

Evaluation of the Effectiveness of Iron Oxide Nanoparticles in the Remediation of Pollutants in Domestic Wastewater from the Chilca River

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Abstract—Magnetite (Fe_3O_4) nanoparticles represent a revolutionary solution to the alarming water pollution crisis, offering an innovative and highly effective approach to remediate pollutants in domestic wastewater. This study evaluates their practical application in the Chilca River in Huancayo, Peru, a water body severely affected by untreated discharges that pose a serious risk to public health and sustainable development. Focusing on key parameters such as Chemical Oxygen Demand (COD), turbidity, Total Suspended Solids (TSS) and oils and fats, the results showed significant reductions: COD from 442.5 mg/L to 135.2 mg/L, turbidity from 98.5 Nephelometric Turbidity Units (NTU) to 50.2 NTU, TSS from 120 mg/L to 62 mg/L and oils and fats from 45.2 mg/L to 11.3 mg/L, while maintaining stable pH levels. Regression analysis confirmed that the concentration of magnetite nanoparticles plays a key role in process efficiency. These findings not only validate the efficacy of this technology in high pollution contexts, but also highlight its scalable and sustainable potential to address similar problems in polluted water bodies worldwide, contributing to improved water quality and public health.

Keywords—magnetite, wastewater, COD, turbidity, total suspended solids, oils and fats, remediation

I. INTRODUCTION

Growing concern about water quality has highlighted the importance of effective wastewater treatment to protect both ecosystems and human health [1]. This problem is critical in regions where water bodies are severely polluted, such as in India, where the Ganges River faces pH alterations caused by nitrates and phosphates from domestic wastewater; the Yamuna has high turbidity levels due to suspended solids; and the Kali suffers from oil pollution from domestic activities. In addition, groundwater in the region contains high concentrations of arsenic, a toxic carcinogen that poses a serious risk to public health [2]. Internationally, other rivers face similar problems: in Switzerland, the Glatt River has pH alterations due to domestic discharges; in Nigeria, the Niger River is highly polluted by organic matter; in Brazil, the Amazon River faces contamination by oil and grease from urban activities; in France, the Rhone River suffers from high turbidity caused by sediment and sewage discharges; and in the United States, the Mississippi River has high turbidity due to suspended solids [2, 3]. In the face of these challenges, nanomaterials, such as Nanoparticles (NPs), have emerged as innovative solutions thanks to their unique properties, enabling applications in environmental biotechnology, such as pollution abatement, wastewater treatment, environmental

remediation, dye degradation and water purification [4]. Nanotechnology applied to wastewater management, through the use of nanocatalysts, nanoadsorbents and nanomembranes, facilitates the efficient removal of heavy metals, pesticides, microorganisms and organic pollutants [5]. Nanoparticles, due to their small size and unique surface properties, have an exceptional ability to treat contaminants that are difficult to remove by conventional methods, achieving recovery rates of up to 95% and aligning with UN goals to improve access to safe drinking water and promote sustainable water management [1]. In particular, iron oxide nanoparticles have proven to be highly effective in remediating contaminated water by adsorbing pollutants such as arsenic, whose presence in groundwater, as mentioned above, represents a serious danger to human health as it is associated with diseases such as skin, bladder and lung cancer, as well as other serious problems such as diabetes, cardiovascular disorders and neurological damage [6]. These technologies not only address critical pollution problems, but also promote sustainable environmental remediation systems, integrating technological advances with practical and accessible solutions, especially in the most vulnerable communities. This innovative approach not only responds to today's environmental challenges, but also drives sustainable development and strengthens human well-being by providing resilient tools that improve water quality and people's living conditions [7].

Due to the problems identified in different countries, this research aims to evaluate the effectiveness of magnetite nanoparticles (Fe_3O_4) in the remediation of domestic wastewater from the Chilca River in Huancayo, Peru. The nanoparticles will be used as catalysts in the oxidation reactions, with the aim of improving the remediation processes, significantly reducing the pollutants present and contributing to the recovery of this highly affected water body. This innovative approach seeks not only to validate the use of nanoparticles under practical conditions, but also to establish them as a viable and sustainable solution to address similar problems in polluted rivers globally, thus promoting the improvement of water quality and public welfare.

II. LITERATURE REVIEW

Research at the Department of Global Smart City, Sungkyunkwan University (SKKU) in Suwon, Republic of Korea, and at China University in Beijing has made

significant progress in the development of nanotechnologies applied to wastewater remediation, such as nano-enhanced sorbents and activated carbon functionalized nanoparticles ($\text{Fe}_3\text{O}_4/\text{AC}$), which have proven to be highly effective in the removal of dyes such as Rhodamine B (RhB) and orange methyl (MO), in addition to facilitating rapid magnetic separation and recycling of the adsorbent, opening new avenues for practical treatments [8, 9]. In parallel, recent studies have proposed the use of an innovative nanocomposite, Fe@N-BC , which incorporates metal oxide and biochar enriched with quaternary ammonium groups, standing out for its superior adsorption capacity and speed compared to commercial adsorbents, and showing the possibility of being effectively regenerated for reuse in the removal of anionic contaminants such as phosphate [10]. In addition, this hybrid material was exhaustively characterized by techniques such as infrared spectroscopy, X-ray diffraction, thermogravimetric analysis and scanning electron microscopy, and its magnetic properties were evaluated through magnetic hysteresis, which has contributed to a better understanding of the adsorption mechanisms and molecular interactions involved in the removal of contaminants [11]. This comprehensive approach reinforces the feasibility of using Fe_2O_3 compounds in environmental remediation, given their low cost, chemical stability, and efficient use of visible light, consolidating them as a sustainable and effective solution for the purification of contaminated waters. Iron nanoparticles, such as magnetite (Fe_3O_4), are essential in wastewater remediation due to their low toxicity, abundance, and ease of procurement. They are synthesized using various techniques such as co-precipitation and microemulsion, but biosynthesis using plant extracts is an eco-friendly alternative that reduces toxicity and costs [12]. In particular, nano- FeS , optimized to increase its dispersion through ultrasonic precipitation, showed a mesoporous structure that facilitates the effective reduction of Cr(VI) to Cr(III) , reaching a removal of up to 94.97% in dynamic tests [13]. In addition, in Quito, Ecuador, a complementary wastewater treatment was applied using the EDTA-modified Fenton process, optimizing molar ratio and agitation conditions, resulting in total fecal coliform inactivation and high reduction of surfactants and COD in a short time, complying with EPA standards. [14]. Advanced oxidation processes, especially Fenton and Fenton-type reactions, have shown great efficacy in wastewater treatment, using iron oxide catalysts such as magnetite, hematite, goethite, and ferrihydrite. These catalysts, valued for their stability and non-toxicity, vary in efficacy depending on the substrate, pH, and reaction conditions. Innovations such as the incorporation of UV-Vis radiation and transition metals promise to further optimize these processes [15].

