

## RESEARCH ARTICLE

# Green Synthesis of Iron Oxide Nanoparticles for Treating Coffee Cherry Pulping Wastewater: Environmental Implications

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**Received:** 5 March 2025 | **Revised:** 14 June 2025 | **Accepted:** 7 July 2025

**Review Editor:** Mingying Yang

**Funding:** The authors would like to extend their sincere appreciation to Tamil Nadu State Council for Higher Education (File No. RGP/2019-20/MTWU/HECP-0075), Government of Tamilnadu, India, for their generous financial support. The authors extend their appreciation to the ongoing project Researchers Funding Program (OFR-2025-224) King Saud University, Riyadh, Saudi Arabia.

**Keywords:** coffee cherry pulping wastewater | green synthesis | iron oxide nanoparticles | *Ricinus communis* L. | wastewater treatment

## ABSTRACT

The disposal of coffee cherry pulping wastewater (CPWW) poses severe environmental risks, including water body eutrophication, soil acidification, and toxicity to aquatic life due to its high organic load (COD: 29,450 mg/L; BOD<sub>5</sub>: 16,500 mg/L), acidic pH (4.8), and elevated solids (TDS: 3240 mg/L; TSS: 4540 mg/L). To address this, we synthesized iron oxide nanoparticles from *Ricinus communis* L. seed extract via a green method and evaluated their efficacy in CPWW treatment. Characterization by XRD, SEM, and FTIR confirmed the formation of the nanoparticles stabilized by phytochemicals, with functional groups such as hydroxyl (—OH) and amine (—NH) critical for pollutant binding. At an optimal dosage of 0.08 g/100 mL, the nanoparticles achieved 74% COD removal, 69% TDS reduction, and 92% decolorization, significantly mitigating the pollutant load of the effluent, thereby minimizing risks to aquatic ecosystems and soil health. Furthermore, FTIR analysis of the treated sludge revealed the potential functional groups facilitating pollutant removal. This study highlights the dual environmental benefit of green-synthesized iron oxide nanoparticles: (1) a sustainable synthesis route avoiding toxic chemicals, and (2) high-efficiency pollutant removal, offering a scalable solution for coffee-processing industries to minimize their ecological footprint. By addressing the dual challenges of waste toxicity and treatment sustainability, this approach aligns with circular economy principles, promoting cleaner production in agro-industrial sectors.

**Abbreviations:** ASTM, American society for testing and materials; BOD<sub>5</sub>, biochemical oxygen demand in 5 days; COD, chemical oxygen demand; CPCB, central pollution control board; CPWW, coffee cherry pulping wastewater; DO, dissolved oxygen; EDX, energy dispersive X-ray; FTIR, fourier-transform infrared spectroscopy; SEM, scanning electron microscope; TDS, total dissolved solids; TS, total solids; TSS, total suspended solids; XRD, X-ray diffraction.

## Summary

- Green synthesized iron oxide nanoparticles as efficient eco-friendly coagulants.
- Iron nanoparticle synthesis using *Ricinus communis* L. seed extract.
- 74% pollutant removal from coffee effluent after iron oxide nanoparticle treatment.
- Pollutant removal via adsorption and precipitation mechanisms.

## 1 | Introduction

Coffee cherry pulping wastewater (CPWW) poses a significant environmental challenge due to its complex composition, characterized by high concentrations of both organic and inorganic compounds. Various studies have highlighted its high levels of chemical oxygen demand (COD) and biochemical oxygen demand (BOD<sub>5</sub>), as well as its acidic nature with pH levels below 4.0 (Pires et al. 2021). Additionally, CPWW contains notable quantities of total solids, total nitrogen, phosphorus, and ammoniacal nitrogen, further accentuating its pollution potential. Residual components such as fertilizers, insecticides, fungicides, and trace metals compound the environmental impact of CPWW (Selvamurugan et al. 2010). CPWW is primarily generated during wet coffee processing, resulting from the mechanical removal of pulp using water (Dadi et al. 2018). The volume of water required for wet coffee processing is substantial, estimated at around 90 to 100 L per kilogram of coffee beans, with approximately half of this volume becoming effluent (Takashina et al. 2018). This process extracts fermentable sugars from the pulp and mucilage components, leading to rapid fermentation and the release of organic matter (Devi et al. 2008). Consequently, CPWW becomes laden with proteins, sugars, and polysaccharides, notably pectins, contributing to its complex composition. Fermentation and acidification of sugars during processing cause a drop in pH, precipitation of digested mucilage, and formation of a thick crust atop the wastewater, exacerbating its environmental repercussions (Gopinandhan et al. 2022). The effluent from CPWW is characterized by high concentrations of suspended and dissolved solids, including recalcitrant macromolecules such as melanoidins, tannins, polysaccharides, and caffeine (Hasan et al. 2022). Discharging untreated CPWW into natural water bodies poses serious ecological threats, including decreased dissolved oxygen levels, eutrophication, light obstruction, and adverse effects on aquatic life (Ijanu et al. 2020). Moreover, the toxic and poorly biodegradable nature of CPWW pollutants, along with its foul odor, further exacerbates its detrimental impact on both the environment and human health. In light of these challenges, effective treatment strategies for CPWW are imperative to mitigate its adverse environmental consequences and safeguard water resources.

Efficient treatment of coffee cherry processing wastewater is crucial for the economic feasibility of water utilization in production. Optimizing post-treatment water retrieval requires environmentally sustainable and economically viable management strategies that meet essential water quality criteria. Biological treatment processes, encompassing aerobic and anaerobic

methods, utilize microorganisms to effectively degrade organic pollutants in coffee wastewater (de Barros et al. 2020). However, toxic compounds and fluctuating composition can hinder microbial activity, reducing efficiency and potentially causing failure (Fia et al. 2013). Physicochemical methods employ chemical and physical processes to eliminate impurities. Techniques like coagulation target suspended solids, while chemical oxidation methods degrade organic compounds. However, these methods produce chemical sludge or residues, adding costs and environmental concerns due to disposal and management needs (Muthukumar et al. 2021). Membrane filtration removes suspended solids, dissolved compounds, and contaminants from coffee wastewater using semipermeable membranes. It offers effective pollutant removal and water reuse potential despite high energy use. However, fouling from organic matter and scaling reduces efficiency, requiring frequent maintenance and increasing costs (Chandrasekhar et al. 2020).

