

Treatment Of Microfibers From Wastewater Using Electrocoagulation And Biological Methods

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Abstract

Conventional wastewater treatment systems are often inadequate in effectively removing microfibers from textile industries and domestic sources, necessitating the development of integrated and sustainable treatment solutions. This research focuses on the treatment of microfiber-contaminated wastewater using a two-stage approach involving electrocoagulation (EC) followed by anaerobic digestion in a lab-scale reactor. Electrocoagulation was employed as a primary treatment to achieve efficient removal of suspended microfibers through the in-situ generation of coagulant species using aluminium and steel electrodes in monopolar and bipolar configurations. Key operational parameters, including current density, electrode material, inter-electrode distance, and pH, were optimized to maximize microfiber removal and reduce chemical oxygen demand (COD). The effluent from the EC unit was subsequently treated in an upflow anaerobic sludge blanket (UASB) reactor to degrade the residual organic pollutants and assess the fate of microfibers under anaerobic conditions. The role of sulfate-reducing bacteria and methanogenic consortia in the partial transformation and surface degradation of biodegradable microfibers was also evaluated. The combined EC-anaerobic process demonstrated significant reduction in microfiber concentration (up to 90%), organic load (COD removal >85%) and the synergistic potential of physicochemical and biological treatment methods. The study presents a viable pathway for decentralised wastewater treatment in textile clusters, contributing to improved environmental protection and resource recovery.

Keywords: Microfibers, Electrocoagulation (EC), Anaerobic digestion, Wastewater treatment, Textile pollution, Sulfate-reducing bacteria, Organic load reduction.

1. Introduction

Microplastics are particles of plastic less than 5 millimetres in size. According to a study conducted by the Swiss non-profit EA Earth Action, India is projected to discharge a total of 391,879 tonnes of microplastics, making it the second-largest contributor to waterbody pollution, after China (787,069 tonnes) (Genchi & Martin, 2023). The last 70 years have seen plastic production grow exponentially, leading to a "plastic world" with the properties of plastic polymers—such as low cost, versatility, water resistance, high strength-to-weight ratio, and high thermal and electrical insulation properties—making them essential in consumer goods, packaging, transportation & storage, and clothing. However, the mass production and disposal of plastics have become a major concern as environmental challenges due to the damage induced by microplastics. In India, two major rivers, the Ganga and the Yamuna, release large amounts of microplastics into the oceans, along with rapid urbanization and inefficient waste management infrastructure (Zhao & Ren, 2024). Microplastics have contaminated ecosystems including soil, water, air, and even food, which endangers the health of humans and marine life. The problem

is only getting bigger, and better regulations, awareness, and new waste management practices are urgently needed.

One of the types of microplastics we are particularly concerned about is microfibers. Microscopic- sized synthetic or natural fibres, commonly from textile sources, are continuously being released to the environment at the production stage, during domestic laundry, and via industrial waste. One of the primary sources of microfiber pollution is the textile industry, which is responsible for shedding synthetic fibers such as polyester, nylon, and acrylic (Torre & Kafritsa, 2024). Microfibers cannot be caught by conventional wastewater treatment plants, and due to their size, they pose a long-term hazard to aquatic life and human health, as they can end up in the food chain. Furthermore, microfibers have been detected in drinking water, affecting not only public health but also the quality of the environment (Huan & Li, 2024). The wastewater treatment of microfibers is one of the most challenging tasks, and electroplating is a potential option for that. Electroplating, traditionally used in metal finishing, has been adapted for environmental applications and attracts particles suspended in the water for collection on electrodes through the use of electricity, including microfibers. This technique has proven to be a feasible method of reducing microfiber contamination and thus a sustainable way to mitigate pollution (Henry & Laitala, 2019).

The increasing concentration of microfibers in wastewater has become a cause for concern with serious environmental implications. These microfibers are frequently made from non- biodegradable materials and end up in the environment, where they are toxic to marine life. Fish can eat microfibers, resulting in toxicity, bioaccumulation, and physical damage to aquatic animals. Moreover, microfibers can also be deposited into soil via air and irrigation of wastewater, which could impact agricultural productivity and soil organisms (Jokara & Bidhendi, 2022).

Microfibers are also harmful to human health, as they can be inhaled or ingested through the food chain. While electroplating shows great promise as a microfiber removal method, the effectiveness of the technique varies with a number of factors, including the properties of the wastewater and the nature of the microfibers present. To address these challenges, a greater number of studies are needed to improve the process, particularly at large scale, as well as to explore complementary solutions, including biological treatment methods (Torre & Kafritsa, 2024).

