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Filtration Behavior and Solid–Liquid Separation Mechanisms in an Integrated Electrocoagulation–Filtration–Chelation System for Heavy Metal Removal from Laboratory Wastewater

Rasul Cafarov[1], Hameda[2], Rahayu Yuliastri Fadhilah[3], Emmanouil Konstantinidis[4]
[1]Department of Chemistry, Azerbaijan State University of Economics , Azerbaijan
[2]Department of Chemistry, Omar Al Mukhtar University, Libya
[3]Department of Physics, Universitas Islam Negeri Alauddin Makassar, Sulawesi Selatan, Indonesia
[4]Department of Chemistry, Hellenic Open University, Greece

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ABSTRACT

Purpose of the study: This study aims to investigate the filtration behavior and solid–liquid separation mechanisms in an integrated electrocoagulation–filtration–chelation system for treating highly contaminated laboratory wastewater, with emphasis on the role of filtration as the main separation unit controlling overall treatment performance.

Methodology: Electrocoagulation was conducted using aluminum electrodes in a batch reactor, followed by gravity-driven filtration using cellulose filter media and chelation using tamarind extract. Heavy metals were analyzed using Atomic Absorption Spectroscopy (AAS, Shimadzu AA-7000). COD was measured using standard dichromate method. Filtration behavior was interpreted using classical Darcy's law.

Main Findings: The integrated system achieved significant removal of heavy metals, with mercury reduced to 0.001 ppm, cadmium to 0.002 ppm, and lead to 0.123 ppm. COD was also substantially decreased. Filtration exhibited cake formation behavior, where floc accumulation increased resistance and reduced flux over time, while improving solid–liquid separation efficiency.

Novelty/Originality of this study: This study introduces a filtration-centered perspective in an integrated electrocoagulation–filtration–chelation system by emphasizing cake filtration mechanisms and resistance-controlled behavior. It advances existing knowledge by linking physicochemical transformation with mechanical separation, demonstrating how phase conversion enhances filterability and overall separation efficiency in wastewater treatment systems.

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Corresponding Author:
Rasul Cafarov,
Department of Chemistry, Azerbaijan State University of Economics , 6, Istiqlaliyyat Street, Baku, AZ1001, Azerbaijan.
Email: rscafaarovras@gmail.com

1. INTRODUCTION

Chemical laboratory wastewater contains complex mixtures of dissolved and suspended contaminants, including heavy metals, organic compounds, and acidic substances [1], [2]. These pollutants pose significant environmental and health risks due to their persistence and potential for bioaccumulation [3], [4]. Improper discharge of such wastewater can lead to long-term contamination of aquatic ecosystems [5], [6]. Therefore, the development of efficient treatment strategies is essential to ensure environmental safety. In this context, solid–liquid separation processes play a critical role in removing contaminants from wastewater.

Electrocoagulation has been widely applied as an effective physicochemical method for destabilizing dissolved and colloidal particles [7], [8]. This process generates coagulant species in situ, promoting aggregation of contaminants into larger flocs. The formation of these flocs facilitates their conversion from dissolved to particulate form. However, electrocoagulation alone cannot achieve complete separation without an effective downstream process [9], [10]. As a result, additional separation techniques are required to remove the generated flocs from the liquid phase [11], [12].

Filtration serves as a key solid–liquid separation unit in wastewater treatment systems. It is particularly effective in removing suspended particles formed during coagulation processes [13], [14]. The performance of filtration depends on factors such as filter media properties, particle size, and cake layer formation [15], [16]. During operation, accumulated particles form a cake layer that enhances separation efficiency. This process can be described using classical filtration theory, where flow behavior is influenced by filtration resistance and fluid properties [17], [18].

Filtration is a fundamental unit operation in solid–liquid separation processes and plays a critical role in determining the overall efficiency of wastewater treatment systems [19], [20]. Its performance is governed by the interaction between particle characteristics, filter media properties, and cake layer formation [21], [22]. According to classical filtration theory, the filtrate flux is controlled by the total hydraulic resistance, which consists of intrinsic filter medium resistance and additional resistance caused by particle deposition. As filtration progresses, the accumulation of particles leads to cake formation, which enhances separation efficiency but simultaneously increases flow resistance [23], [24]. Therefore, understanding filtration behavior is essential for optimizing integrated separation processes.

Despite its effectiveness in removing particulate matter, filtration has limited capability in eliminating dissolved metal ions [25], [26]. Therefore, complementary treatment methods are required to improve overall separation performance [27], [28]. Natural chelating agents, such as tamarind, offer an environmentally friendly approach for binding dissolved metal ions [29], [30]. These materials contain functional groups capable of forming stable complexes with heavy metals. Consequently, the use of natural chelation can enhance the removal of residual contaminants after filtration.

