DOI: 10.2478/eces-2025-0024 ECOL CHEM ENG S. 2025;32(4):471-483

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EXPERIMENTAL RESEARCH ON ORGANIC DYE REMOVAL FROM POLLUTED WATER USING THE OXIDATION METHOD

Abstract: Electrochemical, biological, adsorption, and oxidative methods can be applied for the treatment of synthetic wastewater containing methyl orange (MO). In this study, MO was catalytically oxidised using ferrous sulphate ($FeSO_4$) and hydrogen peroxide (H_2O_2). The effects of reagent concentrations, initial dye concentration, contact time, and pH on treatment efficiency were investigated, and the optimal process conditions were identified. $FeSO_4$ and H_2O_2 are cost-effective and environmentally benign reagents: excess hydrogen peroxide decomposes into water, while the small amount of iron introduced does not significantly impair the quality of the treated effluent. The results showed that increasing the $FeSO_4$ concentration from 0.02 % to 2.00 % enhanced the removal efficiency of *C-MO* from 81.5 % to 98.7 %, as the higher availability of Fe^{2+} ions accelerates the formation of $HO^{\bullet}$ radicals. Increasing the H_2O_2 concentration from 0.6 % to 24 % raised the efficiency from 81.1 % to 94.5 %, and the highest degradation efficiency was achieved at pH 2.00 - 3.00, confirming that optimal Fenton reaction performance occurs under mildly acidic conditions. Investigation of the initial dye concentration revealed that the efficiency ranged from 80.4 % to 89.1 % when the dye concentration increased from 50 mg/L to 750 mg/L, while the reduction at higher concentrations indicates an insufficient amount of $HO^{\bullet}$ radicals. Contact time studies showed that the efficiency increased from 39.8 % to 97.1 %, with the optimal reaction time being 2 hours. Overall, the findings demonstrate that the Fenton process is a highly effective method for the degradation of azo dyes and holds strong potential for application in wastewater treatment systems.

Keywords: dye, methyl orange, oxidative method, Fenton reaction

Introduction

The intensive use of organic substances in everyday activities (e.g., medicines) has increased the release of typical, as well as new organic compounds into wastewater, the presence of which was previously not detected due to the lack of analytical methods and because their negative impact on health was not known. There is a great diversity of organic compounds found in drinking water and wastewater. One of the groups of organic pollutants found in polluted water is dyes. They are widely used in the production of rubber, leather, textiles, plastics, paper, and other materials. Coloured industrial wastewater is formed during production processes. Even very low concentrations of dyes harm the food chain, which is why removing organic substances from water is crucial for environmental protection. To reduce water consumption, it is essential to find strategic ways to protect natural water resources from pollution and to discover and utilise effective and inexpensive technologies for cleaning polluted water [1]. Scientists are investigating the possibilities of

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removing dyes from wastewater using various methods, including electrochemical, biological, adsorption, and oxidative methods [2-15]. Dyes often negatively affect microorganisms used in biological wastewater treatment; therefore, alternatives to biological wastewater treatment are being sought. One of the most effective methods for treating wastewater contaminated with organic substances (dyes) is the oxidative method, using the Fenton reaction. Advantages of the Fenton reaction include the high, rapid generation of hydroxyl radicals for pollutant degradation. Disadvantages: requires acidic pH for optimal performance [16]. Treatment of water contaminated with dyes by the oxidative method allows for reducing the concentration of organic substances (dyes) and removing the colour of polluted water. Methyl orange (MO), a synthetic azo dye, is widely used in the textile, paper, and food industries. Its recalcitrance, vivid coloration, and potential toxicity make it a persistent pollutant in industrial effluents, posing risks to aquatic ecosystems and human health. Conventional biological treatments are often ineffective due to MO's resistance to biodegradation and the formation of toxic aromatic amines upon partial breakdown. Advanced oxidation processes (AOPs), particularly the Fenton reaction, have emerged as promising solutions for the rapid and effective removal of such dyes from wastewater. The Fenton process, based on the catalytic decomposition of hydrogen peroxide by iron ions to generate highly reactive hydroxyl radicals, offers the advantages of high efficiency, relatively low cost, and potential for complete mineralisation of organic contaminants. However, optimising the process for real-world application requires a deep understanding of its mechanisms, operational parameters, and by-product management [17-19]. The formula of MO is $C_{14}H_{14}N_3O_3SNa$ [20]. Its name, according to the JUPAC nomenclature, is sodium 4-{[4-(dimethylamino)phenyl]diazenyl}benzene-1-sulphonate [21]. The work aimed to conduct experimental studies of the treatment of water contaminated with MO using the oxidative method. After analysing the dependence of the oxidation of dyes on various factors affecting the results of the study (concentration of chemical reagents, concentration of dye, contact time, and pH), the optimal efficiency of removing dye from contaminated water was achieved.

