J. Electrochem. Sci. Eng. **16** (2026) 3642; https://doi.org/10.5599/jese.3642

Open Access : : ISSN 1847-9286
https://pub.iapchem.org/ojs/index.php/JESE

Original scientific paper

Green-synthesized zinc ferrite nanoparticle-coated electrode for the electrocoagulation of Coomassie brilliant blue dye

Sridhar Gautham and Ramanujam Saravanathamizhan✉

Department of Chemical Engineering, A. C. Tech Campus, Anna University, Chennai- 600025, India

Corresponding Author: ✉*thamizhan79@rediffmail.com*

Received: August 21, 2026; Accepted: October 16, 2026; Published: October 24, 2026

Abstract

This research focused on the removal of Coomassie brilliant blue G-250 dye from aqueous solution by an electrocoagulation process using mild steel electrodes. Mild steel was employed as both the anode and the cathode, where the anodic dissolution generated in situ electrochemically active coagulants that facilitated dye removal through coagulation and flocculation. To enhance the electrocoagulation performance, the cathode was modified by coating with green-synthesized zinc ferrite ($ZnFe_2O_4$) nanoparticles prepared using Saraca asoca leaf extract. The dye removal of 93.90 % was observed for the uncoated electrode and 95.75 % for the coated electrode for the initial dye concentration of 5 mg L^{-1}. Further, it was observed that 80 % colour removal was achieved with a coagulation time of 50 min for the uncoated electrode and 30 min for the coated electrode. In addition, the energy consumption was found to be lower for the coated electrode (6.37 kWh L^{-1}) compared to mild steel (8.50 kWh L^{-1}). Comparative assessments revealed that the fabricated nanocomposite-coated electrodes enhance dye removal efficiency, offering significant advantages in terms of catalytic activity, pollutant capture, and process sustainability. The coated cathode improves hydrogen generation, which improves the coagulation efficiency and reduces the energy consumption.

Keywords

Synthetic dye; electrochemical dye removal; mild steel electrodes; cathode modification; spinel iron oxide nanoparticles

Introduction

Water pollution is one of the most critical global environmental issues in the present century, driven by rapid industrialization and urbanization. Industries such as textile, leather, food, and paper contribute significantly to water contamination by discharging hazardous organic and inorganic substances, heavy metals, and persistent dyes. These pollutants possess a level of complexity and toxicity that poses a

significant threat to both aquatic ecosystems and human health, necessitating the development of efficient, cost-effective, and environmentally friendly treatment technologies [1-3].

Conventional methods such as coagulation-flocculation, adsorption, ion exchange, and biological processes have been widely used for wastewater treatment. These methods have limitations such as adding chemicals, generating large volumes of secondary sludge, and being less efficient in treating non-biodegradable and toxic pollutants. Membrane-based technologies are more effective, but issues like membrane fouling and high operational costs appear to be a major disadvantage [4-6].

Electrocoagulation (EC) is a promising technique for wastewater treatment. EC involves *in-situ* generation of coagulants through the electrolytic dissolution of sacrificial anodes, typically made of aluminium or iron. The electrochemical reactions result in the formation of metal hydroxides that aggregate suspended particles, colloids, and dissolved contaminants, facilitating their removal *via* sedimentation or flotation techniques [7,8]. EC is an electrochemical water treatment technology that uses electricity to eliminate contaminants rather than expensive chemical reagents typically used in wastewater treatment processes. This technique is very effective in eliminating small colloidal particles along with dissolved impurities. EC is one of the greenest technologies because it requires minimal or no chemicals. In addition, EC produces less sludge than chemical coagulation and exhibits higher treatment efficiencies. Among others, total suspended solids, oil emulsions, metals/metalloids, total organic carbon, colour, turbidity, and chemical oxygen demand (COD) can be removed efficiently through the EC process [9,10].

A large number of research works have been reported on the EC process. EC has been extensively studied for the treatment of dye-containing wastewater, which is particularly challenging due to the complex molecular structures, high stability, and resistance of synthetic dyes to conventional treatment methods [11,12]. Mohan *et al.* [13] studied hospital wastewater using Al as anode and cathode and reported 96.6 % COD removal efficiency. Industrial wastewater treatment using Al and Fe electrodes by conventional EC was studied by Syam Babu *et al.* [14]. The authors reported 85 % COD removal efficiency. Asaithambi *et al.* [15] studied the ozone-assisted EC process for distillery dye effluents, and it was reported that the electrocoagulation-assisted ozonation process enhanced dye removal.

Generally, the choice of electrodes in the EC process has been found important. The anode serves for metal dissolution and electro-coagulant generation, while the cathode serves for hydrogen and hydroxyl ion formation. The EC mechanism for the mild steel electrode is given by Equations (1) to (4) [15]:

Anode reaction:

$$Fe \rightarrow Fe^{2+} + 2e^- \quad (1)$$

Cathode reaction:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (2)$$

Overall reaction:

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2 \quad (3)$$

$$Fe(OH)_2 + \text{dye} \rightarrow \text{sludge} \quad (4)$$

The electrochemically generated $Fe(OH)_2$ is used as a coagulant for the dye removal process. The sludge settled at the bottom can be safely removed and disposed. Recent advancements have highlighted the potential of nanomaterial-based composites to further enhance electrode performance. Composites are formed by combining distinct phases to create hybrids with enhanced properties, such as improved catalytic activity, higher adsorption capacity, and increased structural porosity. In dye decolorization, these nanocomposite electrodes offer a larger surface area for pollutant accumulation and facilitate more efficient removal through electrochemical mechanisms.

(cc) BY

In the present work, the cathode was modified with zinc ferrite ($ZnFe_2O_4$) nanoparticles, and the EC was carried out, and its performance was analysed. This study focuses on the green synthesis of zinc ferrite nanoparticles to enhance the performance of mild steel electrodes for dye removal. Unlike traditional chemical synthesis, this eco-friendly method utilizes phytochemical-rich extracts from *Saraca asoca* leaves as natural reducing and capping agents. The mild steel cathode was coated by the synthesized $ZnFe_2O_4$ nanoparticles, creating a fabricated nanocomposite surface designed to improve catalytic activity and pollutant capture in the EC process.

Experimental

Materials

Industrial dye (Coomassie brilliant blue G-250), deionized water, potassium chloride, ferric chloride, and zinc oxide were obtained from SRL Chemicals Pvt., India, with 99 % purity. Mild steel electrodes were obtained from the local market. Leaves of *Saracaasoca were* collected on the university campus. Teflon-lined stainless-steel autoclave was used in the investigation.