Nanotechnology has become a promising solution for wastewater treatment, offering effective and eco-friendly methods (Aswathi et al. 2023). A notable approach is green synthesis, which uses plant extracts like *Ricinus communis* L., a known bio-flocculant, to produce sustainable nanoparticles with unique biochemical properties (Suppiah et al. 2023; Oukharaz et al. 2023). This study presents the first application of iron oxide nanoparticles synthesized from *Ricinus communis* L. specifically for treating coffee processing wastewater, leveraging its unique phytochemistry for enhanced pollutant removal. The seeds of *Ricinus communis* L. are a rich source of oil that can be utilized as a renewable resource for biofuel production (Abel et al. 2022). *Ricinus communis* L. also helps in reducing soil erosion due to its deep-root system, which stabilizes the soil and prevents degradation, providing significant environmental advantages (Nedjimi 2022). Additionally, the abundance and accessibility of *Ricinus communis* L. make it a cost-effective and sustainable option for wastewater treatment (Bakal and Das 2023). Interest in green-synthesized iron oxide nanoparticles for wastewater treatment has surged due to their exceptional adsorption, recyclability, and minimal environmental footprint (Ijaz et al. 2020). This process uses biological or plant extracts to reduce metal ions into nanoparticles (Hussain et al. 2016). Green synthesis presents numerous advantages over conventional methods. It is environmentally friendly, avoiding toxic chemicals and reducing environmental harm. It is also cost-effective, utilizing readily available, renewable materials to lower production costs (Ying et al. 2022). The approach combines the ecological benefits of green synthesis with targeted treatment of the characteristic high organic load and acidity of coffee effluent, offering a sustainable alternative to conventional methods. Moreover, it allows for precise control over nanoparticle size, shape, and surface properties, and imparts biocompatibility for various biomedical and environmental uses (Harish et al. 2023). Comparatively, green-synthesized nanoparticles offer notable advantages in wastewater treatment. They efficiently remove pollutants due to their large surface area and unique properties, and can be easily customized to target specific contaminants (Muthukumar et al. 2020). Their minimal environmental impact and biodegradability make them a sustainable choice, aligning with green chemistry principles (Wang et al. 2014).

This study aimed to: (1) synthesize and characterize iron oxide nanoparticles using *Ricinus communis* L. seed extract

as a green alternative to conventional chemical methods, with comprehensive characterization via X-ray diffraction (XRD), Scanning Electron Microscope (SEM), and Fourier-Transform Infrared Spectroscopy (FTIR); (2) evaluate the treatment efficiency of these nanoparticles in coffee processing wastewater by quantifying reductions in critical parameters; and (3) elucidate the functional groups relevant to pollutant removal through FTIR analysis of post-treatment sludge. By integrating these objectives, this work provides a sustainable, plant-based solution to coffee wastewater treatment while advancing understanding of nanoparticle-mediated coagulation processes.

## 2 | Materials and Methods

### 2.1 | CPWW Collection and Characterization

Around 50 L of CPWW sample were sourced from a coffee cherry pulping facility situated at Thandikudi, Tamil Nadu (10°18'39" N, 77°38'34" E). Samples were maintained at 4°C to preserve the physicochemical properties of the effluent. Few parameters like pH, temperature, color, odor, dissolved oxygen (DO) were analyzed on the spot. Subsequently, the effluent was analyzed for various chemical parameters, including total solids (TS), total suspended solids (TSS), total dissolved solids (TDS), acidity, COD, BOD5, fluoride, nitrate, sulfate, phosphate, and chloride levels, following standard protocols outlined in Rice et al. (2017). The obtained results were evaluated against the discharge thresholds for wet coffee processing effluent set forth by the Central Pollution Control Board, India (CPCB).

### 2.2 | *Ricinus communis* L. Seed Collection and Defatting

Two kilograms of *Ricinus communis* L. seeds were collected from Kodaikanal, Tamil Nadu (10°14'21.30" N, 77°29'21.55" E). After shallow drying, the outer covering was removed, and the deshelled seeds were ground into a powder. Approximately 50 g of the resulting seed meal was distributed among six conical flasks, each holding 250 mL. To each flask, 150 mL of ethanol was introduced, followed by stirring the mixture at 140 rpm for 24 h at room temperature. After agitation, the seed meal was filtered using 110 mm Whatman No. 1 filter paper, followed by rinsing with fresh ethanol to eliminate all lipid content. The resulting defatted seed meal was air dried before being finely powdered (Kim et al. 2021). The defatted seed powder with particle size of ASTM 120 was subsequently stored at room temperature for future use.

### 2.3 | Preparation of Seed Extract From *Ricinus communis* L.

The defatted seed powder and distilled water were combined at a 1:5 (w/v) ratio. The mixture was stirred at 70°C for 20 min and then cooled at room temperature. Subsequently, the mixture was centrifuged (Remi C-24BL, India) at room temperature for 10 min at 5000 rpm, and the resultant supernatant was collected. The supernatant was then filtered using a 110 mm Whatman

No. 1 filter paper to obtain the seed extract, which was then refrigerated at 4°C until further use (Abdelfatah et al. 2021).

