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Experimental Investigation of Microplastic Removal from Drinking Water Using Aluminium Electrocoagulation: Process Performance and Operating Parameters

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Abstract

Microplastic contamination in drinking water has emerged as a growing environmental concern due to its persistence and potential health risks. In this study, an aluminium-based electrocoagulation process was experimentally evaluated for the removal of microplastic particles from real drinking water samples. A bench-scale reactor equipped with parallel aluminium electrodes was used to investigate the influence of key operating parameters, including pH, current density, electrolyte concentration, and treatment time. The results demonstrated that removal efficiency strongly depended on electrochemical conditions, with optimal performance observed at near-neutral pH and moderate current density. Rapid removal was achieved during the initial treatment stage, followed by stabilisation as the system approached an equilibrium. The removal mechanism was governed by the formation of aluminium hydroxide flocs, enabling particle aggregation through adsorption, sweep flocculation and flotation processes. Under optimised conditions, removal efficiencies of approximately 80% were obtained. The findings indicate that electrocoagulation can serve as an effective supplementary treatment for reducing microplastic contamination in drinking water. However, the results should be interpreted considering the use of real water samples and the limitations of gravimetric estimation, highlighting the need for further validation using controlled synthetic systems.

Keywords: Microplastics; Electrocoagulation; Aluminium electrodes; Drinking water treatment; Operating parameters

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1. Introduction

The widespread use of plastic materials over the past decades has led to a continuous increase in plastic residues in natural and engineered water systems. Due to their durability and resistance to degradation, plastics undergo gradual physical and chemical fragmentation, resulting in the formation of microplastics with characteristic dimensions below a few millimetres [1,2]. These particles have been detected in rivers, lakes, wastewater treatment plants, and even in drinking water supplies, raising concerns regarding their persistence, transport behaviour and potential interactions with biological and chemical systems [3,4].

Microplastics exhibit complex behaviour in aquatic environments owing to their diverse polymer composition, surface properties and size distribution. Their tendency to aggregate, adsorb contaminants and interact with natural colloids enhances

their mobility and persistence within water systems [5]. Several studies have reported the presence of microplastic particles in treated drinking water, indicating that conventional treatment processes are not always sufficient to ensure their complete removal. As a result, microplastics are increasingly regarded as an emerging class of contaminants that require targeted mitigation strategies [6,7].

From a health and environmental perspective, the concern associated with microplastics extends beyond their physical presence. These particles may act as carriers for organic pollutants, heavy metals and microorganisms, potentially increasing exposure risks for aquatic organisms and humans [8]. Their long-term stability and resistance to biodegradation further complicate their management within water treatment systems [9]. Consequently, the development and evaluation of effective removal techniques for microplastics have become an active area of research [10,11].

A wide range of treatment technologies has been investigated for microplastic removal, including membrane filtration, adsorption, magnetic separation, biological processes and advanced oxidation techniques [12–15]. While some of these approaches demonstrate high removal efficiencies under controlled conditions, their practical implementation is often limited by high energy demand, operational complexity, fouling issues, or chemical consumption [16,17]. In recent years, coagulation-based methods have gained attention due to their ability to destabilise suspended particles and promote aggregation through relatively simple operational schemes [18].

Electrocoagulation represents a hybrid electrochemical-physical treatment process in which sacrificial metal electrodes are dissolved in situ under an applied electric field, generating coagulant species without the direct addition of chemicals. The process has been widely applied in wastewater treatment for the removal of suspended solids, oils, dyes and heavy metals [19,20]. From a thermodynamic and electrochemical standpoint, electrocoagulation involves a balance between electrical energy input, metal dissolution kinetics, hydrolysis reactions and gas evolution, all of which influence treatment performance [21].

Recent investigations have explored the applicability of electrocoagulation for microplastic removal from wastewater and drinking water matrices [22,23]. Aluminium electrodes, in particular, have been shown to generate amorphous aluminium hydroxide species with high surface activity, capable of adsorbing and entrapping microplastic particles through charge neutralisation and sweep flocculation mechanisms [24]. However, reported removal efficiencies vary significantly depending on operating conditions such as pH, current density, electrolyte concentration and hydraulic residence time [25].

