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Removal of total suspended solids from dairy wastewater using an electrocoagulation cell in the district of Ayaviri, Puno, Perú

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Abstract*– Effluents from dairy product processing often enter sewage systems untreated, leading to pollution issues such as foul odor emissions and wastewater overflow at treatment plants. In this study, we aimed to provide a technical solution for removing total suspended solids (TSS) from dairy wastewater using electrocoagulation. A factorial design experiment was conducted, and an optimum treatment condition of 35 minutes and a current density of 84.81 A/m² were determined, achieving a TSS removal efficiency of 94.11%. Our findings demonstrate the effectiveness of electrocoagulation in reducing TSS concentration in dairy wastewater, offering a viable treatment option for the district of Ayaviri, Puno, Peru.

***Keywords*-- Electrocoagulation, dairy wastewater, total suspended solids, effluents.**

I. Introduction

Water quality issues are a global concern, primarily driven by rapid population growth, economic expansion, and inadequate wastewater management practices. It is alarming that an estimated 90% of urban waste in developing nations is discharged directly into sewage systems, rivers, lakes, or oceans, posing significant health and environmental risks [45]. In Latin America, the impact is particularly severe on children, as only 14% of wastewater undergoes treatment [35].

In Peru, sanitation coverage extends to only 69.65% of urban areas, leaving a considerable portion of the population without access to adequate services [36]. The dairy industry, reliant on water for cheese production and associated processes, generates substantial volumes of wastewater, ranging from 0.2 to 10 liters per liter of processed milk [49]. This wastewater, essential for maintaining hygienic standards, undergoes various treatments such as sterilization, refrigeration, and pasteurization, accumulating physicochemical contaminants such as biochemical oxygen demand (BOD5), oils, fats, chemical oxygen demand (COD), suspended solids, and nutrients [23].

In the province of Melgar, specifically the Umachiri district, agricultural activities dominate, earning it the moniker "milk basin." With a population of approximately 25,921, the majority residing in rural areas, dairy production plays a significant role in the local economy [27]. However, the lack of adequate wastewater treatment infrastructure poses challenges in meeting discharge standards, attributed to constraints such as limited space, high capital costs, technical expertise, and operational expenses [26].

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The discharge of effluents from dairy operations into the sewer system has detrimental effects, notably impacting the CAISON pumping station, leading to sewage overflow and environmental contamination. This not only poses health risks to the population but also contributes to the spread of diseases and environmental degradation. In response, the Umachiri district municipality, through its environmental and basic sanitation office, has issued directives to dairy manufacturers, urging them to cease discharging wastewater directly into the sewer system. Legal consequences may ensue if compliance is not met, underscoring the seriousness of the situation.

Wastewater generated in the dairy industry:

The dairy industry generates significant volumes of wastewater as a byproduct of processing various dairy products such as cheese, yogurt, and butter. These processes result in the production of gaseous, solid, and liquid waste, with liquid waste being particularly problematic due to its elevated concentration of total suspended solids [45].

Whey, a prominent liquid residue from dairy processing, typically exhibits a neutral pH of 7. However, over time, the fermentation of milk sugars leads to the formation of lactic acid, causing the pH to decrease to the range of 4.5–5.0, a process occurring in anaerobic conditions. Additionally, the cleaning of machinery involved in dairy operations introduces further contaminants into the wastewater stream [16].

Electrocoagulation:

A venerable electrochemical technique dating back to 1906 in the United States, has undergone significant evolution and finds application across diverse fields. It represents a coagulation process devoid of external coagulants, thereby conferring distinct advantages. Through the application of electrical current, the anode generates coagulants that effectively encapsulate contaminant particles, facilitating the formation of large aggregates that are easily separable. Among the array of materials tested for this system, iron and aluminum emerge as recommended electrodes [34].

The principal benefits of electrocoagulation encompass a reduction in sludge volume and streamlined disposal practices. Flocs produced during the process exhibit enhanced binding properties with water, yielding a denser sludge requiring minimal disposal space. Consequently, operating costs are lowered, owing to the utilization of straightforward and user-friendly equipment [39].