### 2.4 | Synthesis of Iron Nanoparticle Using *Ricinus communis* L. Seed Extract

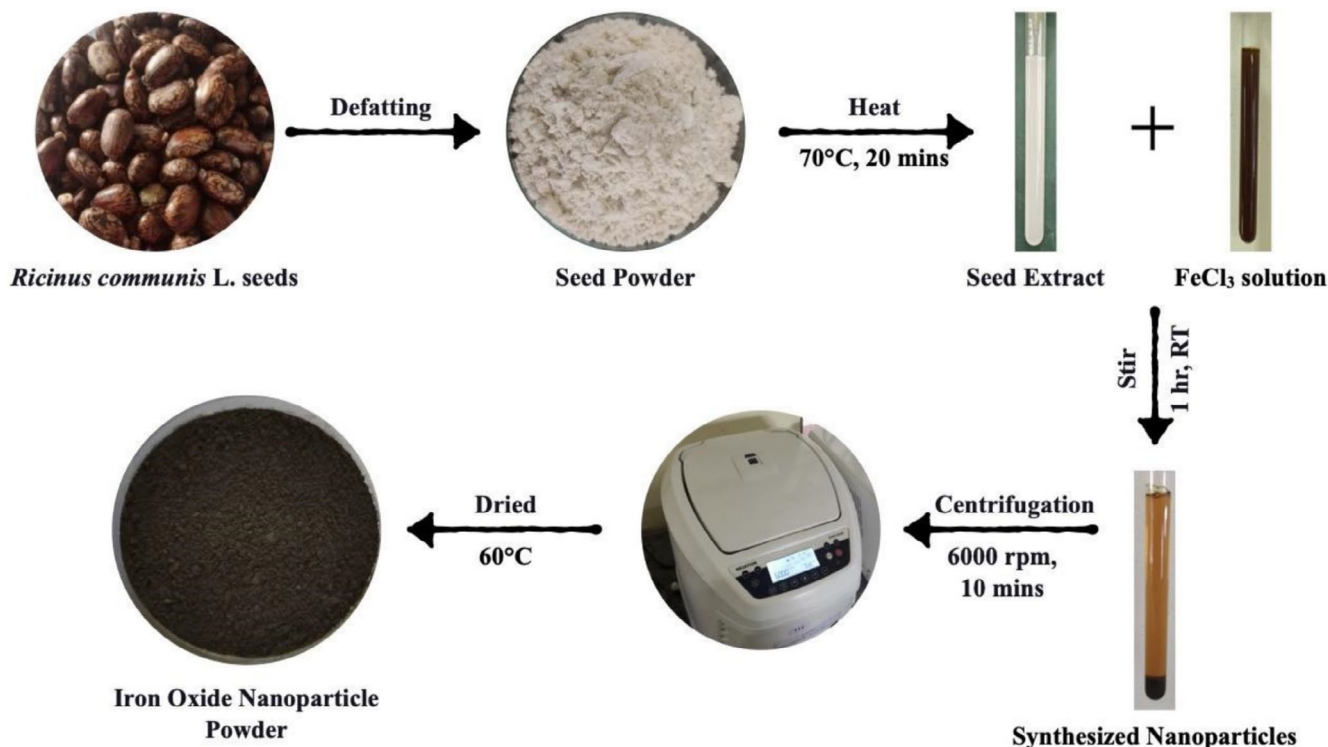
For this study, a mixture of seed extract and 1 M FeCl<sub>3</sub> solution was prepared in a 1:2 ratio. The resulting mixture was continuously agitated for 1 h at room temperature to ensure uniformity in the reaction within the solution. The change in color from reddish-brown to black signified the formation of iron oxide nanoparticles. Subsequently, the solution was centrifuged at 6000 rpm for 10 min at room temperature. The resulting pellet was washed with distilled water and ethanol for 10 min each at 5000 rpm to remove any excess residues. This washing process was repeated three to four times to ensure thorough removal of any remaining residues. The pellet was then dissolved in 1 mL of distilled water and left to dry overnight at 60°C in a hot air oven. Once dried, the powder was finely ground using a mortar and pestle and stored at room temperature until further use (Katata-Seru et al. 2018).

### 2.5 | Characterization of Nanoparticles

The iron oxide nanoparticles (Figure 1) were characterized using several complementary techniques to fully understand their properties. Initial confirmation of nanoparticle formation was obtained through UV-Visible spectroscopy using a Labindia Analytical UV 3092 UV-VIS Spectrophotometer, with scans performed across the 200 to 800 nm wavelength range to identify characteristic absorption peaks. For crystallographic analysis, XRD was performed using a Bruker D8 Advance X-Ray diffractometer operating at 15 mA and 40 kV with CuK $\alpha$  radiation. The XRD scan covered the 10° to 80° (2 $\theta$ ) range at a rate of 7°/min to determine the crystalline structure, phase purity, and crystallite size through analysis of diffraction patterns and application of the Debye-Scherrer equation ( $D = K\lambda / \beta \cos\theta$ ). Functional group identification and capping agent analysis were conducted using FTIR with a Perkin Elmer Spectrum 3 Tri-Range FT-IR Spectrometer. Samples were prepared by mixing with KBr at a 1:100 ratio and pressing into pellets before scanning across the 4000 to 500 cm<sup>-1</sup> range to detect characteristic vibrational modes of molecular bonds. Surface morphology and elemental composition were examined using a TESCAN Mira3 XMH SEM equipped with Energy Dispersive X-Ray (EDX) analysis capability. Samples were analyzed at an accelerating voltage of 20 kV to obtain high-resolution topographical images while simultaneously collecting elemental composition data through EDX.

### 2.6 | Confirmation of the Coagulation Activity of the Synthesized Nanoparticles

The coagulation efficiency of the iron oxide nanoparticles was evaluated using a 1% kaolin/synthetic clay solution test. Initially, 0.1 g of nanoparticle powder was introduced into 100 mL of the kaolin solution, followed by agitation for 1 min at 120 rpm. The solution was then left undisturbed for an hour. The initial and



**FIGURE 1** | Green synthesis of iron oxide nanoparticles using defatted *Ricinus communis* L. seed extract.

final turbidity of the solution was measured at 500 nm. The percentage reduction in turbidity of the solution was calculated to verify the coagulation activity of nanoparticles (Ghebremichael et al. 2005).

## 2.7 | Effect of Iron Oxide Nano Particles on Pollutant Removal From CPWW

The efficacy of *Ricinus communis* L. iron oxide nanoparticles in removing pollutants from CPWW was evaluated using a standard jar test setup (Kemi Make-Floculator). Various doses (0.02, 0.04, 0.06, 0.08, and 0.10g) of nanoparticles were added to 100 mL samples of the effluent. The mixture underwent vigorous stirring and settled for 1 h statically. Afterwards, the contents were centrifuged, and the resulting supernatant was analyzed for color, TDS, and COD removal. A control flask containing CPWW without nanoparticles was included for comparison. Experiments were triplicated, and removal percentages were calculated.