Microplastic and microfiber pollution is also of concern for health and ecological reasons, especially with regards to persistence in aquatic systems and soil. Microplastics refer to particles smaller than 5mm and have multiple sources, including the breakdown of larger plastics and man- made fibers from clothing (Gao, Sun & Liu, 2023). Due to the abundance of these pollutants in water, soil, and air, there is a need to enhance treatment techniques and regulations. In India, innovative microfiber removal technologies are being developed, including microfiber collection filters for washing machines, advanced wastewater treatment systems, and microfiber removal fabrics. These technologies are oriented towards reducing microfibers and better wastewater treatment practices. However, these systems still require optimization for broader use, particularly in regions

with high concentrations of textile industry effluents (Gao, Sun & Liu, 2023).

Based on this, the objective of this study is to assess the efficacy of physicochemical and biological methods for microplastic removal, compare changes in microplastics before and after treatment using analytical techniques, and optimize integrated treatment methods by developing a hybrid degradation system that combines both physicochemical and biological techniques for maximum efficiency.

The significance of this research is that it will contribute to the resolution of one of the most important environmental issues we face today microfiber pollution. The development and optimization of treatment technologies such as electrocoagulation and electroplating, in combination with biological treatment methods, are sustainable and effective treatment techniques for the removal of microfibers from wastewater. In a time when awareness of microfiber pollution and its potential long-term impacts on aquatic ecosystems and human health is on the rise, this type of research is paramount in bringing closer the hope to find positive and scalable solutions for cleaner waters and a more sustainable future. Therefore, this work has the potential to contribute to wastewater treatment policies and technological innovations, which will help mitigate microplastic pollution and its environmental and public health impact on a global scale.

The objectives of the research work is to

- To evaluate the efficacy of physicochemical methods for microplastic removal.
- To investigate the role of biological methods in the degradation of microplastics in the environment.
- To compare the physicochemical and biological changes in microplastics before and after treatment using an analytical technique.
- To optimise integrated treatment methods for developing a hybrid degradation system combining physicochemical and biological techniques for maximum efficiency.

2. Literature Review

Due to washing, synthetic or natural fibers are lost and deposited in the environment, forming a large pollutant composed of microfibers, which are minute-sized fibers of synthetic or natural origin, primarily coming from textiles. With the textile industry being one of the major sources, these fibers are released into the environment as a result of domestic washing and through effluent discharges from industrial processes. Microfibers remain in the environment for a long time because of their non-biodegradable nature, which creates significant ecological and human health issues. Eliminating microfibers from wastewater has thus become a major research subject, and sophisticated treatment techniques such as electrocoagulation (EC) and biological treatment systems, particularly anaerobic treatment systems, have been employed.

2.1. Microfiber Removal by Electrocoagulation

Electrocoagulation (EC) is an emerging electrochemical process of interest, which uses

sacrificial electrodes to produce coagulant species in situ to promote the removal of suspended particles (microfibers) from wastewater. The process entails the passing of electric current through metal electrodes (aluminum or iron are the most common) that are positioned in the wastewater. The resulting current causes the metal ions to be dissolved and create coagulating agents, which attach themselves to suspended particles such as microfibers so that these may settle or be removed by flotation.

Several studies have proven the effectiveness of EC for microfiber removal. For example, studies have revealed that current density, electrode material, inter-electrode distance, and pH are important parameters in optimizing the treatment process. Modification of these parameters has been reported to improve microfiber removal, decrease chemical oxygen demand (COD), and improve overall water quality. In an experimental setup, the application of aluminum and steel electrodes has demonstrated significant microfiber removal (up to 90%) by a combination of coagulation, flocculation, and sedimentation processes. Thus, EC can be used as an alternative for decentralized wastewater treatment, particularly in regions with textile industries (Henry & Laitala, 2019; Gaylarde & Baptista-Neto, 2021).

Also, EC has several advantages over conventional techniques, including reduced chemical usage and less sludge production. It is also versatile with respect to wastewater compositions and can be combined with existing treatment systems. However, the effectiveness of EC in microfiber removal depends on the specific wastewaters and their characteristics, including the types of microfibers and their concentrations present in the wastewater. Literature points out that a better understanding of these variables is necessary in order to optimize the system for large-scale applications (Torre & Kafritsa, 2024; Choi & An, 2024).

2.2. Biological Treatment: Microfibers Anaerobic Degradation

Biological treatment processes, specifically anaerobic digestion, have been explored as adjunctive processes to electrocoagulation for microfiber degradation in wastewater. Anaerobic digestion is the decomposition of organic matter in the absence of oxygen under the action of a consortium of microorganisms, including sulfate-reducing bacteria (SRB) and methanogens. While the role of SRBs is largely known as sulfate reduction to H_2S , they have an indirect but key role in microfiber degradation as they are able to create anaerobic conditions favorable to the activity of other microbial communities able to degrade natural fibers such as cotton and wool (Jokara & Bidhendi, 2022).

For synthetic microfibers (non-biologically degradable from direct biological attack), the function of SRBs is to contribute to the breakup of the fibers, especially by the generation of H_2S . This compound can break chemical bonds in synthetic fibers and make them more vulnerable to further degradation by other microbial communities. Although SRBs do not contribute directly toward the degradation of synthetic fibers such as polyester or nylon, they can help in the breakdown of additives and dyes related to their production, facilitating their ultimate degradation (Torre & Kafritsa, 2024).