Electrocoagulation of dye samples

Electrocoagulation (EC) will be performed using a borosilicate glass reactor equipped with mild steel electrodes connected to a DC power supply. A stock dye solution of 100 mg L^{-1} was prepared and then diluted using distilled water to prepare dye concentrations of 5, 10, 15, 20 and 25 mg L^{-1}. The synthetic dye wastewater of different concentrations was taken in the reactor and stirred using a magnetic stirrer (Remi, Model 1MLH, India) at 1000 rpm. Mild steel was used as electrodes and the electrode dimensions were 13.5 cm in height and 8.5 cm in width. The active surface area of the electrode was 80.75 cm^2, corresponding to an active electrode area of 9.5×8.5 cm. The distance between the electrodes was maintained at 2 cm, and NaCl was used as the supporting electrolyte, and the concentration was kept constant at 1 g L^{-1} throughout all the experiments. The pH of the dye solution was adjusted using either dilute sulphuric acid or dilute sodium hydroxide solution. Experimental parameters such as coagulation time, applied current density and initial dye concentration were optimized for effective dye removal. The dye removal percentage is measured by collecting the sample at regular time intervals and the absorbance is measured using UV-Visible spectroscopy (Make: Lab Man; LMSPUV 1200 Model). From the initial absorbance and final absorbance, using Equation (5), the colour removal, %, is calculated.

$$\text{Colour removal} = \left(\frac{A_i - A_t}{A_i} \right) 100 \quad (5)$$

where A_i is the initial absorbance and A_t is the final absorbance

Synthesis of nanomaterial

In this study, leaves of *Saraca asoca* were washed, dried, and boiled in water to obtain a phytochemical-rich extract**.** The *Saraca asoca* leaf extract has already been employed as a reducing agent for the green synthesis of various nanoparticles, including silver [16], manganese dioxide [17] and zinc oxide nanoparticles [18]. These biomolecules serve as natural reducing and capping agents**.** 1 M solutions of ferric chloride and zinc oxide were prepared. About 20 g of leaf was washed and boiled in water to get the extract. The filtered leaf extract (20 mL) was slowly added to the ferric chloride solution, along with zinc oxide, under laboratory conditions to obtain zinc ferrite nanoparticles. The pictorial representation of the synthesis process is shown in Figure 1.

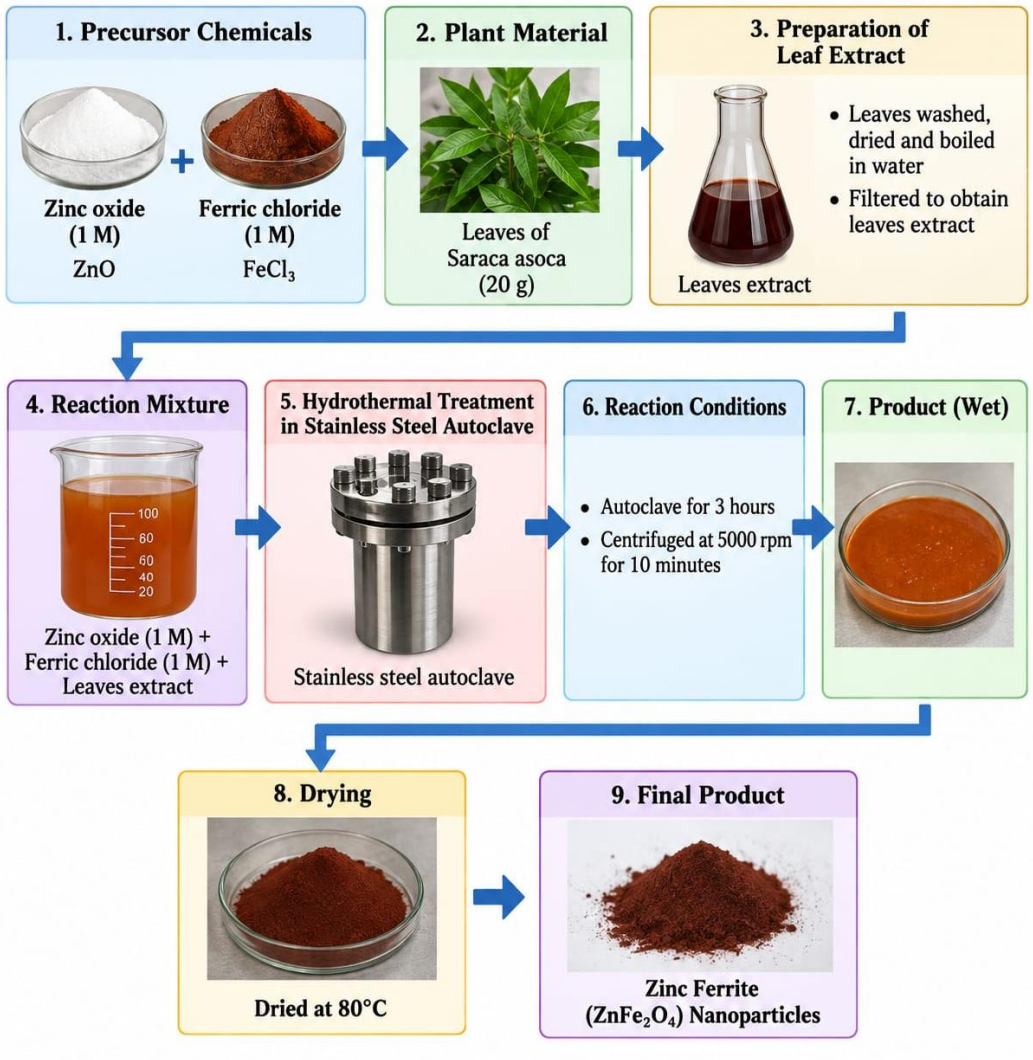


Figure 1. *Pictorial representation of green synthesis route of zinc ferrite nanoparticles*

The synthesis process has been optimized to achieve stable and highly dispersed nanoparticles. The synthesized nanoparticles will be characterized for size, morphology and surface properties using techniques such as XRD and SEM (SEM-EDX, ZEISS EVO, Carl Zeiss Microscopy, Germany). The prepared nanomaterials will be stored under controlled conditions to prevent agglomeration before electrode coating.