Research methodology

In experimental studies, the selection of chemical reagents, their concentrations, reaction time, and pH range was based on experimental studies conducted by scientists [22-25]. MO, which is widely used in chemical laboratories, etc., was chosen as the dye. The object of the study was clean (deionised) water, which was artificially contaminated with organic matter, i.e., dye. Experimental studies were carried out by changing the following parameters: H_2O_2 concentration, $FeSO_4$ concentration, dye concentration (*C-MO*), pH, and reaction time. The concentration of dyes in wastewater is not regulated. Still, knowing the permissible COD (Chemical oxygen demand) value in sewage, it can be converted into the concentration of total organic carbon (Table 1). Here, *W* denotes the carbon mass fraction in the dye molecule, and *C-MO* - the permissible methyl orange concentration calculated from the total organic carbon concentration. The permissible dye concentration was obtained by dividing the total organic carbon concentration by the carbon mass fraction of the dye. And the concentration of total organic carbon can be converted into the permissible concentration of dye. Suppose the permissible COD value in wastewater discharged into the natural environment according to the Wastewater Management Regulation in Lithuania [26] is 125 mg/L O_2. In that case, this corresponds to

a total organic carbon concentration in wastewater of 46.875 mg/L, which in turn corresponds to a dye (methyl orange) concentration of 91.25 mg/L.

The maximum of *C-MO* chosen in the experimental study was approximately 2.74 times higher than the permissible limit value according to the Lithuanian Wastewater Management Regulation, except for the experimental studies that investigated the influence of dye concentration (when other parameters were constant) on the efficiency of the oxidative method. During them, the *C-MO* of dye varied in the range of 50 mg/L - 750 mg/L.

Table 1

Permissible concentrations of individual dyes in wastewater have been recalculated from COD

Dye	**Molecular formula of the dye**	**Molecular weight of the dye [g/mol]**	**Carbon mass fraction *W* in the dye formula in parts per unit [-]**	**Permissible dye concentration [mg/L]**
MO	$C_{14}H_{14}N_3O_3SNa$	327.33	0.5137	91.25

Without separating the organic matter as a whole into individual chemical compounds, the concentration in potentially contaminated water can be assessed according to the COD parameter. If only a single organic compound (dye) is present in contaminated water, its concentration is proportional to the COD value. For experimental assessment, the measurement of the organic carbon content using a TOC (Shimadzu) total carbon analyser was chosen, and the measured total carbon concentration was converted into the dye concentration. The selected method for measuring the total carbon concentration is significantly faster than the COD method, which is why it was chosen in experimental studies. The concentration of organic matter in water can be reduced by applying an oxidative method based on the Fenton chemical reaction.

The concentrations of H_2O_2 and $FeSO_4$ reagents used in the Fenton reaction were selected based on experimental studies conducted by foreign scientists. The Fenton reaction time was chosen from 1 min to 180 min to find the optimal time value corresponding to maximum process efficiency and to study the process kinetics.

The pH values in the experimental studies were selected between 2.00 and 8.00 to find the optimal pH value corresponding to maximum process efficiency and to study the influence of pH on the process. According to the Lithuanian Wastewater Management Regulation, the pH of wastewater must be in the range between 6.5 and 9.5 before being discharged into the sewer, therefore, it is recommended to alkalise or acidify the water contaminated with organic substances (dyes) after the Fenton chemical reaction before discharge, so that the wastewater pH meets the permitted pH values set out in the Lithuanian Wastewater Management Regulation.

The total carbon concentration is measured to assess the rate of decomposition of organic substances (dye) and the efficiency of removal from contaminated water.

A calibration curve for total carbon is created from 7 prepared calibration solutions. Standard solutions are prepared by dissolving the required amount of cellulose in 50 mL of deionised water - determination of Dissolved Total Organic Carbon. The liquid samples were measured using a Shimadzu TOC-VCSH analyser with an ASI-V auto sampler system.

Then, the Fenton oxidation of the test water sample with MO is carried out by adding the appropriate amounts of the following chemical reagents to the test solution with the dye:

- $FeSO_4$ salt;
- H_2O_2 (30 %) solution.

Dyes are decomposed into low molecular weight organic compounds during the Fenton reaction. The dye molecules break down, changing their structure, and the colour of the water sample changes (the solution fades).