Anaerobic digestion combined with electrocoagulation has been confirmed as a good

candidate for improved removal and degradation of microfibers from wastewater. For example, the residual organic loads of the effluent after EC treatment can be further degraded in an upflow anaerobic sludge blanket (UASB) reactor. This two-step process has proven to be very efficient with substantial reductions in microfiber concentration and COD. The use of physicochemical and biological treatment methods synergistically provides a sustainable way for microfiber- contaminated wastewater treatment in textile industries (Ladewig & Bianchi, 2024; El-Hage & Feynerol, 2024).

2.3. Issues and Implications for the Future

Although both EC and biological methods offer great potential for microfiber removal, there are a number of issues that are still challenging. Among these factors is the incomplete elimination of synthetic microfibers in the wastewater treatment process, especially in conventional systems. Microfibers are small and light, making them difficult to capture using conventional forms of filtration. Moreover, the nature of the synthetic polymer used in the production of the microfibers can influence their behavior during the treatment, which makes the standardization of the methods complicated (Zhao & Ren, 2024).

As a result, further studies are required to optimize the electrocoagulation and anaerobic treatment processes in microfiber removal, especially on parameters and reactor design to improve their efficiency. There is also a need for more detailed studies on the ecotoxicological effects of microfibers on aquatic organisms as well as the long-term consequences of microfiber pollution on the aquatic ecosystems. Furthermore, improvements in microfiber monitoring and quantification methods are needed to determine the performance of treatment systems in the field (Genchi & Martin, 2023).

The incorporation of new technologies (e.g., microfiber-specific filtration systems, hybrid treatment solutions combining EC, biological treatment, and advanced filtration) has much to offer in the development of sustainable solutions for microfiber contamination. However, the scale-up of these technologies needs further research on their feasibility, economic feasibility, and environmental impact (Gao, Sun & Liu, 2023; Huan & Li, 2024; Pramanik, 2024; Rossia & Vergara, 2024).

3. Materials and Methods

This section provides a detailed account of the materials and experimental procedures used to remove microplastics and microfibers from wastewater. The materials, setup, and methods are designed to ensure accurate, reliable, and reproducible results.

3.1 Collection of Microplastic Sludge

The sludge was collected from the Sansera industry, which operates in both the automotive and non-automotive sectors. San Sera Engineering Limited is expanding its manufacturing capacity at Ramanagaram in Karnataka with a significant investment of Rs 2,100 crore. This expansion, which is expected to create around 3,500 jobs, focuses on both the automotive and non-automotive sectors and will span three to five years. While the investment is aimed at enhancing manufacturing capabilities, there is no direct

mention of microplastics production or involvement in the microplastic industry. Nonetheless, microplastics remain a concern due to their ubiquity in the environment, stemming from various sources, including industrial and textile waste.

3.2 Original Microplastic Sludge (Initial Stage)

The sludge sample representing industrial waste was collected for treatment and preliminary analysis. The sample was found to contain significant quantities of microplastics which were subject to subsequent treatment processes. Figure 1 presents the initial amount of sludge collected from the Sansera industry which was important to test the effectiveness of the techniques of microplastic removal.



Figure 1: 5 Liters of sludge collected from the industry.

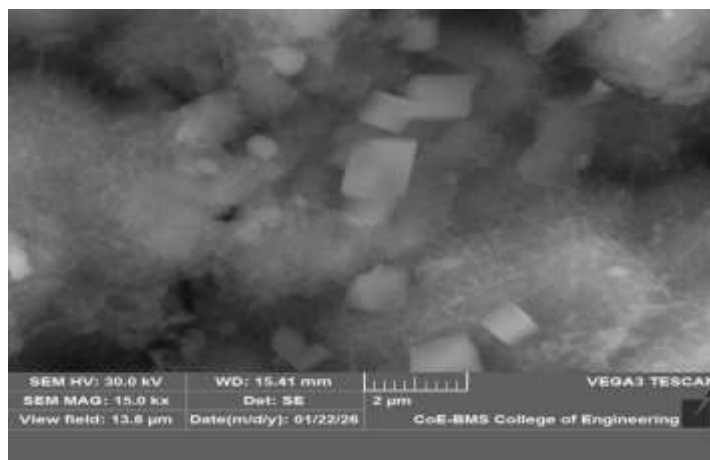


Figure 2: SEM Image of Microplastic Sludge at 10.0 kx Magnification

SEM micrograph showing the morphology and particle distribution of raw microplastic-containing sludge collected from Sansera Industry. The heterogeneous aggregates display irregular shapes with particulate matter embedded in the organic matrix. Image acquired at 30.0 kV accelerating voltage with 5 μ m scale bar.

