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Taguchi-Based Optimization of Ultrasound-Assisted Electrocoagulation Use of Aluminum Electrodes for Laundry Wastewater Treatment

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Abstract: *Sono-electrocoagulation (SEC) has emerged as an effective and eco-friendly hybrid process for the treatment of laundry wastewater containing surfactants and microfibers. In this research, the Taguchi experimental design (L9 orthogonal array) was employed to optimize the operating parameters of the SEC process using aluminum electrodes. The factors investigated were electrocoagulation time (10, 20, and 30 min) and electrode distance (2, 3, and 4 cm). The response variables considered were the percentage removal of surfactants and microfibers, analyzed using the larger-is-better signal-to-noise ratio criterion. The results demonstrated that the sono-electrocoagulation process significantly reduced the concentration of pollutants. The surfactant concentration decreased from 3.46 mg/L to 0.334 mg/L, while the microfiber weight decreased from 0.096 g to 0.011 g. The Taguchi optimization revealed that the optimum operating condition occurred at an electrocoagulation time of 30 minutes and an electrode distance of 3 cm, achieving 90.35% surfactant removal and 88.54% microfiber removal. Based on the analysis of variance, the most influential factor on pollutant removal efficiency was electrode distance, followed by electrocoagulation time. This research highlights the potential of the Taguchi-based optimization approach to improve sono-electrocoagulation performance in laundry wastewater treatment, demonstrating its ability to effectively eliminate both chemical and physical pollutants.*

Keywords: *Aluminum Electrode, Laundry Wastewater, Microfiber, Sono-Electrocoagulation, Taguchi*

INTRODUCTION

The laundry industry in Indonesia has experienced rapid growth recently, driven by the increasing urban lifestyle and demand for convenient washing services. The Indonesian Laundry Association (ASLI, 2024) report that the laundry business has grown by about 10–15% each year, and there are now more than 20,000 service units across the country. While this development contributes positively to employment and the economy, it also generates environmental challenges due to the discharge of untreated wastewater.

Laundry wastewater typically contains surfactants and microfiber-type microplastics originating from synthetic textiles (Fontana et al., 2020). These pollutants pose ecological and health risks, including oxidative stress, inflammation, genotoxicity, and cellular necrosis (Liu et al., 2024). Despite these risks, there are still no established regulatory standards in Indonesia for permissible microfiber concentrations in laundry wastewater.

Several conventional treatment methods such as membrane filtration, coagulation flocculation, adsorption, and advanced oxidation processes have been explored to remove surfactants and microfibers from wastewater (Lapointe et al., 2020; Easton et al., 2022; Atesci & Inan, 2023; Luu et al., 2025; Wulandari et al., 2023). However, these technologies often face challenges such as high energy demand, limited efficiency for nanoscale fibres, or the generation of toxic sludge. Therefore, a more sustainable and efficient treatment method is required to address the increasing pollution from laundry wastewater.

The sono-electrocoagulation (SEC) process represents an emerging hybrid technology that combines ultrasonic cavitation and electrocoagulation to enhance pollutant removal. Ultrasonic waves promote particle dispersion and mass transfer, while electrocoagulation generates coagulant species that destabilize suspended contaminants. Aluminum electrodes have gained attention due to their low cost, high electrochemical efficiency, and ability to form aluminum hydroxide flocs that effectively adsorb and entrap surfactants and microfibers (Ghadami et al., 2024).

Although previous studies have reported the individual benefits of electrocoagulation and sonochemical processes, limited research has explored their hybrid application using aluminum electrodes specifically for the simultaneous removal of surfactants and microfibers from real laundry wastewater. Earlier work focused on synthetic wastewater or single-pollutant systems, leaving a gap in understanding how hybrid SEC performs in complex effluents containing both chemical and physical contaminants.

This research aims to evaluate and optimize the sono-electrocoagulation process using aluminum electrodes for the removal of surfactants and microfibers from laundry wastewater through the Taguchi design method (L9 orthogonal array). The optimization focuses on key parameters such as electrolysis time, electric current, and electrode distance, analyzed using the larger-is-better signal-to-noise (S/N) ratio criterion.