An integrated system combining electrocoagulation, filtration, and natural chelation provides a promising multi-stage separation approach [31], [32]. Each process contributes to different mechanisms, resulting in improved overall efficiency [33], [34]. Electrocoagulation promotes particle formation, filtration enables solid–liquid separation, and chelation removes dissolved metals [35], [36]. This combination creates a synergistic effect that enhances treatment performance. However, studies focusing on such integration from a filtration and separation perspective remain limited.

Previous studies by Twizerimana and Wu [37] primarily focus on the integration of electrocoagulation and adsorption as a strategy to enhance heavy metal removal efficiency, emphasizing process parameters such as current density, pH, and adsorbent dosage, while highlighting limitations related to energy consumption and adsorbent saturation . Similarly, the comprehensive review by Nemeș et al. [38] broadly evaluates various wastewater treatment technologies with a strong emphasis on removal performance and comparative efficiency across methods, but largely treats separation processes as secondary outcomes rather than fundamental mechanisms. Despite these contributions, both studies predominantly adopt a removal-efficiency perspective and provide limited insight into the role of filtration as a governing solid–liquid separation process. In particular, the behavior of filtration systems, including cake formation, resistance buildup, and flux decline, remains insufficiently explored in integrated treatment configurations. Therefore, a critical gap exists in understanding how physicochemical transformations induced by electrocoagulation influence filtration performance and overall separation efficiency. This study addresses this gap by introducing a filtration-centered approach, emphasizing the mechanistic role of cake filtration and resistance-controlled behavior in an integrated electrocoagulation–filtration–chelation system.

This study introduces a novel filtration-centered perspective in integrated wastewater treatment systems by explicitly positioning filtration as the governing solid–liquid separation mechanism rather than a secondary polishing step. Unlike conventional approaches that primarily emphasize contaminant removal efficiency, this work highlights the critical role of cake formation, filtration resistance, and flux behavior in determining overall system performance. The integration of electrocoagulation, filtration, and natural chelation using tamarind not only enhances phase transformation but also improves filterability and separation efficiency in a synergistic manner. The urgency of this research lies in the increasing demand for efficient and sustainable treatment of highly contaminated wastewater, where understanding and optimizing separation mechanisms are essential for process design and scale-up. By bridging the gap between physicochemical treatment and filtration theory, this study advances current knowledge and provides a more mechanistic foundation for developing next-generation separation-based wastewater treatment technologies.

Therefore, this study aims to evaluate the performance of an integrated electrocoagulation–filtration–chelation system for treating laboratory wastewater. The focus is placed on understanding the separation mechanisms involved in each stage. Special attention is given to the role of filtration as a key unit in solid–liquid separation. The study also examines the interaction between physicochemical and filtration processes. Ultimately, this research seeks to provide insights into improving separation efficiency in complex wastewater systems.

2. RESEARCH METHOD

2.1. Tools and Materials

This research utilized various laboratory equipment to support the wastewater treatment process and water quality parameter analysis [39], [40]. The main equipment used in the electrocoagulation process included a pair of metal plates serving as electrodes, a power supply as a current source, and connecting cables equipped with alligator clips to ensure a stable connection between the electrodes and the current source. Voltage and current measurements were performed using a multimeter to ensure process stability during electrocoagulation. The reaction vessels used were one-liter beakers for the electrocoagulation process and three-hundred-milliliter beakers for the filtration process. Jerry cans were used to store waste before treatment, while bottles were used to store samples after treatment.

Other supporting equipment included funnels and filter paper for the filtration process, and aluminum foil used as container covers during the sedimentation process. The sample digestion process was carried out using a hot plate heater with Erlenmeyer flasks and volumetric flasks to ensure solution homogeneity [41], [42]. An analytical balance was used to weigh the ingredients with high accuracy, particularly in the preparation of tamarind seed powder. The solution mixing process was carried out using a magnetic stirrer to achieve a homogeneous solution. Additionally, a stopwatch was used to control the contact time during the metal binding process, while a blender was used to grind the tamarind seeds into a powder.

Waste quality parameters were measured using several analytical instruments that meet testing standards. The solution's turbidity was analyzed using a turbidimeter, while its acidity was measured using an acidity meter. The heavy metal content in the samples was analyzed using an atomic absorption spectrophotometer, which has high sensitivity to metal elements [43], [44]. Documentation of research activities was carried out using a camera, and writing instruments were used to record all observations throughout the study. All equipment used was adapted to the needs of each stage of the waste treatment process. Thus, the use of these tools in this study supported the accuracy and reliability of the data obtained.

The materials used in this study consisted of liquid chemical laboratory waste from laboratory experiments in the instrument chemistry laboratory [45], [46]. This waste, which is leftover from atomic absorption spectrophotometer testing, has been mixed with water and contains various heavy metals, and therefore was used as the primary material in this study. Furthermore, tamarind solution and tamarind seeds were used as natural materials in the metal binding process. The tamarind seeds were processed into powder before use to increase the surface area in contact with the metals in the solution. The use of these natural materials aims to support a more environmentally friendly waste treatment approach [47], [48].