If necessary, pH-adjusting solutions are added to the tested water sample. 0.1 N NaOH and 0.1 N HNO_3 solutions were used to adjust the pH of the solutions. The pH of the sample was measured before and after the oxidation process with a pH meter, WTW InoLab pH 720. The sample with the appropriate amounts of chemical reagents was stirred on a magnetic stirrer for 1 min to 180 min. After that, the water samples were filtered through a 0.45 μm membrane filter to remove suspended substances.

The tests were performed at room temperature, and the temperature of the prepared samples was 21 °C - 23 °C.

Quality assurance. Deionised water was used in the experimental studies, which meets the requirements of the LST EN ISO 3996:1996/P-2009 [26, 27] standard: quality level 3 - water produced by deionisation, suitable for most liquid laboratory tests and the production of chemical reagents. Main parameters: pH: 5.00 - 7.50; *SEL* (specific electrical conductivity) < 0.5 mS/cm; dissolved oxygen content < 0.4 mg/L; residue after evaporation and drying at (105 ± 2) °C < 2 mg/kg.

Chemical reagents corresponding to the "clean for analysis" cleanliness class, class A measuring vessels, were used in the studies. Additionally, blank sample tests were performed.

The pH meter was calibrated with buffer solutions of known pH before measurements.

High-precision (5 digits) analytical balances and a total carbon concentration analyser were used in the studies.

A stopwatch with an accuracy of ± 0.1 s was used for time measurement.

To ensure the reliability of the experimental results obtained, the samples were measured 3 times, and statistical parameters (mean, mean standard deviation, and confidence interval) were calculated, with a significance level of $p = 0.05$.

During the study, the dependence of the dye concentration on the concentrations of the dye and chemical reagents, reaction time, and pH was determined. During the experimental studies, solutions with different H_2O_2 concentrations (respectively without H_2O_2; 0.6 %; 0.9 %; 1.2 %; 1.5 %; 3.0 %; 6.0 %; 12 %, 18 % and 24 %), different $FeSO_4$ concentrations (respectively without $FeSO_4$; 0.02 g/L; 0.10 g/L; 0.2 g/L; 0.40 g/L; 0.60 g/L; 0.8 g/L, 1.0 g/L; 1.4 g/L, 2.0 g/L), various *C-MO* of the dye (50; 75; 100; 125; 150; 175; 200; 225; 250; 300; 500; 750) mg/L were prepared. Experimental studies were performed with different chemical reaction times (1, 5, 10, 30, 60, 120, 180) min.

A calibration curve for total carbon was constructed during the experimental studies. As the total carbon concentration in the aqueous solution increases, the signal in the selected total carbon concentration range rises proportionally. An empirical linear equation was constructed, which describes the calibration curve data well, as shown by the high value of the correlation coefficient R^2 ($R^2 = 0.9893$).

Research results and discussion

The influence of the concentration ratio of chemical reagents on the efficiency of the process

Oxidation by the Fenton reaction is a proven and economically justified process for the destruction of various hazardous pollutants in wastewater. The results of the studies can be helpful in the development of treatment systems for sewage containing multiple dyes.

H_2O_2 plays a vital role as a source of the $HO^{\bullet}$ radical, which is generated in an aqueous solution during the Fenton chemical reaction. The complete mineralisation of MO occurs according to reaction (1) [28]:

$$C_{14}H_{14}N_3O_3SNa + 43H_2O_2 \rightarrow 14CO_2 + 3HNO_3 + NaHSO_4 + 48H_2O \quad (1)$$

The concentration of 3 % H_2O_2 was in the range from 0 mg/L to 24.0 mg/L. The data on the dependence of the dye *C-MO* on the concentration of hydrogen peroxide (H_2O_2) solution used are presented in Figure 1.