RESEARCH METHODS

Materials and Tools

The materials used in this study were laundry wastewater, Linear Alkylbenzene Sulfonate (LAS) powder, phenolphthalein indicator (PP), isopropyl alcohol, aquadest, methylene blue (MB), chloroform p.a., sodium hydroxide (NaOH), and sulfuric acid (H_2SO_4). All chemicals used were of analytical grade and supplied by Merck company, except aquadest. The experimental setup consisted of a 2 L ultrasonic reactor equipped with an ultrasonic generator operating at 28 kHz and a DC power supply. Aluminum plate electrodes were used as anode and cathode, respectively. Additional instruments included a UV-Vis spectrophotometer, digital balance, pH meter, vacuum filtration unit with 0.45 μm and 13 μm filter papers, Buchner funnel, oven, and standard laboratory glassware (beaker glass, measuring cylinder, and pipette). A stopwatch and automatic titrator were also utilized to support the sono-electrocoagulation and analytical processes.

Methods

This study consisted of two main stages: the sono-electrocoagulation process and the analysis of pollutant removal efficiency.

***Stage* 1.** Sono-Electrocoagulation Process

The sono-electrocoagulation experiments were carried out in a 2 L electrochemical reactor equipped with a 28 kHz ultrasonic generator and a DC power supply, as illustrated in Figure 1. Aluminum plates were used as both the anode and cathode. Laundry wastewater containing Linear Alkylbenzene Sulfonate (LAS) and microfibers was introduced into the reactor while, the electrodes were connected to the power supply and the ultrasonic generator was activated simultaneously to promote cavitation and enhance mass transfer.

The operating parameters were selected according to the Taguchi L9 orthogonal array design, which included reaction time, electric current and electrode distance. After each experimental run, the treated samples were filtered and collected for pollutant analysis. The synergistic combination of ultrasonic cavitation and electrochemical oxidation in this system enhances the dissolution of the aluminum anode, thereby improving the formation of $Al(OH)_3$ flocs as active coagulants (Hussein et al., 2024; Mohd et al., 2024).

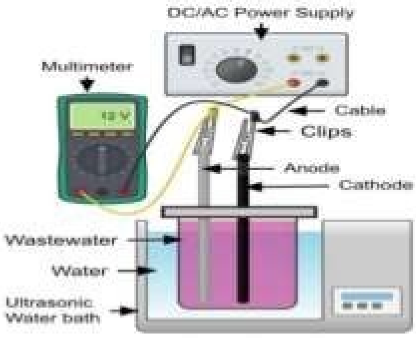


Figure 1. Hybrid sono-electrocoagulation technology (Asaithambi et al., 2024)

***Stage* 2.** Pollutant Removal Analysis

In this study, the process parameters investigated were electrode distance (2, 3, and 4 cm), reaction time (10, 20, and 30 min), and electric current (1, 2, and 3 A) using aluminum electrodes as both anode and cathode. A 1 L sample of laundry wastewater was placed in the sono-electrocoagulation reactor. After each run, treated samples were analyzed for both surfactant and microfiber concentrations.

The concentration of surfactants was determined spectrophotometrically using the Methylene Blue Active Substances (MBAS) method at a wavelength of 652 nm (SNI 06-6989.51-2005). The concentration of microfibers was determined gravimetrically by filtering the sample through 0.45 µm filter paper, drying the residue, and measuring the weight difference (Volgare et al., 2022). The pollutant removal efficiency for both surfactants and microfibers was expressed as a percentage reduction between initial and final concentrations. The removal efficiency of microfibers (% Removal of Microfibers) was calculated using Equation (1):

$$\%Removal = \frac{m_0 - m}{m_0} \times 100\%$$

Where m_0 is the initial mass of microfibers (mg), and m is the mass of microfibers remaining after treatment.

The removal efficiency of surfactants (% Removal of Surfactants) was calculated using equation (2):

$$\%Removal = \frac{C_0 - C}{C_0} \times 100\%$$

Where C_0 is the initial concentration of surfactants (mg/L), and C is the concentration after treatment.

Both parameters were then analyzed together to evaluate the overall effectiveness of the aluminum-based sono-electrocoagulation process in removing pollutants from laundry wastewater.

Optimization

The Taguchi method utilizes the signal-to-noise ratio (S/N ratio) to determine the quality characteristics of a process. The S/N ratio is a logarithmic function of the desired output and is used as an objective function for data analysis and process optimization. It measures the deviation of quality characteristics from the target value, where the signal represents the desired percentage of pollutant removal, and the noise represents the undesirable variation or standard deviation in the response. In this study, the "larger-the-better" quality characteristic was selected to maximize the percentage removal of surfactants and microfibers. The S/N ratio for the larger-the-better criterion is calculated using the following equation:

$$SNR = -log\left(\frac{1}{n}\sum_{1}^{n}\frac{1}{y_i^2}\right)$$

The calculation results of the highest percentage removal of surfactants and microfibers using the Al electrode are presented in Table 1.