Iron nanoparticles have proven to be a valuable tool in wastewater treatment due to their unique physicochemical properties, which allow for the adsorption and removal of various contaminants. Among the different types, magnetite nanoparticles (Fe_3O_4) stand out for their high efficiency in removing heavy metals and dyes, as well as their easy recovery through the application of magnetic fields [16]. These characteristics make magnetite an attractive and cost-effective option for water purification [17]. Moreover, these nanoparticles can act as adsorbents, photocatalysts, and

coagulants in water treatment, depending on their surface modifications or compositions [18, 19]. Another type of iron nanoparticle is hematite ($\alpha\text{-Fe}_2\text{O}_3$), which is eco-friendly, non-toxic, and corrosion-resistant. Studies have shown its significant capacity to reduce contaminants like chromium (VI), achieving a reduction of 96.09% under specific photocatalysis conditions using nanoparticles synthesized via the Sol-Gel method [20].

On the other hand, goethite ($\alpha\text{-FeOOH}$) has proven effective in the remediation of heavy metals such as lead in wastewater. Its efficiency depends on factors such as the amount of adsorbent, pH, and contact time, allowing for a significant reduction in lead concentrations under controlled conditions [21, 22]. Maghemite ($\gamma\text{-Fe}_2\text{O}_3$), obtained through co-precipitation and functionalized with starch, has shown high effectiveness in adsorbing chromium (VI) from wastewater due to its superparamagnetic nature and enhanced adsorption properties [23]. Similarly, iron hydroxide (Fe(OH)_3), though less common, has been utilized for the removal of fluoride ions from water, demonstrating its potential as a promising adsorbent in this field [24–26].

Finally, Zero-Valent Iron nanoparticles (nZVI) are among the most studied due to their ability to efficiently remove contaminants such as heavy metals, phosphates, and nitrates from wastewater. The remediation mechanisms include adsorption, photocatalytic degradation, and reduction-precipitation, depending on the conditions and surface composition of the nanoparticles [27–29]. Despite advancements in the use of these nanomaterials, magnetite (Fe_3O_4) remains of particular interest for this research due to its high performance in contaminant removal and recovery capacity, making it a key tool for efficient wastewater treatment.

Magnetite nanoparticles (Fe_3O_4) have been extensively used for the removal of various contaminants in wastewater, including heavy metals such as As(V) , Cr(VI) , Cu(II) , Pb(II) , and Hg(II) , as well as non-biodegradable dyes and pigments from the textile, paint, and leather industries. Additionally, they have demonstrated efficacy in eliminating bacteria, pathogenic microorganisms, and phosphates, which pose a global environmental challenge [30, 31]. This study will evaluate their effectiveness in remediating contaminants in the Chilca River, Junín region, Peru, where untreated wastewater pollution is a critical issue.

The discussion also extends to the implications of the toxic effects of nanoparticles and strategies to mitigate their release into the environment, such as fouling and encapsulation [16]. These developments not only strengthen the adsorption capacity and chemical reactivity of nanomaterials, but also provide valuable directions for future research and practical application in environmental engineering. By analyzing current and future trends, this study seeks to provide a comprehensive perspective on how nanomaterials are revolutionizing the removal of pollutants from water, offering sustainable and effective solutions to global environmental challenges [17].

III. MATERIALS AND METHODS

A. Study Area and Samples

The study was carried out on the Chilca River, located in

the province of Huancayo, Department of Junín, Peru, due to its high contamination by untreated domestic wastewater, which significantly affects its quality. During the investigation, strict safety protocols were followed, including the use of appropriate Personal Protective Equipment (PPE) for sample collection and proper preservation, in order to avoid any alteration in their original physicochemical characteristics.

The process began with the strategic selection of several sampling points along the river, prioritizing areas where wastewater discharges were most evident. A key sampling point was located at coordinates 12°4'28.19"S and 75°11'50.81"W, due to the visibility of the discharges. During collection, on-site measurements of critical parameters, such as pH and water temperature, were made using pre-calibrated portable equipment, ensuring the accuracy and consistency of the results obtained. To avoid interference from plastic contaminants, high-purity glass and plastic containers were used in sample collection. Each sample was labeled with detailed information about the place and time of collection, ensuring adequate monitoring through the use of identification plates to guarantee the integrity of the samples, these were transported vertically inside thermal boxes (coolers), where the previously packed, labeled and labeled glass containers ensured their protection and conservation.

Preliminary analyses of parameters such as Chemical Oxygen Demand (COD), pH, Ammonia, Sulfide, Suspended Solids (TSS), and (COD) as physicochemical parameters of the water samples collected from the water treatment plant. The results of the analysis are presented in Table 1. The results of the analysis are presented in Table 1. The results of the analysis are presented in Table 1.

B. Synthesis of Iron Oxide Nanoparticles

The synthesis process of iron oxide nanoparticles (Fe_3O_4) by the coprecipitation method, as shown in Fig. 1, starts with the dissolution of iron hydroxide ($\text{Fe}(\text{OH})_3$) in hydrochloric acid (HCl), obtaining a solution of ferric chloride (FeCl_3). Next, a mixture of ferric chloride (FeCl_3) and ferrous sulphate (FeSO_4) is prepared in a molar ratio of 1.5:1 (Fe^{3+} : Fe^{2+}), using 20.3 grams of FeCl_3 in 150 mL of solution and 13.9 grams of FeSO_4 in 100 mL.

The reaction is controlled by slowly adding a sodium hydroxide (NaOH) solution to the mixture under constant stirring, thus facilitating the precipitation of magnetite nanoparticles. The 1.5 M NaOH solution is incorporated at a rate of 0.5 mL per second by vigorous mechanical stirring [32]. To improve homogeneity and to promote the formation of Fe₃O₄ nanoparticles, visible as a black precipitate, ultrasonic agitation is applied. Subsequently, the mixture is heated in a water bath at 65 °C for 30 minutes, promoting the complete precipitation of the particles, which are separated by centrifugation and washed with deionised water and ethanol to remove impurities. Finally, they are dried to obtain magnetite nanoparticles (Fe₃O₄) as the final product [33].

The nanoparticles were characterised using techniques such as X-Ray Diffraction (XRD), Field Emission Scanning Electron Microscopy (FE-SEM), UV-visible and Fourier Transform Infrared Spectroscopy (FT-IR).

spectroscopy [34, 35]. The UV-visible spectrum showed an absorption peak at 340 nm, while the FT-IR analysis identified peaks at 519 cm^{-1} , confirming the formation of magnetite iron oxide. In addition, XRD analysis revealed an average crystallite size of approximately 45 nm, indicating that the nanoparticles have a spherical morphology [36].

