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Identification, removal of microplastics and surfactants from laundry wastewater using electrocoagulation method

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Abstract

Microplastics (MPs) and surfactants are generally recognized 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 kg of synthetic materials releases 92,700 to 1,14,300 synthetic microfibers (MFs). MFs, surfactants, and chemical oxygen demand (COD) removal efficiency are higher at neutral pH. The percentage removal efficiency of MFs, surfactants, and COD was 97.9%, 91.2%, and 86.3%, respectively, at an operating time of 25 min, a current density of 300 A/m^2 with optimum power consumption. 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 and surfactants from laundry wastewater using the electrocoagulation technique.

Keywords: Microplastics, microfibers, surfactant, laundry wastewater, electrocoagulation

INTRODUCTION

Domestic laundry wastewater is a kind of greywater. The report estimates that there are 590 million washing machines in 38 countries, and the average yearly water use of each washing machine is approximately 10 m^3[1,2]. If such a huge volume of laundry effluent is released straight into the environment without treatment, it will enormously impact the ecosystem. Direct discharge of laundry wastewater may not only cause eutrophication but may also impair the functioning of wastewater treatment plants. The majority of laundry effluent enters the wastewater treatment facility directly via municipal wastewater piping, which, if reused after treatment, can conserve water resources. Laundry activities generate a large amount of wastewater high in lint, dye, oils, fats, suspended particles, surfactants, and microplastics (MPs)[3-5]. Surfactants and MPs are two common contaminants in laundry effluent that can affect the ecosystem. Surfactants have been shown in studies to not only harm the morphology and physiology of plants but also to significantly reduce sludge dewaterability[1,6,7]. The substantial majority of research data suggests that a significant source of microfibers (MFs) (Microplastics in the form of fibers: size is less than 5 mm) in the freshwater system is from laundry outlets[8-12]. For instance, De Falco *et al.* (2018), Belzagui *et al.* (2019), and Galvão *et al.* (2020) determined that laundry outlets released MFs at rates of 1.75×10^5 - 5.6×10^5, 12×10^5 and 30×10^5 MFs/kg of cloth loads, respectively[8,9,11]. A significant accumulation of MPs and surfactants, along with their degraded products in aquatic environments, resulted in frequent exposure to living species, causing an ecological imbalance[13-15]. To date, the majority of research has focused on surfactant concentration, microplastic sources, distributions, estimates, and hazardous consequences[1,8,10,11,16-18]. Globally, the removal of MFs and surfactants from laundry outlets is a significant problem as well as a challenging task. There is an immediate need to take steps to eliminate these contaminants from laundry effluent.

Several literatures on the treatment of laundry wastewater based on various methodologies have been reported. The most often used methods include adsorption, chemical coagulation, biological, membrane filtration, electrocoagulation, floatation, and sand filtration or a combination of these techniques[4,17,19-22]. In spite of satisfactory results, each process has its own drawbacks. For example, adsorption is a pH-dependent process that requires longer treatment time, decreases adsorption capacity as the number of cycles increases, and requires high energy for regeneration. Similarly, the chemical coagulation approach necessitates the use of several chemicals. It cannot form flocs across a larger pH range. The pH must be regulated during the process, with the addition of acids and various coagulants. During the coagulation-precipitation process, a significant number of secondary pollutants, such as chloride and sulfates, are produced, and a large amount of sludge is also produced, which causes serious environmental issues[23]. In biological treatment, a large amount of space and prolonged time is required for effluent treatment. When it comes to membrane filtration, it causes fouling, which has a negative influence and reduces permeate flow. In this method, equipment and cleaning costs are expensive[19,24]. Floatation can easily separate microplastics from water or sediment. The drawback of this technique is that the removal efficiency is affected by the surface hydrophilicity of microplastics. The sand filtration technique is an easy and alluring option for wastewater treatment. However, it is reported that MPs can easily escape from sand filtration media in the presence of surfactants[25]. As a result, there is an urgent need for more reliable and cost-effective technologies that use fewer chemicals, consume less energy, and have a high capacity for pollutant removal. Electrocoagulation has gained widespread acceptance for pollutant removal from industrial and municipal wastewater. The reason could include the simple equipment design, ease of operation, rapid reaction rate, integration with various treatment techniques, and low operating costs[26,27].

Various researchers have also studied this process's effectiveness in removing MPs and surfactants from multiple sources. Shen *et al.* (2022) reported the removal of MPs from synthetic wastewater[22]. The findings

indicate that aluminum anodes performed better than iron anodes in terms of removal rate, which was over 90%. Perren *et al.* (2018) reported the removal of microbeads from synthetic wastewater using electrocoagulation with removal efficiency ranging from 90% to 99%[28]. Similarly to this, Elkhatib *et al.* (2021) collected final effluent from municipal wastewater and incorporated the synthesized MPs[21]. The finding indicated that 96.5% of MPs were removed using the aluminum electrode from electrocoagulation. Oktiawan *et al.* (2021), the study focused on the removal of surfactants using electrocoagulation[5]. Study results revealed that the efficiency of removal of surfactants was higher in aluminum electrodes compared to iron electrodes. From the literature, it is envisaged that electrocoagulation with the aluminum electrode is best suited for eliminating MPs and surfactants from wastewater. Therefore, electrocoagulation with an aluminum electrode is selected for the present study for the treatment of laundry wastewater; to the best of our knowledge, the electrocoagulation technique has not been investigated much for the treatment of laundry wastewater, especially focusing on MFs and surfactants.

