The study highlighted the combined effect of oxidation and adsorption in pyrite/carbon/ H_2O_2 systems, showing potential for treating antibiotic-containing wastewater. Shao et al. [26] investigated the removal efficiency of Atenolol (ATL) using a Fenton-like process with multi-walled carbon nanotubes (MWCNT). They found that MWCNT, acting as an electron donor, effectively facilitated the conversion of Fe^{3+} to Fe^{2+} , enhancing ATL removal efficiency. Chen et al. [66] demonstrated that a 100% removal of Ni-EDTA from electroplating wastewater could be achieved using an activated carbon-supported Fenton system. They concluded that AC enhanced the regeneration of Fe^{2+} from Fe^{3+} via electron

Table 3 Efficiency of different carbon-based materials in AC-assisted Fenton and Fenton-like

Catalysts	Contaminants	Reaction conditions	Removal (%)	Reference
Heterogeneous Fenton and Carbon (AC-BC-CNT)	Ciprofloxacin (CIP)	[CIP] = 100 mg/L Pyrite = 1.5 g/L H ₂ O ₂ = 10 mM pH = 3.0 AC = BC = CNT = 0.1 g/L	89.3% (AC) 60.0% (BC) 60.8% (CNT)	[74]
Homogeneous Fenton like and FCNT-H	Atrazine (ATZ)	[ATZ] = 2.16 mg/L Fe ³⁺ = 2 mg/L H ₂ O ₂ = 170 mg/L pH = 5.0 FCNT-H = 20 mg/L	90%	[68]
Homogeneous Fenton like and Powdered activated carbon (PAC) and Carbon nanotubes (CNT)	Methanol	[MeOH] = 200 mM Fe ³⁺ = 0.1 mM H ₂ O ₂ = 1.0 mM pH = 3.0 PAC = CNT = 1.0 g/L	60% (AC) 80% (CNT)	[69]
Homogeneous Fenton-like and GO	Triclosan (TCS)	[TCS] = 0.02 mM Fe ³⁺ = 0.01 mM H ₂ O ₂ = 0.4 mM pH = 4.0 GO = 2 mg/L	90%	[70]
Homogeneous Fenton-like and MWCNTs	Atenolol (ATL)	[Atenolol] = 2.66 µg/L Fe ³⁺ = 0.05 mM H ₂ O ₂ = 1.0 mM pH = 4.0 MWCNTs = 6.0 mg/L	≈ 100%	[26]
Homogeneous Fenton and AC	Ni-EDTA	[Ni-EDTA] = 20 mg/L Fe ²⁺ = 0.8 mM H ₂ O ₂ = 30 mM AC = 0.1 g/L	100%	[66]
Homogeneous Fenton-like and AC	Acid Red G	Fe ³⁺ = 0.1 mM H ₂ O ₂ = 0.4 mM pH = 3.0 AC = 0.6 g/L	99%	[71]
Heterogeneous Fenton and C@FONC	Tetracycline (TC)	[TC] = 150 mg/L pH = 3.0 Fe ₃ O ₄ /PAC = 0.5 g/L H ₂ O ₂ = 5 mM	97.9%	[72]
Heterogeneous Fenton and Fe ₃ O ₄ /CBc	Methyl orange (MO)	[MO] = 100 mg/L H ₂ O ₂ = 16 mmol/L pH = 3.0 Fe ₃ O ₄ /CBc dosage = 10 mg	> 99.4%	[73]
Homogeneous Fenton and AC	Textile wastewater	Fe ²⁺ = 2 mM H ₂ O ₂ = 10 mM pH = 3.0 AC = 2 g/L	83% COD (RAC) 88% COD (CAC)	This study

transfer, rather than merely increasing H₂O₂ decomposition to produce •OH. Zhou et al. [72] investigated the removal of tetracycline (TC) by heterogeneous Fenton process using a C@FONC catalyst and achieved a removal efficiency of 97.9% at pH 3.0, 150 mg/L TC concentration, 0.5 g/L Fe₃O₄/PAC, and 5 mM H₂O₂. Similarly, Xu et al. [73] investigated the degradation of methyl orange (MO) by heterogeneous Fenton process with Fe₃O₄/CBc as a catalyst and achieved a removal efficiency exceeding 99.4%, at 100 mg/L MO, 16 mmol/L H₂O₂, pH 3.0, and 10 mg Fe₃O₄/CBc dosage. In the presented study, it was observed that the AC-assisted Fenton process effectively removed COD (> 80%) from

biologically treated textile wastewater, producing high-quality effluent.