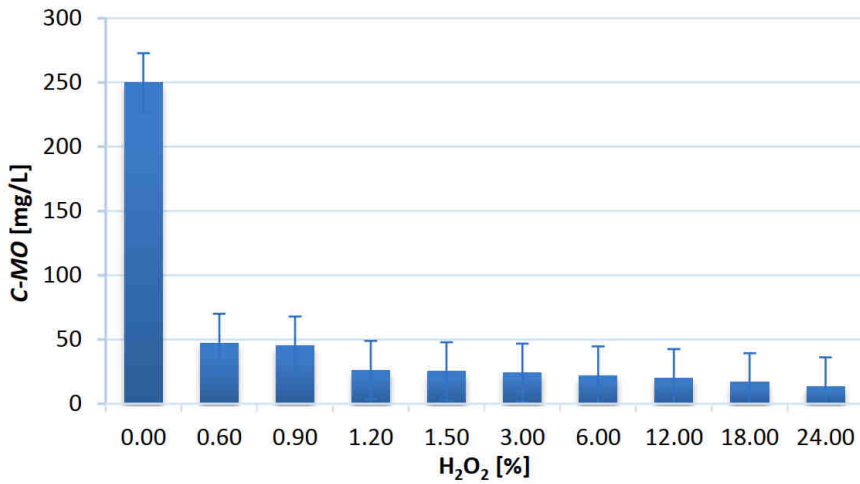

Fig. 1. Dependence of *C-MO* in aqueous solution on hydrogen peroxide concentration, when the dye concentration is 250 mg/L, the $FeSO_4$ concentration is 0.02 %, and the reaction time is 2 hours

It was found that the highest efficiency of the Fenton oxidation reaction in removing MO was achieved when the hydrogen peroxide concentration in the aqueous solution reached 24.0 %. The data obtained during the study were used to calculate the dye removal efficiency and are presented in Table 2.

Table 2

Dependence of the oxidative removal of MO on the concentration of hydrogen peroxide in the solution, C_0-*MO* is 250 mg/L

H_2O_2 concentration [%]	0.00	0.60	0.90	1.2	1.5	3.0	6.0	12.0	18.0	24.0
Dye removal efficiency [%]	0.0	81.1	81.9	89.5	89.9	90.3	91.2	92.0	93.3	94.5

As can be seen from Table 2, the efficiency of MO removal increases from 81.1 % to 94.5 % with increasing hydrogen peroxide concentration in aqueous solution from 0.60 % to 24.0 %. Hydrogen peroxide is a weak acid; therefore, its addition slightly reduces the pH of the solution. As the hydrogen peroxide concentration varies from 0 % to 24 %, the measured pH values of the aqueous solution change from 7.00 to 4.80.

An increase in H_2O_2 concentration enhances the production of hydroxyl radicals and improves dye degradation efficiency. However, excessive dosages can lead to self-decomposition of H_2O_2 and scavenging of $HO^{\bullet}$ radicals, thus lowering the effective radical yield. Literature emphasises that the optimal dosage depends strongly on the initial pollutant load and solution pH; therefore, universal conditions cannot be applied, and process optimisation is required for each specific wastewater type. Overdosing of H_2O_2 may even reduce mineralisation efficiency by 10 % - 20 %, highlighting the importance of balance between reagent dose and radical availability.

Similar trends have been reported in recent studies: Xu et al. [29] observed > 99 % MO removal at an optimal H_2O_2 dosage (16 mmol L^{-1}, pH = 3.00), but efficiency declined when peroxide was overdosed. Likewise, Mukwevho et al. [30] demonstrated ~99 % MO degradation within 60 min using a photo-Fenton-like heterojunction catalyst, highlighting how intensified processes can overcome limitations of the classical system. In contrast, Liuge et al. [31] tested cellulose aerogels for textile dye removal and found that MO removal under mild pH six conditions reached only ~16 %, much lower than in Fenton systems, which underlines the superior oxidative capacity of the Fenton process for azo dyes.

The influence of another chemical reagent - $FeSO_4$, on which Fenton oxidation depends, on the oxidation reaction was studied.

Based on the results obtained during the experimental studies, a graph of the dependence of *C-MO* aqueous solution on the concentration of iron sulphate ($FeSO_4$) is drawn up, which is shown in Figure 2.