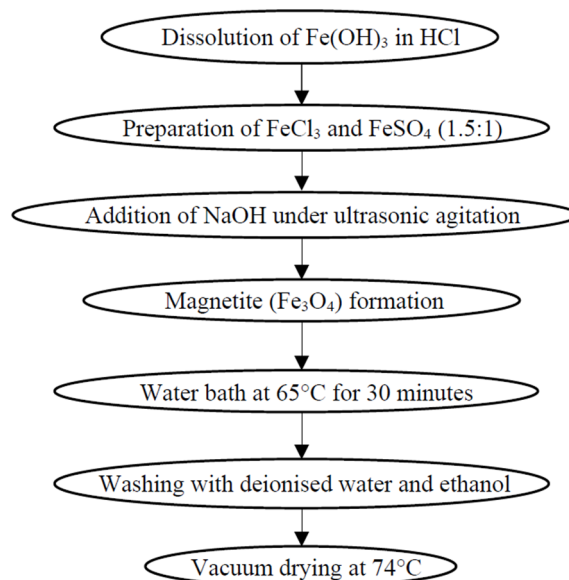


Fig. 1. Preparation scheme for magnetite nanoparticles (Fe_3O_4) using the coprecipitation method. Redrawn with modifications starting from [30].

C. Characterization of Nanoparticles

The characterization of the synthesized iron oxide (Fe_3O_4) nanoparticles was carried out using various analytical techniques to evaluate their composition and morphology. X-Ray Diffraction (XRD) confirmed the crystallization of iron oxide, revealing an average crystallite size of about 45 nm, suggesting a nanometer structure, as shown in Fig. 2 [36].

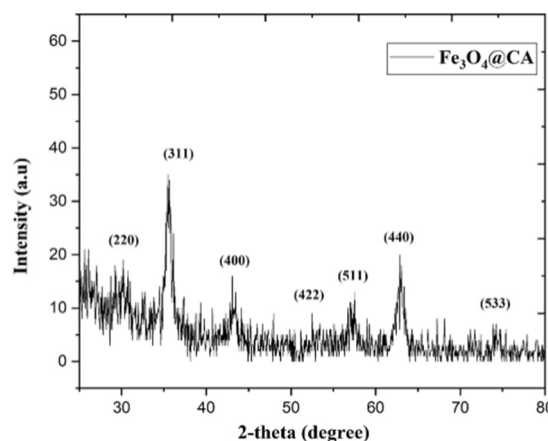


Fig. 2. X-ray diffraction (XRD).

Field Emission Scanning Electron Microscopy (FE-SEM) showed that the nanoparticles have a spherical morphology, which is consistent with the results obtained [33]. In addition, the absorption spectrum in the ultraviolet-visible region peaked at around 340 nm, indicating the presence of nanoparticles in solution [34]. Fourier Transform Infrared Spectroscopy (FT-IR) showed characteristic peaks at 519 cm^{-1} , confirming the presence of the magnetite phase [33]. X-

Ray Diffraction (XRD) confirmed that the samples only present the iron oxide phase in the form of a cubic spinel. Thermogravimetric Analysis (TGA) showed two significant weight losses: one due to evaporation of wastewater below 200 °C and another corresponding to the decomposition of polyols, with losses of 12% for Polyethylene Glycol (PEG) and 10% for Diethylene Glycol (DEG) between 200 and 600 °C [37]. These combined techniques provide a detailed characterization of the structural and morphological properties of Fe₃O₄ nanoparticles, highlighting their potential in various technological applications.

D. Experimental Procedure for the Removal of Contaminants

This study used a 3×3 factorial design to evaluate the effect of magnetite concentration and treatment time on the removal of pollutants in municipal wastewater from the Chilca River. Based on previous studies and experimental observations, an initial range was established for the factors: magnetite concentration (0.5 g, 2 g and 3 g) and treatment time (30, 90 and 120 minutes). Experimental combinations were generated using SPSS (Statistical Package for the Social Sciences) to cover all relevant scenarios and to determine the optimal removal conditions.

The wastewater solutions were prepared in 250 mL Erlenmeyer flasks by dissolving iron oxide nanoparticles (Fe₃O₄) in 20 L of wastewater under constant stirring at a range of 128 to 276 rpm. During the experiment, contact time and pH were varied to optimise pollutant removal efficiency. Key parameters evaluated included Chemical Oxygen Demand (COD), pH, turbidity, Total Suspended Solids (TSS) and oils and fats. Each experiment was conducted in duplicate to ensure reproducibility of results. After adsorption time, ultrasonic agitation was applied to achieve homogeneous dispersion of the nanoparticles, followed by magnetic separation and analysis of residual contaminants in solution.

The structure of the 3×3 factorial design is detailed in Table 1:

Table 1. The structure of the 3×3 factorial design would be as follows

Concentration (g/L)	Time (min)	Experiment
0.5	30	1
0.5	90	2
0.5	120	3
2	30	4
2	90	5
2	120	6
3	30	7
3	90	8
3	120	9

E. Methods of Analysis

The pollutant removal efficiency was assessed using several techniques. COD was determined using the chemical digestion method with potassium dichromate (K₂Cr₂O₇) and spectrophotometry to measure organic matter before and after treatment. pH was measured with a calibrated potentiometer, ensuring accuracy. Turbidity was quantified with a turbidity meter to assess water clarity. Finally, TSS was determined by filtering the samples through a glass fibre filter and weighing the dry residue on an analytical balance [18, 20].

F. Data Analysis

The results were analysed using statistical techniques to

assess their relevance and to understand the efficiency of the process under different experimental conditions. Initially, the Shapiro-Wilk test was applied to verify the normality of the data, a crucial requirement for parametric analyses. A *p*-value < 0.05 indicated that the data did not follow a normal distribution, while a *p*-value ≥ 0.05 suggested normality [38, 39].

Once normality was confirmed, a two-factor Analysis of Variance (ANOVA) was performed to assess the impact of the independent variables (nanoparticle mass and contact time) on the removal efficiencies. A significant F-statistic (*p* < 0.05) indicated relevant differences between the groups, evidencing that the experimental conditions have a significant impact on the results [40]. In addition, descriptive analyses of key metrics (mean, standard deviation and ranges) were performed to get an overview of trends and variability in the data.

Box plots were used to visualise distributions and possible outliers, as well as correlation plots to analyse the relationships between independent and dependent variables. Finally, Response Surface Methodology (RSM) was applied, using a Central Composite Design (CCD) to model the interactions between variables and fit a second-degree polynomial regression model. This allowed response surfaces to be generated that identified the optimal combination of nanoparticle mass and contact time to maximise removal efficiency [41].

The optimal conditions proposed by the model were experimentally validated, confirming the usefulness of RSM as an optimisation tool. In combination with Shapiro-Wilk and ANOVA, a robust statistical framework was established to evaluate, interpret and optimise pollutant removal processes, moving towards more effective and sustainable environmental interventions.

IV. RESULTS

A. Description of the Data

The results of the most representative physico-chemical parameters of the water samples collected reflect the first indicators of water quality. High levels of Chemical Oxygen Demand (COD), turbidity, Total Suspended Solids (TSS) and a significant presence of oils and fats are observed. These initial data show the state of contamination of the river prior to the implementation of the magnetite treatment, and provide a fundamental reference for assessing changes in water quality throughout the treatment process, as shown in Table 2.