This study provides insight into the discharge of MFs and anionic surfactants from regular household washings. Optical microscopy and Attenuated total reflectance - Fourier transform infrared spectroscopy (ATR-FTIR) spectroscopy were used for checking microfiber counts and chemical compositions. In addition, the methylene blue active substance (MBAS) method was used to determine surfactant concentration. A cost-effective and straightforward method was adopted to reduce the MFs, chemical oxygen demand (COD), and surfactant concentration from laundry wastewater. Further, a preliminary economic evaluation of the electrocoagulation process, which includes the overall power consumption and mass of electrode material utilized for treating laundry wastewater, was carried out. Consequently, based on this quantification, an estimate of the number of MFs released into the environment is performed and compared to previously published studies. The current study will assist readers in developing a thorough grasp of the features and treatment of laundry wastewater comprising key contaminants such as MFs and surfactants.

MATERIALS AND METHODOLOGY

Materials

All the chemicals used in the experimental study were Analytical and laboratory reagent-grade chemicals. Chloroform ($CHCl_3$) and phenolphthalein indicator ($C_{20}H_{14}O_4$) were purchased from Finar Chemicals. Methylene blue dye ($C_{16}H_{18}ClN_3S$), and sodium dodecylbenzene sulfonate/linear alkylbenzene sulfonate ($C_{18}H_{29}NaO_3S$) were purchased from Merck Life Science Pvt. Ltd, Mumbai, India. Hydrogen peroxide 30% (H_2O_2), hydrochloric acid 37% (HCL), ethanol 99% (C_2H_6O), sodium hydroxide (NaOH) and sodium chloride (NaCl) were purchased from Sigma-Aldrich Chemical Pvt. Ltd. Sulfuric acid 98% (H_2SO_4) was procured from Thermo Fisher Scientific Pvt. Ltd. Nile red dye ($C_{20}H_{18}N_2O_2$), sodium Lauryl Sulfate ($C_{12}H_{25}NaO_4S$), sodium bicarbonate ($NaHCO_3$) and sodium carbonate anhydrous (Na_2CO_3) were purchased from HI-Media Laboratories Pvt. Ltd, Mumbai, India. Polycarbonate track etching (pore size 0.2 m, dia 25 mm) and nylon (pore size 0.2 m, dia 47 mm) filter papers were purchased from Sterlitech Corporation, USA and Axiva Sichem Pvt. Ltd, respectively. The electrocoagulation technique was carried out using aluminum electrodes. In order to maintain the effectiveness of the electrodes, diluted HCl (0.01 M) was used to clean the electrodes.

Washing machine discharge collection

Polyester lining fabrics were brought from different stores in India and washed (2 kg fabric materials). A top-load convection washing machine and liquid detergent were used. The quick program option in the washing machine was used to conserve energy and water (15 min, 45 L of ambient temperature water). Regularly, the discharge from washing machines was collected from residential areas, and it was determined that the sample's average residual turbidity was 145 NTU (Lutron, TU-2016). The washing machine effluent

was turbid and muddy in color. Before beginning the experiment, the washing machine went through several blank washes to clean it.

Sample preparation

The fabrics were measured in terms of length and weight and classified based on materials before starting the experiments. After washing fabrics, machine outlet samples were collected and stored in glass containers at 4 °C. Further stored samples were characterized and utilized for electrocoagulation tests. To calculate the number of MFs present in washing machine outlet samples, 1 L washing machine outlet samples were taken and digested with hydrogen peroxide to remove organic and dirt materials[29,30]. After digestion, samples were filtered with polycarbonate track etching or nylon filter paper. To prevent contamination, the filters were always stored in glass Petri dishes. Subsequently, the filtered membrane was dried at 50 °C for 24 h and then characterized. Complete sample filtration was conducted in laminar flow to avoid any airborne MPs. Throughout the experiments, no plasticware was used, and special precautions were taken to avoid contamination.

Electrocoagulation experiment

The electrocoagulation operation was carried out using an electrochemical setup (semi-batch process) built of acrylic material with a 1.2 L volumetric capacity. Both of the electrodes were made with aluminum sheets with a surface area of 6.42×10^{-3} m^2 and dimensions of 0.088 m × 0.073 m. In order to deliver consistent current, anode and cathode electrodes were connected to a direct current (DC) power source (0-30 V/10 A, DC Crown regulated power supply). Induced polarization takes place when a voltage is applied to the electrode ends, leading to the monopolization of the whole assembly. The distance between electrodes was maintained at 5 mm. A detailed schematic diagram of the electrocoagulation system is shown in Figure 1. Several current densities, ranging from 100 to 400 A/m^2, were applied. It is observed that the removal effectiveness of the process approaches saturation when trials are carried out at current densities of more than 300 A/m^2. These investigations demonstrated a comparable decrease in percentages in terms of pollutant concentration. However, current densities of less than 200 A/m^2 were unable to completely eliminate all the contaminants that were over the acceptable limit. As a result, the experiments' ideal current density of 300 A/m^2 was chosen. Similarly, an electrocoagulation duration of 25 min was determined as the best working time since continuing the trials beyond this point results in negligible pollutant removal. As a result, the optimum conditions for all following experiments were 300 A/m^2 (current density) and 25 min (treatment duration). To properly spread the coagulant matter generated by anodic oxidation, a magnetic stirrer with a continuous stirring speed of 180 rpm was used. The experiments were carried out using aluminum electrodes. The entire experimental and analysis process took place at room temperature. The after-electrocoagulation process samples were allowed to settle overnight, and then the supernatant solution was decanted for further MFs and surfactant analysis. The reactions that take place during electrocoagulation (at the anode, cathode, and bulk medium) are detailed below[31].