Coating of the electrode with nanomaterial

Zinc ferrite nanoparticles were mixed with ethanol in a 30:70 weight ratio to prepare a stable suspension. The suspension was ultrasonicated for 45 to 60 minutes to achieve uniform dispersion and minimize nanoparticle agglomeration. Prior to coating, the electrode surface was cleaned sequentially with acetone and ethanol, rinsed thoroughly with distilled water, and dried at 60 °C. The well-dispersed nanoparticle suspension was subsequently applied to the electrode surface using a brush-coating technique to obtain a thin and uniform coating. Multiple coating cycles were carried out to improve the film thickness and surface coverage. After each coating cycle, the electrode was dried in a hot-air oven at 60 °C for 60 minutes to facilitate solvent evaporation and stabilize the deposited layer. Then, the coated electrode was thermally annealed in a muffle furnace at 250 to 300 °C for 1 hour to improve adhesion, remove residual organic components, and enhance the electrochemical stability of the coating. The resulting electrode exhibited a porous and rough zinc

(cc) BY

ferrite nanoparticle layer, providing a suitable active surface for electrocoagulation-based dye removal applications. The coated electrode was subsequently dried and stabilized to ensure uniform and well-adhered nanomaterial deposition [19,20].

Electrocoagulation experiments will then be repeated using the fabricated electrode under the same stirring and operational conditions. Dye removal efficiency using the nanomaterial-coated electrode will be compared with that of the uncoated electrode. The effect of the nanomaterial coating on reaction rate, colour removal, and energy efficiency will be evaluated. The results will help determine the effectiveness of electrode modification for enhanced dye removal.

Results and discussion

Characterization of synthesized nanomaterial

X-ray diffraction

X-ray diffraction (XRD) is a widely used technique for analysing the structural properties of crystalline, semi-crystalline, and amorphous materials. It provides information on crystal structure, phase composition, lattice parameters, crystallite size, crystallographic orientation, and degree of crystallinity. During XRD analysis, an incident X-ray beam is scattered by the electrons in the material, producing diffraction patterns according to Bragg's law. These patterns are used to identify crystalline phases, assess phase purity, detect impurities, and confirm the formation of desired crystal structures. In the present work, the XRD pattern of the synthesized zinc ferrite nanoparticle is shown in Figure 2. The resulting diffraction pattern provides information about the material's crystal structure, phase composition, and degree of crystallinity. The crystallographic structure of the obtained $ZnFe_2O_4$ nanoparticles was identified using XRD data. No impurity peaks were observed in the XRD pattern of $ZnFe_2O_4$, which indicates the purity of the sample. It is observed from the figure that the XRD pattern displays distinct, sharp peaks at several 2θ values around 30° (220), 35° (311), 43° (400), 53° (422), 57° (511) and 63° (440). These positions correspond strongly to the planes of the cubic spinel ferrite structure [21,22].

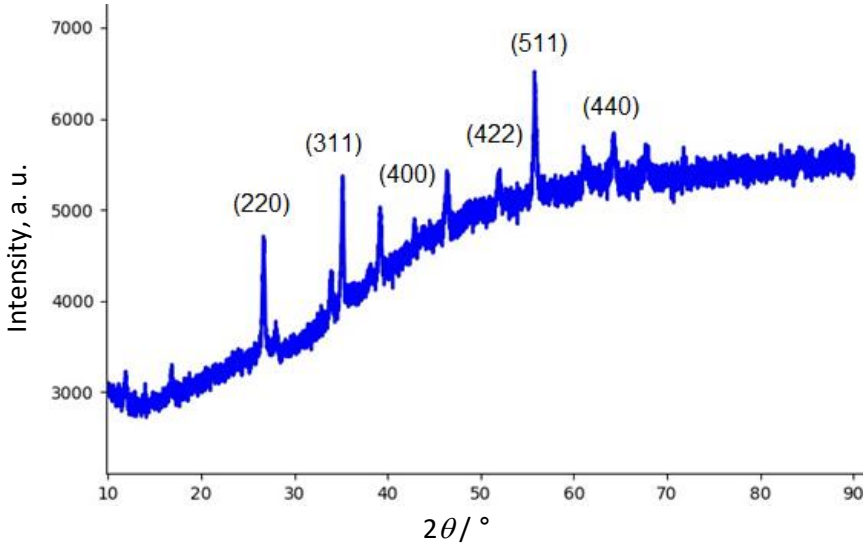


Figure 2. *XRD of zinc ferrite nanoparticles*

Scanning electron microscopy-energy-dispersive X-ray spectroscopy analysis

Scanning electron microscopy (SEM) was used to investigate the surface morphology and microstructural characteristics of the synthesized zinc ferrite nanoparticles. The SEM images revealed

irregular flake-like structures with agglomerated particles at low magnification, while medium- and high-magnification images showed dense nanoclusters with rough and porous surfaces. Energy-dispersive X-ray spectroscopy (EDX), coupled with SEM, was employed to determine the elemental composition of the synthesized nanoparticles and is shown in Figure 3(a). The EDX spectrum of the material is shown in Figure 3(b), confirming the presence of zinc, iron and oxygen, indicating the successful formation of zinc ferrite. The elemental composition consisted of Fe (28.31 wt.%), Zn (21.47 wt.%) and O (16.92 wt.%), which is consistent with the expected Zn-Fe oxide composition. A prominent chlorine peak (25.54 wt.%) was also observed, which may be attributed to residual precursor salts or incomplete washing during synthesis. A minor carbon content (7.76 wt.%) was detected, likely resulting from surface contamination or the carbon tape used during SEM-EDX analysis. Overall, the SEM and EDX analyses confirmed the successful synthesis of zinc ferrite nanoparticles with the expected surface morphology and elemental composition [23-25].

