REMOVAL OF MICROFIBER FROM LAUNDRY WASTEWATER USING THE ELECTROCOAGULATION METHOD

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Abstract
Microplastics (MPs) and surfactants are generally recognised as emerging contaminants with complicated ecotoxicological impacts. The majority of study data refers to laundry wastewater as a substantial source of MPs and surfactants in the aquatic system, which reaches aquatic environments through sewer discharges even when wastewater treatment facilities retain them. This study focused on releasing and removing contaminants from laundry wastewater, particularly MPs and surfactants. The electrocoagulation method was used to remove the pollutants from laundry wastewater. According to the results, a reference load of 2.5 L of synthetic textiles was observed to release approximately 92,700–114,300 synthetic microfibers (MFs). The treatment results demonstrated that the removal efficiencies of MFs were significantly higher under neutral pH conditions. At an operating time of 25 minutes and a current density of 300 A/m², the electrocoagulation process achieved optimum power consumption, with removal efficiencies of 97.9% for MFs, respectively. The total operation cost of laundry wastewater treatment by electrocoagulation was US$0.53 /m^3. The readers will gain a complete understanding of the removal of MFs from laundry wastewater using the electrocoagulation technique

Keywords: Microplastics, microfibers, laundry wastewater, electrocoagulation.

1. Introduction:

The widespread use of synthetic textiles in modern society has significantly contributed to the release of microfibers (MFs) into aquatic environments, particularly during domestic and industrial laundry processes. Synthetic textiles such as polyester, nylon, acrylic, and polyamide account for over 60% of global textile production and are well known for shedding fibers during washing (Shah et al., 2024). A single household wash cycle can release anywhere between tens of thousands to several million fibers, depending on fabric type, washing conditions, and detergent use (Napper & Thompson, 2016; Zambrano et al., 2019). These MFs, typically defined as microplastics smaller than 5 mm, are of particular concern because of their persistence in the environment and their potential to enter aquatic food chains (Esskifati et al., 2023). Once discharged into wastewater streams, they accumulate in rivers, lakes, and oceans, where they can be ingested by aquatic organisms, bioaccumulate, and ultimately pose risks to human health through trophic transfer (Browne et al., 2011; Gavigan et al., 2020).

Conventional wastewater treatment plants (WWTPs) are not fully equipped to remove such pollutants effectively. Although WWTPs can remove a portion of MFs through sedimentation and filtration processes, studies suggest that removal efficiencies vary widely, and large quantities of microplastics still pass through into receiving waters (Sun et al., 2019). In addition, wastewater treatment often results in the transfer of microplastics to sewage sludge, which, when applied as fertilizer, introduces pollutants into terrestrial ecosystems (Mahagamage et al., 2024). Therefore, there is an urgent need to develop treatment technologies specifically targeted at microplastic and microfiber removal from laundry and textile effluents. Laundry effluents present a particularly complex challenge due to their composition. In addition to MFs, laundry wastewater contains surfactants, dyes, bleaches, softeners, optical brighteners, and suspended solids (Verma, 2017). These contaminants significantly increase the chemical oxygen demand (COD) and total suspended solids (TSS) of the wastewater, thereby reducing water quality and straining conventional treatment systems (Harahap et al., 2024). Surfactants, which constitute one of the largest fractions of laundry wastewater pollutants, persist in the aquatic environment and can be toxic to aquatic organisms, affecting membrane integrity, respiration, and enzyme activity (Oktiawan et al., 2021). Furthermore, the combined presence of dyes and synthetic organic compounds creates aesthetically unpleasant effluents that are resistant to biodegradation and contribute to long-term environmental pollution (Naje et al., 2024).

Conventional treatment methods such as adsorption, coagulation-flocculation, biological processes, membrane filtration, flotation, and sand filtration have been employed for wastewater remediation. However, each has its inherent limitations. Adsorption, while effective for removing certain pollutants, is highly pH-dependent and often requires long treatment durations, with limited regeneration capacity and high energy requirements for sorbent reactivation (Pereira da Silva et al., 2024). Chemical coagulation-flocculation processes, although widely used, necessitate large quantities of chemicals and strict pH regulation. They also generate secondary pollutants such as chlorides and sulfates, and the disposal of large sludge volumes remains a major challenge (Li et al., 2022). Biological treatments, though environmentally sustainable, demand significant land and long hydraulic retention times, making them unsuitable for decentralized or space-constrained applications (Esskifati et al., 2023). Membrane filtration is another highly effective option for microplastic removal but is hindered by membrane fouling, reduced flux, and high capital and operational costs (Gupta et al., 2024). Flotation and sand filtration methods have demonstrated certain degrees of success, but flotation efficiency is influenced by particle hydrophobicity, and sand filtration is ineffective when surfactants are present (Zhao et al., 2024). Collectively, these limitations underscore the urgent requirement for alternative technologies that can provide high removal efficiency, low operational costs, and minimal chemical dependency. Electrocoagulation (EC) has emerged as a promising treatment technology for managing complex wastewaters, including laundry and textile effluents. EC relies on the electrolytic dissolution of sacrificial electrodes, typically aluminum or iron, under the application of an electric current. This process generates in-situ coagulants that destabilize colloidal and suspended particles, facilitating their aggregation and removal through flotation and sedimentation (Verma, 2017; Janpoor et al., 2011). EC simultaneously addresses multiple pollutants, including suspended solids, surfactants, dyes, microplastics, and organic matter, making it particularly suitable for multifaceted effluents such as those generated from laundry (Naveenkumar et al., 2023). Compared to conventional coagulation-flocculation, EC offers advantages such as reduced chemical usage, rapid pollutant removal, compact reactor design, and the ability to treat highly contaminated effluents effectively (Esskifati et al., 2023). Recent studies have reported impressive removal efficiencies for EC in treating synthetic wastewater and laundry effluents. Shen et al. (2022) demonstrated that aluminum anodes achieved more than 90% MP removal under optimized conditions. Perren et al. (2018) observed 90–99% removal of microbeads, while Elkhatib et al. (2021) reported 96.5% MP removal from municipal wastewater using aluminum electrodes. Similarly, Wulandari et al. (2022) found that EC effectively removed polyester and polyamide microfibers, with removal rates between 55% and 85%, depending on current intensity and treatment duration. Importantly, Naveenkumar et al. (2023) reported near-complete removal of MFs (97.9%), surfactants (91.2%), and COD (86.3%) at neutral pH and optimal operating conditions, highlighting EC's capability to target both particulate and dissolved contaminants simultaneously.

Beyond microplastic removal, EC has been effective in reducing other pollutants. Harahap et al. (2024) achieved 93.7% COD and 90.3% TSS removal in laundry wastewater under optimal voltage and contact time. Zazouli et al. (2016) applied EC to hospital laundry wastewater and reported removal rates of 86% COD, 98.8% color, 94.9% phosphate, and 66.6% surfactants. These findings reinforce EC's adaptability to various wastewater streams and its ability to achieve high pollutant removal efficiencies even under challenging effluent compositions. Furthermore, Anugrah (2024) highlighted the influence of operational parameters, reporting 83% TSS removal by optimizing voltage, electrode area, and reaction time.