At anode:

$$Al(s) \rightarrow Al^{3+}(aq) + 3e^- \quad (1)$$

$$2H_2O \rightarrow O_2(g) + 4H^+(aq) + 3e^- \quad (2)$$

At cathode:

$$2H_2O + 2e^- \rightarrow H_2\,(g) + 2OH^-\,(aq) \quad (3)$$

In solution:

$$Al^{3+}\,(aq) + 3OH^- \rightarrow Al(OH)_3\,(s) \quad (4)$$

After settling the sludge, the supernatant solution was taken gently to further analyze MFs, anionic surfactants, and COD concentrations. The sludge was separated and then dried for 24 h at 45 °C in a vacuum drying oven. Each experiment was repeated three times. To study the influence of initial pH, the pH values were adjusted by using diluted H_2SO_4 and NaOH solutions.

Visual inspection, quantification, chemical composition, and morphological characterization

After the sample preparation, filtered membranes were subjected to visual sorting under an optical microscope, which is the most generally used approach for identifying MFs. Microfiber particles were categorized based on their forms and sizes. To determine the functional groups contained in the obtained samples, FTIR analysis of the MFs sample was performed using PerkinElmer Spectrum II. This type of spectroscopic investigation enables the accurate identification of the smallest synthetic plastic particles. After each electrocoagulation experiment, the sludge was recovered and dried at 45 °C for 48 h and further examined with a field emission scanning electron microscope (FESEM) (Manufacturer: Carl Zeiss; Model: Gemini 300) to study the morphological characterization of the sludge and MFs.

Anionic surfactant

Anionic surfactants were assessed via spectrophotometric techniques using methylene blue as the active substance, and this standard method was utilized to determine surfactant concentration in tap water (IS 3025: Part 78: 2021, which is identical to ISO 16265: 2009). The technique works by forming an ionic pair between anionic surfactants and methylene blue. Anionic surface-active agents form salts in reaction with methylene blue in an alkaline medium. These salts are extracted with chloroform and acid treatment of the chloroform solution. Later, the absorbance of the isolated organic phase at the maximum absorption wavelength of 650 nm was measured by a double-beam UV spectrophotometer (Shimadzu, UV-2600)[3,32,33]. Identification of surfactant concentration using the UV spectrophotometer method was a tedious process, which has been simplified in the schematic diagram and shown in Figure 2. A detailed analytical procedure for determining anionic surfactant has been mentioned in the Supplementary material.

RESULTS AND DISCUSSION

The characteristics of laundry wastewater effluent parameters are shown in Table 1. Effluent waste from laundry was collected from domestic in October 2022 at IIT Guwahati, Assam, India. In this study, the results shown in Table 1 are the mean values of three test samples. The experiment was conducted at room temperature. Sample pH, turbidity, COD anionic surfactant, and concentration of MFs were analyzed.

Effect of pH

The pH of laundry wastewater is a very significant factor in the performance of the electrocoagulation process. To investigate the influence of pH, the laundry effluent pH was adjusted with dilute aqueous NaOH and H_2SO_4. Figure 3 depicts the removal efficiency of MFs, surfactant concentration, and COD at different pH after 25 min of electrocoagulation operation. From the figure, it can be seen that the removal efficiency of MFs in all the samples was above 90%, with pH levels ranging from 4 to 10. However, the removal efficiency of MFs at pH = 4 and 10 is slightly lower compared with pH = 6-8. Further, the removal efficiency

Table 1. Characteristics of laundry wastewater before and after electrocoagulation treatment

Sl. No.	Parameters	Initial effluent characteristics	Electrocoagulation operating parameters and cost estimation	After electrocoagulation treatment
1	pH	9.1 ± 0.5	T= 25 min, pH= 7, CD 300 $A{\cdot}m^{-2}$, Stirring speed 180; 0.53 US$$\cdot m^{-3}$ (44 $Rs{\cdot}m^{-3}$)	8.9 ± 1
2	Turbidity	145 ± 10 NTU		1.2 ± 0.7 NTU
3	COD	830 ± 25 (mg/L)		112 ± 5 (mg/L) (> 85%)
4	Anionic surfactant	48 ± 3 (mg/L)		4.3 ± 1 (mg/L) (> 90%)
5	MFs	2,300 ± 240 MFs/L		50 ± 18/L (> 95%)

COD: Chemical oxygen demand; MFs: microfibers; NTU: nephelometric turbidity units.

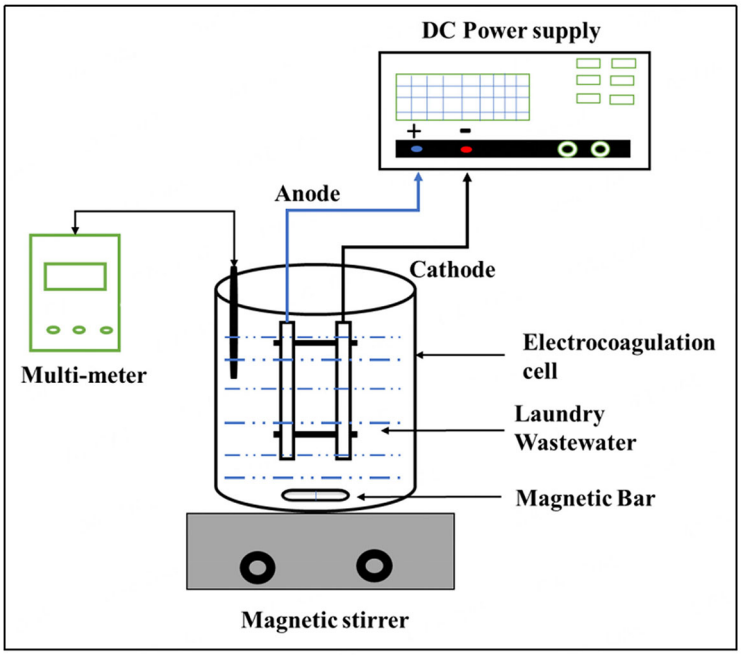

Figure 1. Schematic diagram of the electrocoagulation set up. DC: Direct current.