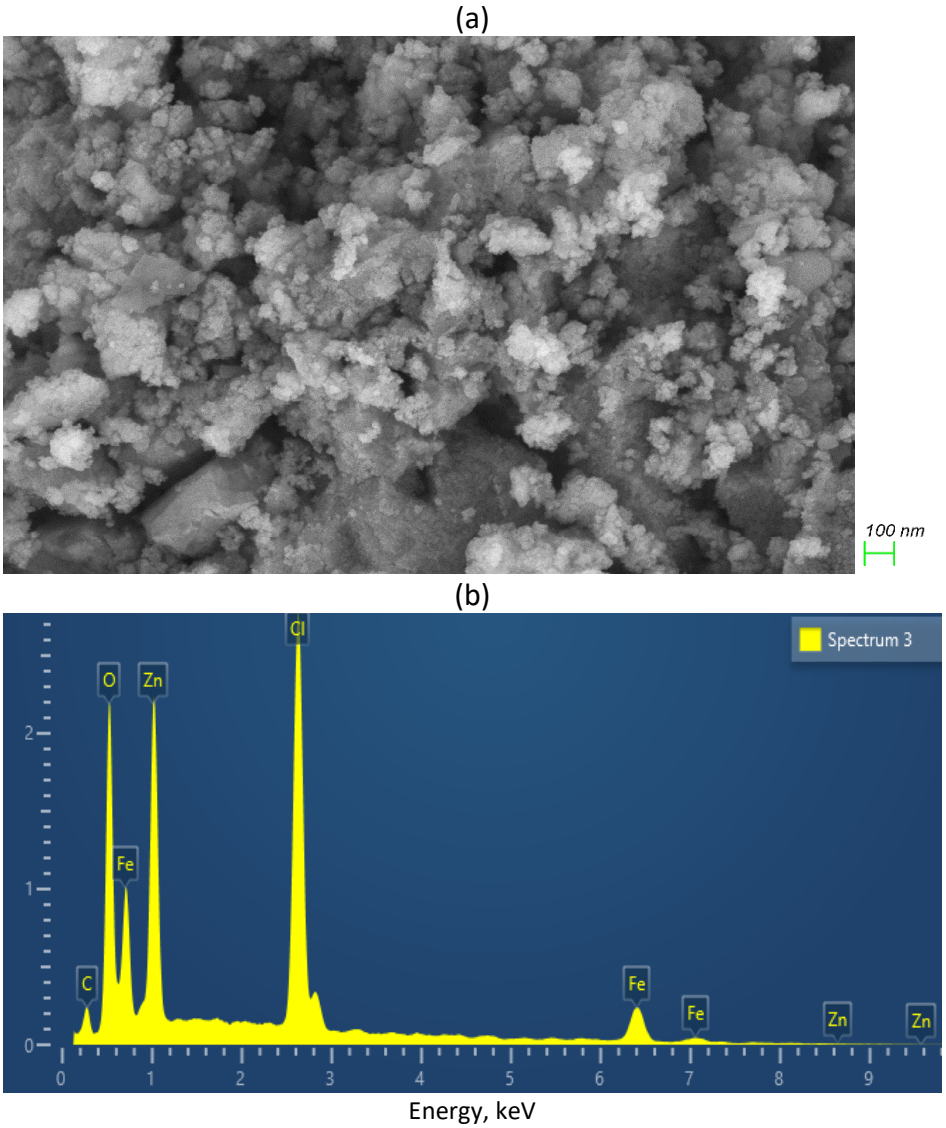


Figure 3. *SEM-EDX analysis of the zinc ferrite sample: (a) SEM image (b) EDX spectrum*

Comparison of colour removal using coated and uncoated electrodes

Effect of initial dye concentration

The effect of initial concentration of Coomassie brilliant blue dye (5 to 25 mg L^{-1}) on the colour removal has been studied using coated and uncoated electrodes and shown in Figure 4. Figure 4(a)

(cc) BY

shows the colour removal without coating. The maximum colour removal of 93.9 % has been observed for the coagulation time of 50 min for the dye concentration of 5 mg L^{-1}. Electrocoagulation experiments conducted using the fabricated ferrite nanoparticles-coated electrode under identical operating conditions are shown in Figure 4(b). After treatment, a sludge layer was formed at the top due to floc flotation by hydrogen bubbles generated at the cathode, while a clear solution remained at the bottom. The clarified solution was collected, and its absorbance was measured to determine the dye removal efficiency. The nanomaterial-coated electrode exhibited enhanced electrocoagulation performance, achieving nearly complete coagulation within 30 min and maximum decolorization after 50 min. The highest removal efficiency for Coomassie brilliant blue exceeded 95.73 % at 50 min, demonstrating the effectiveness of the modified electrode for dye removal.