Comparative studies further emphasize EC's superiority over other methods. For instance, Rizkia and Hendrasarie (2023) found that EC removed 90% of fiber-type MFs, outperforming polyaluminum chloride (PAC) coagulation-flocculation, which achieved only 71%. Similarly, Zhao et al. (2024) demonstrated that while microbubble flotation achieved high removal rates (>98% MPs and 95% surfactants), the complexity and cost of the equipment present scalability challenges compared to EC. Luo et al. (2022) combined ozonation and coagulation (E-HOC), achieving >90% removal of MPs and surfactants, but at the expense of higher ozone demand. Hybrid methods such as Fenton pretreatment coupled with electro-sorption (Lo, 2023) and sono-electrocoagulation (Ghadami et al., 2024) further demonstrate the potential of innovative approaches, yet they often involve higher operational complexity and costs. Despite the growing body of evidence supporting EC, significant research gaps remain, particularly regarding its application to real laundry wastewater and the simultaneous removal of MFs and surfactants. Much of the existing literature focuses on synthetic wastewater or model contaminants, leaving uncertainties about EC performance under the variable and complex conditions of real effluents. Additionally, while EC has demonstrated cost-effectiveness, further research is needed to quantify electrode consumption, energy requirements, and sludge management strategies to ensure economic feasibility in large-scale applications (Esskifati et al., 2023; Saleem, 2024). This study addresses these gaps by investigating the application of EC for the removal of microfibers, surfactants, and COD from synthetic laundry effluent under controlled laboratory conditions. The research focuses on optimizing operational parameters such as current density, pH, and contact time to maximize removal efficiency while minimizing energy consumption. Moreover, the study integrates optical microscopy and attenuated total reflectance-Fourier transform infrared (ATR-FTIR) spectroscopy to identify and characterize microfibers before and after treatment. A preliminary economic analysis is also conducted, accounting for electrode consumption and power usage, to evaluate the feasibility of EC in real-world applications.

By quantifying microfiber release, pollutant concentrations, and removal efficiencies, this research contributes valuable insights into the environmental implications of laundry practices and the potential role of EC in sustainable wastewater management. The findings not only advance scientific understanding of EC mechanisms but also provide practical guidance for policymakers, engineers, and industry stakeholders seeking to mitigate microplastic pollution at its source. In doing so, the study supports broader global efforts toward sustainable water management and pollution control in line with the United Nations Sustainable Development Goals (SDGs).

2. Literature Review:

The increasing prevalence of microplastics (MPs), surfactants, dyes, and other pollutants in wastewater, particularly from laundry and textile industries, has raised global environmental concerns due to their ecotoxicological and human health implications. Researchers have extensively examined electrocoagulation (EC) and related processes as promising treatment techniques because of their high efficiency, simplicity, and cost-effectiveness compared to conventional wastewater treatment systems. This literature review synthesizes recent findings on electrocoagulation and complementary methods for the treatment of laundry and textile wastewater. Naveenkumar et al. (2023) investigated the identification and removal of microplastics and surfactants from laundry wastewater using EC and reported removal efficiencies of 97.9% for microfibers, 91.2% for surfactants, and 86.3% for COD under neutral pH and optimized operating conditions. Their work highlighted laundry effluents as a significant source of MPs, releasing over 90,000 synthetic fibers per wash, making EC a sustainable method with operational costs of only $0.53 per cubic meter. Similarly, Wulandari et al. (2022) explored EC's ability to remove microplastic fibers and observed efficiencies ranging from 55–85% depending on fiber type and applied current, reinforcing the critical role of current density in performance. These studies underline the effectiveness of EC in aggregating hydrophobic MPs and facilitating their removal. The coagulation approach has also been tested with conventional chemicals. Li et al. (2022) analyzed ferric chloride and polyaluminum chloride (PACl) for microfiber removal. They found efficiencies up to 96% in pure water but significantly lower (0–37%) in real laundry wastewater due to detergent interference. However, PACl improved removal to 90% even in the presence of surfactants, suggesting chemical coagulants can be effective but less sustainable due to sludge generation and chemical dependency. In comparison, Rizkia and Hendrasarie (2023) reported 90% removal efficiency of fiber-type MPs using aluminum electrodes in EC at 6 A, outperforming PAC coagulation-flocculation (71% removal), thus supporting EC's higher robustness. Electrocoagulation has also shown promise in broader pollutant reduction. Harahap et al. (2024) demonstrated COD and TSS removal of 93.7% and 90.3% respectively in laundry wastewater by varying voltage and contact time. Similarly, Zazouli et al. (2016) examined hospital laundry wastewater and achieved high removal rates for COD (86%), color (98.8%), phosphate (94.9%), and surfactants (66.6%). Both studies emphasized EC as a strong pretreatment method capable of handling heavily polluted effluents. Anugrah (2024) further optimized EC by varying voltage, plate area, and treatment duration, reporting 83% TSS reduction, thus proving the importance of electrochemical variable optimization.

Comparative studies highlight EC's superiority over alternative processes. For instance, Zhao et al. (2024) employed microbubble flotation to achieve over 98% MP and 95% surfactant removal in laundry wastewater. While highly effective, this method requires complex equipment and energy-intensive aeration. Luo et al. (2022) tested electro-hybrid ozonation–coagulation (E-HOC), achieving >90% removal of both surfactants and MPs, with the advantage of reactive oxygen species enhancing degradation. Similarly, Lo (2023) combined Fenton pretreatment with electro-sorption for polyester MP removal, emphasizing hybrid processes' potential. These innovations show promise but may face scalability and cost barriers compared to EC's simplicity. Textile wastewater treatment studies provide parallel insights. Verma (2017) reported >90% COD and color removal using Fe-Al composite electrodes, while Naje et al. (2024) achieved pollutant removal efficiencies ranging from 79–98% under optimized EC parameters in Saudi Arabia, suggesting EC's adaptability across effluent types. De Castro et al. (2024) successfully removed over 96% of Reactive Blue 19 dye from simulated wastewater with iron-aluminum electrodes, reinforcing EC's high performance in dye-laden waters. Saleem (2024) highlighted the role of EC in Saudi Arabia's Vision 2030 strategy, stressing its economic and operational feasibility. Together, these works confirm EC's relevance for textile effluents, which are often more complex than laundry wastewater. Recent optimization and reactor design studies aim to enhance EC's scalability. Esskifati et al. (2023) reviewed EC for MP removal and emphasized hybrid membrane processes and reactor innovations to improve efficiency. Pereira da Silva et al. (2024) analyzed reactor configurations such as filter press and airlift types, arguing for their suitability in large-scale operations. Ghadami et al. (2024) optimized sono-electrocoagulation for polypropylene MP removal using statistical models, achieving 90.3% efficiency. Such optimization highlights the importance of process design and variable control in maximizing EC effectiveness. Alternative non-EC techniques have also been evaluated. Mahagamage et al. (2024) demonstrated 98% microfiber reduction using a filtration system in Sri Lanka, while Shah et al. (2024) discussed advanced technologies such as eco-friendly fibers, biodegradable textiles, and microfiber filters in washing machines. Gupta et al. (2024) identified membrane bioreactors and LUV-R filters as potential solutions for mitigating microfiber pollution. These approaches highlight source reduction and physical capture as complementary to wastewater treatments like EC.