of surfactant and COD was 91% and 85%, respectively, at pH 7. At pH = 7, the maximum removal efficiency of all contaminants was determined to be optimal. The results show that a more neutral pH is likely to provide greater removal due to the favorable formation of coagulants at neutral pH, which is in line with the results of Perren *et al.* (2018) and Dimoglo *et al.* (2019)[26,28]. The difference in removal efficiency with pH is due to the hydrolysis and polymerization of Al^{3+} in the pH range of 6-8, which leads to the formation of particles $Al(OH)^{2+}$, $[Al_2(OH)_2]^{4+}$, $Al(OH)_3$, and highly charged polymeric hydroxy complexes $[Al_{13}(OH)_{32}]^{7+}$, which are effective for coagulation. As the pH rises over 10, the main hydrolysis product is $Al(OH)_4$, which inhibits the synthesis of anodized aluminum species as well as the adsorption of dispersed particles. The adsorption effect is negligible at low pH = 4 because only aluminum ions are present[14,26,28].

Effect of current density

Current density is an essential parameter in electrocoagulation operations since it is an operating factor that may be directly regulated using the DC power source. Figure 4 depicts the average removal rates for the various current densities from 100 to 400 A/m^2. It can be observed from the figure that the change in current density has a considerable impact on the removal efficiency of MFs, surfactants, and COD

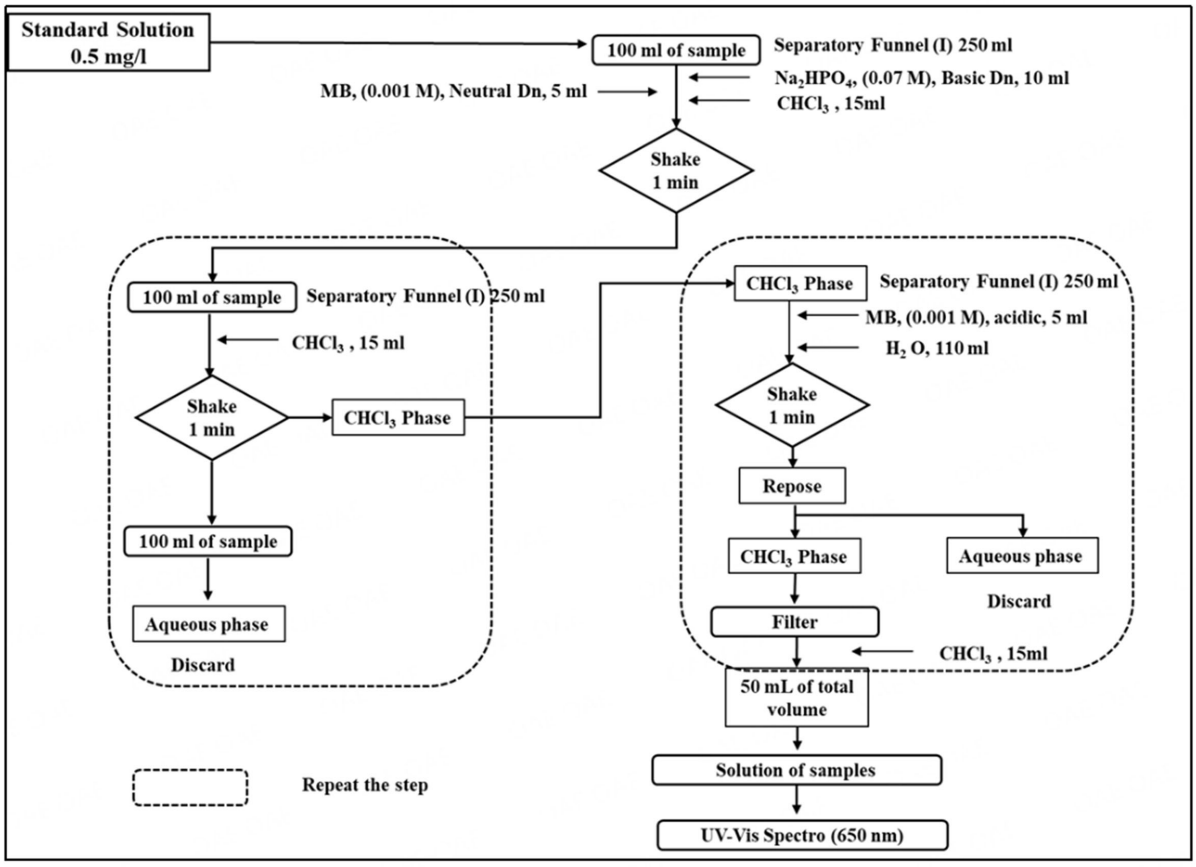

Figure 2. Schematic representation of the normalized analytical method for identifying anionic surfactants.