Reactions involved in electrocoagulation:

The chemical reactions intrinsic to electrocoagulation, particularly employing iron and aluminum electrodes, are elucidated below. Extensive studies affirm the efficiency and cost-effectiveness of these materials, with aluminum, in particular, proving advantageous when utilized as the anode [40].

At the anode:

$$Al \rightarrow Al^{3} + 3e^{-}$$

$$Al^{+3}_{(ac)} + 3H_2O \rightarrow Al(OH)3_{(s)} + 3H^{+}_{(ac)}$$

$$nAl)OH)3 \rightarrow Al_n(OH)_{3N}$$

At the catode:

$$3H_2O + 3e^{-} \rightarrow 3H_2 + 3OH$$

(I) Design of an electrocoagulation cell [3], [6].

The electrochemical system: The power source

The adjustable power supply, equipped with a rectifier for alternating current to direct current conversion, incorporates an ammeter and voltmeter. These instruments are meticulously calibrated to the experimentation matrix, spanning from 0 to 30 V and 0 to 7 A. Such precise regulation facilitates an exhaustive exploration of the electrocoagulation process.

The electrochemical system: The cell

The characteristics of the electrochemical cell are contingent upon the composition of the liquid waste under treatment, as well as variables like electrode size, shape, and positioning [2]. While a rectangular geometry represents the most prevalent and straightforward configuration, the cell's shape can vary based on specific process objectives [3]. Fundamental components of these cells encompass distinct zones for the reaction, sedimentation, and flotation processes. Moreover, provision for an evacuation area is essential to streamline the analysis of total suspended solids [4].

The electrochemical system: The electrodes

Iron and aluminum emerge as the predominant materials utilized in the electrochemical process, serving as the anode and cathode, respectively, owing to their exemplary performance characteristics [5]. Notably, the sacrificial nature of the anode, which undergoes dissolution upon excitation, underscores its cost-effectiveness and ready availability [6].

II. MATERIALS AND METHODS

This research, rooted in applied science, endeavors to alleviate the organic burden in dairy wastewater through electrocoagulation, guided by a nuanced comprehension of specific variables such as current density and residence time, aimed at attaining quantitative outcomes. As elucidated by [30], the essence of applied research lies in the development of novel technologies derived from insights gleaned during strategic investigations, assessing their applicability with or without adjustments.

The current investigation adopts an experimental approach with two independent variables—optimal current density and treatment time—subject to manipulation by the researcher as per the experimental matrix to scrutinize their influence on the dependent variable: the quality of treated wastewater emanating from dairy product manufacturing in the Ayaviri district. Noteworthy interdependent variables encompass atmospheric pressure (582 mmHg), electrode dimensions (1 mm thickness, 1 cm spacing), electrode specifications (aluminum anode: height= 9 cm, width= 7 cm; iron cathode: height= 9 cm, width= 8 cm), total contact area between samples and electrodes (0.08253 m2), electrocoagulation cell volume (2664.9 cm3), and initial sample volume (1.5 liters). This experimental design facilitates iterative observations under standardized conditions for comprehensive result analysis, establishing causal relationships, and embracing a longitudinal timeframe to discern disparities and replicate experiments [15].

Factorial Design

The factorial design methodically evaluates all plausible combinations of factors, delineating the spectrum of variable values [33]. The ensuing relationship was instrumental in ascertaining the total number of experiments:

TABLE I

MAXIMUM AND MINIMUM LEVELS OF INDEPENDENT VARIABLES

Factors	Experimental Domain	Level (-)	Level (+)
X1	Current Density (A/m²)	60.58	84.81
X2	Residence Time (min)	25	35

In the above table, "Level (-)" represents the minimum level, and "Level (+)" represents the maximum level for the respective independent variables: Current Density (X1) and Residence Time (X2).

The present research has employed a complete factorial design with two levels and two independent variables, where:

Number of trials = 22 = 4
Levels of variables: Maximum (+) and minimum (-)
Independent variables: Current density (X1) and Treatment time (X2)

III. RESULTS

Table 2 displays the results of the three initial samples collected on different dates from the effluent generated by a dairy manufacturing process.