Table 1. Experimental Data for Surfactant and Microfiber Removal

Time Electric Current (min)		**Electrode Distance**	**Surfactant Removal**	**Microfiber Removal**	**S/N Ratio**
	(A)	(cm)	(%)	(%)	(dB)
10	1	2	98.82	55.21	36.67
10	2	3	99.25	54.17	36.55
10	3	4	81.82	79.17	38.11
20	1	3	97.60	68.75	38.01
20	2	4	97.05	43.75	35.03
20	3	2	97.92	69.79	38.10
30	1	4	97.49	72.92	38.34
10	1	2	98.82	55.21	36.67
10	2	3	99.25	54.17	36.55

Characterization of Treated Wastewater

The characterization of the treated wastewater was conducted to evaluate the removal performance of the sono-electrocoagulation process. The concentration of surfactants was analyzed using the Methylene Blue Active Substances (MBAS) method, which determines the residual amount of anionic surfactants in the sample through the formation of a blue ion-pair complex measured spectrophotometrically at 652 nm.

To identify the presence and potential degradation of surfactant functional groups and microfibers after treatment, Fourier Transform Infrared Spectroscopy (FTIR) analysis was performed. The FTIR spectra were used to observe changes in characteristic absorption peaks, indicating chemical bond alterations associated with the removal or breakdown of surfactant compounds and organic fibers.

In addition, the amount of remaining microfibers in the wastewater was determined gravimetrically by filtering the sample through a 0.45 µm filter paper, drying the residue at 105 °C, and measuring its mass difference before and after treatment. This analysis provided quantitative information on the effectiveness of microfiber removal during the sono-electrocoagulation process.

RESULTS AND DISCUSSION

Taguchi Optimization

This study has successfully evaluated the effectiveness of the hybrid sono-electrocoagulation method in removing surfactants and microplastics pollutants using the Taguchi experimental design approach. A Taguchi design matrix was used to vary three process parameters at three different levels: electrode distance, electric current, and electrolysis time. Table 1 displays the experimental data for the removal efficiencies of microfibers and surfactants. The S/N ratio was computed using the "larger-the-better" criterion. The signal power to noise power ratio, or S/N ratio, verifies the process variable's fluctuation. Table 2 provides the S/N ratio response table for the removal of surfactants and microfibers.

Table 2. Response to Average Signal to Noise

Level	Time	Electric Current	Electrode Distance
1	36.68	37.61	36.03
2	37.31	36.99	37.93
3	38.1	37.49	38.14
Delta	1.41	0.62	2.11
Rank	2	3	1

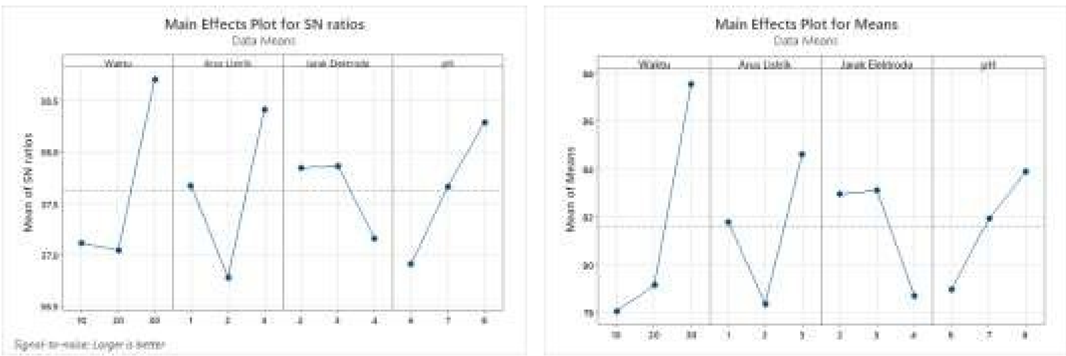
Table 3. Response for Average of Aluminum Electrode

Level	Time	Electric Current	Electrode Distance
1	78.07	81.8	82.96
2	79.14	78.37	83.11
3	87.55	84.6	78.7
Delta	9.48	6.23	4.41
Rank	1	2	3

According to Table 2, the most influential factor was electrode distance (Δ = 2.11, Rank 1), followed by reaction time (Δ = 1.41) and electric current (Δ = 0.62). Electrode distance strongly affects ion mobility and floc formation; an optimal distance allows uniform current distribution and effective generation of Al^{3+} ions that form $Al(OH)_3$ flocs, which enhance pollutant adsorption.