3.3.4 Wastewater quality after Fenton and AC-assisted Fenton treatment

Wastewater quality is an important aspect for the potential reuse applications. Table 4 presents the results of COD, TOC, EC, and colour values obtained after Fenton process, as well as CAC and RAC-assisted Fenton processes. The Fenton oxidation was conducted at 2 mM Fe²⁺, 10 mM H₂O₂, pH 3.0, and reaction time of 10 min. The addition

Table 4 The characteristics of wastewater after Fenton, CAC-assisted Fenton and RAC-assisted Fenton treatment

Parameter		Bio- logically treated wastewater	Fenton	CAC- assisted Fenton	RAC- assisted Fenton
COD (mg/L)		91–98	32.0	10	15
TOC (mg/L)		23–32	12.8	5.3	6.9
EC (μS/cm)		1602–2847	3938	3219	3127
Colour (m ⁻¹)	DFZ _{436nm}	4.25–8.21	0.369	0.385	0.161
	DFZ _{525nm}	3.0–5.09	0.052	0.149	0.088
	DFZ _{620nm}	1.84–3.445	0.0	0.070	0.054

of activated carbon to the Fenton processes significantly enhanced treatment efficiency. The COD values of textile wastewater after biological treatment vary between 91 and 98 mg/L, which meets the discharge limit values of Türkiye (240 mg/L), but exceeds the reuse limits (20–50 mg/L) for processes requiring high-quality water such as dyeing, printing and finishing [74]. Fenton oxidation reduced the COD to 32 mg/L, while the CAC and RAC-assisted processes achieved much lower COD values of 10 mg/L and 15 mg/L, respectively. Although low COD levels indicate efficient removal of organic pollutants and improved the water quality, a desalination step can be applied to make the water suitable for reuse in processes requiring low salinity. The findings demonstrate that combining activated carbon (RAC and CAC) with Fenton process offers a potential for polishing textile wastewater. This approach enhances the degradation of organic pollutants, reduces environmental impacts, and promotes water reuse. The use of low-cost, sustainable materials like reed-derived activated carbon makes the process both economically viable and environmentally friendly. Additionally, the integration of artificial neural networks (ANNs) for process optimization offers improved operational efficiency and scalability, highlighting the method's potential for broader industrial implementation.

3.4 Economic analysis

The economic analysis of a developed technology is crucial for determining its scalability and feasibility. Most research on AOPs has remained at the laboratory scale. However, to assess the economic sustainability of these processes, it is essential to consider all costs encountered in large-scale applications. In this context, economic analysis was conducted to determine the economic viability of a process for the treatment of real textile wastewater. Total costs consist of capital, operating, and maintenance expenses. In a full-scale system, these costs vary significantly depending on the flow rate of the wastewater, reactor design, and characteristics of

Table 5 Chemical and material costs

Material	Price (USD/ton)
Ferrous sulphate (FeSO ₄ ·7H ₂ O)	200
Hydrogen peroxide (H ₂ O ₂ , 35%)	450
H ₂ SO ₄ (95–97%)	100
Ca(OH) ₂	100
CAC	1750
RAC	1146.7

the effluent. In this study, only operating expenses, such as chemical and energy consumption, were considered.

The CAC and RAC costs are the major cost components in estimating the operational cost of the AC-assisted Fenton process. The production cost for 1 ton of RAC was calculated considering the steps of grinding carbonization, chemical activation, washing, and drying.

Chemical activation cost: To produce 1 ton of RAC, 1 ton of free reed and 3 tons of NaOH (costing 300 USD/ton) are needed, making the total chemical cost about 900 USD/ton.