Despite the growing body of literature, several aspects of microplastic removal by electrocoagulation remain insufficiently understood. Many studies focus primarily on wastewater matrices, while fewer investigations address drinking water systems under controlled laboratory conditions [26]. In addition, the combined influence of electrochemical parameters on process stability and removal efficiency has not been consistently evaluated within a unified experimental framework [27,28]. From a thermodynamic perspective, understanding how operating parameters govern coagulant formation, particle aggregation and separation behaviour is essential for optimising process performance and ensuring reliable operation [29–31].

Therefore, the present study investigates the applicability of aluminium-based electrocoagulation for reducing microplastic contamination in real drinking water samples collected from Baghdad. The objective was not to simulate an idealised synthetic suspension, but rather to examine the process behaviour under realistic drinking-water conditions, where microplastic concentrations are expected to be relatively low and variable. This approach provides practical insight into the feasibility of electrocoagulation as a supplementary treatment step for real water matrices. However, it also introduces limitations related to sample heterogeneity and the absence of a controlled synthetic baseline. Accordingly, the results should be interpreted as an experimental feasibility assessment under realistic conditions, while future work should include synthetic microplastic-spiked water to improve reproducibility, mass balance evaluation and mechanistic interpretation.

2. Materials and methods

2.1. Water samples and sampling procedure

Drinking water samples were collected from Baghdad city to represent typical conditions of local supply and consumption. Two categories were considered: (i) tap water collected from different locations, and (ii) commercially bottled drinking water from different manufacturers. For tap water, the faucet was allowed to run for 1 min before sampling to reduce the influence of stagnant water in household plumbing. Each sample was collected in 1 L dark glass containers that had been pre-cleaned and rinsed with distilled water. Bottled water samples were kept in their original containers until analysis and treatment. The selection of local drinking water matrices is consistent with regional observations reporting microplastics occurrence in Baghdad drinking-water-related systems [12].

The use of real tap and bottled drinking water was intended to reflect practical exposure conditions rather than an idealised laboratory matrix. It is acknowledged, however, that natural drinking water generally contains relatively low and variable microplastic concentrations compared with synthetic suspensions. Therefore, the present study should be interpreted as a feasibility-oriented assessment of electrocoagulation performance in real drinking-water matrices. Future investigations should incorporate synthetic water spiked with known microplastic concentrations to provide a more controlled baseline and improve reproducibility.

2.2. Reagents and materials

Analytical-grade sodium chloride (NaCl) was used as supporting electrolyte to adjust electrical conductivity. The solution pH was adjusted using diluted sulfuric acid (H_2SO_4) and sodium hydroxide (NaOH). Cellulose nitrate (or equivalent) membrane filters with pore size 0.45 μm were used for post-treatment filtration. All solutions were prepared using distilled water.

2.3. Electrocoagulation reactor and electrode configuration

Electrocoagulation (EC) experiments were performed in a bench-scale batch reactor consisting of a 1 L Pyrex glass beaker. Two parallel aluminium plate electrodes were vertically installed in the reactor. Each electrode had dimensions of 80 × 130 × 1 mm. The inter-electrode spacing was varied between 1 and 5 cm depending on the experiment. A DC power supply (0–30 V, maximum current 5 A) was used to provide constant-current operation (galvanostatic mode), which is commonly recommended for reproducible EC performance assessment [1]. To maintain uniform mixing and reduce concentration gradients near the electrode surfaces, the reactor contents were stirred using a magnetic stirrer at 250 rpm throughout treatment. After each experiment, the reactor was switched off and the suspension was allowed to settle for 2 h prior to filtration and analytical measurements.

2.3.1. Electrode preparation and cleaning

Before each run, aluminium electrodes were rinsed with distilled water. To remove surface residues and maintain consistent electrode activity, the plates were immersed in diluted H_2SO_4 for 2 min, then thoroughly rinsed with distilled water, dried and weighed. This routine cleaning step is frequently used to minimise passivation and improve repeatability in EC studies [1].