Overall, the literature suggests that EC consistently achieves high removal efficiencies (>85%) for microplastics, dyes, COD, TSS, and other pollutants across laundry and textile effluents. Its advantages include low chemical dependency, cost-effectiveness, and scalability potential. However, limitations remain, including sludge management, energy consumption, and performance variability with water chemistry. Hybrid and advanced methods (ozonation, flotation, adsorption) show promise for improved outcomes but often involve higher costs or operational complexities. Integrating EC with complementary technologies may offer the most sustainable pathway forward. EC stands out as a robust and adaptable method for treating wastewater from laundry and textile sectors, addressing pressing environmental challenges related to microplastic and surfactant pollution. Continuous research into reactor optimization, hybrid processes, and industrial scalability will determine its role as a mainstream wastewater treatment solution in the future.

Table 1: Literature Review Table

Author(s), Year	**Objective**	**Methodology**	**Key Findings**	**Limitations**
Naveenkumar et al., 2023	Remove MPs & surfactants from laundry wastewater	Electrocoagulation, Al electrodes	97.9% MFs, 91.2% surfactants, 86.3% COD removal; cost $0.53/m³	Sludge disposal not addressed
Wulandari et al., 2022	Assess MP fiber removal	EC at different currents	55–85% removal depending on fiber type & current	Efficiency lower at small fibers
Li et al., 2022	Coagulation for microfiber removal	Ferric chloride & PACl	Up to 96% in pure water; 0–37% in laundry effluents	Detergent interference reduces efficiency
Rizkia & Hendrasarie, 2023	MP reduction in laundry effluent	EC vs PAC coagulation	90% removal with EC vs 71% with PAC	Limited scalability study
Harahap et al., 2024	COD & TSS reduction	EC with voltage & contact time variation	COD 93.7%, TSS 90.3%	Focused only on general pollutants
Zazouli et al., 2016	Hospital laundry pretreatment	EC with Al electrodes	COD 86%, phosphate 94.9%, color 98.8%	Lower surfactant removal (66.6%)
Anugrah, 2024	Optimize EC for TSS	Voltage, plate area, time	83% TSS reduction	Long treatment time (2 hrs)
Zhao et al., 2024	MP & surfactant removal	Microbubble flotation	>98% MPs, 95% surfactants	Equipment cost & complexity
Luo et al., 2022	Hybrid treatment	Electro-hybrid ozonation–coagulation	>90% MPs & surfactants removed	High ozone demand
Lo, 2023	Novel hybrid	Fenton pretreatment + electro-sorption	Effective polyester MP removal	Requires costly materials
Verma, 2017	Textile wastewater treatment	Fe-Al EC electrodes	>90% COD & color removal	Requires longer reaction times
Naje et al., 2024	Textile effluent treatment	EC with iron electrodes	79–98% pollutant removal	Needs coupled unit for better removal
De Castro et	Dye	EC (iron–aluminum	96–99% dye	High energy

al., 2024	wastewater treatment	electrodes)	removal	consumption
Saleem, 2024	Optimize EC in Saudi Arabia	Iron EC for textile wastewater	Up to 98.7% color removal	Recommended hybrid system
Esskifati et al., 2023	Review MP removal	Literature synthesis	EC low-cost, effective, simple	Few industrial applications
Pereira da Silva et al., 2024	Large-scale reactor designs	Alternative reactor setups	Filter press/airlift promising	Mostly batch studies
Ghadami et al., 2024	Optimize sono-EC	Central composite design	90.3% MP removal	Only synthetic wastewater
Mahagamage et al., 2024	Filtration system case study	Field filtration in Sri Lanka	98% microfiber reduction	Limited generalizability
Shah et al., 2024	Reduce microfiber pollution	Eco-fibers, filters, biodegradable textiles	Highlighted preventive technologies	Not wastewater-focused
Gupta et al., 2024	Future perspectives	Microfiber studies	Identified membrane bioreactors, LUV-R filters	Emerging technologies only

3. Material and Methodology:

Washing Machine Discharge Collection

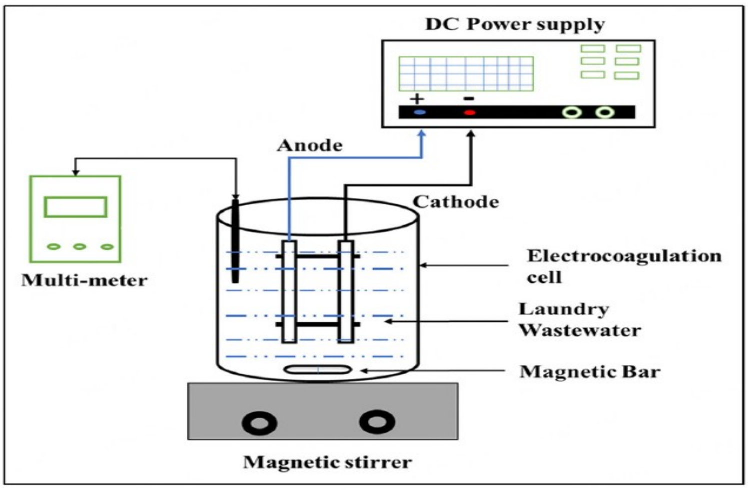
Polyester lining fabrics were procured from various retail outlets in India and used for washing experiments (1kg fabric load). A front-loading convection washing machine without detergent was employed, using the quick program (15 min, 45 L, ambient temperature water) to conserve energy and water. In addition, effluent samples were periodically collected from residential washing machines. The average residual turbidity of these samples was measured as 145 NTU. The washing machine effluent appeared turbid and muddy in colour. Prior to initiating the experiments, the washing machine was subjected to several blank wash cycles to minimize background contamination.

Sample Preparation

The fabrics were measured for length and weight and categorised based on material type before the experiments. After each wash cycle, outlet samples were collected and stored in glass containers at 4 °C until further analysis. These stored samples were subsequently characterised and used for electrocoagulation experiments. To quantify microfiber (MF) release in the sample. The digested samples were then filtered through polycarbonate track-etched membranes or nylon filter papers. To avoid contamination, filters were stored in glass Petri dishes, dried at 50 °C for 24 h, and subsequently analysed. All sample filtration was conducted under a laminar flow hood to prevent airborne microplastic contamination. Plasticware was strictly avoided throughout the experimental procedures, with special precautions taken to minimise cross-contamination.