## 2.8 | FTIR Analysis of Nanoparticles Treated Sludge

FTIR analysis was used to identify the active functional moieties responsible for the removal of pollutants from CPWW in nanoparticle-treated effluent sludge samples. The samples were finely ground and mixed with potassium bromide crystals at a 1:50 ratio to achieve ideal particulate forms. The resulting particles were then analyzed using a Perkin Elmer Spectrum 3 Tri-Range FT-IR Spectrometer. Functional groups were determined by comparing the peaks produced by the sample with those of a reference standard.

## 3 | Results and Discussion

### 3.1 | Physicochemical Characterization of CPWW

The coffee effluent sample was analyzed for various physical and chemical parameters, as shown in Table 1. The CPWW appeared light dark brown in color and emitted a fruity odor with acidic undertones. The visible brown color indicates pollution levels linked to carbonaceous pollutants such as flavonoids, tannin, phenolic compounds, caffeine, and fat, which contribute to the reddish hue of ripe coffee cherries (Campos et al. 2010; Coelho et al. 2024). The fruity odor results from the degradation of organic compounds like esters and aldehydes, along with fermentation of sugars and breakdown of fruit components during processing (Fereja et al. 2020). The effluent was found to be acidic, with a pH of 4.8. The acidic pH is due to several factors inherent in the coffee processing stages. During pulping, organic acids such as chlorogenic acid and citric acid are released from the coffee cherries. Additionally, fermentation processes can produce acidic by-products, and the presence of organic matter from coffee pulp also contributes to the acidity (Gopinandhan et al. 2022).

CPWW showed high levels of TS (7780 mg/L), TSS (4540 mg/L), and TDS (3240 mg/L). These elevated levels can be attributed to various sources within the coffee processing chain. During pulping, large amounts of organic matter, such as coffee pulp, are released, contributing to the total solids. Soluble compounds like sugars, phenolic compounds, and organic acids from coffee cherries and pulp increase the total dissolved solids. The use of water in washing and fermentation further dissolves these substances, raising TDS levels (Dadi et al. 2018; Shah et al. 2023). The DO in the wastewater was entirely depleted, indicating septic conditions due to extensive

**TABLE 1** | Physicochemical characterization of coffee cherry pulping wastewater.

S. No	Parameters	Observation	CPCB standard for effluent discharge (under all mode)
1	Color	Brown	Colorless
2	Odor	Fruity odor	Odorless
3	pH	4.8 ± 0.19	6.5–8.5
4	Temperature	22°C	Shall not exceed 5°C above the receiving water temperature
5	TS	7780 ± 153	—
6	TDS	3240 ± 209	2100
7	TSS	4540 ± 115	100–600
8	Acidity	2956 ± 18	—
9	DO	—	—
10	BOD	16,500 ± 104	30–100
11	COD	29,450 ± 119	250
12	Chloride	150 ± 09	600–1000
13	Fluoride	6 ± 0.02	2–15
14	Phosphate	4 ± 0.01	5
15	Sulphate	409 ± 12	1000
16	Nitrate	28 ± 0.11	10–20

Note: The measurements are expressed in mg/L, with the exception of pH, color, temperature, and odor. The data presented represents the mean ± standard deviation, based on three replicates.

microbial degradation of the abundant organic matter (sugars, proteins, and polyphenols) present in CPWW. The high BOD<sub>5</sub> (16,500 mg/L) demonstrates substantial oxygen demand from aerobic microorganisms, while the complete oxygen depletion suggests prolonged microbial activity has created anoxic conditions (Li et al. 2021). The COD of the effluent was observed to be 29,450 mg/L. High BOD<sub>5</sub> and COD levels are mainly due to the presence of organic matter such as coffee pulp, bean mucilage, and husk, which are soluble organic compounds. These compounds are highly biodegradable, leading to significant oxygen consumption by microorganisms. The fermentation processes also contribute to the release of additional soluble organic compounds, increasing both BOD<sub>5</sub> and COD levels. Furthermore, inadequate treatment and disposal practices exacerbate the problem, as untreated or poorly treated effluent with high organic loads is discharged into water bodies, causing oxygen depletion and environmental degradation. The use of water throughout the coffee processing stages facilitates the leaching of these organic compounds, further elevating BOD<sub>5</sub> and COD levels (Devi et al. 2008; Campos et al. 2020).

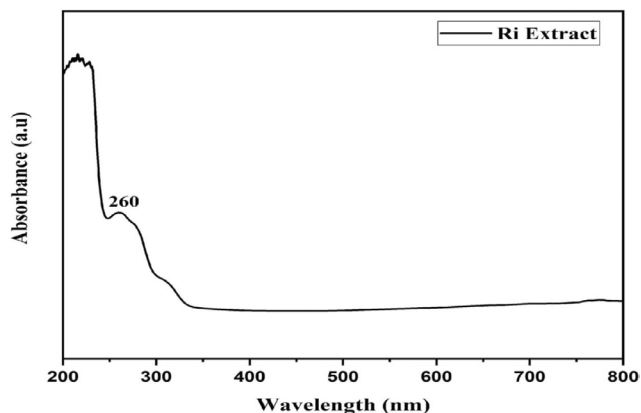
The levels of phosphate (4 mg/L), nitrate (28 mg/L), chloride (150 mg/L), sulfate (409 mg/L), and fluoride (6 mg/L) in CPWW

were within the CPCB standards. The chloride levels can be attributed to chloride-based fertilizers used in coffee plantations, while fluoride may come from natural sources in soil and water or from cleaning agents used in coffee processing facilities (Kafkafi 2011). Excessive fluoride intake can cause health issues like osteosclerosis and kidney dysfunction (Srivastava and Flora 2020). Phosphate, naturally occurring in water, supports aquatic vegetation growth. The nitrate in CPWW likely originated from nitrogen-based fertilizers commonly used in coffee cultivation, which increase soil nitrate levels. These nitrates are absorbed by coffee plants and enter the wastewater during the pulping process (Kobusinge et al. 2023). Furthermore, the decomposition of organic matter and agricultural residues in the soil can release nitrates into surrounding water sources (Radini et al. 2018).