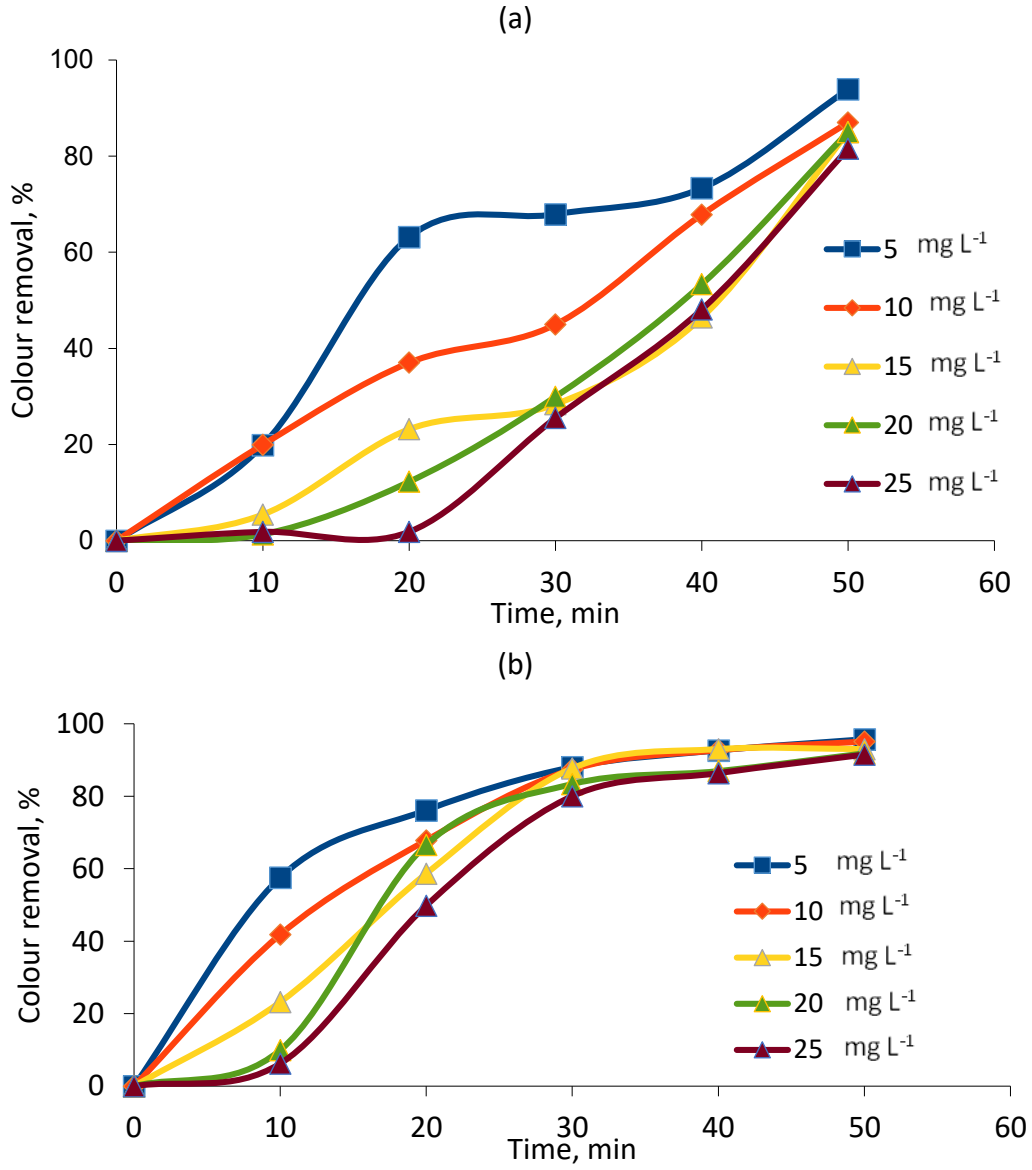


Figure 4. *Effect of initial dye concentration on colour removal: (a) uncoated cathode, (b) coated cathode. pH 7.0, current density 7.5 mA* cm^{-2}

Effect of solution pH

The effect of dye solution pH is an important parameter in the electrocoagulation process. Many authors have studied and reported the influence of pH on the electrocoagulation process. [26-28]. The effect of initial dye solution pH is shown in Figure 5 for the coated and uncoated electrodes. Figure 5(a)

clearly shows that pH has a significant influence on colour removal efficiency in the electrocoagulation system. Under acidic conditions (pH 2.75), the removal efficiency is highest, reaching around 85% within 50 minutes, indicating faster coagulation. In neutral conditions (pH 7.35), the efficiency increases gradually and attains moderate removal (~84 %), but at a slower rate compared to acidic conditions. Under basic conditions (pH 11.35), the removal efficiency is significantly lower, showing poor performance even after 50 minutes (~45 to 50 %). The enhanced performance in acidic medium is attributed to better anode dissolution and formation of active coagulant species (Fe^{2+}). In contrast, alkaline conditions lead to the formation of less effective hydroxide species and reduced destabilization of dye molecules, resulting in lower removal efficiency.

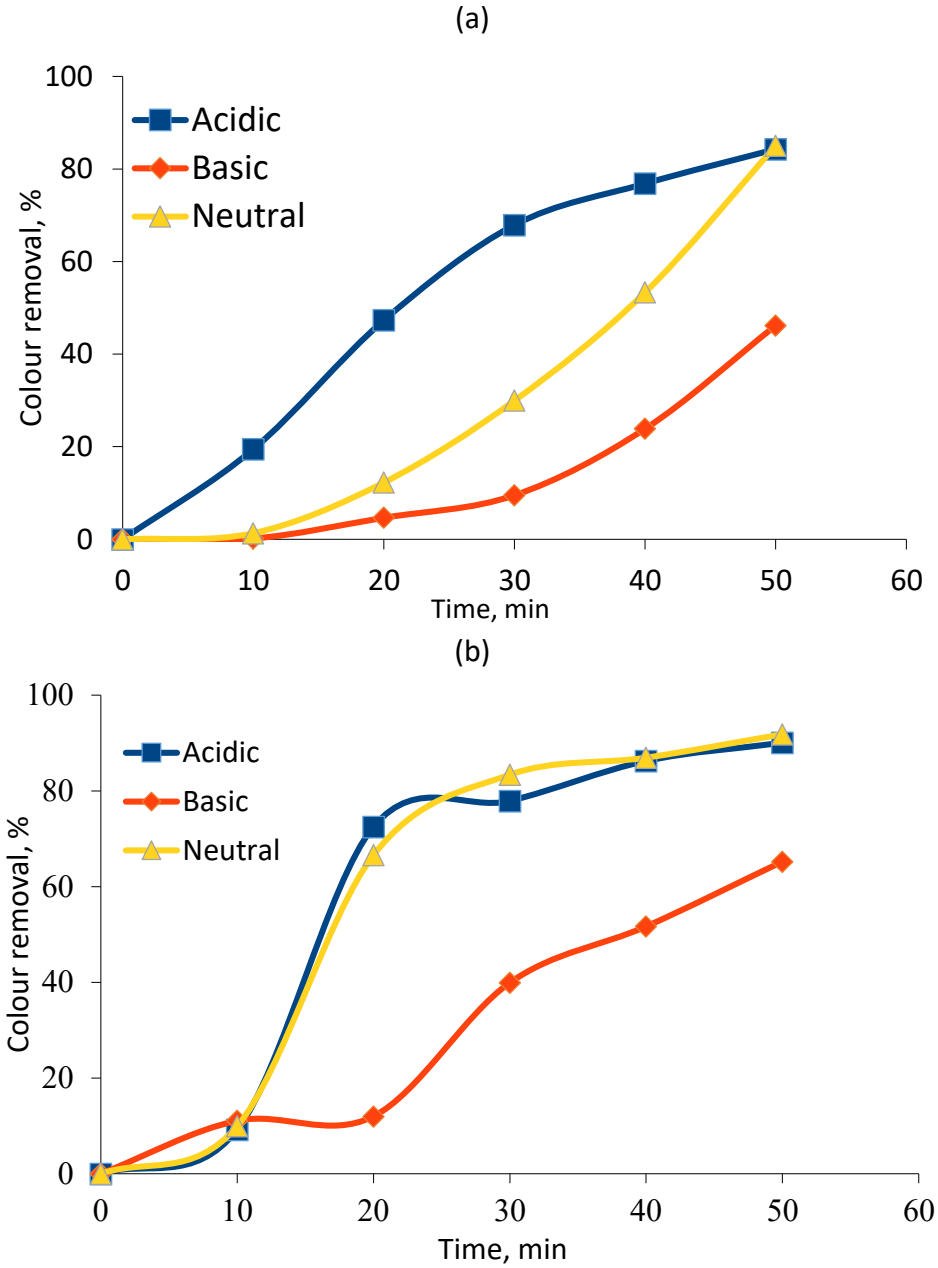


Figure 5. *Effect of dye solution pH on colour removal: (a) uncoated electrode (b) coated electrode. Initial concentration of dye 20 mg L^{-1}; current density 7.5 mA cm^{-2}*

Figure 5(b) shows that colour removal efficiency of the coated electrode increases with time under all pH conditions, but the rate and extent of removal vary significantly. In acidic (pH 2.75) and neutral conditions, there is a rapid increase in efficiency after 20 minutes, reaching around 85 to

CC BY

92 % by 50 minutes, indicating highly effective coagulation. Neutral pH shows slightly higher efficiency than acidic conditions at later stages, suggesting better floc formation and adsorption. In contrast, basic conditions (pH 11.35) exhibit much lower removal efficiency throughout the process, with a slower increase from about 10 % at 10 minutes to only ~65 % at 50 minutes. This indicates that alkaline pH is less favourable for electrocoagulation, likely due to reduced formation of effective hydroxide flocs. Overall, the results demonstrate that acidic to neutral pH conditions are optimal for achieving high colour removal efficiency.