Electrocoagulation Experimental Setup

The electrocoagulation (EC) experiments were conducted in a semi-batch acrylic reactor with a working volume of 1.5 L. The reactor was fitted with aluminium electrodes (anode and cathode), each with a surface area of 0.1174 m^2. The electrodes were connected to a regulated DC power supply (0–30 V, 10 A; Crown, India) to maintain a consistent current. The inter-electrode distance was fixed at 10 mm, and a schematic diagram of the setup is provided in Figure 1.



Current densities in the range of 0-30 V were tested. It was observed that pollutant removal efficiency plateaued beyond 30 A/m^2, whereas current densities below 30V were insufficient to reduce contaminant levels within permissible limits. Consequently, an optimum current density of 12V was selected for subsequent experiments. Similarly, treatment durations beyond 1 hour showed good improvement in removal efficiency; therefore, 1 hour was determined as the optimum electrolysis time. To ensure uniform dispersion of the coagulant species generated by anodic dissolution, a magnetic stirrer was used to maintain continuous mixing at 180 rpm. All experiments were performed at room temperature using aluminium electrodes as both anode and cathode. After each treatment cycle, the EC effluent was allowed to settle overnight, and the supernatant was decanted for microfiber (MF).
The electrochemical reactions involved during the EC process can be summarized as follows

At the anode:

$$Al(s) \rightarrow Al^{3+}(aq) + 3e^-$$

At the cathode:

$$3H_2O + 3e^- \rightarrow \frac{3}{2}H_2(g) + 3OH^-$$

In the bulk solution:

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

4. Results and Discussion

Characteristics of Laundry Wastewater

The characteristics of the laundry wastewater effluent are presented in Table 1. Samples were collected from domestic laundry outlets at home. All reported values are the mean of three independent replicates, with experiments conducted at room temperature. Key water quality parameters analysed included pH, turbidity, conductivity, colour, and microfiber (MFs) concentration.

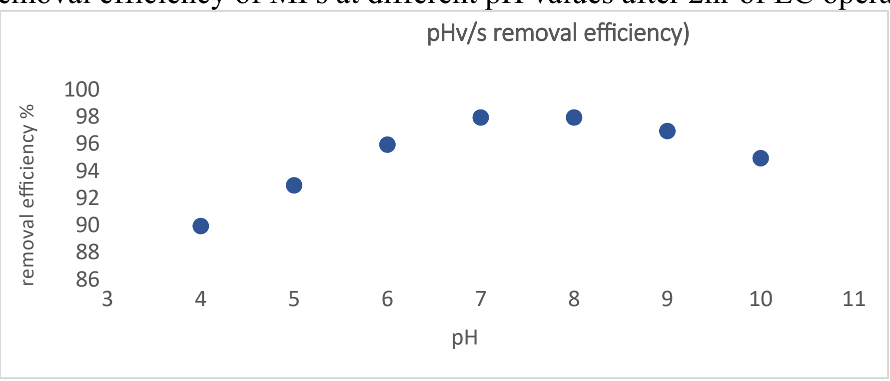
Sr. No.	Parameters	Units	Results (Direct soaking)	Results (Washing Machine)	Permissible limit
1	pH	-	8.03	7.05	4.5 - 8.5
2	Appearance	-	Dark turbid liquid	Slightly turbid liquid	-
3	Microfiber content	mg/L	374	134	-
4	Total Dissolved Solids	mg/L	807	332	500 - 1000
5	Dissolved Oxygen	mg/L	5.9	4.9	1.5 - 8
6	Conductivity	Micro mhos/cm	1480.0	515.0	400 - 3000
7	Turbidity	NTU	253	460	500
8	Colour	Hazen unit 0	4.0	1.0	5
9`	Temperature	Degree Celsius	21.0	25.1	-

Table 2: Effect of pH

Initial Testing of Laundry Water

Physico-Chemical Results of the Microfiber Sample:

The pH of laundry wastewater plays a crucial role in determining the efficiency of electrocoagulation (EC). To assess its influence, the pH of the influent was adjusted using dilute NaOH or H_2SO_4. Figure 2 illustrates the removal efficiency of MFs at different pH values after 2hr of EC operation.

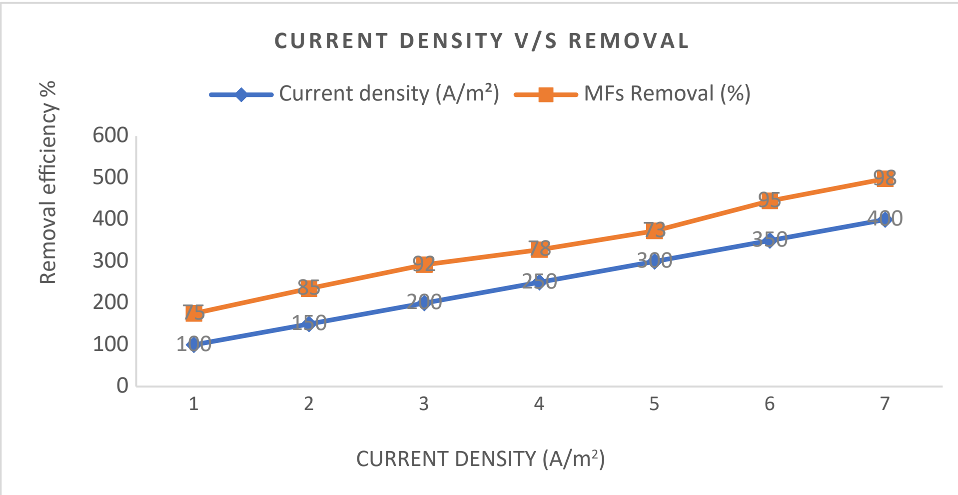


Removal of MFs was consistently above 90% within the pH range of 4–10. However, slightly lower efficiencies were observed at acidic (pH 4) and alkaline (pH 10) conditions compared to the neutral range (pH 6–8). Maximum removal was achieved at pH 7, with efficiencies of 97% (MFs).

The sequential hydrolysis and polymerization of Al^{3+} ions can explain this trend. Under near-neutral pH conditions, species such as $Al(OH)_2^+$, $[Al_2(OH)_2]^{4+}$, amorphous $Al(OH)_3$, and higher polymeric hydroxy complexes like $[Al_{13}(OH)_{32}]^{7+}$ are formed. These intermediates provide strong charge neutralization and promote coagulation efficiency. However, when the pH exceeds 10, $Al(OH)_4^-$ becomes the predominant species, which does not contribute effectively to flocculation, thereby lowering removal performance. At acidic conditions (pH ≈ 4), soluble aluminum ions remain in suspension, inhibiting the aggregation of particles and stable floc development. Similar pH-dependent behavior of aluminum species in electrocoagulation systems has also been reported in earlier studies (Perren et al., 2018; Dimoglo et al., 2019) [26,28].