Table 2. Physico-chemical parameters for water quality evaluation

COD (mg/L)	pH	Turbidity (NTU)	TSS (mg/L)	Oils and Fats (mg/L)
42.5	7.92	98.5	120	45.2

Subsequently, the experiment was carried out by applying different concentrations of magnetite nanoparticles during various contact times. The results obtained are presented in Table 3, which shows a trend in the reduction of COD, turbidity, TSS and oils and greases as contact time and magnetite concentration increases. This indicates the effectiveness of iron oxide (magnetite) nanoparticles in

remediating contaminants in wastewater.

Table 3. Final frame after the experiment

Magnetite Concentration (g)	Time (min)	COD (mg/L)	pH	Turbidity (NTU)	TSS (mg/L)	Oils and Fats (mg/L)
0.5	30	315.1	7.95	76.2	111	9.5
1	30	310.6	7.93	75.4	108	8.3
2	30	298.2	7.97	73.1	92	10.2
3	30	294.5	7.98	73	78	11.4
0.5	90	272.4	7.98	62.4	106	8.7
1	90	264.1	7.97	60.3	101	10.5
2	90	243.2	7.97	58.8	91	8.4
3	90	228.1	7.98	55	72	7
0.5	120	200.3	7.96	58	98	12.5
1	120	193.8	7.98	55.3	74	7.1
2	120	161.4	7.98	55.1	65	7.9
3	120	135.2	8.01	50.2	62	11.3

B. Normality Analysis

Normality tests were performed using the Shapiro-Wilk test to evaluate the distribution of data for the parameters studied. The results are summarized in the following Table 4, where the normality tests (Shapiro-Wilk) indicate that all the parameters analyzed (COD, pH, Turbidity, TSS and Oils and Fats) comply with the normality hypothesis, since their p -values are greater than 0.05.

Table 4. Normality testing (Shapiro-Wilk)

Parameter	p -Value
COD (mg/L)	0.4420
pH	0.1645
Turbidity (NTU)	0.0747
TSS (mg/L)	0.3261
Oils and Fats (mg/L)	0.6644

C. Analysis of Variance (ANOVA)

A two-factor Qnalysis of Qariance (ANOVA) was performed to evaluate the effect of magnetite concentration (in grams) and contact time (in minutes) on various dependent variables related to treated water quality. Below are the ANOVA results for each parameter analyzed in Table 5 which provides a comprehensive analysis on the impact of iron oxide nanoparticles and treatment time on various water quality parameters, including Chemical Oxygen Demand

(COD), pH, turbidity, Total Suspended Solids (TSS), and oils and fats. The ANOVA results reveal that magnetite concentration and contact time have significant effects on COD, turbidity and TSS variables. However, no significant effects were found on pH or on the removal of oils and fats, suggesting that adjustments in the process or in the concentrations used to improve these parameters could be required.

Table 5. ANOVA

Parameter	Fountain	Mexico City	F	PR(>F)
COD	C(magnetite-g)	3	11.045954	0.007414
	C(time-min)	2	162.78157	0.000006
pH	C(magnetite-g)	3	2.684932	0.140073
	C(time-min)	2	3.246575	0.110774
Turbidity	C(magnetite-g)	3	13.595918	0.004385
	C(time-min)	2	292.6477	0.000001
SST	C(magnetite-g)	3	19.270952	0.001753
	C(time-min)	2	16.479251	0.003653
Oils and Fats	C(magnetite-g)	3	0.426054	0.741621
	C(time-min)	2	0.393103	0.69115

D. Analysis of Variance (ANOVA)

Analysis of the data in Table 6 reveals important trends in the reduction of contaminants in magnetite-treated wastewater. The median Chemical Oxygen Demand (COD) is 243.65 mg/L, indicating a notable decrease in organic and inorganic matter, although the Interquartile Range (IQR) of 97.9 mg/L suggests considerable variability in treatment efficacy, reflected in the outliers of 135.2 and 315.1 mg/L. The pH remains stable at a median of 7.97, with no outliers, implying that treatment conditions do not significantly affect this parameter. Turbidity has a median of 62.4 NTU and an IQR of 18.0 NTU, suggesting a moderate and consistent reduction. As for Total Suspended Solids (TSS), the median is 92 mg/L, with an IQR of 34 mg/L, indicating a decrease in concentration, despite the presence of an outlier of 62 mg/L. Finally, the levels of oils and fats, with a median of 10.5 mg/L and an IQR of 3.0 mg/L, demonstrate that magnetite treatment is effective in reducing magnetite, although an outlier of 7.0 mg/L highlights the possibility of unusual treatment conditions. Overall, the results indicate that the application of magnetite in wastewater treatment is effective, although variability in some parameters suggests the need for continuous monitoring to optimize the process.

Table 6. Analysis of the data obtained from the boxplot

Variable	Median	Q1 (First Quartile)	Q3 (Third Quartile)	Interquartile Range (IQR)	Minimal	Maximum	Outliers
COD (mg/L)	243.65	200.3	298.2	97.9	135.2	315.1	135.2, 315.1
pH	7.97	7.96	7.98	0.02	7.93	8.01	None
Turbidity (NTU)	62.4	55.1	73.1	18	50.2	76.2	None
TSS (mg/L)	92	74	108	34	62	111	62
Oils and Fats (mg/L)	10.5	8.4	11.4	3	7	12.5	7

Fig. 3 shows the boxplots graph showing the variability of the different water quality variables (COD (a), pH (b), Turbidity (c), STS (d) and Oils and Fats (e)) as a function of magnetite concentration and treatment time. For COD, a tendency to decrease is observed with increasing magnetite concentration, suggesting a positive effect of the treatment on the removal of organic and inorganic matter. The pH remains relatively constant, indicating that the treatment conditions do not significantly affect the acidity of the water. Turbidity and

STS also show a progressive reduction as magnetite concentration and treatment time increase, reflecting an improvement in the clarity of the treated water. On the other hand, the levels of oils and fats decrease markedly with the increase in magnetite, although with a higher variability in the lower concentrations. These results suggest that magnetite may be an effective agent in improving the quality of treated water, although attention should be paid to the variability observed in some treatments.