Figure 6 indicates that colour removal efficiency is consistently higher for coated electrodes compared to uncoated ones under all pH conditions. Maximum removal is observed at neutral (pH 7.35), where the coated electrode achieves about 92 %, slightly higher than the uncoated (~85 %). Under acidic conditions (pH 2.75), both electrodes perform well, but the coated electrode still shows superior efficiency (~90 %) compared to the uncoated (~84 %). In contrast, basic conditions (pH 11.35) show a significant drop in efficiency, especially for the uncoated electrode (~46 %), while the coated electrode performs moderately better (~65 %). This suggests that alkaline conditions are less favourable for electrocoagulation. Overall, coating enhances electrode performance by improving coagulation efficiency across all pH levels. The results also confirm that neutral and acidic conditions are more suitable for achieving higher colour removal. A similar observation was observed by David *et al.* [29] for the colour removal of the distillery effluent by electro-coagulation using an iron electrode. The author observed that at acidic and neutral conditions, higher colour removal was reported, while at basic pH conditions, less colour removal was reported.

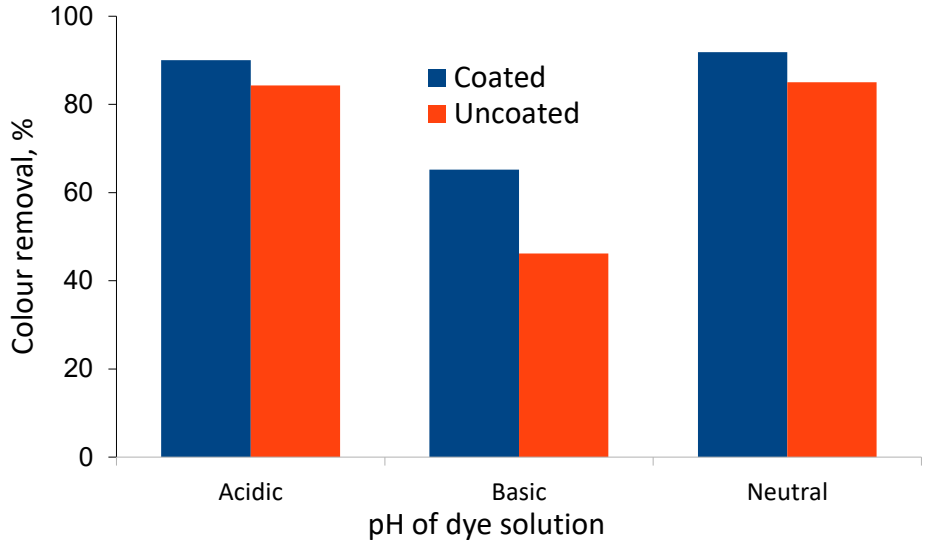


Figure 6. *Colour removal efficiency at different pH of initial dye solution (20 mg L^{-1}). Current density: 7.5 mA cm^{-2}, coagulation time: 50 min*

Comparison of colour removal for different dye concentrations

In Figure 7, dye removal efficiency is compared for different dye concentrations (5 to 20 mg L^{-1}). It is observed from the figure that the coated electrode shows higher colour removal compared with the uncoated electrode. In electrocoagulation, the sacrificial anode still supplies the main coagulant by metal dissolution, but coating of the cathode with $ZnFe_2O_4$ nanoparticles speeds up dye removal. The nanostructured coating raises cathode surface area and adds active sites for adsorption, enhancing floc attachment and aggregation. It also increases the hydrogen evolution at the cathode, generating abundant fine H_2 bubbles that attach onto coagulant flocs and float them rapidly.

Moreover, the $ZnFe_2O_4$ spinel structure improves cathodic electron transfer and redox activity, further accelerating reaction kinetics.

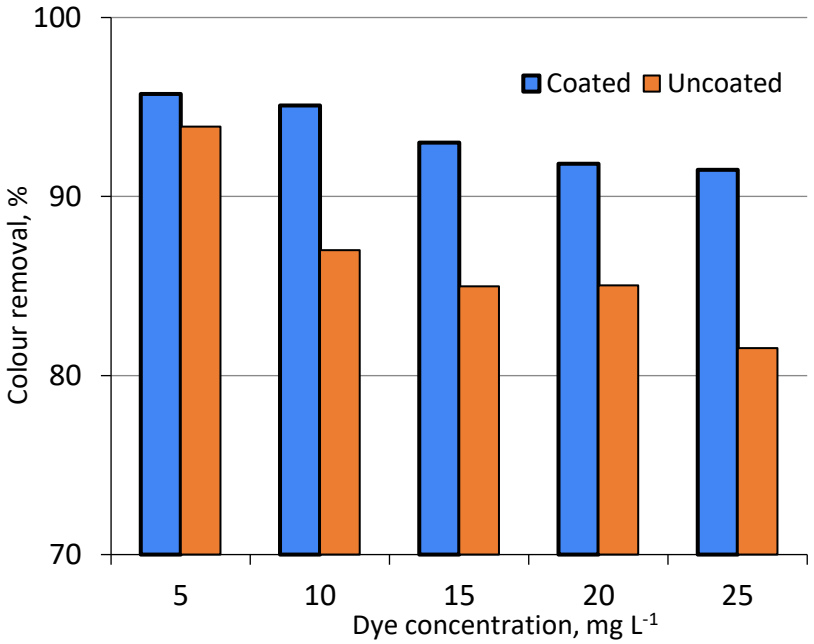


Figure 7. *Comparison of colour removal of different dye concentrations (5 to 25 mg L^{-1}) with coated and uncoated electrodes. Current density: 7.5 mA cm^{-2}, coagulation time: 50 min*

Energy consumption

Energy consumption is a key factor in evaluating the efficiency and economic feasibility of the electrocoagulation process. It mainly depends on operating parameters such as applied current density, voltage, electrolysis time, electrode material, and the conductivity of the solution. Higher current density and longer treatment time generally increase pollutant removal, but they also lead to greater energy usage. The energy consumption is typically expressed as kWh per unit volume of treated water, making it an important metric for process optimization. Additionally, solution characteristics like pH and electrolyte concentration influence electrical resistance and, consequently, power requirements. Therefore, balancing treatment efficiency with minimal energy consumption is essential for making electrocoagulation a sustainable and cost-effective water treatment method.