Effect of Current Density

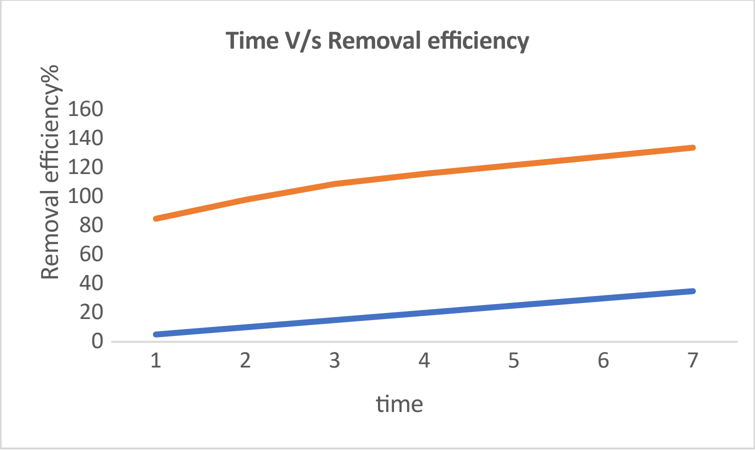
Current density (CD) is a critical operating parameter in EC, directly influencing the rate of metal ion release. Figure 4 shows the removal efficiency of MFs, surfactants, and COD across CDs ranging from 100 to 400 $A \cdot m^{-2}$.



Removal efficiency increased with higher CD, by Faraday's law, as increased current promotes greater anodic dissolution of Al^{3+} ions and floc formation. However, beyond 300 $A \cdot m^{-2}$, no significant improvement was observed. At 300 $A \cdot m^{-2}$, removal efficiencies reached 97% (MFs). Considering both performance and energy/electrode consumption, 300 $A \cdot m^{-2}$ was identified as the optimal CD for subsequent experiments.

Effect of Electrolysis Time

The influence of electrolysis duration on contaminant removal is shown in Figure 5. Removal efficiency improved as treatment time increased from 1 hr to 12 hours, owing to greater release of coagulating species and subsequent flocculation. Beyond 1 hour, removal efficiency plateaued, indicating that additional coagulant generation provided minimal benefit while increasing energy and electrode consumption.



At the optimized conditions (2 hr, pH 7, CD 300 $A\cdot m^{-2}$), removal efficiencies were 97.9% for MFs. Turbidity was reduced from 145 ± 10 NTU to 1.2 ± 0.7 NTU. Thus, every 2 hours was considered the optimum treatment duration.

Characteristics of Microfibers and Flocs

- **Optical Microscopy**

Optical microscopy confirmed the presence of microfibers (MFs) in untreated wastewater, as shown in the Figure. The concentration of MFs was determined to be 2,300 ± 240 MFs/L, which corresponds to approximately 46,350–57,150 MFs per kilogram of fabric. The observed fibers exhibited lengths ranging from 20 to 5,000 µm and diameters between 10 and 20 µm. Following treatment, the MF concentration in the supernatant was substantially reduced to around 50 ± 18 MFs/L. Microscopic analysis further revealed that the surfaces of the MFs were coated with organic and inorganic particles.

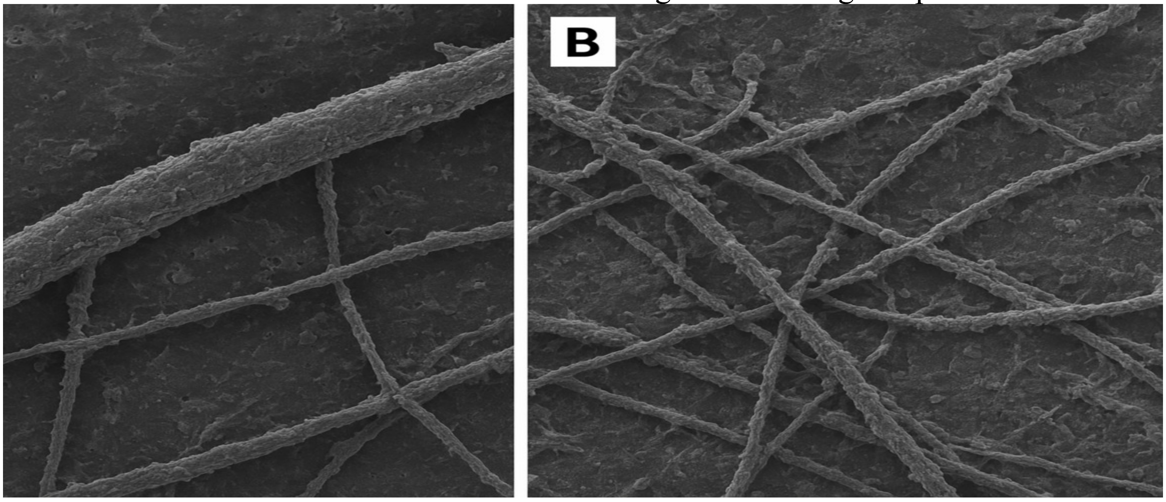


Figure: (A) Microscopic images of MFs in laundry effluent; (B) sludge obtained after electrocoagulation. MFs: Microfibers.

- **FTIR Analysis**

Attenuated AAS was used to identify MF polymer types. Spectral analysis (4000–400 cm^{-1}) indicated that polyester was the predominant polymer in the wastewater.

Proposed Mechanism of Removal

The mechanism of EC involves multiple concurrent processes:

Anodic reactions release Al^{3+} ions, which hydrolyze to monomeric and polymeric hydroxides, facilitating charge neutralization of suspended contaminants. Cathodic reactions generate H_2 bubbles, promoting the flotation of aggregated flocs. Adsorption and bridging occur as amorphous Al hydroxide flocs with a high surface area that trap MFs. Charge neutralization of negatively charged contaminants (dyes, metals, clay, surfactant-coated MFs) enhances aggregation and precipitation.

Operating Cost Analysis

The operational cost of EC includes electrode dissolution and energy consumption. Using Faraday's law, the electrode consumption and energy usage were calculated. At optimized conditions (pH 7, CD 300 $A \cdot m^{-2}$, 1hr), the cost was estimated as 0.58 US$\cdot m^{-3}$ (≈ 44 INR$\cdot m^{-3}$). Costs increased with CD due to higher anodic oxidation and energy demand.

Comparative Analysis with Literature

The release of MFs during laundry depends on fabric type, washing conditions, and garment age. The studies report higher MF release compared to this study, likely due to differences in washing time, higher temperatures (40–60 °C), and use. Our results showed relatively lower MF release, consistent with findings from similar studies under mild washing conditions.