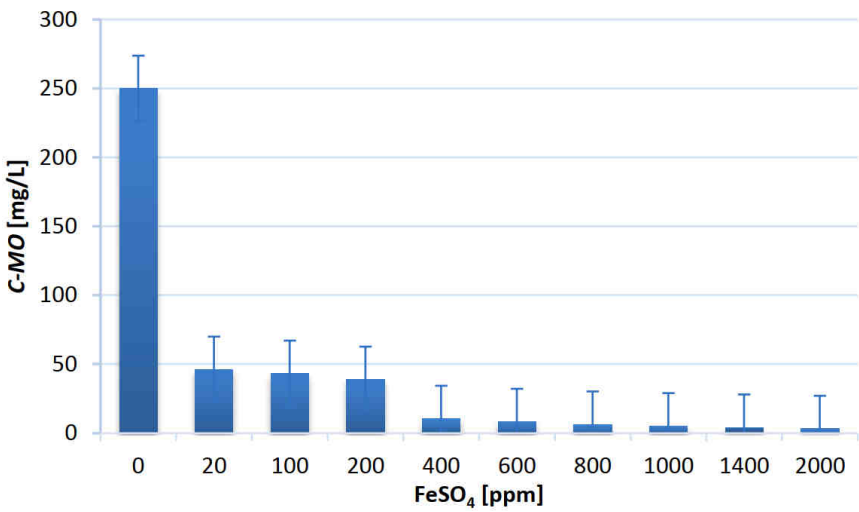

Fig. 2. Dependence of *C-MO* in aqueous solution on iron sulphate concentration, when the dye concentration is 250 mg/L, H_2O_2 concentration is 0.60 %, and the reaction time is 2 hours

In this experimental study, the $FeSO_4$ concentration in the aqueous solution ranged from 0.02 % to 2.00 %. It was found that the highest efficiency of the Fenton oxidation reaction in removing MO was achieved when the $FeSO_4$ concentration in the aqueous solution reached 2.00 %. Iron sulphate is a weak acid; therefore, its addition to the tested aqueous solution slightly reduces the pH value of the solution. The amount of ferrous sulphate added is small (ranging between 1 mg and 100 mg), so this effect is of little significance.

The data obtained during the study were used to calculate the dye removal efficiency and are presented in Table 3.

Table 3

Dependence of the oxidative removal of *C-MO* of ferrous sulphate in the solution, when the initial dye concentration is 250 mg/L

$FeSO_4$ concentration [ppm]	0	20	100	200	400	600	800	1000	1400	2000
Dye removal efficiency [%]	0.0	81.5	82.7	84.4	95.8	96.6	97.5	97.9	98.3	98.7

As can be seen from Table 3, the efficiency of MO removal increases from 81.5 % to 98.7 % with increasing iron sulphate concentration in aqueous solution from 0.02 % to 2.00 %.

The increase of Fe^{2+} dosage accelerates $HO^{\bullet}$ radical formation, yet excessive concentrations may generate large amounts of Fe(III) sludge, creating additional treatment costs. This is particularly important in real applications, since sludge disposal significantly affects overall process economics. To mitigate these drawbacks, hybrid catalysts such as Fe/Cu foams, Fe/zeolites, or magnetically retrievable composites are being tested, allowing high radical yields with reduced sludge formation.

Recent findings by Vainoris et al. [32] reported nearly 100 % MO decolourisation within 90 s using a heterogeneous Fe/Cu foam catalyst, suggesting that engineered catalysts can achieve very high efficiencies while reducing sludge-related issues. Furthermore, Makara et al. [33] investigated meat and bone meal wastewater treatment using a Fenton-coagulation system and obtained ~97 % colour removal and ~70 % COD reduction, confirming that Fe-based systems are efficient even in complex effluents.

The role of pH in the efficiency of the process

Another factor that affects the Fenton oxidation reaction, and at the same time the decomposition of organic substances (dyes) in the solution, is pH. The optimal pH for Fenton oxidation was determined during experimental studies. The observed dependence on pH is critical for practical implementation. Although the laboratory results confirm that the most efficient degradation occurs at acidic pH values (2.00 - 4.00), in real wastewater treatment, this requires pre-acidification and subsequent neutralisation, which increases operating costs. Therefore, research is increasingly focusing on modified Fenton systems (e.g., photo-Fenton, heterogeneous Fenton) that can operate efficiently at a wider pH range, reducing the need for extensive chemical conditioning of wastewater.

The results of the dependence of the dye *C-MO* on the solution pH during the Fenton reaction are presented in Figure 3.

The highest *C-MO* in the solution was determined when the pH value reached 7.0 and 8.0, and was equal to 147.37 and 157.89 mg/L, respectively.

Figure 4 shows that the highest efficiency was obtained at pH 2.00 and 3.00, when *C-MO* in aqueous solution reached 5.26 and 6.32 mg/L, respectively.

Based on the analysis of scientific literature, it was observed that the pH value range required for an effective Fenton oxidation process is from 2.00 to 4.00 [29]. Other scientists [32, 33] provide the optimal pH for the oxidation process according to the Fenton reaction in an aqueous medium to be 3.00 - 4.00; therefore, it can be stated that the optimal pH values for the Fenton reaction were determined during experimental studies, which corresponded to the experimental results obtained by other scientists.