Equation (6) was used for calculating the specific energy consumption, Wh L^{-1}, in an electrocoagulation process [30,31]:

$$\text{Energy consumption} = \frac{VIt}{v} \quad (6)$$

where V / V is the applied voltage, I / A is the current, t / h is the electrocoagulation time, and v / L is the volume of treated dye.

The calculated specific energy consumption values for mild steel and zinc ferrite-coated mild steel electrodes are presented in Table 1.

Table 1. *Comparison of energy consumption for the coated and uncoated electrode*

Electrode material	Applied voltage, V	Maximum current, A	Dye solution volume, L	Energy consumption, kWh L^{-1}
Mild steel	8.5	0.60	0.5	8.50
Zinc ferrite coated mild steel	8.5	0.75	0.5	6.37

(cc) BY

Data in Table 1 show a clear improvement in electrocoagulation performance when using zinc ferrite-coated mild steel compared to plain mild steel electrodes. Although both systems operate at the same applied voltage (8.5 V) and solution volume, the coated electrode draws a slightly higher current (0.75 A), indicating enhanced conductivity and electrochemical activity. Notably, the coagulation time required to achieve 80 % colour removal is significantly reduced from 3000 s (mild steel) to 1800 s with the coated electrode. This faster treatment directly contributes to improved process efficiency. In addition, the energy consumption is slightly lower for the coated electrode (6.37kWhL^{-1}) compared to mild steel (8.50 kWh L^{-1}), despite the higher current. This suggests that the coating enhances coagulation and reduces the overall operational cost. Overall, zinc ferrite coating improves both energy efficiency and treatment performance in the electrocoagulation process.

Conclusion

The study successfully demonstrates the work of fabricated mild steel electrodes coated with green-synthesized zinc ferrite nanoparticles for wastewater remediation. These modified electrodes efficiently removed Coomassie brilliant blue G-250 dye, reaching 80 to 90 % decolourization within 50 minutes of treatment. Characterization through X-ray diffraction confirmed the high-quality crystalline structure of the nanomaterials, which significantly enhanced catalytic activity. Compared to uncoated electrodes, the nanocomposite coating improved pollutant capture, catalytic efficiency, and energy utilization during the electrocoagulation process. Utilizing *Saraca asoca* leaf extract ensured an eco-friendly and sustainable synthesis approach, avoiding the requirement for harsh chemical reagents. This innovative method offers a cost-effective and environmentally benign alternative that minimizes secondary pollution compared to conventional industrial water treatment. The results highlight a powerful synergy between electrochemical processes and advanced materials, with future phases focusing on further process optimization.

References

[1] J. Shamshad, R. U. Rehman, Innovative approaches to sustainable wastewater treatment: a comprehensive exploration of conventional and emerging technologies, *Environmental Sciences: Advances* **4** (2025) 189-222. https://doi.org/10.1039/d4va00136b

[2] J. A. G.Cardenas, B. E.García, A. Agüera, J. A. S.Pérez, F. M.Agugliaro, Wastewater treatment by advanced oxidation process and their worldwide research trends, *International Journal of Environmental Research and Public Health* **17** (2020) 170. https://doi.org/10.3390/ijerph17010170

[3] J. R. Adewumia, A. A. Ilemobadea, J. E. van Zyl, Treated wastewater reuse in South Africa: Overview, potential, and challenges, *Resources, Conservation and Recycling* **55** (2010) 221-231. https://doi.org/10.1016/j.resconrec.2010.09.012

[4] A. Saravanan, P. S. Kumar, S. Jeevanantham, S. Karishma, B. Tajsabreen and P. Yaashikaa, B. Reshma, Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development, *Chemosphere* **280** (2021) 130595. https://doi.org/10.1016/j.chemosphere.2021.130595

[5] S. Ganesan, *Sustainable Water Treatment and Ecosystem Protection Strategies*, Chapter 11 in *Promising Technologies in Wastewater Treatment: The Current Standpoint*, Apple Academic Press, 2024, 313-325. https://doi.org/10.1201/9781003470014

[6] G. Gedda, K. Balakrishnan, R. U. Devi, K. J. Shah, Introduction to conventional wastewater treatment technologies: limitations and recent advances, *Materials Research Foundations* **91** (2021) 1-36. https://doi.org/10.21741/9781644901144-1