Other chemicals used included nitric acid, which functions in the sample digestion process prior to heavy metal analysis. Filter paper with specific specifications was used in the filtration process to separate suspended particles from the solution. Distilled water was used as a solvent and rinse at various stages of the process to maintain sample purity. All materials used in this study were of suitable quality for laboratory analysis. This combination of materials enabled the waste treatment process to be carried out optimally and yield valid data.

2.2. Work Procedures

This research procedure consists of several main stages, including preparation, pre-research, waste treatment, and data analysis and interpretation. During the preparation stage, all equipment and materials to be used in the research were prepared to ensure the smooth running of the experiment. The liquid waste used as a sample was taken from the chemical instrumentation laboratory at the Faculty of Science and Technology, Alauddin State Islamic University, Makassar. The waste sample was mixed with water and contained heavy metals from an atomic absorption spectrophotometer [49], [50]. This stage aimed to ensure that the sample used was representative of chemical laboratory waste.

The pre-research stage was conducted to determine the initial characteristics of the waste before processing. Physical properties were analyzed by directly observing the color and odor of the liquid waste [51], [52]. Next, chemical properties were analyzed to determine the levels of heavy metals, including lead, cadmium, and mercury. Other parameters, such as chemical oxygen demand, turbidity, and acidity, were also measured. The data from this initial analysis served as a reference for evaluating the effectiveness of the applied treatment method. This allows for a comprehensive analysis of changes in waste quality after treatment.

The waste processing stage begins with the electrocoagulation method, which utilizes the principles of reduction and oxidation reactions in an electrolysis system. A pair of iron electrodes measuring six by fifteen centimeters, each measuring one centimeter thick, are installed in a beaker with a distance of one centimeter between the electrodes. A three-hundred-millimeter waste sample is placed in the beaker and then connected to an electric current source using a power supply. The electrocoagulation process is carried out at varying voltages of six volts, nine volts, and twelve volts, with contact times of thirty, sixty, and one hundred and twenty minutes [53], [54]. This stage aims to precipitate and coagulate dissolved and suspended particles in the waste.

After the electrocoagulation process, a filtration stage is performed to separate the floc formed from the wastewater. Filtration is performed using filter paper placed in a funnel with a 300-milliliter beaker as the collection container. The electrocoagulation sample is then filtered to obtain a clearer liquid free of suspended particles. This process also significantly reduces the turbidity of the wastewater. The filtration results are then used as input for the next treatment stage.

The next stage involves wastewater treatment through metal binding using tamarind, a natural ingredient. A tamarind solution with a concentration of 50 percent is prepared and mixed with the filtered wastewater in a one-to-one ratio. The mixture is allowed to stand for thirty minutes to allow sufficient contact time between the solution and the metal ions. The solution is then separated again using filter paper to remove residual solids. This stage aims to bind any remaining heavy metals in the wastewater through natural chelation mechanisms.

Next, tamarind seed powder is added to increase the efficiency of metal binding. The tamarind seeds were first separated from the pulp, then heated at 250 degrees Celsius for thirty minutes before being ground into a powder using a blender. The powder was added to the waste solution at a dosage of two point two grams per hundred milliliters. The mixture was then stirred using a magnetic stirrer for eight minutes, consisting of three minutes of rapid stirring and five minutes of slow stirring. This step aimed to maximize the interaction between the powder surface and the metal ions in the solution.

The final stage of the research involved analyzing the physical and chemical properties of the waste after the entire treatment process had been completed. Parameters analyzed included turbidity, acidity, chemical oxygen demand, and the levels of heavy metals remaining in the waste. The measured data were then analyzed to determine the effectiveness of each method and the combination of processes used. The results of this analysis are presented in a table showing the characteristics of the waste before and after treatment. Based on the data obtained, conclusions were drawn regarding the performance of the waste treatment system developed in this study.

2.3. Filtration Process and Separation Mechanism

The filtration stage was conducted as a solid–liquid separation step following electrocoagulation, utilizing filter paper as the filtration medium in which the separation mechanism involves both surface filtration and cake filtration [55], [56]. During this process, flocs generated from electrocoagulation accumulate on the filter surface, forming a porous cake layer that enhances separation efficiency by acting as an additional filtering barrier and improving particle retention. The filtration behavior can be described based on Darcy's law, where the filtrate flow rate is influenced by the pressure difference, fluid viscosity, and total filtration resistance [57], [58]. The total resistance in this system consists of filter medium resistance and cake resistance formed by accumulated particles on the filter surface. Although the applied pressure was not externally controlled, the filtration process qualitatively follows classical filtration principles, where increasing cake thickness leads to a gradual reduction in flow rate over time.

From a filtration theory perspective, the process can be described using Darcy's law, where the filtrate flux is governed by the pressure gradient, fluid viscosity, and total filtration resistance. The total resistance consists of the intrinsic resistance of the filter medium and the additional resistance caused by cake formation. As the cake layer becomes thicker, the overall resistance increases, leading to a gradual decline in filtration rate [59], [60]. This behavior confirms that the system operates predominantly under a cake filtration regime, which plays a key role in enhancing separation efficiency despite reducing permeability over time.