Grinding cost: The electricity cost for grinding material to the desired size has been calculated to be approximately 5.09 USD/ton.

Carbonization cost: The specific heat capacity needed for the carbonization process was calculated using a weighted average based on the masses of reed and NaOH, allowing for the determination of energy requirements (in kWh) for the 1 h carbonization at 600 °C [75, 76]. To reduce costs and achieve a more economical production, it was assumed that natural gas would be used instead of electricity. Consequently, the carbonization cost was calculated to approximately 22.54 USD/ton.

Washing cost: Based on the amount of water used in the washing process during the laboratory-scale study, the water required to produce 1 ton of RAC was calculated, with an associated cost of 215.5 USD/ton.

Drying cost: The energy required for water evaporation is the sum of the energy needed to heat the water to its boiling point and the energy needed for the phase change. Considering a 10% moisture content, the drying cost is approximately 3.57 USD/ton [76].

Total production cost: Total production cost for 1 ton of RAC was calculated as 1146.7 USD/ton.

The operational cost of Fenton and AC-assisted Fenton processes was estimated based on the chemical and energy costs. The unit costs of materials used in the Fenton and AC-assisted Fenton processes are summarized in Table 5 as USD/ton.

Table 6 presents a comprehensive comparison of specific energy consumption (SEC), operational costs, and COD removal efficiencies for the three Fenton-based processes. Classical Fenton process operates at the lowest cost 0.660

Table 6 Specific energy consumption (SEC) and operating costs of Fenton and AC-assisted Fenton processes

	Operational costs (USD/m ³)					COD removal efficiency (%)		SEC (Wh/mgCOD/L)
	Energy	FeSO ₄ ·7H ₂ O	H ₂ O ₂	H ₂ SO ₄	AC	Total		
Fenton	0.021	0.168	0.437	0.034	-	0.660	64	0.00293
CAC-assisted Fenton	0.021	0.168	0.437	0.034	3.5	4.160	88	0.00228
RAC-assisted Fenton	0.021	0.168	0.437	0.034	2.29	2.950	83	0.00253

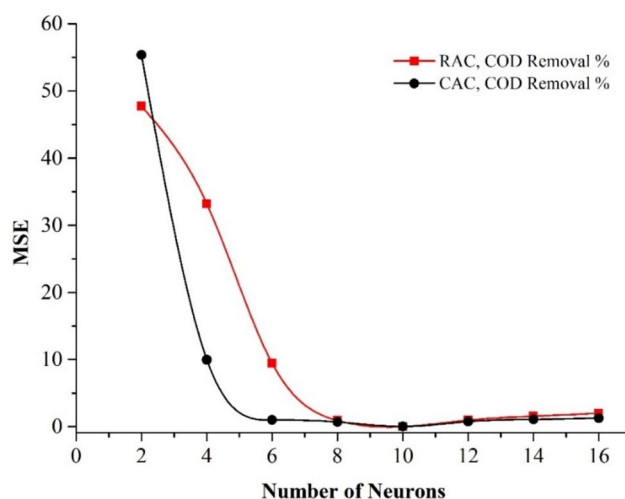
The cost of Ca(OH)₂ is negligible and has not been included in the calculation. Energy consumption was calculated based on 1 kWh/m³ for 10 min of mixing at 100 rpm on a commercial scale

USD/m³ with a moderate COD removal efficiency of 64% and an SEC value of 0.00293 Wh/mgCOD/L, indicating lower energy efficiency. The CAC-assisted Fenton process achieves the highest removal efficiency (88%) and the lowest SEC value (0.00228 Wh/mgCOD/L) but is the most expensive option at 4.160 USD/m³. RAC-assisted Fenton process offers an effective balance of cost and efficiency with a cost of 2.950 USD/m³, COD removal efficiency of 83%, and SEC value of 0.00253 Wh/mgCOD/L.