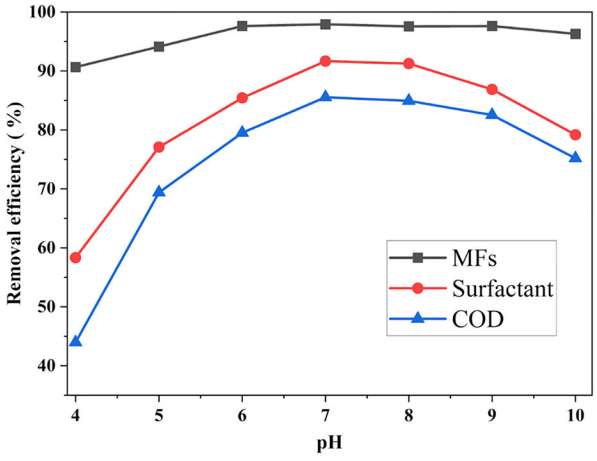

Figure 3. Efficiency of removing MFs, surfactants, and COD after 25 min of electrocoagulation at various starting pH levels. Electrode spacing is 0.5 cm, stirring speed is 180 rpm, and current density is 300 A/m^2. COD: Chemical oxygen demand; MFs: microfibers.

concentrations. The removal efficiency increased with an increase in current densities. This is in line with Faraday's law of electrolysis. When the current density of the cell is increased, metal ions released from the electrodes are also increased, and flocculants are likely to be present at high current density. Yet, there was

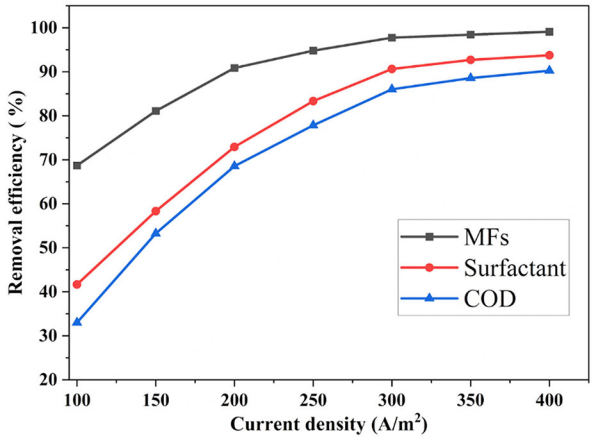

Figure 4. The effect of current density on MFs, surfactant, and COD removal efficiency reaction time 25 min time, pH 7, electrode spacing 0.5 cm, and stirring speed of 180 rpm. COD: Chemical oxygen demand; MFs: microfibers.

no apparent change in removal efficiency between 300 and 350 A/m²; taking operational cost into consideration, a current density of 300 A/m² was found to be optimum, with a removal efficiency of 97%, 90.6%, and 86% for MFs, surfactants, and COD, respectively. Hence, 300 A/m² has been considered for further experiments.

Effect of processing time

The results of MFs, surfactant, and COD removal from laundry wastewater by electrocoagulation as a function of processing time are depicted in Figure 5. Contaminant removal efficiency starts increasing when the electrolysis duration is raised from 5 to 35 min, as seen in the figure. The results show that reaction time has a favorable influence on electrochemical treatment efficiency. Anodic electro-dissolution causes the release of coagulating species during electrocoagulation. Pollutant removal efficiency is directly related to metal ion dissolution concentration. The concentration of metal ions and associated hydroxide flocs in the water solution increases as the electrolysis duration increases. An increase in the treatment time results in a significantly greater removal. The time when coagulants are in excess and flocculation takes control appears to be between 20 and 25 min since current density seems to have a greater impact on contaminate elimination during this time period. Running the reactor for more than 25 min would result in excess coagulant with minimum effect on removal efficiency.

Additionally, prolonged operation results in increased electrode and energy consumption. Therefore, the operating time of 25 min was found to be optimum with a removal efficiency of 97.9%, 91.2%, and 86.3% for MFs, surfactant, and COD, respectively, at pH 7 and 300 A/m². The initial turbidity decreased from 145 ± 10 to 1.2 ± 0.7 NTU.

Characteristics of microfibers and flocs

Optical microscopic analysis

Laundry wastewater was observed under an optical microscope. The results confirmed the existence of MFs in all of the laundry wastewater samples [Figure 6A]. It was observed that laundry wastewater contained around 2,300 ± 240 MFs/L or 46,350 -57,150 MFs/kg fabrics. The length of the collected MFs varied between 20 to 5,000 μm with a diameter between 10 to 20 μm. After electrocoagulation, the supernatant solution and sludge were observed under the optical microscope.

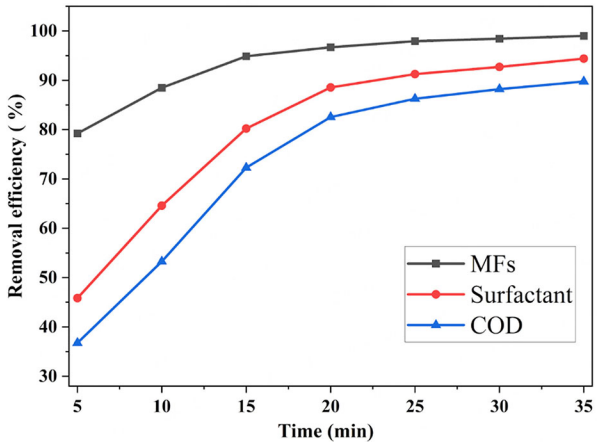

Figure 5. Effect of electrolysis time on the removal efficiency of MFs, surfactants and COD. Reactor CD 300 is A/m^2, pH 7, electrode spacing 0.5 cm, and stirring speed 180 rpm. COD: Chemical oxygen demand; MFs: microfibers.