2.4. Experimental design and operating conditions

A parametric experimental plan was adopted to examine the influence of operating variables on microplastic removal, focusing on factors known to affect EC performance through coagulant generation rate, hydrolysis pathways and gas evolution behaviour [1]. The main investigated variables were:

- pH: 3, 5, 7, 8, 9 and 10.
- Supporting electrolyte (NaCl): 1, 2, 3 and 4 g/L.
- Current density (CD): 5, 10, 20, 30 and 40 mA/cm^2.
- Electrode spacing: 1–5 cm.
- Treatment time: 15, 30, 45, 60, 75 and 90 min.

Unless otherwise stated, each set of tests was conducted at room temperature under constant stirring. Samples were withdrawn at 15 min intervals for analysis.

The chosen ranges were guided by previous studies on EC operation and microplastic removal behaviour, where pH and current density strongly control aluminium hydrolysis species and separation efficiency [6].

2.5. Electrochemical reactions and process description

The EC process was conducted using sacrificial aluminium electrodes. The primary reactions can be represented as follows [1]:

Anode: $Al\ (s) \rightarrow Al^{+3}\ (aq) + 3e.$ (1)

Cathode: $3H_2O\ (l) + 3e^- \rightarrow 3/2\ H_2\ (g) + 3OH^-\ (aq).$ (2)

In solution: $Al^{+3}\ (aq) + 3OH^-\ (aq) \rightarrow Al(OH)_3\ (s).$ (3)

The in-situ formation of amorphous $Al(OH)_3$ flocs provides active surfaces for particle destabilisation, adsorption and sweep flocculation, while hydrogen evolution contributes to flotation of aggregated particles [1,6,9]. These mechanisms are particularly relevant to microplastic removal, where aggregation and capture into larger flocs is typically the dominant separation pathway [6,13].

2.6. Sample handling, filtration and drying

After the settling step, the treated suspension was filtered using a vacuum filtration unit equipped with 0.45 µm membrane filters. Filters were dried in an oven at 45°C for 48 h before gravimetric measurements and microscopic inspection. This approach aligns with established workflows used in microplastic separation and EC-related microplastic studies, while recognising that polymer confirmation requires spectroscopic verification [6].

2.7. Microplastic analysis methods

2.7.1. Gravimetric estimation of retained solids and apparent microplastic removal

Retained solids on the membrane were quantified by filter mass difference before and after filtration. The removal efficiency was estimated based on the relative reduction in retained mass compared to the initial concentration, following approaches commonly reported in electrocoagulation-based microplastic studies [6].

Because electrocoagulation with aluminium electrodes produces $Al(OH)_3$ flocs and may also capture other suspended matter, the gravimetric result does not represent a direct measurement of pure microplastic mass alone. Instead, it provides an apparent estimate of microplastic-associated retained solids after treatment. For this reason, gravimetric measurements were supported by fluorescence microscopy and Fourier transform infrared spectroscopy (FTIR) analysis to strengthen the interpretation that the retained material included polymeric particles. Accordingly, the reported removal efficiencies should be interpreted as estimated values under the adopted analytical procedure rather than absolute polymer-specific removal.

2.7.2. Fluorescence microscopy (visual inspection)

Dried filters were examined using a fluorescence microscope (MEIJI MX, Japan). Microplastic particles were identified by visual sorting under magnification, and categorised according to morphology (e.g. fragments, pellets/fibres) following a practical classification approach used in field and drinking-water-related microplastic screening studies [15]. Representative images were recorded for documentation.

2.7.3. FTIR spectroscopy

To confirm polymeric signatures, selected retained material on dried filters was analysed by FTIR using an IRPrestige-21 (Shimadzu). Spectra were recorded and compared qualitatively to known polymer functional-group regions reported in the microplastics literature [37]. FTIR confirmation was used as the pri-

mary evidence to support microplastic presence before treatment and reduction after EC, consistent with widely adopted identification practices [35].

It should be noted that no independent chemical digestion or density-separation step was applied to completely isolate polymer particles from aluminium hydroxide flocs prior to gravimetric assessment. Therefore, microscopy and FTIR were used as confirmatory tools to support the presence of polymeric material on the filters. This analytical limitation should be considered when interpreting the absolute magnitude of the reported removal efficiencies.