As shown in Table 3, and the main effects plot, the highest removal efficiencies were achieved at a reaction time of 30 minutes, a current of 3 A, and an electrode distance of 3 cm, resulting in 90.35% surfactant removal and 88.54% microfiber removal. Longer reaction times increased anodic dissolution, while higher current accelerated Al^{3+} generation and improved mixing.

The S/N ratio response trends are further illustrated by the main effect plots of average response and S/N ratio in Figure 2(a) and Figure 2(b), which confirm the dominance of electrode distance and reaction time in determining the overall process performance.



(a) *(b)*

Figure 2. (a) Yield average response graph, (b) SNR average response graph

Overall, the Taguchi analysis confirmed that electrode distance and reaction time were the dominant factors influencing sono-electrocoagulation efficiency. The optimized conditions produced high and stable pollutant removal, demonstrating the effectiveness of aluminum electrodes for combined surfactant and microfiber removal.

In the analysis of variance (ANOVA), the F-value and P-value play a crucial role in determining the validity of the experimental findings. The relationship between the F-value and the P-value is an inverse one used to determine the significance of a research parameter. If the F-value is sufficiently large (exceeding the critical value in the F-distribution table), the P-value will typically fall below the alpha threshold (generally 0.05), indicating that the factor is statistically significant.

Table 4. ANOVA Test Results for SNR Values

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Time	2	2.1118	31.04%	2.1118	1.0559	0.59	0.628
Electric	2	0.7497	11.02%	0.7497	0.3749	0.21	0.826
Electrode Distance	2	0.3811	5.60%	0.3811	0.1905	0.11	0.903
Error	2	3.5608	52.34%	3.5608	1.7804		
Total	8	6.8035	100.00%				

Table 5. Experimental Design Accuracy Value

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
513.842	95.88%	83.50%	1069.34	16.48%	*	59.04

Table 6. Average Response of Aluminum Electrode

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	67.94	3.98	(50.81, 85.07)	17.07	3	
			Time (A)			
10	-5.09	5.63	(-29.32, 19.13)	-0.90	461	1.33
20	-7.18	5.63	(-31.40, 17.05)	-1.27	331	1.33
30	12.27	5.63	(-11.95, 36.49)	2.18	161	*
			Electric Current (B)			
1	-2.31	5.63	(-26.54, 21.91)	-0.41	721	1.33
2	-8.91	5.63	(-33.14, 15.31)	-1.58	254	1.33
3	11.23	5.63	(-13.00, 35.45)	1.99	184	*
			Electrode Distance (C)			
2	0.12	5.63	(-24.11, 24.34)	0.02	985	1.33
3	2.55	5.63	(-21.68, 26.77)	0.45	695	1.33
4	-2.66	5.63	(-26.89, 21.56)	-0.47	683	*

Based on Table 4, the total variation in the S/N ratio response was 6.8035. The largest contribution was derived from reaction time (31.04%), followed by electric current (11.02%) and electrode distance (5.60%). Although the F-value of the reaction time factor (0.59) was below the statistical significance threshold ($P > 0.05$), it still represented the most influential parameter affecting the system's stability and pollutant removal efficiency. This finding aligns with Praful et al. (2025), who emphasized that reaction time significantly influences coagulant formation and pollutant interaction in electrocoagulation systems optimized by the Taguchi method.

The high R^2 value (95.88%) indicated that the developed regression model explained approximately 95% of the total response variation, confirming excellent model fitness. However, the lower adjusted R^2 (83.50%) and predicted R^2 (16.48%) values suggested limited predictive capability, mainly due to the relatively small number of experimental runs (Taguchi L9 design). The AICc value of 59.04 and PRESS value of 1069.34 further indicated that the model remained statistically efficient and acceptable for laboratory scale analysis.