3.3 Real Microplastic Containing Sludge

The collected sludge parameters were tested to determine its physical, chemical and microplastics content. These characteristics are essential in determining the methods of

treatment that can be brought effectively. Table 1 shows the results of the test for the first sludge sample with relevant features such as moisture content, chemical oxygen demand, and microplastics. This data is important for looking at the initial contamination levels, and how to treat the situation.

Table 1 Test Results for Microplastic Sludge

Sl. No	Parameters	Unit	Results	Test method
1	Physical Status	-	Black Color Oily Liquid	-
2	Colour	-	Black	-
3	Reacts Violently with Water	-	Immiscible	-
4	Generation of Toxic Fumes with Water	-	No	-
5	Moisture	-	10	IS 2720 (Part-2) 1173 (RA 2020)
6	Ash Content	%	87	ETH/TR/SS/SOP/013
7	pH	-	6.85	IS 2720 (Part-26) 1987 (RA 2021)
8	Fluoride	mg/L	200	ETH/TR/SS/SOP/014
9	Nitrate	mg/L	2800	ETH/TR/SS/SOP/015
10	Ammonia	mg/L	2900	ETH/TR/SS/SOP/016
11	Chemical Oxygen Demand (COD)	mg/L	246960	IS:3025 (P-58)2006(RA2022)
12	Biochemical Oxygen Demand (BOD)	mg/L	141000	IS:3025 (P-44)1993(RA2019)
13	Microplastic Content	Absent or Present	Present	ETH/TR/MB/SOP/042

3.4 Electrocoagulation Setup in Laboratory

In laboratory, an electrocoagulation system was prepared in order to test the removal of microplastics from the sludge sample. The following steps are used for setting it up:

- 1) **Set up the test apparatus:** The test apparatus was set up with the necessary components such as a power supply, electrodes, reactor, and monitoring equipment.

- 2) **Sludge sample:** A thoroughly mixed sludge sample was prepared for treatment.
- 3) **Adjust the parameters:** Voltage and current parameters were adjusted according to the properties of the sludge sample.
- 4) **Place the electrodes:** Electrodes were placed correctly within the reactor in order to ensure effective coagulation.
- 5) **Start the electrocoagulation process:** Power supply was turned on to start the coagulation process and attract microplastics to the electrodes.
- 6) **Monitoring the process:** Parameters such as voltage, current, pH, and turbidity were monitored throughout the process.
- 7) **Collect and analyse treated sludge:** After the treatment process, the sludge was analysed for microplastic removal efficiency.

3.5 About Bipolar Electrode Connection

A Bipolar Electrode (BPE) system was used in this study. In this configuration, BPE is placed between the anode and cathode electrodes in the electrolyte solution. The BPE is not directly connected to the power supply but is subject to a potential difference because of the voltage applied between the anode and cathode. This causes oxidation at one end and reduction at the other which is a very important factor in the removal of microplastics. Figure 3.2 shows the setup of the bipolar electrode system that explains the role of the anode and cathode in running the electrochemical reactions that enable the removal of microplastics.

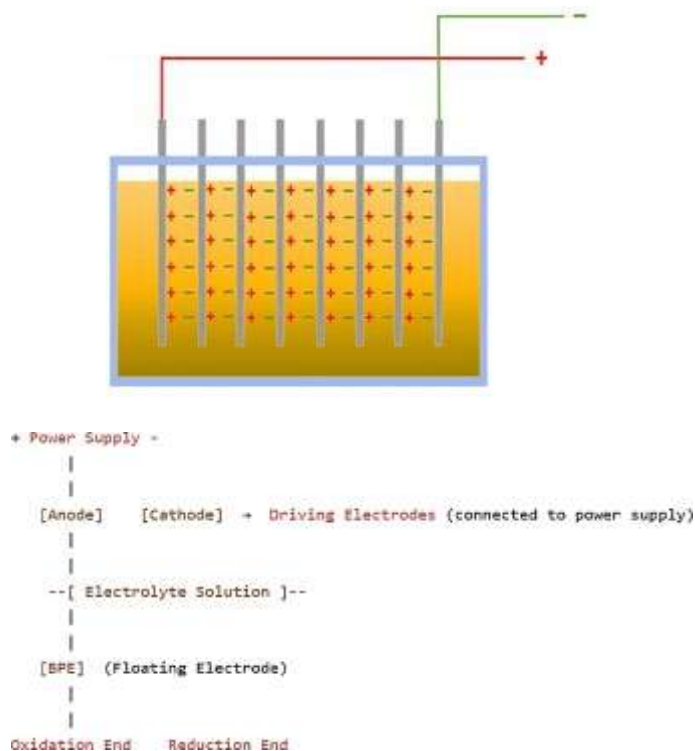


Figure 2 Bipolar Connection.