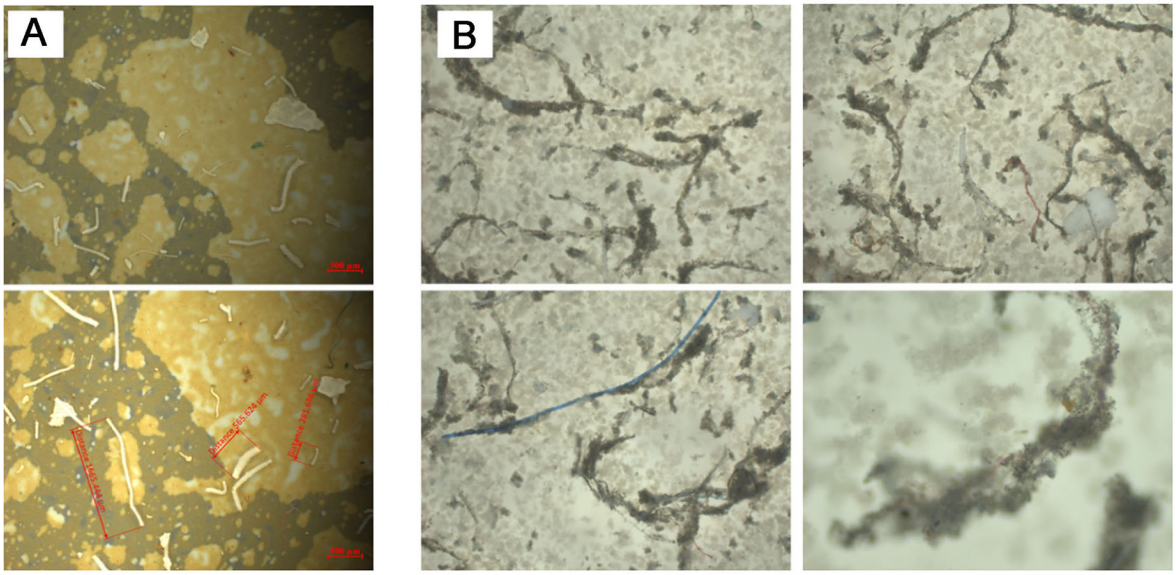

Figure 6. (A) Microscopic images of MFs in laundry effluent; (B) sludge obtained after electrocoagulation. MFs: Microfibers.

Around 50 ± 18 MFs/L was observed in the supernatant solution. It was found that there was a huge deposition of organic and inorganic particles (soil/dust, surfactants, dye, heavy metals) on the surface of MFs, which makes the MFs precipitate easily [Figure 6B].

FTIR analysis

A total of ten samples of laundry effluent were collected, including replicates. After the procedure, the validation of microfiber polymer types was performed using ATR-FTIR. Spectra were scanned in the range of 4,000-400 cm^{-1}. The raw spectra were processed using Bio-Rad KnowItAll software and identified the composition of MFs polymers. The graph obtained from the ATR-FTIR of microfiber particles was examined and depicted in Supplementary Figure 1. It can be seen from the figure that laundry wastewater contained a polyester type of polymer. The results were compared with reference samples using Bio-Rad KnowItAll software.

FESEM analysis

After electrocoagulation, the flocs were analyzed using scanning electron microscopy. The presence of MFs in the sludge can be clearly seen in FESEM images, as shown in Figure 7. The FESEM study is reliable, consistent, and accurate, making it possible to measure the size of fibers present in laundry wastewater and sludge. The MFs are long and thick and often occur in aggregates within flocs. The size of the flocs was > 50 μm, which was confirmed using a scanning electron microscopic technique.

A proposed possible mechanism

Electrocoagulation is a complicated process that uses a combination of procedures that work together to remove contaminants from wastewater. It allows for anodic oxidation and the formation of *in situ* active adsorbent (for example, aluminum hydroxides). Simultaneously, cathodic reactions take place, and H_2 gas is generated, allowing the absorbents to float[28,34]. The produced Al^{3+} ions instantaneously hydrolyze to form equivalent hydroxides and poly hydroxides at a suitable pH. Generated aluminum hydroxides and aluminum poly hydroxides have a stronger attraction to collect the contaminants in the wastewater, producing more coagulation compared to the typical aluminum coagulants[35,36]. Furthermore, the gas bubbles produced by water electrolysis might promote the floating of contaminants and coagulated materials. A possible mechanism is proposed based on the results obtained [Figure 8].

Natural clay particles, heavy metals, and dyes are usually negatively charged[28,37,38]. Monomeric species such as $Al(OH)^{2+}$, $Al(OH)_2^+$, $Al_2(OH)_2^+$, $Al(OH)_4$, and polymeric species such as $Al_6(OH)_{15}^{3+}$, $Al_7(OH)_{17}^{4+}$, $Al_8(OH)_{20}^{4+}$, $Al_{13}O_4(OH)_{24}^{7+}$, $Al_{13}(OH)_{34}^{5+}$, can neutralize the surface charges of heavy metals[23,31] dye, and clay particles[35,39], which ultimately leads to their surface deposition onto MFs during electrocoagulation.

(ii) Amorphous flocs of aluminum hydroxides have a wide surface area, which is advantageous for faster MFs adsorption[22,37].

(iii) Anionic surfactants are adsorbed on MFs, and the negative surface charges can be neutralized with an opposite charge or floc of aluminum hydroxides generated during the process. Further, it leads to the formation of larger flocs, and these flocs can be removed from the aqueous medium by precipitation or hydrogen flotation.

Operating cost analysis of electrocoagulation

The operating cost (US$·m^{-3} of effluent) of the electrocoagulation process mainly includes electricity and electrode costs. The operational cost was calculated using Equation 5[23].

$$Operating\ cost_{(electrocoagulation)} = a \times Q_{electrode} + b \times Q_{energy} \quad (5)$$

where $Q_{electrode}$ and Q_{energy} denote electrode material and electrical energy usage, respectively. "a" indicates the cost of the electrode (2.82 US$·kg of aluminum), and "$b$" means the cost of electricity use (0.0924 US$·kW·h^{-1}). Faraday's law was used to determine the consumption of electrode material[31]:

$$Q_{energy} = \frac{I \times V \times t}{V_L} \quad (6)$$

$$Q_{electrode} = \frac{I \times t \times M.W}{F \times z \times V_L} \quad (7)$$