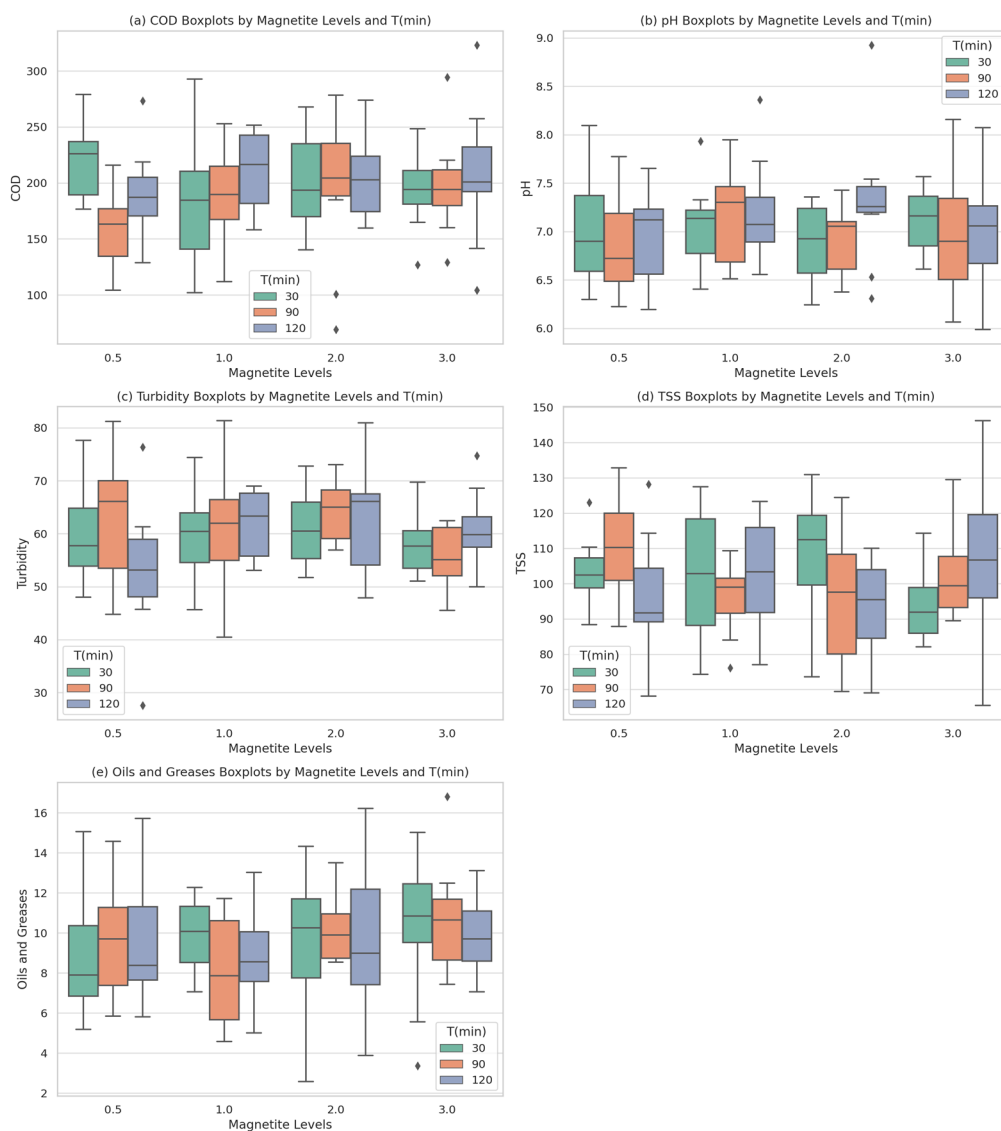


Fig. 3. Boxplots graph of dependent variables.

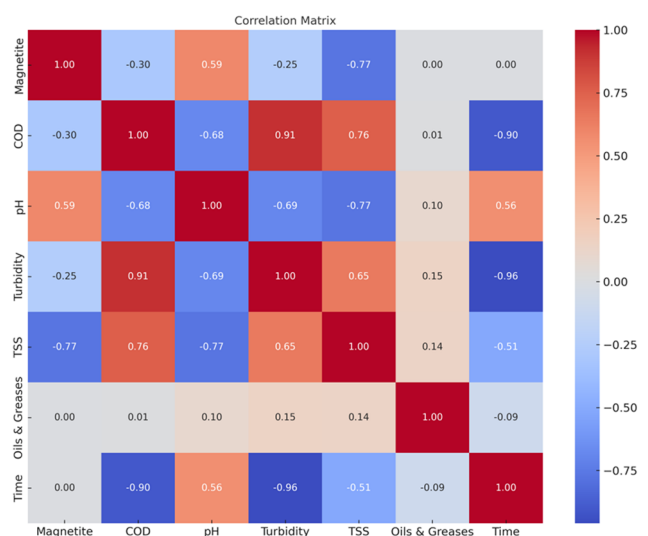


Fig. 4. Correlation matrix.

The correlation matrix Fig. 4 reveals that the concentration of magnetite has a weak negative correlation with COD (-0.300), indicating that, although magnetite can contribute to the reduction of organic and inorganic matter, its effect is limited. On the other hand, it shows a moderate positive

correlation with pH (0.593), suggesting that an increase in magnetite concentration is associated with an increase in pH. Likewise, a significant negative correlation is observed with turbidity (-0.251) and Total Suspended Solids (TSS) (-0.768), which indicates that magnetite helps to clarify water by agglomerating and removing suspended particles. In contrast, the correlation with oils and fats is virtually zero (0.003), suggesting that magnetite is not effective in removing these contaminants. Regarding time, the correlation with COD is very strong (-0.901), which indicates that a longer contact time with magnetite allows a more effective reduction of organic and inorganic matter; in addition, a moderate positive correlation with pH (0.562) is observed. Turbidity presents a strong negative correlation with time (-0.956), suggesting that the increase in contact time also results in a notable decrease in turbidity, while the correlation with TSS is moderate (-0.509). Finally, the relationship between time and oils and fats is weak (-0.094), indicating that contact time has little impact on the removal of this type of contaminants.

The results of the multiple regression analysis indicate that the model is highly significant for Chemical Oxygen Demand (COD), with an R^2 of 0.889 , suggesting that 88.9% of the variability in COD can be explained by magnetite

concentration and treatment time. For each unit increase in magnetite, COD decreases by 21.75 units ($p = 0.042$), which supports the hypothesis that magnetite contributes significantly to the reduction of organic and inorganic matter. Additionally, treatment time reduces COD by 3.42 units for each additional unit ($p < 0.001$), improving process efficiency. For pH, the adjusted coefficient of determination (R^2) is 0.881, showing that magnetite decreases pH by 1.44 units ($p = 0.619$), although this effect is not statistically significant. For oils and fats, the R^2 is 0.644, with a minimal reduction of 0.13 units per unit of magnetite ($p = 0.833$). Turbidity has an R^2 of

0.491, with a decrease of 4.46 units for each increase in magnetite ($p = 0.314$), and finally, total suspended solids (TSS) show an R^2 of 0.893, with a reduction of 13.54 units ($p = 0.0001$). Overall, treatment time has a significant impact on improving water quality, especially on COD, turbidity, and TSS, with reductions of 3.42 mg/L in COD ($p = 0.0016$), 0.058 NTU in turbidity ($p = 0.0049$), and 1.21 mg/L in TSS ($p = 0.0145$) per additional unit of time, reinforcing the importance of time for contaminant removal, although pH and oils and fats do not show significant changes over time. All of this is shown in Table 7.