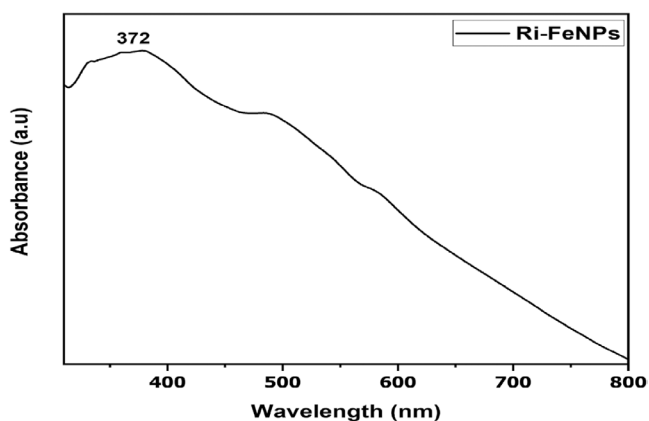
The investigated parameters provide clear indications of the substantial pollution burden within the CPWW, underscoring its harmful composition. The presence of intense coloration alongside elevated levels of TDS and COD indicated the toxicity of CPWW. As a result, it is imperative to prevent the discharge of CPWW into land or water bodies and refrain from utilizing it for irrigation purposes. Consequently, prioritizing the treatment of CPWW before its release from the processing unit becomes essential to mitigate its environmental impact.

### 3.2 | Characterization of Nanoparticles

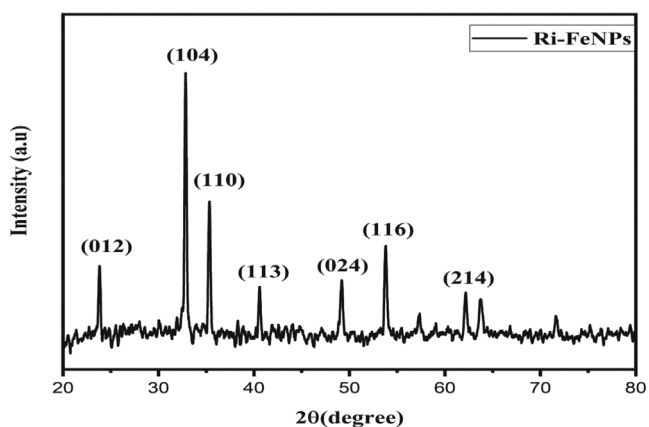
A total of 100 mL of the reaction mixture for the nanoparticles synthesis yielded 0.132 g of iron oxide nanoparticles. The synthesized nanoparticles were characterized using several techniques. The UV-Visible spectra of the seed extract exhibited strong absorption peaks at 216 and 260 nm, as illustrated in Figure 2, indicating the presence of natural organic compounds, particularly polyphenolic flavonoids (Fujii and Hayakawa 2023). After the addition of the seed extract, the UV-Visible spectra (Figure 3) of the synthesized iron oxide nanoparticles revealed a new absorption peak at 372 nm, signifying the reduction of Fe<sup>3+</sup> ions and the successful formation of iron oxide nanoparticles (Bibi et al. 2019; Yan et al. 2020). This observation aligns with findings by Budlayan et al. (2019), who also identified iron oxide nanoparticles with sharp peaks between 366 and 371 nm. The XRD analysis indicated the crystalline nature of iron nanoparticles derived from *Ricinus communis* L. The XRD pattern exhibited prominent diffraction peaks at 2 theta angles of 23.80°, 32.82°, 35.29°, 40.53°, 49.14°, 53.75°, and 62.13°, corresponding to crystallographic planes indexed as (012), (104), (110), (113), (024), (116), and (214), respectively, consistent with the (JCPDS Card No. 00-024-0072) (Bouafia and Laouini 2020). The crystallite size was determined using the Debye-Scherrer equation, yielding an average crystallite size of approximately 16 nm for the iron oxide nanoparticles. The XRD spectra of the synthesized nanoparticles are shown in Figure 4. The EDX spectrum (Figure 5) of the iron oxide nanoparticles showed strong peaks of Fe and O. The elemental composition of iron oxide nanoparticles was analyzed, and the Fe, C, and O composition was found to be 50.48%, 18.59%, and 30.92%, respectively. The results indicated the purity of green synthesized iron oxide nanoparticles. No unidentified elemental peaks were observed in EDX. The EDX quantitative data affirmed the purity, composition, and formation of iron oxide nanoparticles of *Ricinus communis* L. seed extract. The shape, dispersity, and