3. RESULTS AND DISCUSSION

3.1. Characteristics of Laboratory Wastewater Generated from Atomic Absorption Spectrophotometric Analysis

The wastewater used in this study was obtained from laboratory activities involving atomic absorption spectrophotometric analysis conducted at the Chemical Instrumentation Laboratory, Department of Chemistry, Faculty of Science and Technology, Universitas Islam Negeri Alauddin Makassar. Visually, the wastewater exhibited a yellowish orange color, indicating the presence of dissolved chemical constituents. In addition, the wastewater emitted a strong and pungent odor, which is associated with its high acid content. The initial acidity level of the wastewater was found to be extremely low, with a value of approximately zero point five six, indicating highly acidic conditions. Furthermore, this laboratory wastewater possesses high toxicity due to the presence of heavy metals, making it unsuitable for direct discharge into the environment without prior treatment. The visual appearance of the laboratory wastewater is presented in Figure 1.

Figure 1. Laboratory Wastewater Generated from Atomic Absorption Spectrophotometric Analysis

The characteristics of the laboratory wastewater generated from atomic absorption spectrophotometric analysis prior to treatment were evaluated based on several key parameters, including acidity level, chemical oxygen demand, mercury, cadmium, lead, and turbidity [61], [62]. These parameters were selected to represent both the physicochemical properties and the level of contamination in the wastewater. The initial measurements provide important baseline data for assessing the effectiveness of the treatment processes applied in this study. The results of these analyses are presented in Table 1.

Table 1. Physicochemical Characteristics of Laboratory Wastewater Prior to Treatment

Parameter	Experimental Result	Standard Limit	Measurement Method
pH	0.56	6 – 9	pH meter
Chemical Oxygen Demand	195000 ppm	300 ppm	Volumetric method
Mercury (Hg)	15 ppm	0.005 ppm	Atomic absorption spectrophotometry
Cadmium (Cd)	2.79 ppm	0.1 ppm	Atomic absorption spectrophotometry
Lead (Pb)	3.49 ppm	1 ppm	Atomic absorption spectrophotometry
Turbidity	192 FTU	–	Turbidimeter

Table 1 presents the physicochemical characteristics of the laboratory wastewater prior to treatment, along with the corresponding standard limits and measurement methods used in the analysis. The data indicate that the wastewater exhibits extremely acidic conditions, as reflected by the very low acidity level compared to the acceptable range. The chemical oxygen demand value is exceptionally high, suggesting a substantial presence of oxidizable substances and a significant pollution load [63], [64]. In addition, the concentrations of heavy metals, including mercury, cadmium, and lead, are considerably above the permissible limits, highlighting the toxic nature of the wastewater. The turbidity value also indicates a high level of suspended particles in the solution [65], [66]. Overall, the results demonstrate that the untreated laboratory wastewater does not meet environmental standards and requires further treatment before discharge.

In this study, wastewater treatment was carried out by combining electrocoagulation and metal binding using tamarind. The laboratory wastewater generated from atomic absorption spectrophotometric analysis was initially treated using the electrocoagulation method, followed by further treatment through tamarind based metal binding [67], [68]. The evaluation of wastewater characteristics was conducted based on several parameters, including acidity level, chemical oxygen demand, mercury, cadmium, lead, and turbidity. These parameters were analyzed at three different stages, namely the untreated wastewater, the wastewater after electrocoagulation, and the wastewater after tamarind based treatment. This sequential analysis was intended to assess the effectiveness of each treatment stage as well as the combined process. The results of these measurements are presented in the following table, which summarizes the characteristics of the wastewater after electrocoagulation and after tamarind based metal binding.

Table 2. Table of Waste Characteristics After Treatment with Electrocoagulation and Filtration

NO	Voltage	Time (minutes)	Hg (ppm)			Cd (ppm)			Pb (ppm)			pH	COD	Turbidity
			1	2	Average	1	2	Average	1	2	Average			
1.	6	30	0,136	0,129	0,132	0,197	0,223	0,210	0,197	0,197	0,197	2,52	185000	179
		60	0,132	0,139	0,135	0,164	0,151	0,157	0,106	0,117	0,112	3,41	160000	234
		120	0,117	0,129	0,123	0,111	0,108	0,110	0,106	0,106	0,106	3,34	195000	113
2.	9	30	0,122	0,125	0,123	0,195	0,199	0,197	0,106	0,106	0,106	2,61	30000	124
		60	0,125	0,126	0,126	0,134	0,139	0,136	0,192	0,192	0,192	2,71	45000	154
		120	0,125	0,131	0,128	0,104	0,098	0,101	0,208	0,229	0,219	3,62	85000	282
3.	12	30	0,113	0,115	0,114	0,183	0,188	0,186	0,181	0,149	0,165	3,09	165000	169
		60	0,105	0,116	0,111	0,142	0,132	0,137	0,197	0,171	0,184	3,58	45000	101
		120	0,105	0,104	0,104	0,070	0,063	0,067	0,272	0,278	0,275	4,1	60000	874