The driving electrodes are connected with the DC power supply, the left side of the electrodes is the anode (+) and the right side of the electrodes is the cathode (-). The Bipolar Electrode (BPE) is a strip of a conductor, such as aluminum or steel, which is used in between the anode and cathode. Even on one end BPE is anode (oxidation) and the other end of BPE is cathode (reduction). The electrolyte solution allows the ions to move to complete the circuit.

3.6 Lab Setup Description

In the laboratory, 2.5 liters of filtered sludge were placed into the reaction container and stirred using two stir magnets. Four aluminum or steel plates were washed with hydrochloric acid (HCL) and distilled water, then placed in the container to function as electrodes. The first plate was connected to the anode and the last one to the cathode. The rpm was set to 200, and the voltage was varied every two hours. Voltages of 6, 8, and 12 were used in the experiment. A sample was taken for testing every 2 hours, and the process parameters were adjusted accordingly. Figure 3 shows the experimental setup, including the container, stir magnets, and electrodes. This setup illustrates the process for removing microplastics using electrocoagulation.



Figure 3 Electrocoagulation Setup Using Sludge Sample

3.7 Description and Composition of Microfiber

Microfibers are synthetic or natural fibers that are primarily used in textiles. These fibers are small, non-biodegradable, and present significant environmental challenges. The composition of microfiber typically includes polymer anisole and polyamide. The production of microfibers involves the extrusion of polymer threads through specialized fine meshes, resulting in fibers that are much smaller than traditional fibers. Microfibers are widely used in cleaning cloths, clothing, and sports equipment due to their durability and ability to dry quickly. Overview of apparatus used for physicochemical analysis is shown in Table 2. Each parameter is measured with specific instruments in order to measure the water and sludge samples accurately..

Table 2 Physico-Chemical Analysis Parameters and Apparatus Used

SL. No	Test Name	Apparatus
1	pH	pH paper, pH meter, Universal indicator, glass beaker, buffer tablet, etc.
2	Electrical conductivity	EC Meter with measuring cell, beaker
3	Total dissolved solids (TDS)	China dish, Muffle furnace, hot air oven, balance, filter paper, conical flask
4	Dissolved oxygen	BOD bottle of 300ml capacity
5	Microfiber	DC power supply, Electrodes, plates, magnetic stirrer, Electrocoagulation tank
6	Turbidity	Turbidimeter/Nephelometer
7	Colour	Spectrophotometer
8	Temperature	Thermometer

Figure 4 presents the experimental setup for testing the microfibers removal including the placement of electrodes and the washing machine sample for analysis.



Figure 4 Setup Arrangement with Washing Machine Sample and Electrodes

4. Results and Discussion

4.1 Test Results of Physicochemical Method (Laundry Sample)

Experimental tests on the laundry wastewater samples with electrocoagulation demonstrated the significant variations of different parameters with time. Results in Table 3 show that the improvements in pH, electrical conductivity and turbidity after treatment were achieved by using the bipolar electrodes (two steel plates and two aluminium plates) for 1 hour. Specifically, the pH dropped from 8.30 to 7.21, and electrical conductivity was reduced albeit slightly in all of the voltage settings. The most significant outcomes were found at 12V, showing the effectiveness of the higher voltage settings.

Table 3 Bipolar (2-Steel & 2-Aluminium Plates) – 1 Hour Duration

SI	Parameters	Units	Initial	6V	8V	12V	Permissible Limit
1	pH	--	8.30	8.04	7.69	7.21	6.5-8.5
2	Electrical conductivity	$\mu\text{mhos/cm}$ or US/cm	1480.0	1472	1464	1457	0-1500
3	Total dissolved solids (TDS)	Mg/L	8.07	773	711	654	500-2000
4	Dissolved oxygen	Mg/L	5.9	7.0	8.2	9.1	6.5-8
5	Microfiber	Mg/L	374	370	365	363	-
6	Turbidity	NTU	253	250	244	239	500
7	Colour	Hazen unit 0	4.0	3.5	3.0	2.5	5
8	Temperature	$^{\circ}\text{C}$	21.0	32.0	40.0	46.0	-

Further subsequent observations on 2-hour and 3-hours treatment indicated the reductions in turbidity and increases in dissolved oxygen (DO) concentrations and a decrease in microplastic load. The pH was changed to 6.63, which further increased the removal efficiency. The TDS and DO levels were decreased and improved, respectively, which proved the efficacy of electrocoagulation in diminishing contaminants. These results are also confirmed by the degree of degradation for TDS was nearly 33.42%, which shows the potential of electrocoagulation for wastewater treatment.