TABLE 2

INITIAL VALUES OF WASTEWATER CHARACTERIZATION

Parameter	Unit	Initial sample 1 12/12/22	Initial sample 19/12/22	Initial sample 3 26/12/22
TSS	mg/L	9275	9698	9137
pH		4.63	4.64	4.63

This study was conducted in triplicate for each treatment, and the quantitative results of the evaluated variables are documented in Table 3.

TABLE 3
EXPERIMENTAL RESULTS AND REMOVAL PERCENTAGES

Sample	Test	Factors		Electrocoagulation	
		X1 - Current Density (A/m^2)	X2 - Residence Time (min)	mg/L	% Removal
Sample 1 12/12/22	1	60.58	25	5889.6	36.5
	2	60.58	35	2948.6	68.2
	3	84.81	25	1594.7	82.8
	4	84.81	35	526.5	94.3
Sample 19/12/22	1	60.58	25	5421.1	44.1
	2	60.58	35	3187.6	67.1
	3	84.81	25	2047	78.8
	4	84.81	35	440.1	95.4
Sample 3 26/12/22	1	60.58	25	5354.2	41.4
	2	60.58	35	3474.8	61.9
	3	84.81	25	1885.7	79.3
	4	84.81	35	684.5	92.5

Figure 1 depicts the average percentage removal of Suspended Solids (SST) for samples treated in four different combinations:

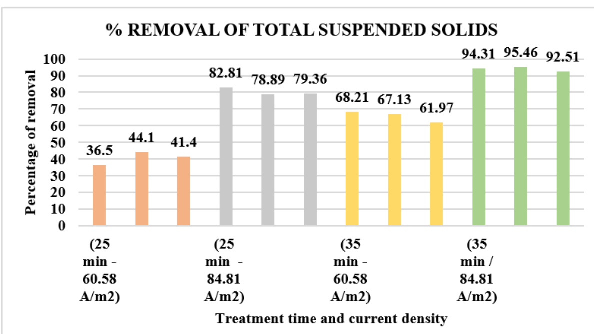

Fig 1. Bar chart of the percentages of removal of Suspended Solids (SST) from dairy wastewater.

<u>Statistical Analysis: Linear Regression Model</u>

In Figure 2, a direct relationship between residence time and current density can be identified. Achieving a high percentage of SST removal will depend on the combination of variables that exhibits the highest value.

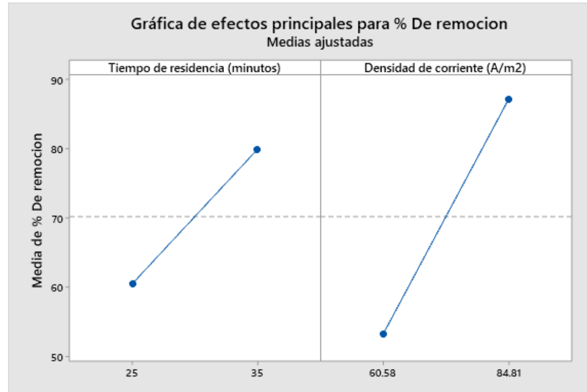

Fig 2. Main effects for the percentage removal of Suspended Solids (SST)

Figure 3 suggests that with higher current density and longer residence time, the percentage of Suspended Solids (SST) removal will increase.

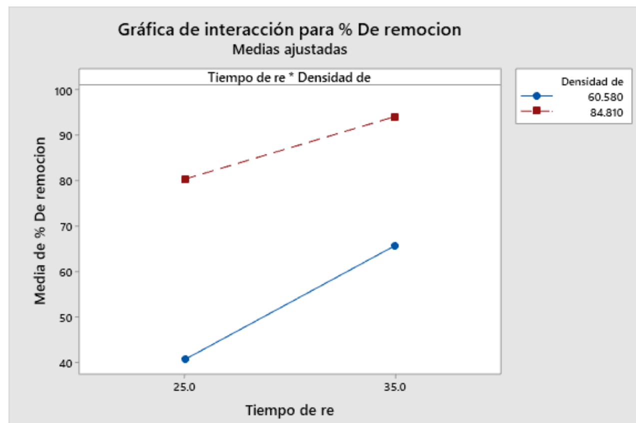

Fig 3. Interaction effects for the percentage removal of Suspended Solids (SST)

In Figure 4, each point on the graph represents the average SST removal from the 3 repetitions in different combinations.