**FIGURE 2** | UV spectrophotometric characterization of *Ricinus communis* L. Seed extract.

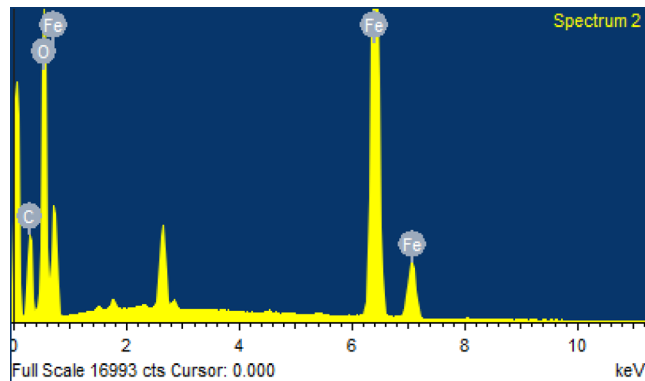


**FIGURE 3** | UV spectrophotometric characterization of *Ricinus communis* L. iron oxide nanoparticles.

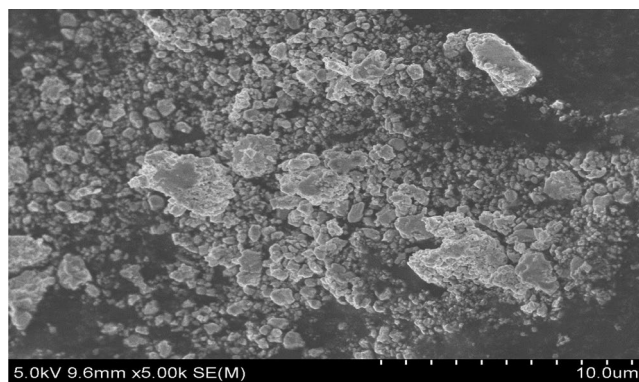


**FIGURE 4** | XRD spectra of *Ricinus communis* L. iron oxide nanoparticles.

topology of the synthesized nanoparticles were determined using SEM. The SEM analysis showed the irregular shaped cluster of the iron oxide nanoparticles (Figure 6). The FT-IR spectrum (Figure 7) of the synthesized iron oxide nanoparticles revealed key functional groups involved in nanoparticle formation and stabilization. The broad peaks at 3727.23 and 3174.67 $\text{cm}^{-1}$ , corresponding to O—H stretching vibrations, confirm the presence of surface-bound



**FIGURE 5** | Energy Dispersion X-ray spectroscopy (EDX) spectrum of *Ricinus communis* L. iron oxide nanoparticles.



**FIGURE 6** | SEM image (5.00 kx) of *Ricinus communis* L. iron oxide nanoparticles.

hydroxyl groups characteristic of plant-extract mediated synthesis (Chaudhary et al. 2019). Notably, the spectrum showed evidence of nitrogenous compounds through three distinct features: (1) a prominent N—O stretch at 1528.67 $\text{cm}^{-1}$ , indicative of nitro groups; (2) a characteristic C=O stretch at 1632.44 $\text{cm}^{-1}$  confirming secondary amides; and (3) a C—N stretch at 1103.63 $\text{cm}^{-1}$  suggesting amine presence—all likely derived from the proteinaceous components of the seed extract of *Ricinus communis* L. (Chambi et al. 2014). The observed alkane signatures (C—H bend at 1436.89 $\text{cm}^{-1}$ ) and halo-organic compounds (peaks at 698.52 and 572.45 $\text{cm}^{-1}$ ) further support the involvement of diverse phytochemicals in nanoparticle capping, consistent with the multi-component stabilization mechanisms reported for plant-mediated syntheses (Rehman et al. 2023). These functional groups indicate that the bioactive compounds from the seed extract are likely involved in the reduction and stabilization of the iron nanoparticles. These groups play a critical role in capping and stabilizing the nanoparticles, preventing aggregation and enhancing their dispersion. These findings align with the results reported by Demirezen et al. (2019) which are attributed to the formation of iron oxide nanoparticles.

### 3.3 | Confirmation of the Coagulation Activity of the Nanoparticles

The coagulation efficacy of the iron oxide nanoparticles was assessed using the 1% kaolin/clay coagulation activity assay. Initially, floc formations were observed, followed by a settling

process. The resulting clear supernatant was then analyzed for turbidity. The initial and final optical density of the solution was observed to be 1.683 and 0.051, respectively, indicating a 96.96% reduction in turbidity. The interaction between the nanoparticles and kaolin is influenced by the surface characteristics of the nanoparticles. Iron oxide nanoparticles have surface charges and reactive sites that bind to the negatively charged kaolin particles. This binding neutralizes charges and leads to floc formation, where the aggregates increase in size. The larger flocs then settle more rapidly from the suspension (Mohamad et al. 2022). This confirmed the ability of the synthesized nanoparticles to assist in the removal of impurities from the effluent (Ghebremichael et al. 2005).

### 3.4 | Effect of *Ricinus communis* L. Iron Oxide Nano Particles on Pollutant Removal From CPWW

Different dosages of *Ricinus communis* L. iron oxide nanoparticles were employed to treat CPWW, aiming to remove color, TDS,

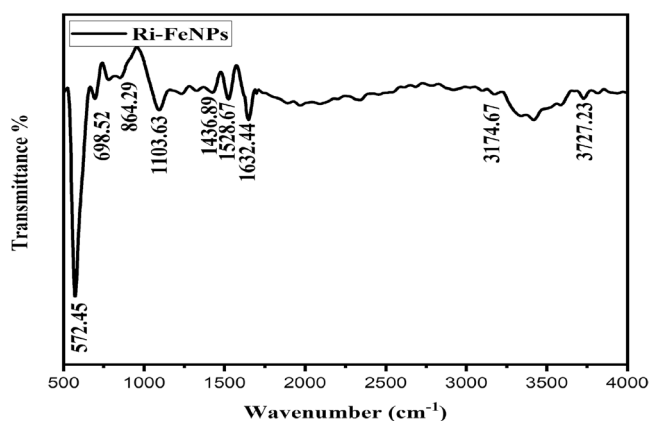


FIGURE 7 | FT-IR spectra of *Ricinus communis* L. iron oxide nanoparticles.