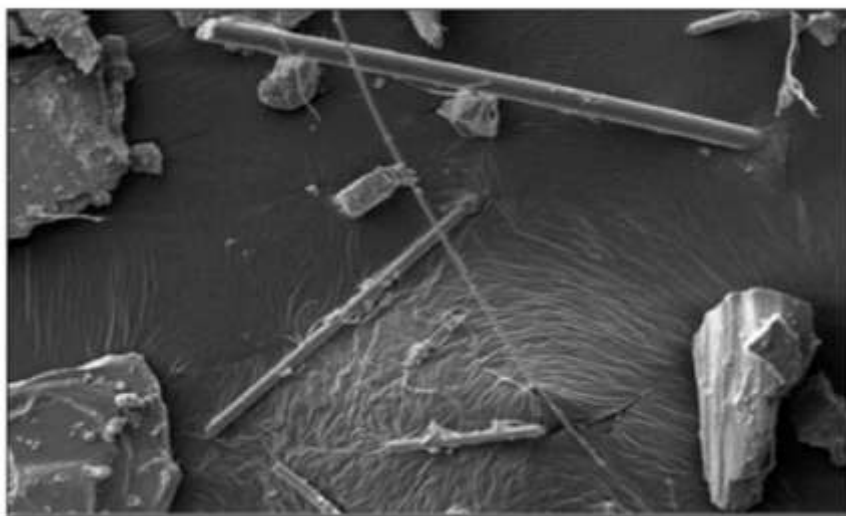


Figure 5. SEM Analysis of Microfibers Before Treatment

High-resolution SEM image displaying synthetic microfibers with characteristic

elongated morphology. The fibers show smooth surfaces typical of polyester/nylon materials, with visible particulate contamination. Individual fibers range from 10-50 μm in length, demonstrating the microscopic nature of textile pollution in wastewater samples.

4.2 Test results of Physicochemical method (Washing machine sample)

The electrocoagulation technique was also found effective in the reduction of different parameters of the wastewater from washing machine as presented in Table 4 for the period of 1 hour. The pH of the sample was reduced from 8.05 to 6.65 under different voltage conditions (6V, 8V, 12V). The change in the pH value is a reflection of the improved removal efficiency at the highest voltage (12V) where there is also a reduction in conductivity, indicating removal of more particles out of the wastewater.

Table 4 Bi-Polar (2 Steel & 2 Aluminium Plates) – 1 Hour Duration (Washing Machine Sample)

SL. No	Parameters	Units	Initial	6V	8V	12V	Permissible limit
1	pH	--	8.05	7.90	7.41	6.65	6.5-8.5
2	Electrical Conductivity	$\mu\text{mhos/cm}$ or $\mu\text{S/cm}$	1440	1432	1429	1405	0-1500
3	Total Dissolved Solids (TDS)	Mg/L	802	776	659	599	500-2000
4	Dissolved Oxygen (DO)	Mg/L	5.5	5.8	7.0	8.2	6.5-8
5	Microfiber	Mg/L	356	350	345	309	-
6	Turbidity	NTU	203	200	194	182	500
7	Colour	Hazen Units	3.7	3.0	1.8	1.1	5
8	Temperature	$^{\circ}\text{C}$	21.0	32.0	40.0	46.0	-

Additionally, significant removal of microfiber content was observed especially in the presence of higher voltages (8V and 12V). The concentration of microfiber was reduced from an initial microfiber concentration of 356 mg/L to 309 mg/L under optimal conditions, which again demonstrated the efficacy of electrocoagulation for the removal of microfibers.

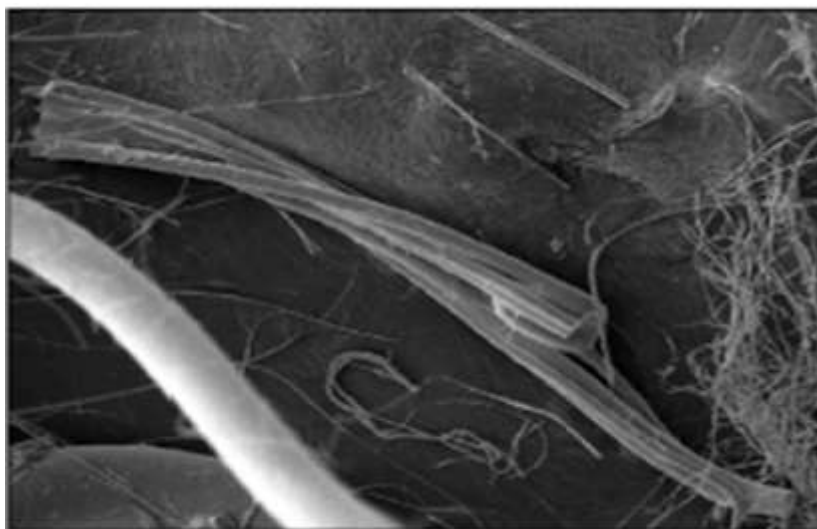


Figure 6. Microfibers and Debris After Electrocoagulation Treatment

SEM image illustrating microfibers post-electrocoagulation at 12V for 3 hours using bipolar electrode configuration. The image shows fragmented fibers with coagulated particles adhered to fiber surfaces, indicating the physical entrapment mechanism. Surface modifications and partial degradation are evident, with reduced fiber integrity compared to untreated samples.