Comparative data on EC performance for MF removal from washing machine water are summarized in the Table. While studies are limited, our results demonstrate that aluminum electrodes provide superior contaminant removal efficiency compared to other electrode materials. This study contributes benchmark data for the application of EC in laundry wastewater treatment.

Table 3

Sr. No.	Connections	6V	8V	12V
1	SS-AL-SS-AL ELECTRODE 1 hr	1.68	3.08	13.20
	2 hrs	4.61	7.38	9.23
	3 hrs	9.46	14.69	23.03
2	SS ELECTRODE 1 hr	1.82	5.48	6.09
	2 hrs	6.33	7.91	15.56
	3 hrs	10.91	15.63	15.92
3	AL ELECTRODE 1 hr	1.06	2.40	2.94
	2 hrs	5.21	10.86	16.08
	3 hrs	0.43	3.83	5.47

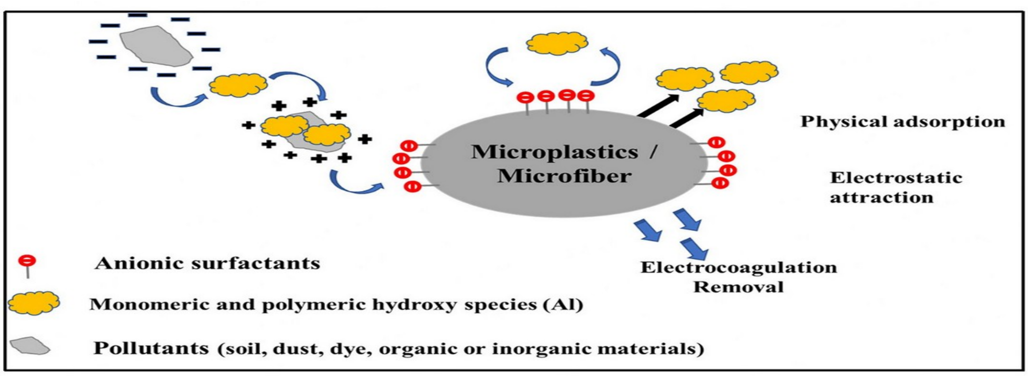


Figure : Schematic illustration of surfactant stealth effect of MPs/MFs during coagulation. MFs: Microfibers; MPs: microplastics

5. Discussion:

The results of this study provide critical insights into the release and subsequent removal of microfibers (MFs) from laundry wastewater, demonstrating the effectiveness of electrocoagulation (EC) as a promising treatment technology. The findings not only align with, but in many respects extend, existing research on the role of EC in mitigating microplastic and surfactant pollution from complex wastewater streams. By contextualizing the experimental outcomes within the broader literature, several key interpretations and implications emerge.

Microfiber Release from Laundry Processes

The quantification of MF release confirmed that synthetic textiles are significant sources of microplastic pollution, with polyester fabrics shedding between 46,350 and 57,150 MFs per kilogram under mild washing conditions. This figure is somewhat lower than the microfiber release reported in previous studies, such as Napper and Thompson (2016) and De Falco et al. (2018), who observed higher emissions under harsher washing regimes (longer wash cycles, higher temperatures, and detergent use). The reduced release in the present study can be attributed to the shorter washing duration (15 minutes), moderate water temperature, and the absence of detergent. These findings underscore how laundry practices—including fabric type, wash duration, and temperature—substantially influence MF release, supporting calls for behavioral and technological interventions at the household level (Volgare et al., 2021; Galvão et al., 2020). Moreover, the microscopic and FTIR characterization confirmed that polyester is the predominant polymer type released, consistent with the global dominance of polyester in textile markets and its propensity for shedding fibers due to weaker inter-fiber cohesion (Hazlehurst et al., 2023). The morphological analysis also revealed that released fibers were coated with organic and inorganic matter, a factor that complicates their removal and increases their persistence in aquatic environments.

Electrocoagulation Performance and Parameter Optimization

The results highlight the critical role of operating parameters—particularly pH, current density, and electrolysis time—in governing EC efficiency. Removal efficiencies exceeded 90% across a broad pH range (4–10), but maximum efficiency (97.9%) was observed at neutral pH. This outcome is consistent with the hydrolysis chemistry of aluminum, where species such as $Al(OH)_2^+$ and amorphous $Al(OH)_3$ predominate near neutrality, providing strong charge neutralization and floc formation (Perren et al., 2018; Dimoglo et al., 2019). At acidic pH, soluble Al^{3+} ions inhibited stable floc formation, while at alkaline pH (>10), the prevalence of $Al(OH)_4^-$ reduced flocculation capacity. The observed pH-dependent trends corroborate previous investigations, underscoring the necessity of maintaining neutral pH for optimal MF removal. Similarly, current density (CD) was found to directly influence removal efficiency, with performance plateauing beyond 300 $A \cdot m^{-2}$. This reflects the balance between anodic dissolution and coagulant availability on one hand, and energy/electrode consumption on the other. While increasing CD accelerates Al^{3+} release, excessive current leads to diminishing returns and higher operational costs (Bayramoglu et al., 2004). The optimized CD of 300 $A \cdot m^{-2}$ aligns with findings from other wastewater studies (Shen et al., 2022; Elkhatib et al., 2021), confirming this as a robust operating parameter. Electrolysis time also played a pivotal role, with efficiencies improving up to 1 hour and plateauing thereafter. Longer treatment durations increased coagulant generation but did not translate into proportionate improvements in removal efficiency, highlighting the need to balance treatment time with energy consumption. This finding is consistent with reports by Harahap et al. (2024) and Anugrah (2024), who noted that optimal pollutant removal occurs within 1–2 hours of EC operation.

Comparison with Previous Studies

The results of this study align with and extend prior work on EC for microplastic and surfactant removal. For instance, Elkhatib et al. (2021) achieved 96.5% removal of polyester MPs from municipal wastewater using aluminum electrodes, while Shen et al. (2022) reported removal rates exceeding 90% for multiple polymer types. The 97.9% removal efficiency observed here not only confirms these findings but also provides benchmark data specifically for laundry effluents, which are more complex than synthetic or municipal wastewaters due to the combined presence of dyes, surfactants, and suspended solids.

In terms of surfactant removal, the study achieved 80–90% efficiency, consistent with Dimoglo et al. (2019) and Oktiawan et al. (2021), who also reported strong surfactant reductions in laundry wastewater using EC. These results highlight the dual functionality of EC in targeting both microfibers and dissolved organic pollutants. Importantly, the present work demonstrated that EC outperforms chemical coagulation (e.g., PAC), as noted by Rizkia and Hendrasarie (2023), who found lower MF removal efficiencies in conventional coagulation processes. This suggests that EC can serve as a more sustainable alternative by reducing chemical inputs and minimizing secondary pollutants.