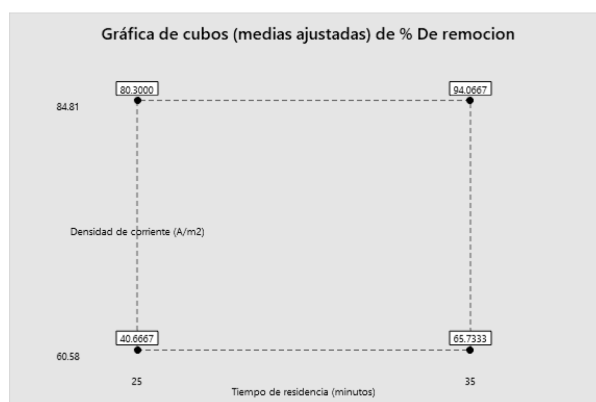

Fig 4. Cube plot (adjusted means) of the percentage removal of Suspended Solids (SST)

In Figure 5, it can be observed that both process variables and their interaction are relevant in the removal of Suspended Solids (SST).

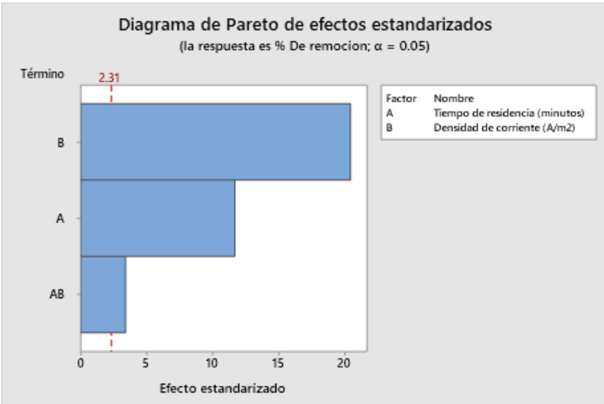

Fig 5. Pareto chart of standardized effects for the percentage removal of Suspended Solids (SST)

Statistical Analysis: ANOVA Test

Analysis of variance (ANOVA) was used, comparing the null hypothesis (H0) with the alternative hypothesis (H1) to verify whether treatment using an electrocoagulation cell influences the removal of total suspended solids from wastewater generated in the production of dairy products through an electrocoagulation cell in the Ayaviri district. To accept the alternative hypothesis, at least one of the experimented treatments had to be different. Table 4 shows P(Sig.) values below alpha 0.05. This allows us to reject H0 and confirm H1 that at least one treatment significantly influences the removal of total suspended solids (TSS).

TABLE 4
ANALYSIS OF VARIANCE (ANOVA)

Source	GL	SC Adjust.	MC Adjust.	F Value	p Value
Current density	1	3469.02	3469.02	423.60	0.000
Treatment time	1	1131.60	1131.60	138.18	0.000
Current density * Treatment time	1	96.84	96.84	11.83	0.009
Error	8	65.51	8.19		
Total	11	4762.98			

IV. DISCUSSION

Concentration of Initial and Final Total Suspended Solids in Wastewater

The removal efficiency of total suspended solids (TSS) reached 94.06%, reducing from an initial concentration of 9370 mg/L to a final concentration of 550.3 mg/L. This substantial reduction can be attributed chiefly to the electrocoagulation process employed, characterized by the release of aluminum ions that precipitate colloids, forming flocs subsequently removed as metal hydroxides. The efficacy of this process escalates with increased generation of aluminum ions during electrocoagulation [9].

The electrocoagulation cell's capacity played a pivotal role, with a volume of 1.5 L utilized in this study. This capacity directly correlates with colloid mobility, fostering enhanced particle agglomeration and, consequently, augmented floc production. The selected adjustable power supply was apt for this volume of treated water. Previous studies, such as those by [33]., conducted experiments with electrocoagulation cells of 2.5 L, achieving a 55.31% TSS removal, analogous to the findings of [26]., who attained a 91% removal with a 2 L capacity.