4.3 Results of Testing of Biological Method

The biological process was applied to laundry wastewater with the composition shown in Table 5 and 6, where the initial values for microfiber (394 mg/L), pH (8.30) and turbidity (253 NTU) were treated over 5 days, resulting in microfiber (346 mg/L), pH (7.5) and turbidity (217 NTU). The results show that the microfiber content and turbidity decreased after biological treatment for 5 days. These results show that biological treatment has a role in microfiber degradation but the degradation is slower than the electrocoagulation process.

Table 5 Initial Test of Sludge

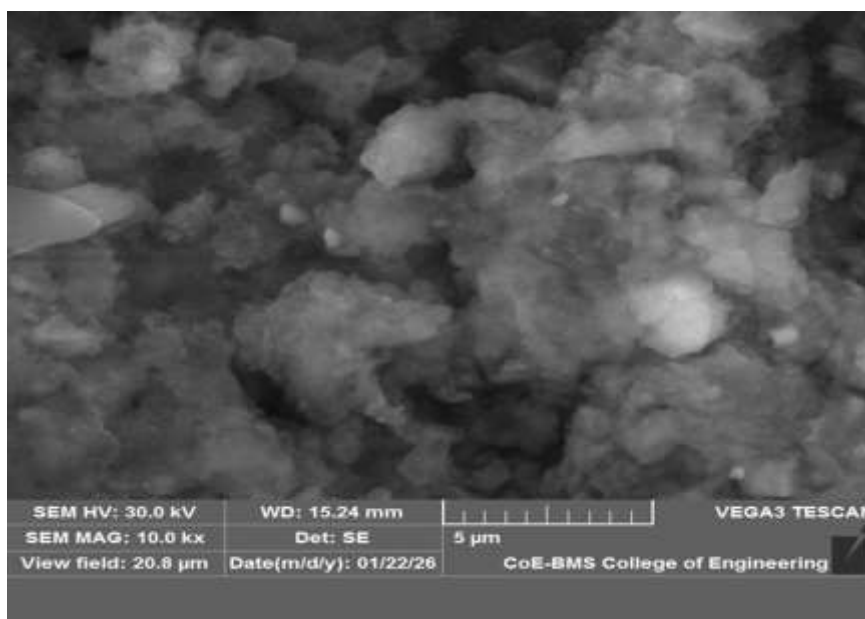
SL. No	Parameters	Units	Results	Permissible limit
1	pH	--	8.30	6.5-8.5
2	Electrical conductivity	$\mu\text{mhos/cm}$ or $\mu\text{S/cm}$	1480	0-1500
3	Total dissolved solids (TDS)	Mg/L	944	500-2000
4	Dissolved oxygen	Mg/L	6.7	6.5-8
5	Microfiber	Mg/L	394	-

6	Turbidity	NTU	253	500
7	Colour	Hazen unit 0	4.0	5
8	Temperature	°C	21.0	-

Table 6 Test of Sludge After 5 Days

SL. No	Parameters	Units	Results	Permissible limit
1	pH	--	7.5	6.5-8.5
2	Electrical conductivity	μmhos/cm or μS/cm	1307	0-1500
3	Total dissolved solids (TDS)	Mg/L	712	500-2000
4	Dissolved oxygen	Mg/L	5.6	6.5-8
5	Microfiber	Mg/L	346	-
6	Turbidity	NTU	217	500
7	Colour	Hazen unit 0	3.0	5
8	Temperature	°C	26.0	-

The effectiveness of the biological degradation showing the decreases in DO, TDS, and microfibers. The microfiber degradation efficiency was 42.63%, which is a great progress for the biological processes for microfiber treatment, but still lower than the electrocoagulation.

**Figure 7. Microplastic Particles Post-Biological Treatment (5 Days)**

SEM micrograph (15.0 kx magnification) revealing microplastic particles after anaerobic

digestion treatment. The image demonstrates surface erosion, microbial colonization patterns, and partial biodegradation of organic contaminants. Scale bar: 2 μm . The roughened surfaces indicate microbial activity by sulfate-reducing bacteria and methanogenic consortia.

4.4 Graphical Presentation of Degradation Efficiency

Figure 5 is a graphical representation that provide a better insight of the impact of the electrocoagulation treatment on the laundry wastewater parameters of pH, conductivity, turbidity, and microfiber content at various treatment times. It shows the changes in pH, electrical conductivity, turbidity and microfiber content in time (1hr, 2hr and 3hr) using three electrocoagulation methods: Bipolar (2-Steel & 2-Aluminium Plates), Four steel plates and Four aluminium plates. The data points also contain Initial and 12V conditions to offer a comprehensive view of the performance with time.

The results depict a consistent trend of a decreasing of pH, electrical conductivity, turbidity and microfibers content with Bipolar (2-Steel & 2-Aluminium) generally showing the most important degradation for all parameters. The data show the effectiveness of electrocoagulation in water quality improvement with longer treatment times resulting in better removal of contaminants.