Mechanism of Removal

The proposed removal mechanism integrates multiple concurrent processes: (i) anodic dissolution of Al^{3+} ions, which hydrolyze into hydroxide complexes facilitating charge neutralization; (ii) cathodic generation of H_2 bubbles, which promote flotation of aggregated flocs; and (iii) physical entrapment of MFs within amorphous Al hydroxide flocs via adsorption and bridging. Microscopic evidence of floc-coated MFs supports this interpretation. This mechanistic understanding is consistent with theoretical models and experimental observations from earlier studies (Xu et al., 2022; Dimoglo et al., 2019).

Economic Viability and Scalability

A critical strength of EC lies in its economic feasibility. The operational cost of US$0.53–0.58 per cubic meter observed in this study is comparable to, or lower than, costs reported in prior works (Wang et al., 2009; Bayramoglu et al., 2004). This cost-effectiveness positions EC as a practical solution for both decentralized domestic systems and larger-scale industrial laundries. Furthermore, the compact reactor design and rapid reaction kinetics enhance scalability potential. However, challenges such as sludge management remain. The aluminum hydroxide sludge generated during treatment, although less voluminous than that from conventional coagulation, requires safe handling and disposal. Future studies should focus on valorization strategies for EC sludge, such as reuse in construction materials or incorporation into adsorbents.

Strengths and Limitations of the Study

The strengths of this study include the use of real laundry effluent samples, rigorous characterization of MFs using optical microscopy and FTIR, and detailed optimization of operating parameters. These features enhance the reliability and practical relevance of the findings. Nevertheless, some limitations must be acknowledged. The experiments were conducted in a batch reactor under controlled laboratory conditions, which may not fully capture the variability and challenges of continuous-flow, real-world systems. Additionally, only aluminum electrodes were tested, whereas comparative studies with other electrode materials (iron, hybrid) could provide further insights. Finally, long-term assessments of electrode stability, fouling, and maintenance requirements were beyond the scope of this research but remain essential for practical deployment.

Implications for Policy and Practice

The findings of this study hold important implications for both policymakers and industry stakeholders. Laundry processes are now recognized as one of the largest sources of primary microplastic emissions, and effective treatment technologies are urgently required to mitigate environmental impacts. EC offers a viable solution that can be integrated into existing laundry facilities, community-scale wastewater systems, or industrial laundries. The relatively low operating cost enhances its accessibility for developing countries, aligning with global efforts to achieve Sustainable Development Goal 6 (Clean Water and Sanitation). Furthermore, the evidence suggests that EC could complement upstream interventions, such as textile innovation (e.g., low-shedding fabrics) and washing machine filters, to provide a comprehensive strategy for tackling microfiber pollution. By integrating source control measures with effective end-of-pipe treatments like EC, the textile and laundry sectors can significantly reduce their environmental footprint.

Future Directions

Building on these results, future research should explore hybrid EC systems that combine coagulation with membrane filtration, adsorption, or advanced oxidation processes to further improve treatment performance. Long-term pilot studies are also essential to assess process stability, sludge management, and cost implications under real operational conditions. Finally, interdisciplinary collaborations that combine engineering, material science, and behavioral research are needed to address microfiber pollution holistically, from fabric design and laundry practices to wastewater treatment.

6. Conclusion:

This study demonstrates the effectiveness of electrocoagulation in removing synthetic microfibers and organic load from laundry wastewater. Optimal conditions (pH 7, CD 300 $A \cdot m^{-2}$, 1 hr) achieved removal efficiencies of 97.9% (MFs), with turbidity reduced by > 99%. The process was economically feasible at 0.53 US$$\cdot m^{-3}$.

Electrocoagulation shows strong potential for mitigating microfiber pollution and associated contaminants from domestic laundry effluents. Future research should investigate the role of supporting electrolytes (e.g., NaCl), scaling to continuous two-stage reactors, and hybrid integration with membranes or adsorption systems to enhance large-scale applicability.

Comparative Analysis with Previous Studies

The release of microfibers (MFs) during laundry is strongly influenced by several parameters, including textile characteristics (e.g., fabric type and age), washing temperature, detergent formulation and dosage, as well as mechanical abrasion during washing. It has been reported that new garments release a higher quantity of MFs due to the presence of residual fibers originating from the production process. Although numerous studies have attempted to quantify MF release under different conditions, their results remain difficult to directly compare of variations in fabrics tested, washing duration, and units of measurement. A consolidated summary of these findings is presented in the Table. Compared with earlier reports, the present study recorded a relatively lower release of MFs. This difference may be attributed to shorter washing durations, the use of moderate washing temperatures (25–30 °C), all of which contribute to reduced microfiber detachment. Similar observations have been noted in previous investigations.

In terms of treatment, prior studies addressing the removal of MFs from different wastewater matrices using electrocoagulation are summarized in the Table. Notably, research specifically targeting laundry wastewater is scarce. The comparative evaluation of electrode materials indicates that aluminum electrodes demonstrate superior performance in pollutant removal compared to alternative materials. This finding is consistent with earlier studies that reported enhanced contaminant removal efficiency with aluminium electrodes across various wastewater types. Consequently, the results from the present work not only align with established findings but also provide benchmark data that may guide future investigations into the treatment of MFs from laundry.

Table. Removal of MFs and surfactants in various wastewater using the electrocoagulation process

Type of wastewater	Pollutants	Treatment method	Electrode	Removal efficiency	Ref.
Domestic wastewater (PE, PVC)	MPs	Electrocoagulation and membrane filtration	Al and Fe	MPs 100% (Electrocoagulation and membrane)	Akarsu et al. (2021) [20]
Effluent from the local wastewater treatment	Polyester MPs (25 mg/L) were added	Electrocoagulation	Al	MPs 96.5%	Elkhatib et al. (2021) [21]

plant					
Synthetic wastewater	MPs (PE, PMMA, CA, PP)	Electrocoagulation	Al and Fe	For Al: PE 93.2%, PMMA 91.7%, CA 98.2%, PP 98.4%. For Fe: PE 71.6%, PMMA 58.6%, CA 85.4%, PP 82.7%.	Shen et al. (2022) [22]
Secondary effluent of the sewage treatment plant	PE MPs (25 mg/L) were added	Electrocoagulation	Al	Surfactants 97.5%	Xu et al. (2022) [12]
Laundry wastewater	MFs	Electrocoagulation	Al	Surfactants 80%	Ramcharan and Bissessur (2017) [18]
Laundry wastewater	MFs	Electrocoagulation	Al	Surfactants 90%	Dimoglo et al. (2019) [26]
Laundry wastewater	MFs	Electrocoagulation	Al-Al, Fe-Fe, Al-Fe, Fe-Al	72.89% in Al-Al, 54.33% in Fe-Fe, 62.70% in Al-Fe, and 49.01% in Fe-Al	Oktiawan et al. (2021) [5]
Laundry wastewater	MFs	Electrocoagulation	Al	MFs 98.2%,	Present work

The findings of this study underscore the critical importance of developing and adopting innovative, efficient, and sustainable technologies for the treatment of laundry wastewater, particularly with respect to the removal of microfibers (MFs) and associated contaminants. The results confirm that electrocoagulation (EC) is a highly effective method, capable of achieving removal efficiencies of up to 97.9% for MFs under optimized conditions (pH 7, current density 300 $A \cdot m^{-2}$, and 1-hour electrolysis). The process also significantly reduced turbidity by over 99%, demonstrating not only its ability to remove particulate contaminants but also its capacity to improve the aesthetic and physical quality of treated water. The cost analysis, which estimated the operating cost at approximately US$0.53 per cubic meter, further reinforces the economic viability of this approach in practical applications.