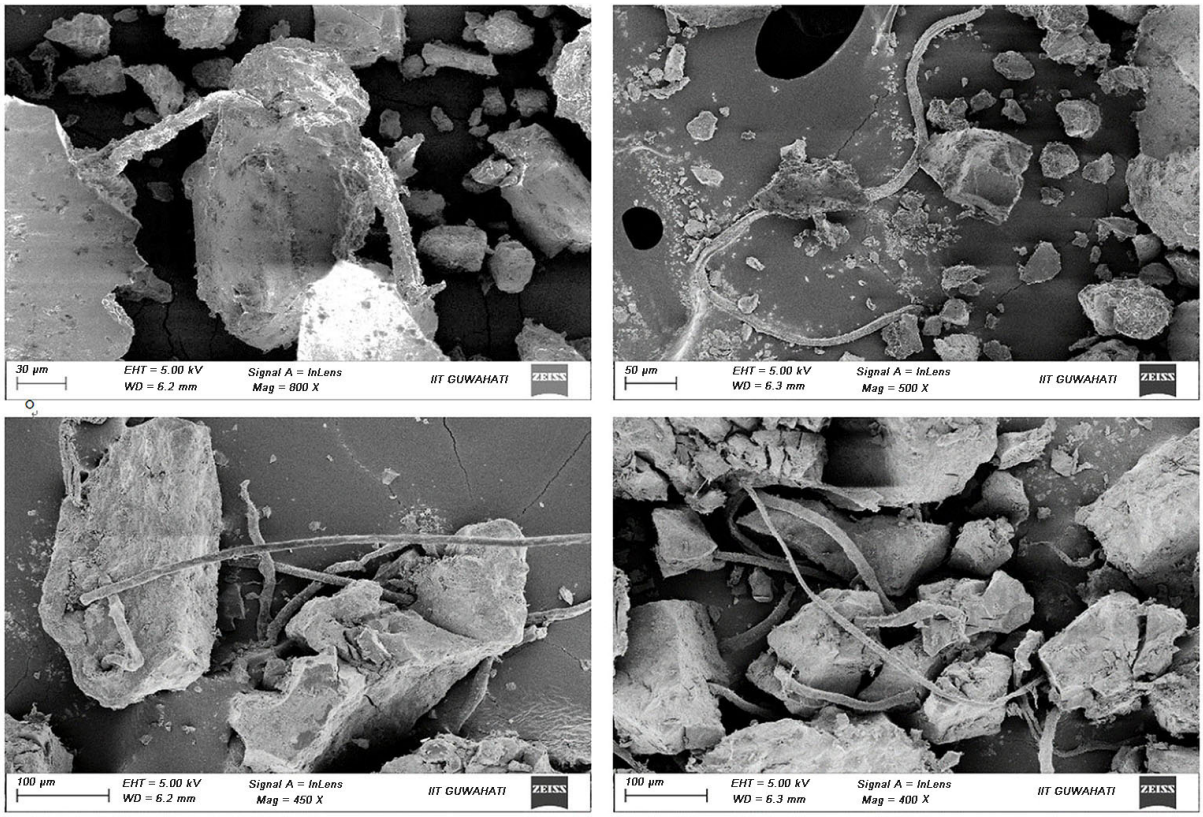

Figure 7. Scanning electron microscopic images of MFs flocs after electrocoagulation. MFs: Microfibers.

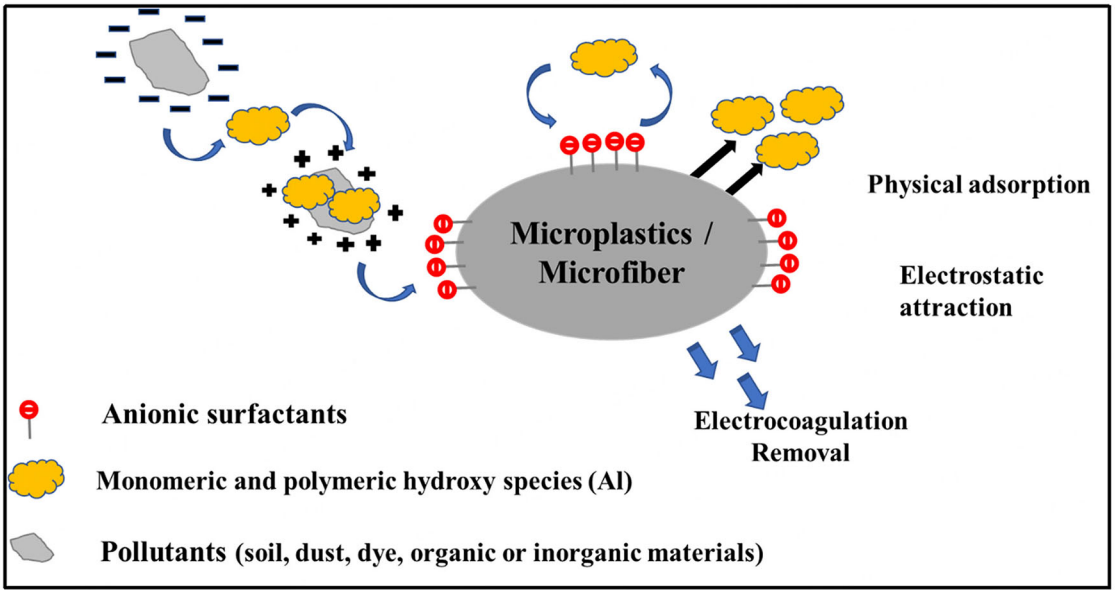

Figure 8. Schematic illustration of surfactant stealth effect of MPs/MFs during coagulation. MFs: Microfibers; MPs: microplastics.

where I designates the current (A), t indicates the time of electrocoagulation process (s), $M.W$ is the molar mass of aluminum (26.98 g·mol^{-1}), V is the voltage (V), V_L is the effluent volume (m^3), F is the Faraday's

constant (96,487 C·mol^{-1}), and z is the number of electrons transported (z = 3). The energy and electrode costs for the electrocoagulation process increase with increasing current density. This is due to increased energy consumption and greater anodic oxidation. At 25 min of study, the total operation cost was 0.53 US$·m^{-3} with a rising current density of 300 A·m^{-2}.