Based on Table 5, the obtained R-Sq value was 95.88%, indicating that the results are statistically acceptable. The coefficient of determination (R^2) represents the correlation between the dependent and independent variables. A smaller R^2 value indicates a weaker relationship between these variables, whereas an R^2 value closer to 1 suggests a stronger influence of the independent variables on the dependent variable.

According to Table 6, the regression model equation for the optimum response of the aluminum electrode was obtained as follows:

$$Removal\ (\%) = 67.94 - 5.09A_1 - 7.18A_2 + 12.27A_3 - 2.31B_1 - 8.91B_2 + 11.23B_3 - 0.12C_1 + 2.55C_2 - 2.66C_3$$

Overall, both the ANOVA and regression results confirmed that reaction time and electrode distance were the dominant parameters influencing the sono-electrocoagulation performance using aluminum electrodes. Longer electrolysis time enhanced the generation of Al^{3+} ions and subsequent formation of $Al(OH)_3$ flocs, improving pollutant removal through adsorption and entrapment mechanisms, as also reported by recent optimization studies (Praful et al., 2025).

Under the optimal conditions reaction time of 30 minutes, current of 3 A, and electrode distance of 3 cm the process achieved high removal efficiencies for both surfactant and microfiber pollutants. These results demonstrate that the aluminum-based sono-electrocoagulation system provides stable and effective pollutant removal performance when properly optimized.

Characterization of Treated Wastewater

Fourier Transform Infrared (FTIR)

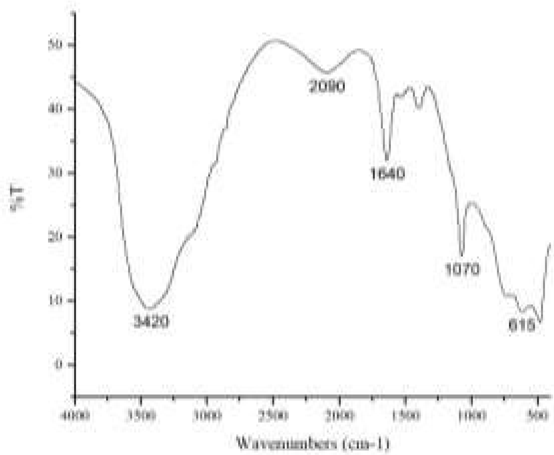


Figure 3. FTIR analysis

Based on Figure 3, FTIR analysis was performed to identify the functional groups formed on the aluminum electrode surface after the sono-electrocoagulation process. The

FTIR spectrum exhibits several significant absorption peaks at 3424.76 cm^{-1}, 2985.20 cm^{-1}, 1638.48 cm^{-1}, 1530.86 cm^{-1}, 1403.44 cm^{-1}, and 1071.86 cm^{-1}.

The broad absorption band at 3424.76 cm^{-1} corresponds to the stretching vibration of hydroxyl (–OH) groups, which may originate from adsorbed water molecules or the formation of aluminum hydroxide (Al–OH) during electrocoagulation. This result is consistent with the findings of Al-Busafi and Al-Shafouri (2021), who reported similar – OH stretching peaks in Al-based coagulant materials.

The peak observed at 2985.20 cm^{-1} is attributed to C–H stretching vibrations, indicating the presence of residual organic matter that may have interacted with the aluminum surface during pollutant removal. Strong bands at 1638.48 cm^{-1} and 1530.86 cm^{-1} are associated with C=O stretching vibrations of carboxylate groups ($–COO^-$), suggesting that organic surfactant molecules were successfully bound to the aluminum hydroxide flocs. This finding supports previous studies by Hussein et al. (2024) and Rahman et al. (2022), which reported the formation of metal–organic complexes between Al^{3+} and carboxylate species in electrocoagulation sludge.

Meanwhile, the absorption band at 1071.86 cm^{-1} corresponds to Al–O stretching vibrations, characteristic of aluminum oxide or hydroxide species that act as primary coagulant agents. Similar Al–O peaks were also observed by Al-Busafi and Al-Shafouri (2021) and Rahman et al. (2022), confirming the generation of $Al(OH)_3$ and Al–O–Al networks as active flocculating components. The peaks at 794.79 cm^{-1} and 615.94 cm^{-1} further indicate the presence of Al–O–Al bonding, confirming the formation of polymeric aluminum hydroxide species ($Al_2O_3 \cdot xH_2O$), which enhance pollutant removal efficiency.