3.5 Artificial neural network modelling

A total of 156 data sets were available for each of the RAC and CAC datasets individually. These were randomly divided into subsets, and 68% were allocated for training the respective ANN models. The remaining 32% was evenly split between testing (16%) and validation (16%). Accordingly, for each model, 106 data sets were used for training, while 25 data sets were designated for testing and 25 data sets were designated for validation. Different neuron configurations were explored for the hidden layer, with 10 neurons were identified as the optimal architecture, yielding the highest correlation coefficient and lowest mean squared error. The optimal number of neurons was determined by identifying the configuration that yielded the minimum MSE for both the training and validation datasets. Utilizing the Levenberg–Marquardt algorithm (LMA) for training, the number of neurons was systematically varied from 2 to 16. As depicted in Fig. 11, the MSE exhibited a decreasing trend with an increasing number of neurons up to 10. Beyond this threshold, additional neurons did not produce a significant reduction in MSE. Therefore, 10 neurons emerged as the most effective configuration.

The models achieved coefficients of determination (R^2) of 0.98143 and 0.98453 for the RAC and CAC-assisted Fenton processes test datasets, respectively. Figure 12 a and b illustrate the comparison between experimental and calculated values of the output variable across for training, validation,

**Fig. 11** Relationship between the number of neurons and MSE

test, and overall sets using the ANN model for both RAC and CAC-assisted Fenton processes.

Notably, the correlation coefficient for the observed and predicted COD removal efficiency (%) of the ANN is 0.9504 for the RAC and 0.9440 for the CAC-assisted Fenton process (Fig. 13a, b). Concurrently, the MSE values were minimized to 0.2504 for RAC and 0.2705 for CAC. These results demonstrate that the ANN model accurately reproduces COD removal efficiency within acceptable experimental ranges, indicating a reliable fitting model. The R^2 values approaching unity highlight the strong agreement between model predictions and experimental results, underscoring the predictive strength of the ANN for these datasets.

The effects of various parameters, namely activated carbon dose, reaction time, iron doses, and oxidant doses, were simulated using ANN models developed separately for RAC and CAC-assisted Fenton systems. The variable ranges are as follows: reaction time is 10–180 min, iron doses are set at 1, 2, and 3 mM, activated carbon doses ranges from 0.5 to