Table 7. Regression table

Parameter	Adjusted coefficient of determination (R^2)	Magnetite Coefficient	Time Coefficient	p -value of Magnetite	p -Value Time
COD (mg/L)	0.889558	-21.74965	-3.424433	0.042935	0.001557
pH	0.881739	-1.441454	0.072077	0.61867	0.1505
Turbidity (NTU)	0.490555	-4.464965	-0.058146	0.31408	0.004895
TSS (mg/L)	0.893265	-13.542734	-1.211646	0.000096	0.014521
Oils and Fats (mg/L)	0.644285	0.130452	0.079569	0.833448	0.631024

The results of the regression analysis reveal significant trends in magnetite treated water quality. For Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS), both magnetite concentration and treatment time show negative coefficients (-21.74965 and -3.424433 for COD; -13.542734 and -1.211646 for TSS), indicating that their increase effectively reduces these pollutants. Likewise, pH shows a decreasing trend with magnetite (-1.441454), suggesting that a higher concentration of magnetite decreases the acidity of the water, while treatment time has a slight

positive effect (0.072077). On the other hand, turbidity also decreases with both factors (-4.464965 and -0.058146), confirming the effectiveness of the treatment. However, oils and fats show positive coefficients (0.130452 and 0.079569), indicating that higher magnetite concentration and prolonged treatment time are associated with an unexpected increase in these pollutants, suggesting the need for further investigation. Taken together, these results support the hypothesis that magnetite and treatment time are key variables in improving water quality, as shown in Fig. 5.

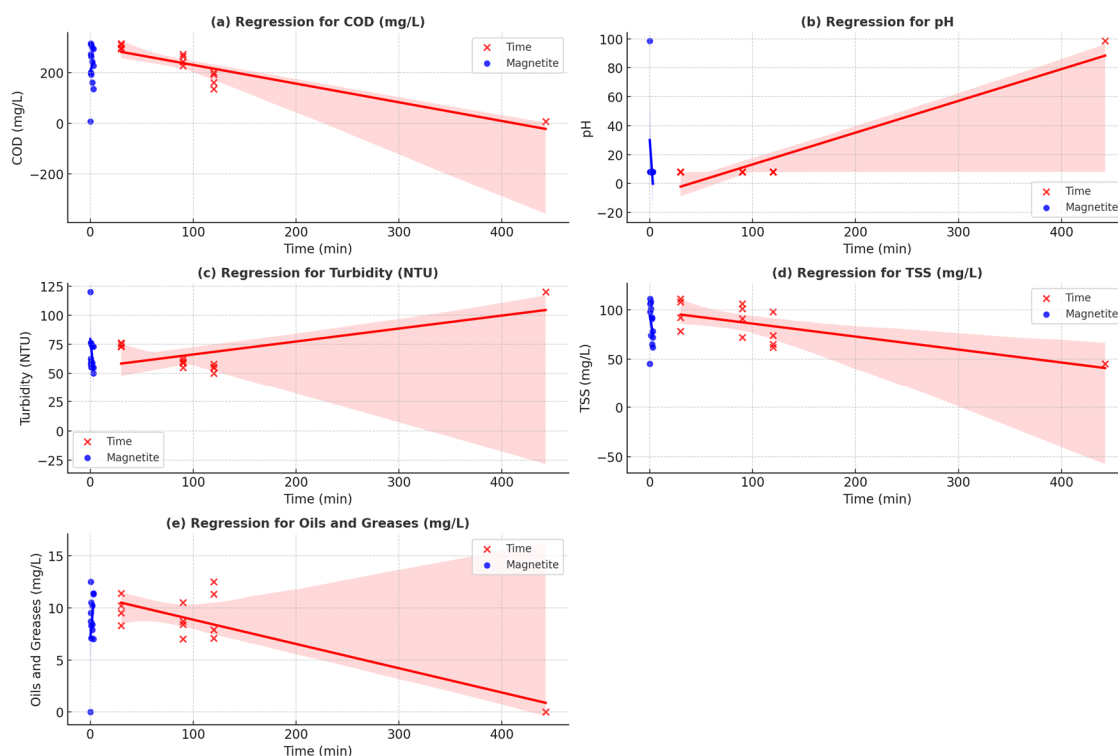


Fig. 5. Multiple regression of dependent variable.

E. Response Surface Analysis (RSM)

A Response Surface Analysis (RSM) was conducted to determine the optimal combination of magnetite concentration and treatment time that maximises the reduction of Chemical Oxygen Demand (COD) and minimises the levels of pH, turbidity, Total Suspended Solids

(TSS), and oil and grease in the treated wastewater [41, 42]. This analysis used a second-order model to establish the relationship between the input parameters (magnetite concentration in grams and treatment time in minutes) and the water quality parameters. Eqs. 1–4 fitted for each parameter, are presented below:

$$COD = 282.9110 + (-4.6530) \times Fe_3O_4 + (1.7986) \times t + (0.7369) \times Fe_3O_4^2 + (-0.1986) \times Fe_3O_4 \times t + (-0.0196) \times t^2 \quad (1)$$

$$pH = 7.9355 + (-0.0036) \times Fe_3O_4 + 0.0004 \times t + (0.0050) \times Fe_3O_4^2 + (-0.000) \times Fe_3O_4 \times t + (-0.0000) \times t^2 \quad (2)$$

$$Turbidity = 86.6067 + (-0.5881) \times Fe_3O_4 + (-0.3695) \times t + (-0.1126) \times Fe_3O_4^2 + (-0.0164) \times Fe_3O_4 \times t + 0.0012 \times t^2 \quad (3)$$

$$TSS = 110.8984 + (-20.1850) \times Fe_3O_4 + 0.5870 \times t + 1.7270 \times Fe_3O_4^2 + 0.0106 \times Fe_3O_4 \times t + (-0.0057) \times t^2 \quad (4)$$

The model parameters and the optimal conditions

calculated from the equations presented provide a framework for optimising the use of magnetite in wastewater treatment by adjusting the input variables to achieve the greatest reduction in contaminants. This systematic approach reinforces the usefulness of RSM for decision-making in water treatment processes, especially in identifying effective combinations of operating parameters. The partial derivatives (∂/∂) indicate how each water quality parameter (such as COD, pH, turbidity, TSS, and oil and grease) changes with respect to variations in magnetite concentration and time. Specifically, $\partial/(\partial \text{Magnetite})$ shows the rate of change of each parameter when the magnetite concentration is adjusted, keeping time constant, and $\partial/(\partial \text{Time})$ indicates how the parameter changes as the treatment time changes, keeping the magnetite concentration constant. These derivatives provide information on the sensitivity of the parameters to magnetite and time, helping to identify the optimal conditions for water treatment. All of this is shown in Table 8.