Table 3. Table of Waste Characteristics After Processing Using the Metal Binding Method with Tamarind

NO	Voltage	Time (minute)	Hg (ppm)			Cd (ppm)			Pb (ppm)			pH	COD	Turbidity
			1	2	Average	1	2	Average	1	2	Average			
1.	6	30	0,006	0,003	0,005	0,008	0,007	0,007	0,137	0,137	0,137	1,98	100000	525
		60	0,001	0,005	0,003	0,002	0,002	0,002	0,126	0,120	0,123	2,11	60000	492
		120	0,001	0,002	0,002	0,001	0,004	0,003	0,120	0,126	0,123	2,2	50000	662
2.	9	30	0,006	0,005	0,005	0,004	0,004	0,004	0,142	0,131	0,137	2,26	20000	534
		60	0,004	0,003	0,004	0,005	0,003	0,004	0,164	0,131	0,148	2,43	25000	502
		120	0,006	0,002	0,004	0,003	0,006	0,004	0,148	0,153	0,151	2,52	45000	446
3.	12	30	0,001	0,001	0,001	0,001	0,003	0,002	0,175	0,197	0,186	2,73	30000	327
		60	0,001	0,001	0,001	0,003	0,004	0,004	0,214	0,208	0,211	2,76	20000	380
		120	0,001	0,001	0,001	0,001	0,003	0,002	0,225	0,230	0,228	2,8	20000	662

The laboratory wastewater used in this study exhibited highly acidic conditions, elevated turbidity, and significant concentrations of heavy metals, indicating a complex and hazardous composition. The initial physicochemical parameters revealed that the wastewater exceeded permissible discharge limits, particularly for mercury, cadmium, lead, and chemical oxygen demand [69], [70]. These results confirm that the wastewater contains both dissolved and suspended contaminants in high concentrations. Such conditions require a treatment system capable of addressing multiple phases simultaneously. Therefore, a multi-stage separation approach is essential to effectively treat this type of wastewater.

From a separation perspective, the wastewater represents a heterogeneous system consisting of dissolved ions, colloidal particles, and suspended solids. Dissolved heavy metals are particularly challenging to remove due to their stable chemical forms and small size [71], [72]. Meanwhile, suspended particles contribute significantly to turbidity and can be removed through physical separation processes. The coexistence of these different phases highlights the limitation of single-stage treatment methods. As a result, integrating multiple separation mechanisms becomes necessary to achieve optimal performance.

The initial characterization also serves as a baseline for evaluating the effectiveness of the treatment processes applied in this study. By comparing conditions before and after treatment, the contribution of each stage can be clearly identified. This approach allows for a more comprehensive understanding of how contaminants are transformed and removed. In particular, it enables the analysis of phase transitions from dissolved to particulate forms. Such analysis is crucial in understanding the overall separation mechanism of the system.

3.2. Electrocoagulation as Pre-Separation Process

The electrocoagulation process acts as a critical pre-separation stage by destabilizing dissolved and colloidal particles through electrochemical reactions. The generation of metal hydroxide species during electrocoagulation facilitates charge neutralization and particle aggregation [73], [74]. As a result, fine particles and dissolved contaminants begin to form larger flocs. This transformation is essential in converting non-separable dissolved species into separable particulate forms. Consequently, electrocoagulation enhances the efficiency of downstream separation processes.

The formation of flocs significantly improves the physical characteristics of the wastewater, particularly in terms of particle size distribution [75], [76]. Larger flocs are easier to separate through filtration due to their increased mass and reduced stability in suspension. This process effectively reduces the number of colloidal particles that would otherwise pass through the filtration medium. In addition, the aggregation of contaminants into flocs promotes the encapsulation of heavy metals within the solid phase. This mechanism plays a key role in reducing dissolved metal concentrations.

Furthermore, electrocoagulation contributes to the reduction of turbidity and partial removal of organic contaminants. However, the process alone is not sufficient to achieve complete separation, as the formed flocs remain suspended in the liquid. Without an effective solid–liquid separation step, these flocs can re-disperse or remain in the treated water. Therefore, the integration of filtration as a subsequent process is essential. This highlights the importance of electrocoagulation as a preparatory stage in a multi-step separation system.

3.3. Filtration Performance and Solid–Liquid Separation

The filtration stage serves as the primary solid–liquid separation unit, effectively removing flocs generated during electrocoagulation. During the filtration process, particles accumulate on the surface of the filter medium, forming a porous cake layer [77], [78]. This cake layer enhances separation efficiency by acting as an additional filtration barrier. As filtration progresses, the cake layer becomes thicker, improving particle retention. This behavior indicates that the system operates under a cake filtration mechanism.