The electrocoagulation process showed better results than the biological process in the removal of microfibers and other contaminants from wastewater slurry streams. Electrocoagulation at higher voltages and longer treatment times improved the target parameters (turbidity, pH and microfiber removal), in particular. Although the biological treatment was comparatively slow, it proved effective over the course of 5 days, increasing the level of DO and removing organic contaminants. Such a combination of both methods would therefore provide a more sustainable and efficient wastewater treatment system for microfibers.

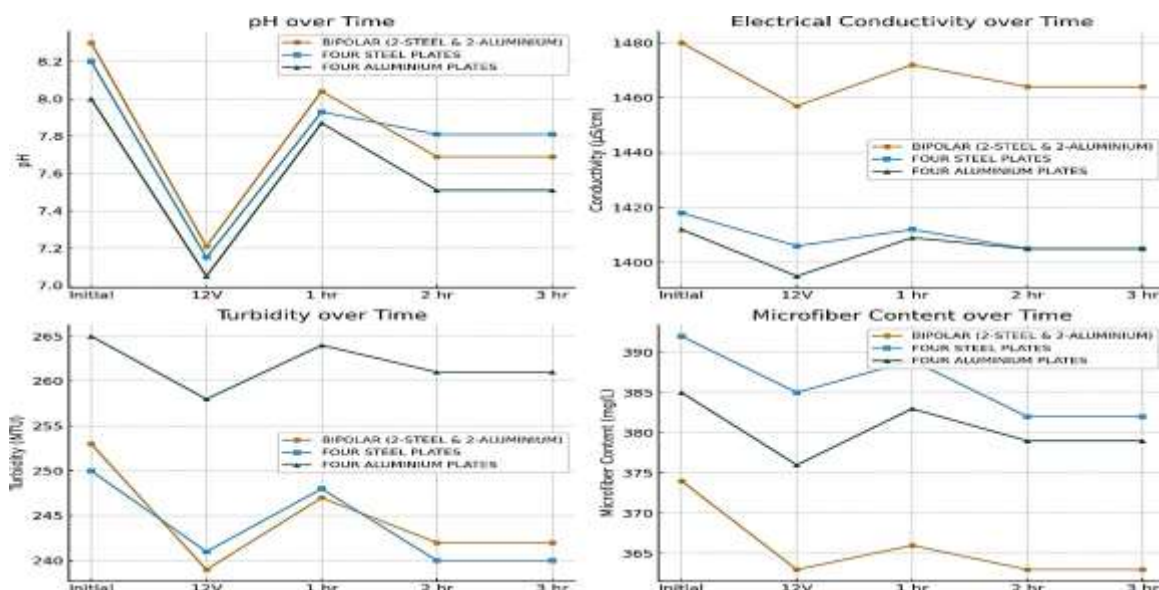


Figure 5 Degradation Efficiency of pH, Electrical Conductivity, Turbidity, and Microfiber Content across Time and Electrocoagulation Methods

4.5 Future Recommendations

Treatment Parameter Optimization: Further research should focus on further optimizing the treatment parameters for both electrocoagulation and biological methods to maximize efficiency and minimize operational costs. Tailoring of these parameters according to the type of wastewater and desired results could greatly improve the treatment performance.

- **Long-Term Performance Study:** Performing a long-term performance study will help to determine the stability and reliability of the electrocoagulation and biological methods. This will yield useful information about the longevity and effectiveness of these treatments in practical use.
- **Comparison with Other Treatment Procedures:** Comparison of electrocoagulation and biological methods with other advanced treatment procedures such as membrane filtration, advanced oxidation processes, etc. is required in order to find the most efficient and cost-effective solution to microfibers removal from wastewater.
- **Scale-Up for Industrial Applications:** To bridge the gap between laboratory-scale experiments and industrial applications, future studies should investigate the possibility of scaling up the electrocoagulation process for industrial applications. This would include optimizing energy use and minimizing operational costs with the same or higher degradation efficiency.

5. Conclusion

The electrocoagulation method for wastewater treatment, especially microfibers removal, demonstrated a better degradation effect in the bipolar connection compared to

the four aluminium plate connection. Specifically, the bipolar connection showed degradation efficiency of 7.85% at 3 hours duration and 12V; the four aluminium plate connection showed slightly lower degradation efficiency of 6.08%. This method proves to be cost-effective in order to remove microfibers, however, energy consumption and operating costs must be optimized for use on a large scale implementation. In comparison, the biological degradation efficiency reached 42.63%, which is better than the electrocoagulation method. However, the biological processes are more time-consuming, which restricts their immediate use when compared with the electrocoagulation method. Hence, electrocoagulation using steel and aluminium plates is a possible and scalable solution to microfibers removal from wastewater.

Conflict of Interest Statement

The authors declare that they have no conflicts of interest regarding the publication of this manuscript.

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Ethics Approval

This study did not involve human or animal subjects

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