Table 8. Table of partial derivatives for the influence of magnetite and time on water quality parameters

Parameter	$\frac{\partial}{\partial}$	$\frac{\partial}{\partial}$
	$\frac{\partial \text{Magnetite}}$	$\frac{\partial \text{Time}}$
COD	$-4.6530 + 2 \cdot (0.7369) \cdot \text{Magnetite} - 0.1986 \cdot \text{Time}$	$1.7986 - 0.1986 \cdot \text{Magnetite} - 2 \cdot (0.1986) \cdot \text{Time}$
pH	$-0.0036 + 2 \cdot (0.0050) \cdot \text{Magnetite}$	$0.0004 - 2 \cdot (0.0000) \cdot \text{Magnetite}$
Turbidity	$-0.5881 - 2 \cdot (0.1126) \cdot \text{Magnetite} - 0.0164 \cdot \text{Time}$	$-0.3695 - 0.0164 \cdot \text{Magnetite} + 2 \cdot (0.0012) \cdot \text{Time}$
TSS	$-20.1850 + 2 \cdot (1.7270) \cdot \text{Magnetite} + 0.0106 \cdot \text{Time}$	$0.5870 + 0.0106 \cdot \text{Magnetite} - 2 \cdot (0.0057) \cdot \text{Time}$
Oil and Grease	$-2.2454 + 2 \cdot (0.9585) \cdot \text{Magnetite} - 0.0140 \cdot \text{Time}$	$-0.0706 - 0.0140 \cdot \text{Magnetite} + 2 \cdot (0.0006) \cdot \text{Time}$

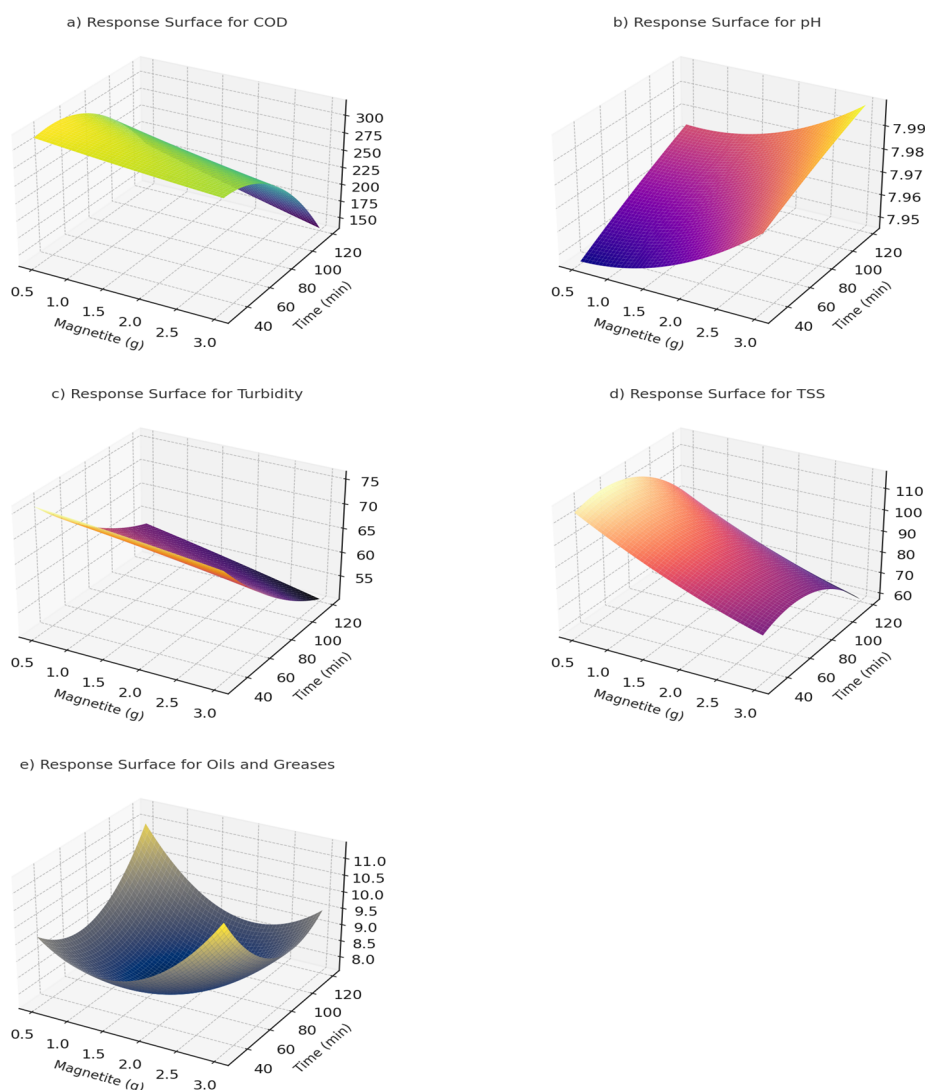


Fig. 6. Response surface analysis (RSM).

Fig. 6. The Response Surface Methodology (RSM) plots show the relationship between magnetite concentration and treatment time with various water quality parameters. The results indicate that as both magnetite concentration and treatment time increase, the Chemical Oxygen Demand (COD) decreases significantly, reaching a minimum of approximately 135 mg/L, which indicates effective removal of organic and inorganic matter. Similarly, turbidity is reduced to around 50 NTU, demonstrating a notable improvement in water clarity. Total Suspended Solids (TSS) decrease to approximately 62 mg/L, reflecting the high efficiency of the process in particle removal. The pH remains stable within a neutral range (7.93–8.01), suggesting that the studied factors do not affect this parameter. However, the plots also show that oil and grease levels decrease, but to a lesser extent, highlighting the need for complementary methods for their effective removal. The optimal conditions identified in the RSM model, which are 3 grams of magnetite and 120 minutes of treatment time, are based on the best results obtained within the experimental range, contributing to the maximization of contaminant removal. The obtained equations describe the individual and combined effects of these factors, allowing for partial derivative calculations to identify the optimal values that maximize contaminant removal.

V. DISCUSSION

In this study, the use of magnetite nanoparticles (Fe_3O_4) for wastewater treatment demonstrated remarkable effectiveness, achieving significant reductions in key parameters such as Chemical Oxygen Demand (COD), turbidity, Total Suspended Solids (TSS) and oil and grease, the latter being the most prominent, with a 75% decrease. These results are consistent with previous research showing the effectiveness of magnetite in removing pollutants, such as the study by Mohammed and Zuheri, which reported a reduction in residual oil content in treated water from 22.2 ppm (22.2 mg/L) to 8.9 ppm, equivalent to a 59.91% decrease. Both studies reinforce the potential of magnetite nanoparticles as a practical, efficient and sustainable solution to address wastewater treatment challenges [43].