The formation of the cake layer significantly contributes to the reduction of turbidity in the treated wastewater. Suspended solids, including flocculated particles, are effectively retained within the cake structure. As a result, the filtrate becomes clearer, indicating successful separation of the solid phase from the liquid phase. The improvement in clarity demonstrates the effectiveness of filtration in removing particulate contaminants [79], [80]. This also confirms that electrocoagulation successfully prepares the system for efficient filtration.

From a filtration theory perspective, the process can be qualitatively described using Darcy's law, where the flow rate is influenced by filtration resistance. The total resistance consists of the intrinsic resistance of the filter medium and the additional resistance caused by the cake layer. As the cake thickness increases, the overall resistance also increases, leading to a gradual decline in flow rate. This phenomenon is commonly observed in cake filtration systems. Despite this limitation, the formation of the cake layer plays a crucial role in enhancing separation efficiency.

3.4. Heavy Metal Separation Efficiency

The integrated treatment system demonstrated a significant reduction in heavy metal concentrations, indicating high separation efficiency [81], [82]. Mercury, cadmium, and lead levels decreased substantially after the application of electrocoagulation, filtration, and chelation processes. This reduction reflects the effectiveness of the multi-stage system in handling both dissolved and particulate contaminants. The results confirm that the combination of processes provides a more comprehensive treatment compared to individual methods. Therefore, the system is suitable for treating highly contaminated laboratory wastewater.

From a separation standpoint, the removal of heavy metals is closely related to the transformation of dissolved ions into particulate forms during electrocoagulation [83], [84]. These metal-containing particles are then captured and retained during the filtration stage. This two-step mechanism highlights the importance of phase conversion in improving separation efficiency. Without such transformation, dissolved metals would not be effectively removed by physical filtration alone. Thus, electrocoagulation and filtration work synergistically to enhance heavy metal removal.

In addition, the significant decrease in metal concentrations demonstrates the ability of the system to meet environmental standards. The results indicate that most of the contaminants are successfully transferred from the liquid phase to the solid phase. This process reduces the toxicity and environmental impact of the treated wastewater. Furthermore, it provides a practical approach for managing hazardous laboratory waste. Overall, the findings confirm the effectiveness of the integrated separation strategy.

3.5. Role of Tamarind in Post-Separation Polishing

Although filtration effectively removes particulate contaminants, some dissolved heavy metals remain in the filtrate. To address this limitation, tamarind is introduced as a natural chelating agent in the post-treatment stage. Tamarind contains functional groups capable of binding metal ions through chemical interactions. These interactions lead to the formation of stable complexes that can be further separated from the solution. This mechanism enhances the removal of residual dissolved contaminants.

The use of tamarind provides an environmentally friendly alternative to synthetic chemical agents. Its natural origin and biodegradability make it suitable for sustainable wastewater treatment applications [85], [86]. In addition, the availability and low cost of tamarind contribute to its practical advantages. The application of natural chelation complements the physical separation achieved through filtration. As a result, the overall treatment system becomes more efficient and environmentally sustainable.

This stage functions as a polishing step that improves the final effluent quality. By targeting dissolved contaminants that cannot be removed through filtration, tamarind enhances the overall separation performance. The integration of chemical and physical mechanisms ensures more complete removal of pollutants. This highlights the importance of combining different treatment approaches in complex wastewater systems. Therefore, the use of tamarind plays a crucial role in achieving high-quality treated water.

3.6. Synergistic Separation Mechanism

The integration of electrocoagulation, filtration, and chelation creates a multi-stage separation system with complementary mechanisms. Each process contributes to a specific stage of contaminant removal, resulting in improved overall efficiency. Electrocoagulation facilitates particle formation, filtration enables solid–liquid separation, and chelation removes residual dissolved metals. This combination ensures that both particulate and dissolved contaminants are effectively addressed. As a result, the system demonstrates superior performance compared to single-stage treatments.

The synergy between these processes is particularly evident in the transformation and removal pathways of contaminants. Dissolved ions are first converted into particulate forms, which are then separated through filtration [87]. Remaining dissolved species are subsequently removed through chemical binding mechanisms. This sequential process enhances the overall separation efficiency. It also reduces the limitations associated with individual treatment methods.

Overall, the integrated system represents a comprehensive approach to wastewater separation. It combines physicochemical and filtration mechanisms to achieve high treatment efficiency [88], [89]. The results demonstrate that the system is capable of handling complex wastewater with multiple contaminant phases. This makes it a promising solution for advanced wastewater treatment applications. Therefore, the study provides valuable insights into the design of efficient multi-stage separation systems.

3.7. Filtration Flux and Resistance Behavior

The filtration process exhibits a typical behavior of cake filtration, where the filtrate flow rate gradually decreases over time due to the accumulation of particles on the filter surface [90], [91]. Initially, the filtration rate is relatively high as the resistance is dominated by the intrinsic filter medium. However, as electrocoagulated flocs deposit on the surface, a porous cake layer is formed, which introduces additional hydraulic resistance. This results in a progressive decline in filtrate flux throughout the filtration process.