2.8. Quality assurance and contamination control

Because microplastic measurements can be affected by airborne fibres and secondary contamination, practical contamination-reduction measures were adopted during sampling and analysis. Glass containers were preferred over plastic during sampling and storage, and filters were handled using clean metal tweezers. Work surfaces were cleaned prior to filtration and microscopy. These precautions are consistent with the general recommendations in microplastic analytical studies aiming to minimise false positives [15].

2.9. Energy-related process indicators

Electrical energy consumption can be reported using a specific energy consumption (SEC) metric, widely used in electrochemical water treatment analysis [1]:

$$\mathrm{SEC}\ (\mathrm{kWh/m^3}) = \frac{U\ I\ t}{V} 10^{-3}, \qquad (4)$$

where U is voltage (V), I current (A), t operating time (h) and V treated volume (m^3). This indicator allows comparison between operating cases and supports optimisation discussions based on energy demand, not only removal percentage.

2.10. Methodological limitations

The present work was designed to assess electrocoagulation performance in real drinking-water samples rather than in synthetic microplastic suspensions. While this improves practical relevance, it limits strict reproducibility because the initial microplastic content in natural samples is inherently low and variable. In addition, gravimetric filtration may include aluminium hydroxide flocs and other retained solids in addition to microplastic particles. Therefore, the reported removal efficiencies should be interpreted together with the supporting microscopy and FTIR observations. Future work should include synthetic microplastic-spiked water, polymer-specific quantification and additional water-quality indicators such as turbidity, total suspended solids (TSS), conductivity and total dissolved solids (TDS).

3. Results and discussion

3.1. Identification of microplastics in drinking water samples

3.1.1. Visual inspection using fluorescence microscopy

Prior to electrocoagulation treatment, microplastic particles were visually identified on the filtered membranes using fluorescence microscopy. Irregular fragments as well as spherical plastic-like particles were observed, indicating the presence of different microplastic morphologies in drinking water samples. After electrocoagulation, the number of visually distinguishable plastic particles on the membrane surface was noticeably reduced, suggesting aggregation and removal during the treatment process. Representative microscopy images are presented in Fig. 1.

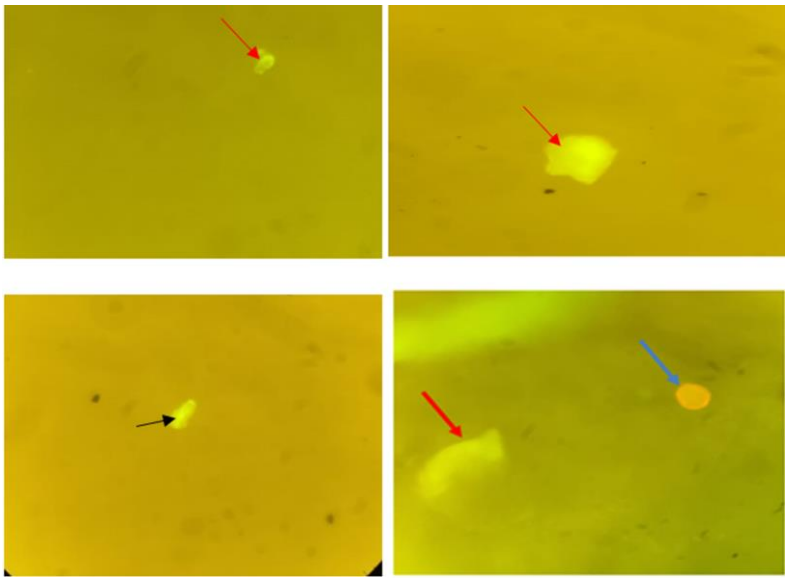


Fig. 1. Fluorescence microscopy images of microplastic particles in drinking water samples before electrocoagulation, showing the presence of irregular fragments and spherical particles.