Turbidity in our investigation with magnetite, which was initially 98.5 NTU, was reduced to 50.2 NTU, representing a significant improvement of 49.04% in visual water quality. This result is consistent with the study by Praveena, Xin-Yi, Chyi and Khan, who achieved turbidity removal between 88.5% and 92.8% using magnetite functionalised with banana peel extracts. However, although a combination of magnetite and a natural functionalising agent was used in that study, our results show that, even using magnetite alone, effective turbidity reduction performance was achieved. This reinforces the versatility and potential of magnetite as an effective technology for wastewater treatment, without the need for additional modifications in certain applications [44].

The results in our research show that Total Suspended Solids (TSS) were reduced from 120 mg/L to 62 mg/L, which is equivalent to a 48.3% decrease. This is supported by the study of Bestawy, El-Shatby and Eltaweil, who, in their research on the use of a bacterial consortium with magnetite for the treatment of oil-contaminated wastewater, achieved an improvement in TSS of 99.10% [45]. Although that study did

not focus on domestic wastewater, oil remains a critical constituent that represents a high pollutant load and whose treatment is essential in various remediation contexts. These results highlight the efficacy and potential of magnetite in the treatment of different types of wastewater.

In the characterisation of magnetite nanoparticles, the crystallinity and magnetic properties of iron oxide played a key role in their efficacy for wastewater treatment. In this study, the crystallisation of magnetite nanoparticles was confirmed by an average crystallite size of approximately 45 nm, resulting in a nano-scale structure that provided a high specific surface area, favouring the interaction and adsorption of pollutants. These findings were in agreement with the research of [46], who analysed Fe_3O_4 nanoparticles with sizes between 10 and 300 nm, highlighting that the crystalline structure improved chemical stability and contaminant removal ability. In addition, the magnetic properties of the nanoparticles enabled their recovery and reuse through the application of external magnetic fields, which reduced operational costs and minimised secondary waste. Together, these properties optimised the nanoparticles' ability to adsorb organic pollutants and other materials, consolidating their effectiveness in environmental remediation processes [46].

In this study, the co-precipitation technique was used to synthesise magnetite nanoparticles (Fe_3O_4), which showed a remarkable efficiency in reducing Chemical Oxygen Demand (COD) from 442.5 mg/L to 135.2 mg/L, representing a decrease of 69%. Co-precipitation is a widely preferred method due to its simplicity, low cost and ability to control nanoparticle size and morphology without the need for extreme conditions, unlike other methods such as hydrothermal synthesis or the sol-gel process, which require high temperatures or the use of complex reagents. These results are in agreement with previous research on the use of iron oxides in organic matter removal, such as in the case of an Fe_2O_3 - TiO_2 - TiO_2 system applied to Activated Carbon Fibres (ACF), where efficient mineralisation of pollutants was achieved under visible light. However, unlike the Fe_2O_3 - TiO_2 - TiO_2 system, which relies on photocatalysis to remove pollutants, magnetite nanoparticles act by coagulation-adsorption without the need for light irradiation, which gives them an operational advantage by not relying on light sources, thus reducing costs and complexity in their large-scale implementation, consolidating their use as a viable and efficient solution for wastewater treatment [47, 48].

Recent studies have demonstrated that magnetite (FeO) and copper-iron (CuFeO) nanoparticles exhibit high efficiency in eliminating both Gram-negative (*E. coli*) and Gram-positive (*S. aureus*) bacteria, even with very short contact times (only 1 minute), making them a promising, low-cost alternative for water treatment, especially in situations with limited contact time [49]. Furthermore, research on the toxicity of magnetite-based nanocomposites has found that at the evaluated concentrations, these nanocomposites have low toxicity and do not significantly affect the survival, behavior, or reproduction of model organisms such as zebrafish (*Danio rerio*). Although the observed effects were minimal, further investigation is needed to assess long-term impacts and their effects on other organisms and the environment, as it cannot be concluded that magnetite nanoparticles are completely harmless [50]. Overall, these studies suggest that magnetite nanoparticles could be a viable option for water remediation,

but more research is essential to fully understand their potential and ecological risks.

Finally, magnetite nanoparticles (Fe_3O_4) have proven to be an effective and sustainable solution for wastewater treatment, reducing key parameters such as turbidity, TSS, COD, oils and fats. Its crystalline structure optimises the adsorption of pollutants, while its magnetic properties allow for easy recovery, minimising waste. In addition, its ability to eliminate bacteria and its low toxicity level at the concentrations tested reinforce its viability for water treatment applications. These characteristics, together with its operational simplicity and scalability, consolidate magnetite as an efficient tool to address wastewater treatment challenges in a sustainable manner.

VI. CONCLUSION

Treatment with 3 g of iron oxide nanoparticles (magnetite) for 120 minutes showed high efficacy in the remediation of pollutants in wastewater. COD was reduced from 442.5 mg/L to 135.2 mg/L (69.5%), turbidity from 98.5 NTU to 50.2 NTU (48.9%), TSS from 120 mg/L to 62 mg/L (48.3%) and oils and fats from 45.2 mg/L to 11.3 mg/L (75%). During treatment, the pH remained stable between 7.93 and 8.01, indicating that the nanoparticles do not generate adverse conditions for aquatic life.

Statistical analysis (ANOVA and multiple regression) confirmed that both magnetite concentration and treatment time have a significant impact on COD, turbidity and TSS remediation, with p -values < 0.05 . The combination of both factors explained 88.96% of the variability in COD and 89.33% in TSS. The negative coefficients associated with magnetite indicate that an increase in its concentration significantly reduces these pollutants.

In the context of Response Surface Methodology (RSM), experiments should be extended to a wider range of conditions to more accurately identify optimal remediation sites. Also, combining magnetite nanoparticles with other treatments could improve their effectiveness against complex contaminants, such as oils and greases, broadening their applicability in more challenging scenarios.

Future research should focus on broadening the range of contaminants treated with magnetite nanoparticles, including those that are less biodegradable or more difficult to remove, to ensure their versatility in diverse applications. In addition, long-term studies assessing the sustainability and efficacy of these nanoparticles under real-world conditions, considering their reactivity, leaching and behaviour over time, are essential. It is also required to optimise the experimental range in the context of Response Surface Methodology (RSM), adjusting and extending the conditions evaluated to identify optimal points with greater precision. Finally, exploring combinations of magnetite nanoparticles with other treatments could enhance their efficacy against specific pollutants, such as oils and greases, extending their applicability to more complex and demanding scenarios.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Isabella Esther Arosemena Chavez conducted an

exhaustive review of existing research and participated in the writing of the materials and methods section, as well as in the interpretation of the experimental data, which were subsequently used in the results section. Jhoselyn Campos Lindo was in charge of writing the materials and methods section and collaborated with Miguel Jaime Laura Peña in the elaboration of the results. Both also contributed to the discussion and conclusions. Steve Dann Camargo Hinostroza, as research advisor, provided support from the validation of the topic and offered valuable comments and guidance to improve the content of the work. All team members actively participated in each stage of the project and approved the final version of the article.

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