and COD (Figure 8). The results are illustrated in Table 2. The color removal efficiency was measured as approximately 88% for a dosage of 0.02g, 88% for 0.04g, 88% for 0.06g, 92% for 0.08g, and 91% for 0.10g of iron nanoparticle treatment. At a dosage of 0.08g, the treatment achieved the maximum reduction in TDS (69%) and COD (74%). Further increases in iron oxide nanoparticle dosage concentration did not yield any significant improvement in TDS and COD removal rates. The reduced efficacy at higher doses may be due to a reversal in the net charge of the pollutants in the wastewater. Additionally, exceeding the optimal dosage can lead to the destabilization of colloidal particles, which decreases the effectiveness of the nanoparticles in pollutant removal (Shahrodin et al. 2020). Based on these findings, 0.08g was determined as the optimum dosage for treating CPWW with *Ricinus communis* L. iron oxide nanoparticles. The TDS and COD removal from CPWW can be attributed to the surface precipitation or adsorption mechanism of the iron oxide nanoparticles. Akintayo et al. (2021) also reported such reduction in the removal of organics from refinery wastewater by the synthesis of iron oxide nanoparticles. Iron oxide nanoparticles exhibit high surface area-to-volume ratios and surface functional groups, such as hydroxyl (–OH) and carboxyl (–COOH), rendering them efficient adsorbents for diverse pollutants found in wastewater. These groups enhance the adsorption of pollutants through both physical and chemical interactions. The adsorption mechanism involves the attachment of pollutant particles to these functional groups, leading to their aggregation and subsequent removal from the solution (Alprol et al. 2023). Iron oxide nanoparticles are also capable of undergoing redox reactions and facilitating the degradation of organic pollutants via Fenton-like reactions. During this process, the nanoparticles generate reactive oxygen species, which oxidize organic compounds, transforming them into smaller, less harmful molecules (Chakraborty et al. 2022). While this study demonstrates promising results, several limitations should be acknowledged. First, the nanoparticle synthesis process may show batch-to-batch variability due to natural variations in the plant extract composition. Second, while the tested dosage range showed effective pollutant removal, lower dosages

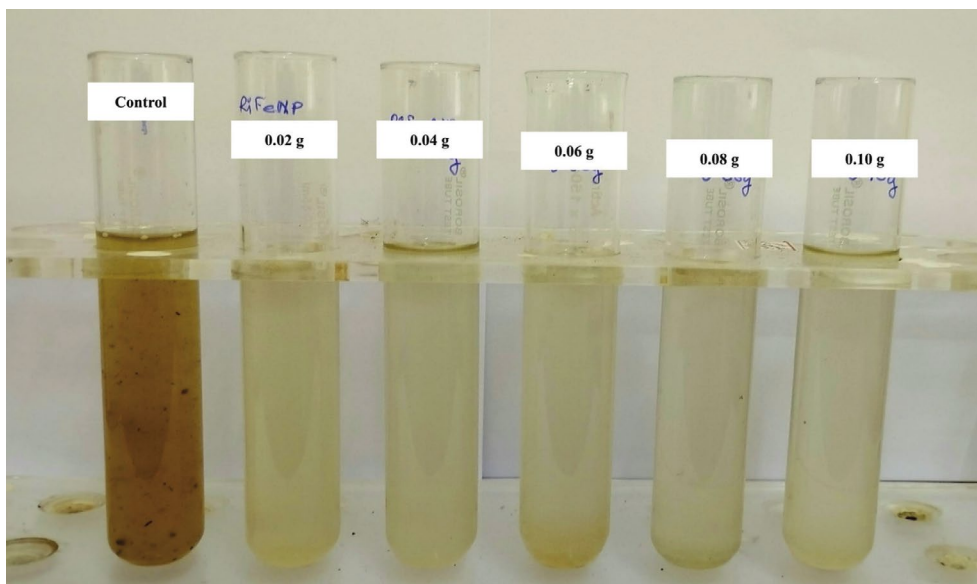


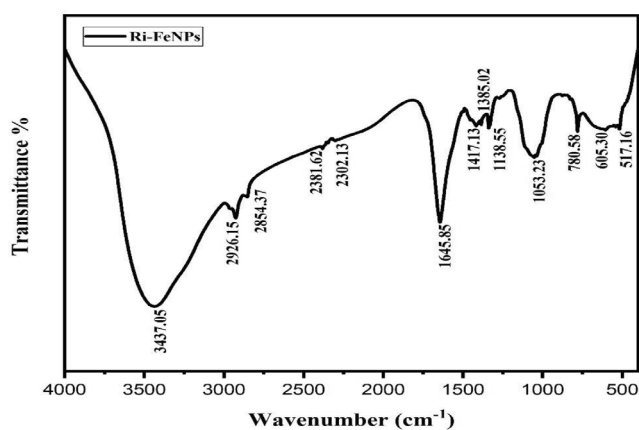
FIGURE 8 | Coffee effluent treatment using different doses of *Ricinus communis* L. iron oxide nanoparticles.

**TABLE 2** | Effect of *Ricinus communis* L. iron oxide nanoparticles on color, TDS, and COD removal from the CPWW.

S. No	<i>Ricinus communis</i> L. iron oxide nanoparticle dosage (g)	Reduction percentage (%)		
		Color	TDS	COD
1	0.02	88 ± 0.03	54 ± 0.01	49 ± 0.04
2	0.04	88 ± 0.02	55 ± 0.06	57 ± 0.01
3	0.06	88 ± 0.06	57 ± 0.03	62 ± 0.05
4	0.08	92 ± 0.01	69 ± 0.02	74 ± 0.03
6	0.10	91 ± 0.02	62 ± 0.01	67 ± 0.07

Note: The data presented represents the mean ± standard deviation, based on three replicates.

Abbreviations: COD: Chemical Oxygen Demand; TDS: Total Dissolved Solids.



**FIGURE 9** | FT-IR spectra of *Ricinus communis* L. iron oxide nanoparticles-treated sludge.

were not evaluated due to resource constraints; future studies should investigate reduced concentrations to minimize potential metal oxide leaching while maintaining treatment efficacy. Third, the treatment efficiency was evaluated under controlled laboratory conditions, and performance may differ in real-world, large-scale applications with fluctuating wastewater characteristics. Furthermore, sludge characterization parameters including volume, weight, and volatile solids content were not measured, which would provide valuable insights into practical treatment plant operation. Additionally, the long-term stability of the nanoparticles and potential secondary environmental impacts of the treated sludge require further investigation. Future studies should address these limitations by optimizing synthesis protocols, conducting pilot-scale tests, and performing comprehensive lifecycle assessments of the treatment process.