These results are consistent with recent findings by Mohd et al. (2024), who reported similar FTIR profiles in aluminum-based electrocoagulation for greywater treatment, showing strong O–H and Al–O absorptions between 3400–600 cm^{-1}. The presence of C– H and C=O functional groups also suggests adsorption of organic surfactants onto $Al(OH)_3$ flocs, as noted by Prasetyo et al. (2023) in their study of surfactant removal via Al–graphite electrodes.

Therefore, the FTIR analysis confirms that the sono-electrocoagulation process with aluminum electrodes not only produces $Al(OH)_3$ as an active coagulant but also facilitates the chemical interaction between Al^{3+} species and organic pollutants through the formation of –COOH and C=O groups. This indicates that pollutant removal occurs through both adsorption and complexation mechanisms, consistent with the reported mechanisms of Al-based electrocoagulation systems (Hussein et al., 2024; Rahman et al., 2022).

Methylene Blue Active Substance

The MBAS (Methylene Blue Active Substances) analysis was conducted to determine the concentration of anionic surfactants in the wastewater before and after the sono-electrocoagulation process using aluminum electrodes. The results are presented in Table 7.

Table 7. Result MBAS Analysis

Parameters	Identification of Sample	Unit	Result	Method
MBAS	Blanko	mg/L	3.26	SNI 06-6989.51-2005
MBAS	Sample Al (1)	mg/L	0.3	SNI 06-6989.51-2006
MBAS	Sample Al (2)	mg/L	0.24	SNI 06-6989.51-2007

The blank sample exhibited an initial MBAS concentration of 3.26 mg/L, representing the surfactant level prior to treatment. After the sono-electrocoagulation process, a substantial reduction was observed, with Sample Al (1) showing 0.30 mg/L and Sample Al (2) showing 0.24 mg/L. This indicates a removal efficiency exceeding 90%, demonstrating the high capability of aluminum electrodes in removing surfactants from laundry wastewater.

This removal efficiency can be attributed to the formation of amorphous aluminum hydroxide species ($Al(OH)_3$) that act as active coagulants, adsorbing and destabilizing anionic surfactant micelles through charge neutralization and bridging mechanisms. The introduction of ultrasonic waves further enhances the efficiency by promoting microbubble cavitation, which increases mass transfer and produces finer coagulant flocs with larger reactive surfaces.

According to Rahman et al. (2022) and Mohd et al. (2024), aluminum-based electrocoagulation is highly effective for removing anionic surfactants due to electrostatic attraction between the positively charged Al^{3+} ions and negatively charged sulfonate groups ($-SO_3^-$) in the surfactant molecules. Moreover, Hussein et al. (2024) reported that the presence of ultrasonic energy in hybrid electrocoagulation systems accelerates floc formation and improves surfactant degradation through localized oxidation.

The final MBAS concentrations obtained in this study (0.24–0.30 mg/L) comply with the discharge standards for domestic wastewater (below 1 mg/L, based on SNI 06- 6989.51-2005). These results align with findings by Prasetyo et al. (2023), who achieved over 90% LAS (Linear Alkylbenzene Sulfonate) removal using Al/graphite electrodes. Similarly, Iskandar et al. (2021) observed significant MBAS reduction through aluminum electrocoagulation, confirming that $Al(OH)_3$ flocs provide excellent adsorption sites for surfactant molecules.

Therefore, the MBAS analysis validates that the sono-electrocoagulation process using aluminum electrodes is highly effective for surfactant removal in laundry wastewater, combining both chemical coagulation and physical enhancement from ultrasonic cavitation.

CONCLUSIONS

Based on the research results, the following conclusions can be drawn:

1. The sono-electrocoagulation (SEC) process using aluminum electrodes effectively removed surfactants and microfibers from laundry wastewater, achieving up to 90.35% and 88.54% removal, respectively, under optimal conditions of 30 minutes reaction time, 3 A electric current, and 3 cm electrode distance.
2. Characterization using FTIR and MBAS analyses confirmed the formation of aluminum hydroxide ($Al(OH)_3$) as an active coagulant and a significant reduction of surfactant concentration from 3.26 mg/L to 0.24 mg/L, indicating that removal occurred through adsorption and complexation mechanisms enhanced by ultrasonic cavitation.
3. This study demonstrates the potential of aluminum-based sono-electrocoagulation as a sustainable hybrid treatment method for greywater and laundry wastewater, and future work should focus on process scalability and energy optimization for practical industrial applications.

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