Moreover, aluminum and iron electrodes were chosen, measuring 9 cm x 7 cm and 9 cm x 8 cm, respectively, providing a total contact area of 0.08253 m² between the sample and electrodes. Aluminum, renowned for its high electrical conductivity, releases ions upon current application, expediting the electrocoagulation and flocculation processes while remaining cost-effective [21]. The crucial role of electrode electrical conductivity is emphasized by reference [21]., with aluminum highlighted as one of the optimal options.

Lastly, an electrode separation distance of 1 cm was maintained. Experimental trials with narrower electrode gaps resulted in prolonged removal times due to sludge deposition on electrode surfaces, impeding aqueous medium circulation for foam ascent and floc precipitation, thereby yielding inferior TSS removals. Prior research by reference [26]. advocated for a minimum 1 cm electrode separation to ensure effective electrocoagulation without electrode fouling [38]. Additionally, reference [38]. concluded that a 1 cm separation yields superior removal efficiencies.

Influence of Current Density on Total Suspended Solids Removal in Wastewater

Observations indicate that at a current density of 60.58 A/m², TSS removal was relatively low at 53.2%. This phenomenon stemmed from the application of low current intensity, resulting in diminished anode electro-dissolution and, consequently, reduced aluminum ion generation. Furthermore, inadequate production of H+ molecules at the cathode constrained TSS flotation [33]. Conversely, at a current density of 84.81 A/m², TSS removal surged to 87.18%, indicative of heightened aluminum ion release due to the applied current density [52].

Influence of Treatment Time on Total Suspended Solids Removal in Wastewater

Treatment duration proved pivotal for effective particle destabilization and achieving high TSS removal percentages. Experiments conducted over 35 minutes demonstrated an average TSS removal of 79.9%, attributed to sustained aluminum ion production during extended operational periods, facilitating floc formation. Additionally, increased H+ molecule production aided oxide particle transport to the surface as foam [34]. In contrast, experiments lasting 25 minutes yielded a lower TSS removal of 60.48%.

Concluding the factorial design experiments, optimal conditions were determined to be a current density of 84.81 A/m² and a treatment time of 35 minutes, resulting in a remarkable 94.06% TSS removal. This underscores the efficacy of electrocoagulation in significantly mitigating TSS. A comparison with [9], who achieved a 97% TSS removal from whey using electrocoagulation with a current density of 29.7 A/m² over 60 minutes, corroborates the impact of treatment duration on TSS reduction. Similarly, [33] attained a 55.31% removal with a treatment time of 30 minutes and a current density of 56.7 A/m². The disparity of 18.48% in TSS removal can be attributed to the applied current density.

Implications

This study addresses municipal restrictions on wastewater discharge from the dairy industry into the sewer system, advocating for a viable treatment solution and underscoring producers' responsibility in wastewater management. Direct discharge of whey into sewers has adverse repercussions, including sewage overflow, environmental contamination, and health hazards due to foul odors. The exploration of electrocoagulation reactor assembly serves as an alternative for daily wastewater treatment.

Limitations

The experimental design primarily focused on TSS as an electrocoagulation efficiency indicator, omitting parameters such as chemical oxygen demand (COD) and biochemical oxygen demand (BOD5) due to prevailing circumstances in the country. Nonetheless, materials and equipment were readily available for TSS analysis.

V. CONCLUSIONS

The initial physicochemical characterization of wastewater from the dairy manufacturing facility revealed a total suspended solids (TSS) concentration of 9370 mg/L and a pH of 4.6, indicating potential adverse effects on the sewer network.

Following electrocoagulation treatment, the final physicochemical characterization of the wastewater showed a significant reduction in TSS concentration to 550.3 mg/L, with a slight increase in pH to 4.8.

The electrocoagulation method achieved an impressive 94.06% removal of TSS from dairy wastewater, highlighting its efficacy in pollutant removal.

Optimal operating conditions for electrocoagulation were determined as a current density of 84.81 A/m², utilizing a total contact area of 0.08253 m² and a current intensity of 7 A, coupled with a treatment duration of 35 minutes.

Statistically, the key variables influencing the TSS removal process in dairy wastewater were identified as current density and treatment time, with their synergistic interaction significantly enhancing the efficiency of liquid waste contaminant removal.

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