3.1.2. FTIR confirmation of polymeric material

Because the study relied on real drinking-water samples, the detected microplastic content and retained solids should be interpreted within the natural variability of the sampled matrices. FTIR analysis was performed to confirm the polymeric nature of retained particles before and after electrocoagulation treatment. The untreated water samples exhibited characteristic absorption bands associated with common polymer functional groups, while several of these bands were absent or significantly reduced after treatment. The observed reduction in oxygenated and aromatic functional groups indicates preferential removal of polymers such as polyethylene terephthalate (PET) and polystyrene (PS), whereas nonpolar polymers showed lower sensitivity to electrocoagulation. The corresponding FTIR spectra are presented in Fig. 2.

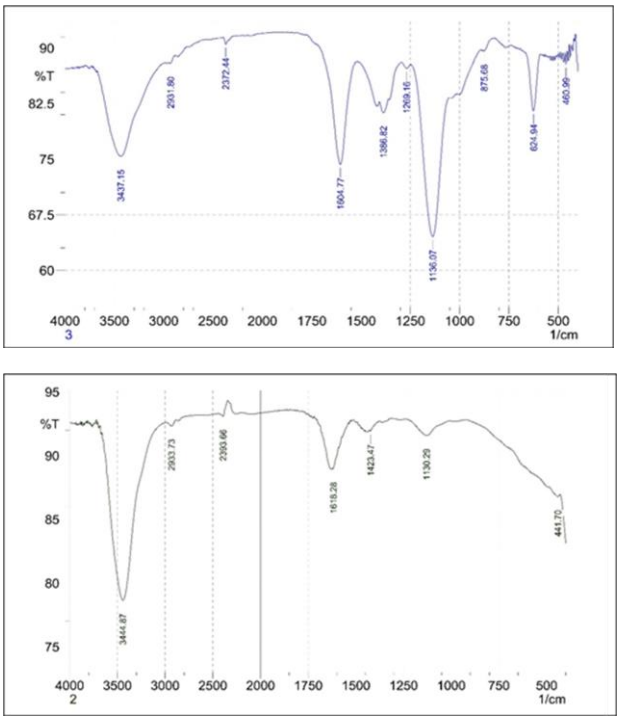


Fig. 2. FTIR spectra of retained particles before and after electrocoagulation treatment, indicating the reduction of characteristic polymer functional groups.

3.1.3. Observation of floc formation during electrocoagulation

During the electrocoagulation process, the formation of visible flocs was clearly observed in the treated water samples. As the treatment progressed, the initially transparent or slightly turbid water gradually developed suspended whitish, gelatinous aggregates characteristic of aluminium hydroxide formation. These flocs increased in size and density with time, leading to noticeable settling at the bottom of the reactor after the treatment was stopped.

The observed flocs exhibited typical behaviour associated with sweep flocculation, where suspended particles are enmeshed within growing aluminium hydroxide structures. In addition, fine gas bubbles generated at the cathode contributed to the flotation of aggregated particles toward the water surface. This combined sedimentation–flotation behaviour was consistently observed under optimal operating conditions, particularly at near-neutral pH and moderate current density.

Although photographic documentation is not included, the consistent reduction in measured retained solids and the corresponding decrease in visually identifiable microplastic particles (as confirmed by microscopy) strongly support the occurrence of effective floc formation and particle aggregation during electrocoagulation.

3.2. Effect of electrocoagulation time on microplastic removal

The influence of treatment time on microplastic removal efficiency was investigated under constant operating conditions. A rapid increase in removal efficiency was observed during the first 15 min of operation, reaching approximately 70%. Extending the treatment time to 30 min resulted in an increase in removal efficiency to about 80%, while further prolongation produced only marginal improvement. This trend suggests that most microplastic aggregation occurs during the early stages of electrocoagulation. The variation of removal efficiency with time is illustrated in Fig. 3, and the corresponding concentrations are summarised in Table 1.

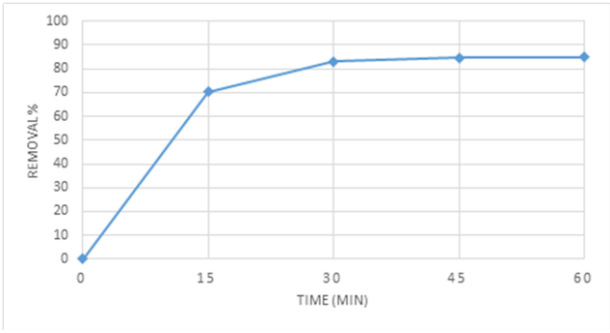


Fig. 3. Variation of microplastic removal efficiency with treatment time, showing rapid initial removal followed by stabilization due to floc saturation and reduced particle availability.