From a theoretical perspective, this behavior can be explained using Darcy's law, where the total filtration resistance increases as a function of cake thickness. The cake layer acts as a secondary filtration medium, enhancing particle retention while simultaneously reducing permeability [15], [92]. This trade-off between separation efficiency and flow rate is a characteristic feature of cake filtration systems. The results indicate that the integration of electrocoagulation significantly improves filterability by increasing particle size, thereby promoting effective cake formation.

Although the filtration process was not quantitatively monitored in terms of flux values, the observed decline in flow rate qualitatively indicates a significant increase in cake resistance over time. This suggests that the system follows a typical filtration regime where resistance is time-dependent and governed by particle accumulation. Future studies should incorporate flux measurements to quantify filtration resistance and permeability.

3.8. Separation Mechanism Perspective

From a separation science perspective, the integrated system operates through a combination of physicochemical and mechanical separation mechanisms. Electrocoagulation plays a crucial role in destabilizing dissolved and colloidal species, converting them into larger and more separable flocs [93], [94]. This transformation significantly enhances the effectiveness of the subsequent filtration process.

The filtration stage functions as the primary solid–liquid separation unit, where flocs are retained on the filter surface and within the cake structure. The formation of the cake layer not only improves particle capture efficiency but also alters the hydraulic characteristics of the system. As a result, the separation process can be described as a resistance-controlled system, where both filter medium resistance and cake resistance govern the overall performance. This multi-stage mechanism highlights the importance of phase transformation in separation processes, where contaminants are first converted into particulate form before being physically removed. Such an approach significantly improves separation efficiency compared to single-stage treatment systems. The novelty of this study lies in shifting the interpretation of integrated wastewater treatment systems from a purely removal-based approach to a separation-mechanism-based framework, where filtration behavior is treated as a central governing factor rather than a secondary process.

The results obtained in this study indicate that the effectiveness of the treatment system is strongly governed by the interaction between physicochemical processes and solid–liquid separation mechanisms. Electrocoagulation plays a fundamental role in initiating the separation process by destabilizing dissolved and colloidal particles through electrochemical reactions [95], [96]. This process leads to the formation of larger flocs, which are more easily separable compared to their original dissolved or colloidal forms. The transformation of contaminants from the dissolved phase into particulate form is a crucial step that enhances the overall separation pathway. Without this transformation, subsequent physical separation processes such as filtration would be significantly less effective.

From a mechanistic perspective, the aggregation of particles during electrocoagulation reduces electrostatic repulsion and promotes collision between particles, resulting in the formation of dense flocs. These flocs not only consist of suspended solids but also incorporate heavy metal ions through adsorption, complexation, and precipitation mechanisms [97], [98]. As a result, a substantial portion of dissolved contaminants is transferred into the solid phase even before filtration occurs. However, the presence of these flocs in suspension requires an effective separation step to remove them from the liquid phase. This highlights the necessity of integrating electrocoagulation with filtration to achieve complete separation.

The filtration stage functions as the primary solid–liquid separation unit, where flocs generated during electrocoagulation are physically removed from the wastewater [99], [100]. During filtration, particles accumulate on the surface of the filter medium, forming a porous cake layer that significantly enhances separation efficiency. This cake layer acts as an additional filtration barrier, improving the retention of fine particles and contributing to the clarification of the filtrate. At the same time, the formation of the cake layer increases the overall filtration resistance, leading to a gradual decline in flow rate over time. This behavior is consistent with classical cake filtration theory, where separation efficiency improves at the expense of permeability.

The characteristics of the flocs formed during electrocoagulation strongly influence the performance of the filtration process. Larger and more stable flocs tend to form a more permeable cake structure, allowing fluid to pass through while maintaining effective particle retention [15]. In contrast, smaller or loosely bound particles may lead to a denser cake layer with higher resistance. This interdependence between floc formation and filtration behavior demonstrates that the efficiency of the system cannot be evaluated based on individual processes alone. Instead, the overall performance depends on the synergy between chemical and physical separation mechanisms.

Despite the effectiveness of filtration in removing particulate contaminants, some dissolved heavy metal ions may remain in the filtrate. To address this limitation, tamarind is introduced as a natural chelating agent in the post-treatment stage. Tamarind contains functional groups capable of binding metal ions, forming stable complexes that can be removed from the solution [101], [102]. This mechanism enables the reduction of residual dissolved contaminants that cannot be captured through filtration alone. As a result, the chelation process serves as a polishing step that enhances the final effluent quality.