[7] A. Tahreen, M. S Jami, F. Ali, Role of electrocoagulation in wastewater treatment: a developmental review, *Journal of Water Process Engineering* **37** (2020) 101440. https://doi.org/10.1016/j.jwpe.2020.101440
[8] P. P. Das, M. Sharma, M. K. Purkait, Recent progress on electrocoagulation process for wastewater treatment: a review, *Separation and Purification Technology* **292** (2022) 121058. https://doi.org/10.1016/j.seppur.2022.121058
[9] A. S Naje, S. A Abbas. Electrocoagulation Technology in Wastewater Treatment: A Review of Methods and Applications. *Civil and Environmental Research* **3** (2013) 29-43. http://www.iiste.org/Journals/index.php/CER/article/view/8115/8209
[10] D.T. Moussa, M.H. El-Naas, M. Nasser. M.J. Al-Marri, A comprehensive review of electrocoagulation for water treatment: potentials and challenges, *Journal of Environmental Management* **186** (2017) 24-41. https://doi.org/10.1016/j.jenvman.2016.10.032 .
[11] S. Nigar, R. Naresh Kumar, Electrocoagulation technology for wastewater treatment: insights on design, applications, and challenges, *Water Science & Technology* **93** (2026) 969-983. https://doi.org/10.2166/wst.2026.250
[12] M. Bharti, P.P. Das, M.K Purkait, A review on the treatment of water and wastewater by electrocoagulation process: advances and emerging applications, *Journal of Environmental Chemical Engineering* **11** (2023) 111558. https://doi.org/10.1016/j.jece.2023.111558
[13] K. A. Mohan. Z. A. Al-Ridah, Hospital wastewater treatment using electrocoagulation process in comparison with conventional chemical coagulation, *International Journal of Environmental Sciences* **10(3)** (2024) 1-16. https://theaspd.com/index.php/ijes/article/view/35
[14] D. Syam Babu, T. S. A. Singh, P. V. Nidheesh, M. S. Kumar, Industrial wastewater treatment by electrocoagulation process, *Separation Science and Technology* **55** (2020) 3195-3227. https://doi.org/10.1080/01496395.2019.1671866
[15] P. Asaithambi, Modepalli Susree, R. Saravanathamizhan, M. Matheswaran, Ozone assisted electrocoagulation for the treatment of distillery effluent, *Desalination* **297** (2012) 1-7. https://doi.org/10.1016/j.desal.2012.04.011
[16] R.M. Tripathi, D. Rana, A. Shrivastav, R.P. Singh, B.R. Shrivastav, Biogenic synthesis of silver nanoparticles using *Saraca indica* leaf extract and evaluation of their antibacterial activity, *Nano Biomedicine and Engineering* **5(1)** (2013) 50-56. https://doi.org/10.5101/nbe.v5i1.p50-56
[17] S.S. Majani, S. Sathyan, M.V. Manoj, N. Vinod, S. Pradeep, C. Shivamallu, K.N. Venkatachalaiah, S.P. Kollur, Eco-friendly synthesis of MnO_2 nanoparticles using Saraca asoca leaf extract and evaluation of in vitro anticancer activity, *Current Research in Green and Sustainable Chemistry* **6** (2023) 100367. https://doi.org/10.1016/j.crgsc.2023.100367
[18] S. C. Sahu, H.G. Pavithra Kumari, S. Kumar, R. Gami,Eco-Friendly Synthesis of Zinc Oxide Nanoparticles Using Saraca Asoca Extract: Antifungal Activity Against Aspergillus Niger *International Journal of Environmental Sciences* **11** (2025) 5373-5377. https://theaspd.com/index.php/ijes/article/view/8755/6327
[19] L. Mohan Prasad, R. Saravanathamizhan, V. T. Perarasu, Corrosion protection of mild steel using nanomaterials coating, *Zaštita Materijala* **64(4)** (2023) 365-371. https://doi.org/10.5937/zasmat2304365P
[20] A. Othmani, *Electrodes Coated with Nanomaterials and Their Use for Environmental and Electrochemical Applications,* in *Advancements in Nanotechnology for Energy and Environment*, D. Tripathi, R. K. Sharma, H. F. Öztop Eds., Springer, Singapore, 2022, 13-33. https://doi.org/10.1007/978-981-19-5201-2_2
[21] J. Babu, J. Jacob, N. S. Thulasi, K. Mohandas, Synthesis of zinc ferrite nanoparticles and evaluation of their antifungal properties at different temperatures, *Indian Journal of Pharmacy and Pharmacology* **10(1)** (2023) 28-32. https://doi.org/10.18231/j.ijpp.2023.008

(cc) BY

[22] S. Ferrari, R.S. Kumar, F. Grinblat, J.C. Aphesteguy, F.D. Saccone, D. Errandonea, In-situ high-pressure X-ray diffraction study of zinc ferrite nanoparticles, *Solid State Sciences* **56** (2016) 68-72. https://doi.org/10.1016/j.solidstatesciences.2016.04.006

[23] N. M. Deraz, A. Alarifi, Microstructure and Magnetic Studies of Zinc Ferrite Nanoparticles, *International Journal of Electrochemical Science* **7** (2012) 6501-6511. https://doi.org/10.1016/S1452-3981(23)19498-3

[24] J. Bosco Franklin, G. Theophil Anand, G. Merline Sujitha, S. John Sundaram, A. Dhayal Raj, K. Kaviyarasu, Synthesis and characterization of zinc ferrite nanoparticles using *prunus dulcis* (almond gum) for antibacterial applications, *Materials Today: Proceedings* **68** (2022) 593-601. https://doi.org/10.1016/j.matpr.2022.08.429

[25] A. A. Alakshara, M. E. Goherb, M. G. A. El-Moghnya, M. S. El-Deaba, Synthesis and characterization of zinc ferrite nanoparticles@GO for the photocatalytic degradation of Methylene Blue dye under visible light, *Desalination and Water Treatment* **320** (2024) 100676. https://doi.org/10.1016/j.dwt.2024.100676

[26] S. Sinna Lebbe, N. Abdul Rahim, N. Aryal, U. S.P.R. Arachchige, P. A. Koliyabandara, Electrocoagulation in textile wastewater treatment: Amaranth azo dye removal, *Sustainable Chemistry for the Environment* **14** (2026) 100323. https://doi.org/10.1016/j.scenv.2026.100323

[27] A. Rezagama, D. S. Handayani, B. A. Rahardjo, S. Ashifa, M. Y. Wafa, Treatment of textile industry wastewater by electrocoagulation technology, *IOP Conf. Series: Earth and Environmental Science* **896** (2021) 012078. https://doi.org/10.1088/1755-1315/896/1/012078

[28] S. Najari, M. Delnavaz, D. Bahrami, Application of electrocoagulation process for the treatment of reactive blue 19 synthetic wastewater: Evaluation of different operation conditions and financial analysis, *Chemical Physics Letters* **832** (2023) 140897. https://doi.org/10.1016/j.cplett.2023.140897

[29] C. David, Karpagaraj A. A. Thangavelu, Degradation of distillery effluent by twisted-type Iron electrodes: experimental with ANN approach, *International Journal of Environmental Analytical Chemistry* **102**(**18**) (2022) 6121-6133. https://doi.org/10.1080/03067319.2020.1807532

[30] M. S. Asath Murphy, D. Jovitha Jane, R. S Robin, S. Sahaya Leenus, An Investigation on the Treatment of Wastewater Disperse Dye by Electrocoagulation and Examine the Use of the Treated Dye for Flora and Fauna, *Iranian Journal of Chemistry and Chemical Engineering* **43** (2024) 1970-1983. https://doi.org/10.30492/ijcce.2023.2003823.6057

[31] J. Zeng, M. Ji, Y. Zhao, T. H. Pedersen, H. Wang, Optimization of electrocoagulation process parameters for enhancing phosphate removal in a biofilm-electrocoagulation system, *Water Science and Technology* **83(10)** (2021) 2560-2574. https://doi.org/10.2166/wst.2021.132

©2026 by the authors; licensee IAPC, Zagreb, Croatia. This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/4.0/)