Table 1. Variation of microplastic concentration with treatment time during electrocoagulation.

Time (min)	0	15	30	45	60
Concentration (ppm)	101	30	15.1	15	15

This behaviour is consistent with the progressive formation and growth of aluminium hydroxide flocs during electrocoagulation, which enhance particle aggregation and facilitate their removal through sedimentation and flotation.

The experimental setup was constructed following standard bench-scale electrocoagulation configurations commonly reported in the literature [1], including parallel aluminium electrodes, controlled current supply and continuous mixing. Although a photographic image of the setup is not included, all op-

erational parameters and reactor configurations are described in sufficient detail to ensure reproducibility.

The rapid increase in removal efficiency during the initial 15 minutes indicates that the early stage of electrocoagulation is dominated by availability of active adsorption sites on freshly formed aluminium hydroxide flocs, which facilitates the rapid capture of microplastic particles. As the treatment progresses, the system gradually approaches a quasi-equilibrium condition, where removal efficiency stabilises due to the partial saturation of available adsorption sites and the reduction in the number of remaining particles in the solution. This behaviour is consistent with coagulation mechanisms governed by mass transfer and surface interaction processes.

3.3. Effect of pH on microplastic removal efficiency

Solution pH had a pronounced effect on electrocoagulation performance. The highest removal efficiencies were achieved under near-neutral conditions (pH 7–8), while acidic and alkaline conditions resulted in lower efficiency. This behaviour is attributed to the formation of amorphous aluminium hydroxide species at neutral pH, which enhances aggregation and flocculation of microplastic particles. The effect of pH on removal efficiency is shown in Fig. 4.

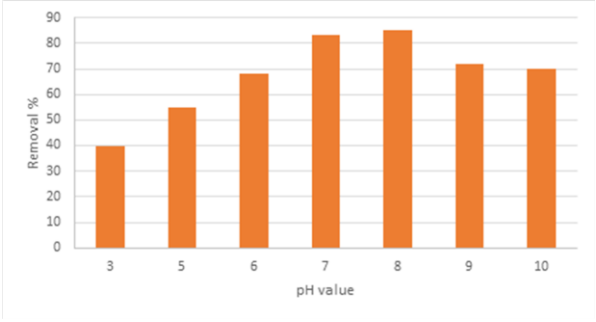


Fig. 4. Influence of initial pH on microplastic removal efficiency, highlighting optimal performance under near-neutral conditions due to favourable aluminium hydroxide speciation.

The improved removal efficiency at near-neutral pH further supports the formation of amorphous $Al(OH)_3$ flocs with high adsorption capacity, which play a dominant role in microplastic capture through sweep flocculation mechanisms.

The dependence of removal efficiency on pH can be interpreted based on aluminium speciation. At near-neutral pH, the dominant species are amorphous $Al(OH)_3$ with high surface area, which enhances adsorption and sweep flocculation. In contrast, under acidic conditions, soluble Al^{3+} species dominate, reducing floc formation, while at high pH, negatively charged $Al(OH)_4^-$ species limit particle aggregation due to electrostatic repulsion.

3.4. Influence of electrolyte (NaCl) concentration

Increasing sodium chloride concentration improved microplastic removal efficiency due to enhanced solution conductivity and more stable current flow. Removal efficiency increased with electrolyte concentration up to 4 g/L, beyond which excessive

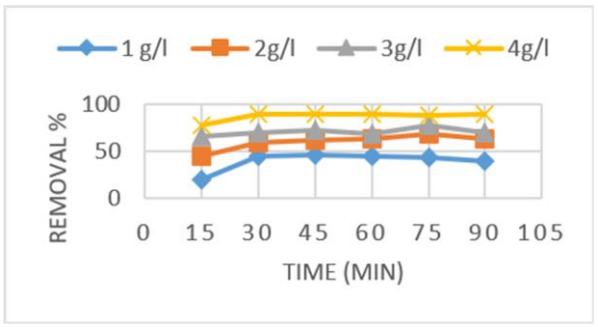


Fig. 5. Effect of electrolyte (NaCl) concentration on microplastic removal efficiency, illustrating the role of solution conductivity and its impact on electrocoagulation performance.

gas evolution and sludge formation were observed, negatively affecting operational stability. The influence of electrolyte concentration on removal efficiency is presented in Fig. 5.