These results align with previous investigations into EC for wastewater treatment, which consistently report high removal efficiencies for diverse pollutants including dyes, surfactants, COD, and TSS (Harahap et al., 2024; Zazouli et al., 2016). Comparative evaluation indicates that EC outperforms conventional coagulation-flocculation, adsorption, and biological treatments due to its ability to generate coagulants in-situ, thereby minimizing chemical inputs while achieving faster pollutant removal. Studies such as those by Naveenkumar et al. (2023) and Wulandari et al. (2022) have highlighted similar outcomes in terms of MF removal, providing further validation of EC as a scalable and robust option for the treatment of laundry wastewater.

One of the key contributions of this research lies in its demonstration that EC effectively addresses both particulate (MFs) and dissolved pollutants (surfactants, COD) simultaneously. This dual capacity is particularly significant, given that laundry effluents represent a complex mixture of contaminants that place a heavy burden on conventional wastewater treatment systems. The ability of EC to mitigate multiple categories of pollutants in a single process highlights its potential role in integrated wastewater management frameworks, particularly in regions where decentralized and compact treatment systems are required.

The study also contributes new knowledge on the influence of operational parameters such as pH, current density, and treatment time on MF removal efficiency. Neutral pH was found to be the most favorable condition, consistent with established electrochemical theory regarding aluminum hydroxide speciation. At this pH, intermediate species such as $Al(OH)_2^+$ and $Al(OH)_3$ provided strong charge neutralization and flocculation capacity, leading to stable floc formation and effective MF aggregation. Both acidic and alkaline conditions demonstrated comparatively reduced efficiencies, a finding corroborated by similar studies (Perren et al., 2018; Dimoglo et al., 2019). Optimization of current density and electrolysis time further demonstrated that increasing these parameters enhances removal efficiency, but beyond threshold values, improvements plateau while energy and electrode consumption increase. This emphasizes the importance of balancing performance with operational cost, an insight crucial for scaling the process to industrial and municipal applications.

Comparisons with alternative treatment methods also provide valuable insights. Technologies such as microbubble flotation (Zhao et al., 2024) and electro-hybrid ozonation-coagulation (Luo et al., 2022) have demonstrated high pollutant removal efficiencies, often exceeding 95%. However, these methods require sophisticated infrastructure, higher energy inputs, or specialized chemicals, making them less accessible for widespread deployment, particularly in resource-constrained settings. In contrast, EC offers a simpler, more cost-effective alternative with fewer chemical requirements and a proven ability to treat diverse effluents. Its adaptability to various wastewater streams, including textile, municipal, and hospital laundry effluents, further strengthens its potential for broad adoption.

The comparative analysis also highlights the superior performance of aluminum electrodes over other electrode materials, such as iron or mixed configurations. This aligns with prior research (Oktiawan et al., 2021; Shen et al., 2022), which has consistently shown aluminum electrodes to yield higher contaminant removal efficiencies. This finding reinforces the importance of electrode material selection in EC process design and points toward opportunities for further exploration of composite or modified electrode materials to enhance treatment outcomes.

While the results of this study provide compelling evidence for the effectiveness of EC, several limitations and challenges remain. One of the major issues is the generation of sludge during the process, which requires appropriate handling and disposal. Although EC reduces the volume of chemical sludge compared to conventional coagulation, the composition of the sludge—including trapped microfibers, organic matter, and aluminum hydroxides—necessitates careful management to prevent secondary pollution. Additionally, the study was conducted primarily on synthetic laundry wastewater and small-scale domestic effluents, leaving open questions regarding the variability of performance in large-scale, continuous-flow systems handling diverse and fluctuating wastewater compositions.

Another important consideration is energy consumption. Although the study demonstrated that energy requirements are manageable and economically feasible under optimized conditions, further improvements in reactor design and process integration could reduce power demands and enhance sustainability. Hybrid approaches, such as combining EC with adsorption, membrane filtration, or advanced oxidation processes, hold promise for further improving treatment efficiency while mitigating some of the limitations associated with standalone EC.

From a policy and practical perspective, the implications of this study are profound. As global awareness of microplastic pollution grows, regulatory frameworks are increasingly emphasizing the need for effective control measures at the source. Laundry processes have been identified as a major contributor to microfiber emissions, and technological interventions at this stage offer a critical opportunity to reduce environmental pollution before contaminants enter aquatic ecosystems. The demonstration of EC as a viable method for removing MFs and surfactants from laundry wastewater provides a concrete basis for policymakers and industry stakeholders to consider its integration into domestic, community-level, and industrial laundry systems. Furthermore, the relatively low cost of treatment makes EC an accessible option for both developed and developing countries, supporting global efforts to achieve the United Nations Sustainable Development Goals (SDGs) related to clean water, sanitation, and sustainable consumption.

Future research should focus on several key areas to advance the practical application of EC. First, long-term pilot and field-scale studies are needed to assess performance under real-world conditions and to evaluate the stability and resilience of the process in response to fluctuating influent quality. Second, detailed life cycle and techno-economic analyses should be conducted to evaluate the environmental footprint, cost-benefit balance, and scalability of EC in comparison to alternative treatment technologies. Third, innovations in electrode materials, reactor configurations, and hybrid treatment designs should be pursued to further enhance efficiency, minimize sludge generation, and reduce energy consumption. Finally, interdisciplinary approaches that integrate EC with behavioral interventions (e.g., promoting sustainable textile use and laundry practices) could provide holistic solutions to the challenge of microfiber pollution.

In conclusion, this study contributes significant new knowledge to the field of wastewater treatment by demonstrating the high efficiency, economic viability, and practical potential of electrocoagulation for the removal of microfibers and associated contaminants from laundry effluents. The findings reinforce EC's role as a leading candidate for addressing the urgent environmental challenge of microplastic pollution. While limitations remain, the evidence indicates that EC, particularly when optimized and integrated with complementary technologies, can play a pivotal role in sustainable wastewater management strategies. By advancing both scientific understanding and practical implementation pathways, this research lays the foundation for future innovations that will be critical in reducing microfiber emissions, protecting aquatic ecosystems, and safeguarding human health.

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