A comparative study with various literature

The release of MFs from the laundry is influenced by various parameters, including textile properties (for example, fabric type and age), washing temperature, detergent properties and dosage, and abrasion during laundry[40,41]. New clothes shed more MFs during washing because of residues from the fabric production process[9]. Various literature estimates MFs detachment from fabrics. However, their results are difficult to compare since they employed utilized materials, different washing durations, and other detergents are presented in different units. A summary of these previously published works is shown in Table 2. According to what can be observed in the table, our data show fewer MFs than those of earlier studies. This may be due to less washing time, lower water temperature (25-30 °C), and use of liquid detergent, which resulted in less release of MFs in laundry outlets. Similar interference was also reported by[40,41].

The studies on the removal of MFs and surfactants in various wastewater using the electrocoagulation process are shown in Table 3. Significantly, the available research on the removal of MFs and surfactants from laundry wastewater by the electrocoagulation process is very limited. The comparison of targeted parameters and data based on pollutant removal obtained in this work suggests that aluminum electrodes are best suited compared to other electrodes. This is also comparable with the studies that have used aluminum electrodes for pollutant removal from various wastewater, as shown in the table. Further, the research conducted in this work could serve as benchmark data in the field of treatment of MFs and surfactants from the laundry industry.

CONCLUSION

Synthetic MFs accumulation and deposition in the aquatic ecosystem are presently undeniable. This work aimed to evaluate the presence of MFs in laundry wastewater and the effective removal of pollutants by the electrocoagulation process. From the study, it was envisaged that initial pH, operating time, and current density have a substantial impact on the removal of contaminants from laundry wastewater. The removal efficiency of MFs, surfactants, and COD is higher at neutral pH. The percentage removal efficiency of MFs, surfactants, and COD was 97.9%, 91.2%, and 86.3%, respectively, at an operating time of 25 min, a current density of 300 A/m^2 with optimum consumption of electrodes. The Electrocoagulation system was effective in reducing more than 86% of the amount of pollutant concentration in laundry wastewater. Further research should look at the impact of NaCl percentage and current density on the efficiency and cost operations. A two-stage, continuous electrocoagulation reactor with membrane or adsorption or sand-based separation appears to be the most practical solution for a large-scale industrial electrocoagulation process. Additional studies may be conducted to investigate different reactor designs and combinations to improve the process.

Table 2. Comparison of various works of literature with the present work

Type of fabric	New clothes	MFs numbers	MFs length	Surfactant concentration	Ref.
Commercial garments (polyester, polypropylene)	Yes	12×10^5 - 35.40×10^5 MFs/kg	20 to 2,000 m	n.d	De Falco *et al.* (2018)[9]
Commercial garments (polyester)	Yes	6.40×10^5 - 15×10^5 MFs/kg	Avg. 360-660 m	n.d	De Falco *et al.* (2019)[10]
Textile garments (Polyester, polyester-elastane and polyamide-elastane)	Yes	30,000-465,000 MFs/m^2	20 to 5,000 m (avg. 0.2-0.4 mm)	n.d	Belzagui *et al.* (2019)[8]
Household clothes and linens (cotton, polyester, polyamide, viscose, elastane, acrylic)	No	30×10^5 MFs/kg	0.17 mm (50 to > 500 m)	n.d	Galvão *et al.* (2020)[11]
Polyester, polyamide, and polyacetate fabrics	Yes	74,816 ± 10,656 MFs/m^2	5-4,000 m (avg. polyester: 499.49 ± 505.65 µm, polyamide: 1,056.53 ± 761.42 µm, acetate: 1,128.00 ± 750.72 µm)	n.d	Yang *et al.*, (2019)[41]
Household clothes	No	4,400-10,800 MFs/L	6-4,000 µm	8 ± 2 to 800 ± 50 (mg/L)	Luo *et al.* (2022)[1]
Household lining fabric	No	2,300 ± 240 MFs/L or 46,350-57,150 MFs/kg	> 50 to 5,000 µm	48 ± 3 (mg/L)	Present work

Avg.: Average length; MFs: microfibers; n.d: not determined.

Table 3. 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-electroflotation and membrane filtration	Al and Fe	MPs 100% (Electrocoagulation and membrane)	Akarsu *et al.* (2021)[20]
Effluent from the local wastewater treatment plant	Polyester MPs (25 mg/L) were added	Electrocoagulation	Al	MPs 96.5%	Elkhatib *et al.* (2021)[21]
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	Surfactants	Electrocoagulation	Al	Surfactants 80%	Ramcharan and Bissessur (2017)[18]
Laundry wastewater	Surfactants	Electrocoagulation/ electroflotation	Al	Surfactants 90%	Dimoglo *et al.* (2019)[26]
Laundry wastewater	Surfactants	Electrocoagulation	Al-Al, Fe-Fe, Al-Fe, and 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 and surfactants	Electrocoagulation	Al	MFs 97.9%, Surfactants 91.2%,	Present work

Al: aluminum; CA: Cellulose acetate; Fe: iron; MFs: microfibers; MPs: microplastics; PE: polyethylene; PMMA: polymethyl methacrylate; PP: polypropylene; PVC: polyvinyl chloride.

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