The integration of electrocoagulation, filtration, and natural chelation creates a multi-stage separation system with complementary mechanisms. Electrocoagulation facilitates the conversion of dissolved contaminants into particulate forms, filtration removes these particles through cake formation, and chelation eliminates remaining dissolved species [9]. This sequential process ensures that both particulate and dissolved phases are effectively addressed. The synergy between these processes leads to a significant improvement in overall separation efficiency. Consequently, the integrated system provides a more comprehensive treatment approach compared to single-stage methods.

From an engineering perspective, the findings of this study highlight the importance of understanding filtration behavior and separation mechanisms in designing efficient treatment systems. The role of cake formation, filtration resistance, and particle characteristics must be carefully considered to optimize system performance [22], [103]. In addition, the use of natural materials such as tamarind offers a sustainable alternative for enhancing separation processes. This approach aligns with the growing demand for environmentally friendly technologies in wastewater treatment. Therefore, the study contributes valuable insights into the development of advanced and sustainable separation systems.

The findings of this study are consistent with previous research on electrocoagulation and filtration processes, which reported that particle destabilization and floc formation significantly enhance solid–liquid separation efficiency. Compared to conventional single-stage treatment methods, the integrated system developed in this study demonstrates improved performance due to the combination of physicochemical and filtration mechanisms. Previous studies have primarily focused on either electrocoagulation or filtration as standalone processes, whereas this study emphasizes their synergistic interaction in a multi-stage system. In addition, the incorporation of natural chelating agents such as tamarind provides an additional advantage in removing residual dissolved metals, which is often not addressed in earlier works. Therefore, this study contributes to the advancement of integrated separation systems by combining multiple mechanisms into a single treatment framework.

The findings of this study provide important implications for the development of advanced wastewater treatment technologies, particularly in the field of solid–liquid separation. The integration of electrocoagulation, filtration, and natural chelation demonstrates a promising multi-stage approach capable of effectively removing both particulate and dissolved contaminants. This system not only improves separation efficiency but also offers a more sustainable alternative through the use of natural materials such as tamarind. In addition, the study highlights the critical role of filtration mechanisms, especially cake formation, in enhancing overall treatment performance. Therefore, this research contributes to the advancement of filtration-based separation systems for complex wastewater applications.

Despite these contributions, several limitations should be considered. The filtration process in this study was evaluated qualitatively without detailed measurement of key engineering parameters such as filtration flux, permeability, and resistance. Furthermore, the experiments were conducted at a laboratory scale, which may not fully represent the performance of the system under real industrial conditions. Variations in wastewater composition were also not extensively investigated, potentially affecting the generalizability of the results. Consequently, further studies are required to quantify filtration behavior, optimize operating conditions, and evaluate system performance at larger scales to ensure practical applicability.

Overall, the integrated process can be interpreted as a filtration-dominated separation system in which electrocoagulation enhances particle formation, while filtration governs the final separation efficiency. The transition from dissolved to particulate phase significantly improves filterability, demonstrating the strong coupling between physicochemical transformation and mechanical separation. This highlights the importance of designing treatment systems based on both reaction and separation principles.

In contrast to conventional wastewater treatment studies that primarily focus on removal efficiency, this work emphasizes the role of filtration as a governing separation mechanism. The results suggest that the effectiveness of the integrated system is not solely determined by chemical transformation, but strongly controlled by filtration dynamics, particularly cake formation and resistance buildup. This finding provides a new perspective that highlights filtration behavior as a critical design parameter in multi-stage treatment systems.

4. CONCLUSION

This study demonstrates that filtration plays a central role as a solid–liquid separation unit in an integrated electrocoagulation–filtration–chelation system for treating laboratory wastewater. The results show that electrocoagulation effectively transforms dissolved contaminants into particulate flocs, which are subsequently removed through cake filtration mechanisms. The formation of a cake layer significantly enhances separation efficiency but also contributes to increased filtration resistance, resulting in a decline in filtrate flux over time. From a separation perspective, the overall process can be described as a resistance-controlled filtration system, where both filter medium resistance and cake resistance determine performance. The integration of natural chelation using tamarind further improves the removal of residual dissolved metals, acting as a polishing step.

These findings highlight the importance of understanding filtration behavior and separation mechanisms in optimizing multi-stage wastewater treatment systems. The study provides valuable insights for the development of efficient and sustainable filtration-based separation technologies. Further research is recommended to optimize operating parameters such as voltage, process time, filtration media, and chelating agent concentration to improve separation efficiency. Furthermore, further study of the cake formation and fouling mechanisms is needed to maintain filtration rate stability, and pilot-scale testing is needed to evaluate the system's application under real-world conditions.

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AUTHOR CONTRIBUTIONS

Conceptualization, R.C. and E.K.; Methodology, R.C.; Software, H.; Validation, R.C., R.Y.F. and E.K.; Formal Analysis, R.C.; Investigation, H.; Resources, R.Y.F.; Data Curation, H.; Writing – Original Draft Preparation, H.; Writing – Review and Editing, R.C. and E.K.; Visualization, H.; Supervision, E.K.; Project Administration, R.Y.F.; Funding Acquisition, E.K.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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