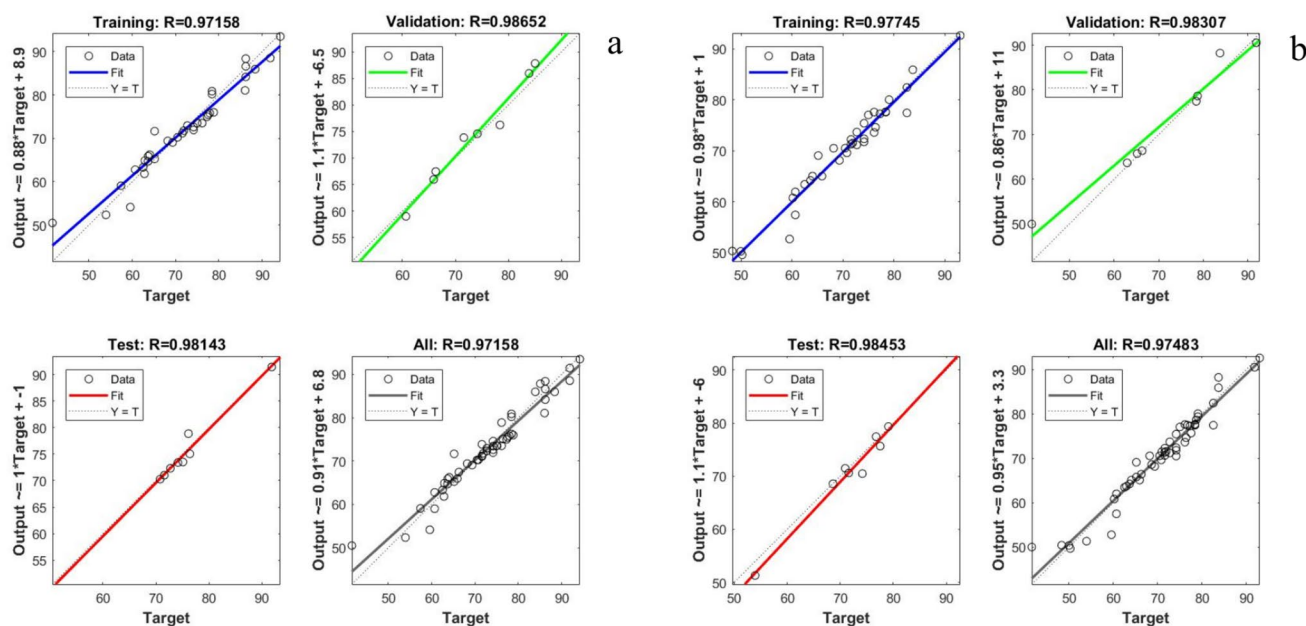


Fig. 12 Comparison between experimental and neural network modeled removal efficiency (%) for the test sets was conducted for **a** RAC and **b** CAC-assisted Fenton process

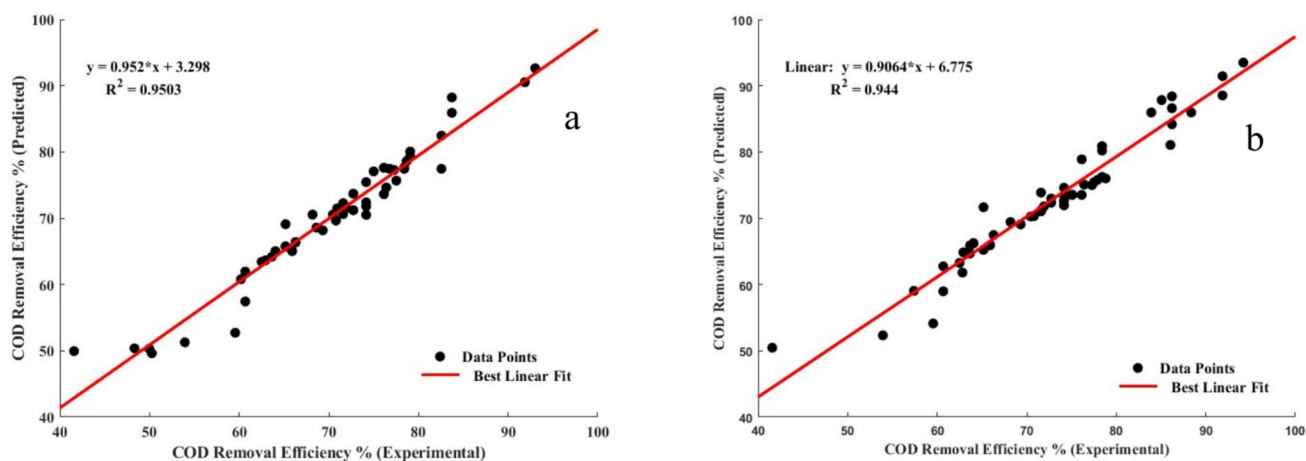


Fig. 13 Plot displaying both the observed and predicted COD removal efficiency (%) of ANN for Fenton systems with both **a** RAC and **b** CAC assistance

5 mg/L, and oxidant doses are 5, 10, and 15 mM. A comparison between the COD removal efficiencies predicted by the ANN models and experimental observations demonstrated the models' ability to accurately estimate the behaviour of the RAC and CAC-assisted oxidation processes across different experimental conditions. Figure 14 a and b illustrate the significance of input parameters affecting COD removal (%) in both RAC and CAC-assisted Fenton systems. The pivotal operating parameters were identified based on the significance of input parameters for each process. In Fig. 14a, iron dose emerges as the most crucial factor with importance of 32.7%, succeeded by oxidant at 27.4%, time at 24.4%,

and AC dose at 15.5% for RAC-assisted Fenton. Conversely, Fig. 14 b demonstrates that for CAC-assisted Fenton, the relative importance of input variables is as follows: iron dose (32.2%), AC dose (23.8%), oxidant dose (22.1%), and reaction time (21.9%).