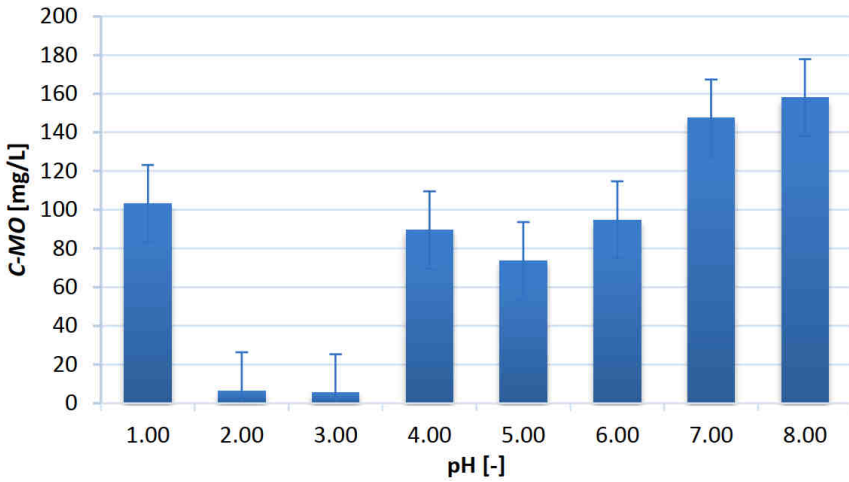

Fig. 3. Dependence of *C-MO* in aqueous solution on pH, when the dye concentration is 250 mg/L, H_2O_2 concentration is 0.60 %, $FeSO_4$ concentration is 0.02 %, and the reaction time is 2 hours

The data obtained during the study were used to calculate the dye removal efficiency and are presented in Table 4.

Table 4

Dependence of the oxidative removal of *C-MO* of ferrous sulphate in the solution, when the initial dye concentration is 250 mg/L

pH [-]	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
Dye removal efficiency [%]	58.72	97.48	97.88	64.2	70.52	62.12	41.04	36.84

As can be seen from Table 4, the efficiency of MO removal varies between 36.84 % and 97.88 % in the pH range of 1.00 - 8.00.

According to the Lithuanian Wastewater Management Regulation, the pH of wastewater must be between 6.50 and 9.50 before being discharged into the sewer; therefore, it is recommended to alkalise the treated water after the Fenton reaction before being discharged into the sewage network.

The optimal pH range of 2.00 - 4.00 observed here corresponds well with recent literature. Bi et al. [34] showed ~96 % MO removal using a pyrite-activated Fenton-like process at acidic pH, while efficiency dropped significantly under neutral or alkaline conditions. This confirms that acidic conditions are essential for effective $HO^{\bullet}$ generation and dye degradation.

Influence of initial dye concentration

The decline in removal efficiency with increasing C_0-*MO* illustrates the radical-limited nature of the process: at high dye load, available hydroxyl radicals become insufficient for complete degradation. This indicates the importance of adjusting oxidant dose according to pollutant concentration, or combining Fenton oxidation with supplementary processes (e.g., UV irradiation, adsorption, or ozonation) to maintain high efficiency even under high pollutant loads. The results of the dependence of *C-MO* in an aqueous solution on the initial dye concentration (C_0-*MO*) are presented in Figure 4.

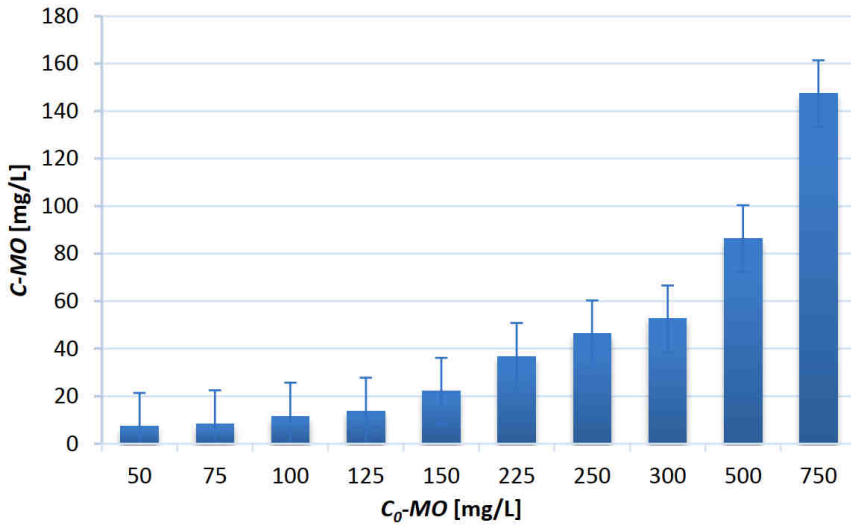

Fig. 4. The dependence of *C-MO* in an aqueous solution on C_0-*MO*, when the H_2O_2 concentration is 0.60 %, the $FeSO_4$ concentration is 0.02 %, and the reaction time is 2 hours

The data obtained during the study were used to calculate the dye removal efficiency and are presented in Table 5.