### 3.5 | FTIR Analysis of Iron Oxide Nanoparticles-Treated Sludge

After the CPWW was treated with iron oxide nanoparticles, the resulting sludge was subjected to FTIR analysis to determine functional moieties based on peak values (Figure 9). The

findings are presented in Table 3. The peak at 1645.85 cm<sup>-1</sup> indicated the presence of C=N stretching, suggesting the existence of the imine functional group. At 1385.02 cm<sup>-1</sup>, the presence of C-H bending suggested the occurrence of aldehyde. Peaks observed at 1338.55 and 1053.23 cm<sup>-1</sup> corresponded to C-N stretching, indicating the presence of amine groups. The peak at 780.58 cm<sup>-1</sup> indicated C-H bending, implying the presence of 1,2,3-trisubstituted functional groups. Additionally, peaks observed at 605.30 and 517.16 cm<sup>-1</sup> were associated with C-Cl stretching and C-I stretching respectively, suggesting the presence of halo compounds in the treated sludge. Furthermore, peaks observed at 3437.05, 2926.15, 2854.37, and 1417.13 cm<sup>-1</sup> collectively indicated hydroxyl groups, suggesting alcohol and carboxylic acid functionalities in the green synthesized iron oxide nanoparticles. This observation implied the potential formation of hydrogen bonds between the -OH groups in the nanoparticles and the pollutants present in CPWW. Notably, the absence and shift in peak values associated with various functional groups of the nanoparticles after the coagulation process were observed (Shabanizadeh and Taghavijelouidar 2023). This absence and alteration in the group peaks served as additional confirmation of the coagulation properties of the iron oxide nanoparticles and their effectiveness in removing pollutants from CPWW (Mbachu et al. 2023). These functional groups, as observed in Table 3, likely reacted with anionic compounds in the wastewater through electrostatic interactions, leading to the removal of color, TDS, and COD. Comparable findings were reported previously by Olusegun et al. (2019).

## 4 | Conclusion

The present study focused on the coagulant activity of iron oxide nanoparticles synthesized from *Ricinus communis* L. seeds and reveals significant potential for wastewater treatment applications. Analysis of CPWW highlighted its highly contaminated nature, characterized by elevated levels of TDS, COD, and BOD5, among other parameters, surpassing permissible discharge limits. The nanoparticles achieved significant pollutant removal efficiencies of 74% for COD, 69% for TDS, and 92% for color at an optimal dosage of 0.08 g/100 mL. These results highlight the capacity of nanoparticles to treat highly contaminated CPWW. The treatment efficiency stems from the dual mechanisms of action of the nanoparticles: (1) surface adsorption facilitated by their high surface area-to-volume ratio and bioactive capping agents identified through FTIR analysis, and (2) redox activity enabling degradation of organic pollutants. Characterization studies confirmed the purity of the nanoparticles (50.48% Fe content by EDX) and crystalline structure (16 nm average size by XRD). The demonstrated efficiencies, combined with the environmental sustainability of the method and cost-effectiveness due to the plant-based synthesis, establish this approach as a promising alternative for coffee industry wastewater treatment.

## 5 | Future Perspectives

This study highlights several important directions for future research on green-synthesized iron oxide nanoparticles for wastewater treatment. First, dosage optimization studies should establish the minimum effective concentration while

**TABLE 3** | FTIR analysis of iron oxide nanoparticles-treated sludge.

S. No	Peak value $\text{cm}^{-1}$	Stretching	Interpretation
1	3437.05 $\text{cm}^{-1}$	O–H stretching	Alcohol
2	2926.15 $\text{cm}^{-1}$	O–H stretching	Carboxylic acid
3	2854.37 $\text{cm}^{-1}$	O–H stretching	Alcohol
4	2381.62 $\text{cm}^{-1}$	O=C=O stretching	Carbon dioxide
5	2302.13 $\text{cm}^{-1}$	O=C=O stretching	Carbon dioxide
6	1645.85 $\text{cm}^{-1}$	C=N stretching	Imine/oxime
7	1417.13 $\text{cm}^{-1}$	O–H bending	Alcohol
8	1385.02 $\text{cm}^{-1}$	C–H bending	Aldehyde
9	1338.55 $\text{cm}^{-1}$	C–N stretching	Aromatic amine
10	1053.23 $\text{cm}^{-1}$	C–N stretching	Amine
11	780.58 $\text{cm}^{-1}$	C–H bending	1,2,3-trisubstituted
12	605.30 $\text{cm}^{-1}$	C–Cl stretching	Halo compound
13	517.16 $\text{cm}^{-1}$	C–I stretching	Halo compound

assessing long-term ecotoxicity. Second, integrating these nanoparticles with complementary technologies like biochar or anaerobic digestion could improve treatment efficiency. Scaling up to continuous-flow systems will be essential for industrial applications, requiring evaluation of nanoparticle recovery and reuse. The approach should also be tested on other challenging wastewaters, such as palm oil mill or dairy effluents. Life cycle assessments would help quantify environmental benefits compared to conventional methods. Finally, advanced characterization techniques could reveal structure–activity relationships to guide the development of more effective nanoparticles. These investigations will help transition this promising technology from laboratory research to practical implementation.

#### Author Contributions

**Thamaraiselvi Chandran:** conceptualization, funding acquisition, writing – original draft, writing – review and editing, validation, methodology, project administration, supervision. **Athira Sudarsanan Thulasi:** writing – original draft, writing – review and editing, formal analysis, software, data curation. **Manikandan Elayaperumal:** writing – original draft, writing – review and editing, formal analysis. **Fatimah S. Al-Khattaf:** writing – original draft, writing – review and editing. **Ashraf Atef Hatamleh:** writing – original draft, writing – review and editing. **Kathikeyan Ravi:** writing – original draft, writing – review and editing. **Soon Woong Chang:** writing – original draft, writing – review and editing. **Balasubramani Ravindran:** conceptualization, methodology, writing – original draft, writing – review and editing, supervision, data curation, validation.

#### Acknowledgments

The authors would like to extend their sincere appreciation to Tamil Nadu State Council for Higher Education (File No. RGP/2019-20/MTWU/HECP-0075), Government of Tamilnadu, India, for their generous financial support. The authors extend their appreciation to the ongoing project Researchers Funding Program (OFR-2025-224) King Saud University, Riyadh, Saudi Arabia.

#### Data Availability Statement

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

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