The improvement in removal efficiency with increasing NaCl concentration is primarily attributed to enhanced electrical conductivity, which reduces ohmic resistance and promotes uniform current distribution. However, excessive electrolyte concentration leads to intensified gas evolution and turbulence, which may disrupt floc structure and reduce separation efficiency.

3.5. Effect of current density

Current density controlled the rate of aluminium dissolution and gas evolution within the reactor. Removal efficiency increased with current density up to 20 mA/cm^2. Further increases led to reduced efficiency and operational instability, including short-circuiting between electrodes. The effect of current density on removal efficiency and final concentration is shown in Fig. 6 and Table 2.

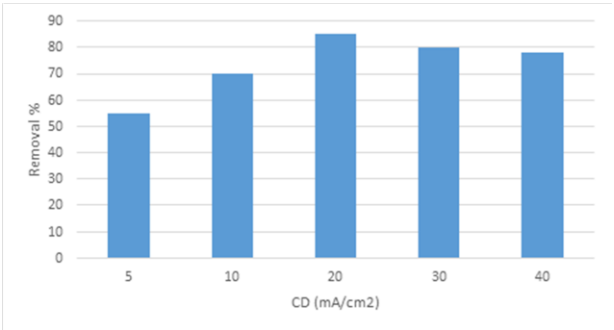


Fig. 6. Influence of current density on microplastic removal efficiency, showing the existence of an optimal value governed by coagulant generation and system stability.

The removal of microplastic particles during electrocoagulation can be attributed to multiple simultaneous mechanisms. Initially, charge neutralisation reduces electrostatic repulsion between particles, promoting aggregation. Subsequently, the in situ generated aluminium hydroxide flocs act as a sweep flocculant, entrapping microplastic particles within a growing three-

dimensional network. In addition, hydrogen gas bubbles produced at the cathode enhance flotation by carrying aggregated particles toward the surface. Therefore, the overall removal process is governed by a combination of adsorption, sweep flocculation and electroflotation mechanisms.

Table 2. Effect of current density on microplastic-associated solids concentration after electrocoagulation.

Current density (mA/cm^2)	5	10	20	30	40
Concentration (ppm)	45	30	15	30	45

The existence of an optimal current density indicates a balance between coagulant generation and system stability. At low current densities, insufficient Al^{3+} ions are generated, limiting floc formation. Conversely, at high current densities, excessive gas evolution and electrode passivation may reduce the effective contact between flocs and microplastic particles, resulting in a decrease in removal efficiency.

Overall, the results obtained from varying operating parameters consistently indicate that electrocoagulation performance is governed by the interplay between aluminium hydroxide floc formation, solution chemistry and electrochemical operating conditions. The observed trends across different parameters reinforce the role of adsorption, sweep flocculation and flotation as the dominant removal mechanisms.

4. Conclusions

This study demonstrated the potential of aluminium-based electrocoagulation as a supplementary treatment for microplastic removal from drinking water. The process efficiency was strongly influenced by operating parameters, particularly pH, current density and treatment time. Optimal removal was achieved under near-neutral conditions and moderate current density, where aluminium hydroxide flocs effectively promoted particle aggregation and separation. The removal mechanism was governed by a combination of adsorption, sweep flocculation and flotation processes.

Despite the promising results, the findings should be interpreted in light of the use of real drinking water samples and the limitations associated with gravimetric estimation of retained solids. Further investigations using controlled synthetic microplastic suspensions and advanced analytical techniques are recommended to enhance accuracy and reproducibility.

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