Table 5

Dependence of the final *C-MO* on the dye concentration, when the H_2O_2 concentration is 0.60 % and the $FeSO_4$ concentration is 0.02 %

***C-MO* [mg/L]**	50	75	100	125	150	225	250	300	500	750
Dye removal efficiency [%]	85.3	88.8	88.4	89.1	85.3	83.6	81.5	82.5	82.7	80.4

After evaluating the data in Table 5 and calculating the efficiency of azo dye (MO) removal from aqueous solution, it was found that it ranges between 80.4 and 89.1 %.

The decline in removal efficiency with increasing C_0-*MO* indicates a radical-limited regime, where available HO• radicals are insufficient to oxidise all dye molecules. Zhang et al. [35] found a similar decrease in MO removal efficiency from ~93 % to ~77 % as initial dye concentration increased from 15 mg/L to 60 mg/L in a WO_3/H_2O_2 system. Advanced configurations, such as photo-Fenton or heterogeneous catalysts, have been proposed to sustain high efficiency even at higher pollutant loads.

The role of contact time in dye removal efficiency

Reaction time in oxidation reactions is also a very important factor in the degradation of organic substances, such as dyes. For this reason, it was chosen to determine the dependence of dye degradation efficiency on reaction time in experimental studies.

Reaction time analysis clearly demonstrates that most of the degradation occurs in the first 60 - 120 minutes. Prolonged reaction does not significantly improve removal efficiency but increases energy and reagent costs. Similar trends are described in other studies, confirming that optimisation of contact time is essential to balance treatment efficiency and operating costs. From a practical perspective, limiting the reaction to 2 h ensures high degradation while avoiding unnecessary expenditures [36, 37].

The rate of chemical reaction can be affected by ambient temperature; therefore, in an effort to reduce this influence, all experimental studies were carried out at room temperature - 21 ±1 °C, and an air conditioner was used to maintain the temperature. The data on the dependence of dye concentration on reaction time are presented in Figure 5.

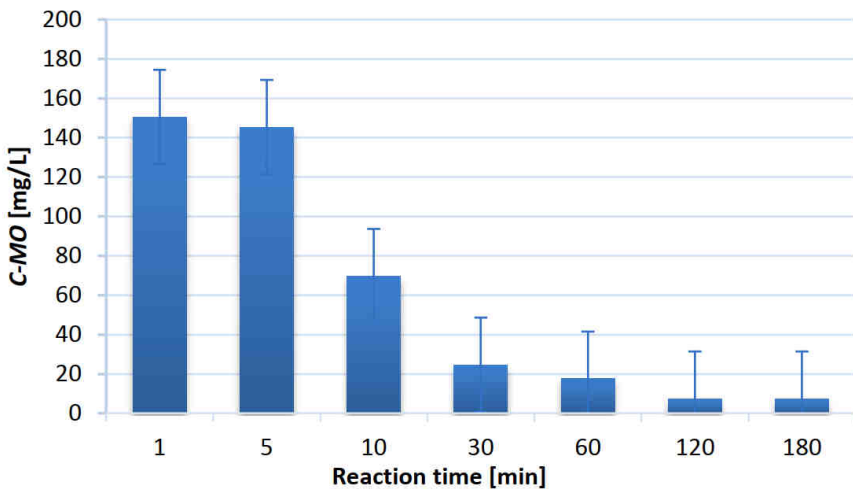

Fig. 5. Dependence of *C-MO* on reaction time, when the dye concentration is 250 mg/L, H_2O_2 concentration is 12 %, and $FeSO_4$ concentration is 1 %

From Figure 6, it is seen that the *C-MO* decreased uniformly with the increase in the chemical reaction time. When the oxidation reaction took place for 1 min and 5 min, the dye concentration reached 150.5 mg/L and 145.3 mg/L, respectively. After 10 minutes, the dye concentration reached 69.58 mg/L; after 30 minutes, 24.7 mg/L; after 60 minutes, the concentration reached 17.6 mg/L, and after 120 minutes, it decreased significantly and

reached 7.4 mg/L. It was observed that when the experiment was carried out for a longer time, i.e., 3 hours, the dye concentration in the aqueous solution was similar to that after two hours; therefore, it was concluded that it was inappropriate to carry out the chemical reaction for more than 2 hours. The observed rapid removal within the first 60 min and the plateau after 120 min are consistent with recent studies. Bi et al. [36] reported that pyrite-activated Fenton-like reactions achieved ~96 % MO removal within 120 min, while Mukwevho et al. [30] observed nearly complete degradation within 60 min using a photo-Fenton-like heterojunction catalyst, with little additional benefit beyond this time.