4 Conclusions

This study has successfully demonstrated the effectiveness activated carbon (AC)–assisted Fenton oxidation for the treatment of biologically pre-treated textile wastewater. Reed

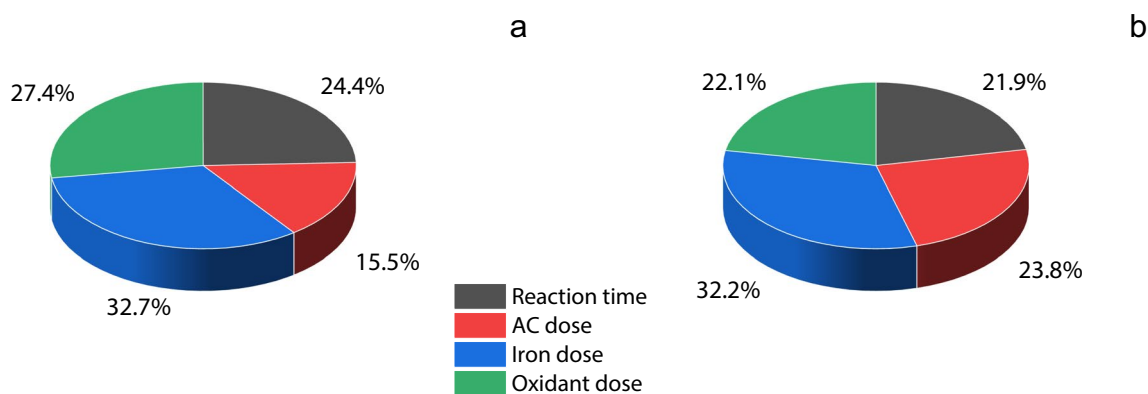


Fig. 14 Importance of dependent variables of ANN model. **a** RAC-assisted Fenton process and **b** CAC-assisted Fenton process

activated carbon (RAC) obtained from *Phragmites australis* demonstrated similar performance in improving wastewater quality, providing a sustainable and cost-effective alternative to commercial activated carbon (CAC). In the Fenton process, after 10 min, COD removal was 64%, TOC removal was 51%, and colour removal efficiencies at wavelengths of 436, 525, and 620 nm were 93%, 98%, and 100%, respectively. Under the same conditions, with the addition of 2 g/L activated carbon (AC) to the Fenton process, COD removal in the CAC-assisted Fenton process increased to 88%, TOC removal to 77%, and colour removal at the same wavelengths reached 99.6%, 99.9%, and 100%, respectively. In the RAC-assisted Fenton process, COD removal was 83%, TOC removal was 73.95%, and colour removal efficiencies at 436, 525, and 620 nm were 97%, 98%, and 98%, respectively. The total operational costs for textile wastewater treatment were calculated as 0.659 USD/m³ for Fenton, 4.159 USD/m³ for CAC-assisted Fenton, and 2.949 USD/m³ for RAC-assisted Fenton. The application of artificial neural networks (ANNs) allowed for accurate prediction of system performance, highlighting the potential for scalable implementation of AC-assisted Fenton systems. The AC-assisted Fenton process offers several advantages, including enhanced organics removal efficiency and ensuring that the treated water meets stringent quality criteria. Additionally, activated carbon can be regenerated and reused. This allows multiple adsorption and catalysis cycles, extending the lifetime of the activated carbon and reducing sludge formation. For large-scale applications, research is needed to determine the performance of activated carbon in repeated use in the Fenton process. In this way, enhanced pollutant removal can be achieved while reducing operational costs and sludge production.

Author contribution Elif Nihan Kadioğlu: investigation, visualization, formal analysis, writing — original draft. Handan Atalay Eroğlu: visualization, validation, formal analysis, software. Hacer Öztürk: investigation, visualization, formal analysis. Feryal Akbal: conceptualization,

writing — review and editing, project administration. Ayşe Kuleyin: data curation, validation, methodology.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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