It is from these results that one can judge the optimal chemical reaction time for more complete oxidation according to Fenton. After two hours, MO was most efficiently decomposed.

The data obtained during the study were used to calculate the dye removal efficiency and are presented in Table 6.

Table 6

Dependence of *C-MO* on Fenton reaction time, when dye concentration is 250 mg/L, H_2O_2 concentration is 12 %, and $FeSO_4$ concentration is 1 %

Time [min]	1	5	10	30	60	120	180
Dye removal efficiency [%]	39.8	41.9	72.2	90.1	93.0	97.1	97.1

After evaluating the data in Table 6 and calculating the efficiency of removing azo dye (MO) from aqueous solution, it was found that it varies between 39.8 % and 97.1 %.

The advantage of the oxidative method (according to the Fenton reaction) is that when purifying contaminated water with this method, organic pollutants (dyes) are not transferred from one phase to another. During the purification process of the tested contaminated water, small amounts of precipitates containing insoluble Fe(III) compounds (hydroxides) are formed. The precipitates formed are easily separated by filtration.

Conclusion

1. The efficiency of MO removal from aqueous solution increases from 81.5 % to 98.7 % with increasing iron sulphate concentration in aqueous solution from 0.02 % to 2.00 %. This trend can be explained by the higher availability of Fe^{2+} ions, which promotes hydroxyl radical ($HO^{\bullet}$) generation and accelerates the oxidation of dye molecules.
2. Experimental studies demonstrated that the efficiency of MO removal is significantly influenced by both the hydrogen peroxide concentration and the solution pH. Increasing the H_2O_2 concentration from 0.6 % to 24 % enhanced the removal efficiency from 81.1 % to 94.5 %, as a higher H_2O_2 content provides more favourable conditions for the formation of $HO^{\bullet}$ radicals; however, excessively high concentrations may promote H_2O_2 self-decomposition and radical scavenging, thereby reducing the overall process efficiency. Investigation of the pH influence in the range from 1.00 to 8.00 revealed that the highest degradation efficiency is achieved at pH 2.00 - 3.00, as under these conditions, iron ions remain soluble and catalytically active while hydrogen peroxide remains sufficiently reactive, leading to optimal Fenton reaction performance. Accordingly, a pH of 3.00 is recommended for conducting the Fenton process. Since Lithuanian wastewater management regulations require the final pH to

be within the range of 6.50 - 9.50 before discharge into the sewer network, the treated solution must be neutralised to the required interval after the Fenton reaction.

3. During experimental studies of the influence of the concentration of azo dye (MO) on its removal efficiency, it was determined that the removal efficiency from aqueous solution ranges between 80.4 % and 89.1 %, when *C-MO* in the solution ranged from 50 mg/L to 750 mg/L. The decrease in efficiency at higher concentrations indicates that the number of hydroxyl radicals becomes insufficient to oxidise all dye molecules, leading to incomplete degradation.
4. In experimental studies of the influence of contact time on the degradation efficiency of the selected dye, the efficiency ranged from 39.8 % to 97.1%. The optimal oxidation reaction time for the removal of the selected dye is 2 hours, which corresponds to a maximum efficiency value of 97.1 %, and the efficiency no longer increases when it is extended; therefore, it is inappropriate to carry out the oxidation reaction for more than 2 hours. This suggests that most degradation occurs in the first 60 min - 120 min due to rapid HO· radical activity, while prolonged reaction times only increase energy and reagent consumption without significantly improving removal.
5. Considering the obtained results, it can be stated that the Fenton oxidation process is a promising method for practical industrial wastewater treatment, as it demonstrates high efficiency in the degradation of azo dyes even at high pollutant concentrations and in complex wastewater matrices. Nevertheless, to enhance the sustainability of the method, further studies are needed to optimise reagent dosages, reduce iron sludge generation, and explore the application of hybrid Fenton-like processes (e.g., photo-Fenton or catalyst-based systems), which, as recent studies have shown, can ensure high degradation efficiency even under near-neutral pH conditions.

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