



The present work was submitted to the German Mongolian Institute for Resources and Technology

# INVESTIGATION OF NON-CHEMICAL METHODS FOR WOOL SCOURING INDUSTRIAL WASTEWATER TREATMENT

Bachelor Thesis

by

**Narangua Khongorzul**

Study program: Environmental Engineering

Student ID: B2100421

1<sup>st</sup> Supervisor/Examiner: Dr. Ariuntuya. Ts

2<sup>nd</sup> Supervisor/Examiner: Mr. Baasandorj. M

Ulaanbaatar, Nalaikh

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2025

## Statutory Declaration

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I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

### **Investigation of Non-Chemical Methods for Wool Scouring Industrial Wastewater Treatment**

I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

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## Abstract

This study investigates non-chemical technologies for treating wastewater from Mongolia's cashmere and wool scouring industry. The treatment process consisted of three stages: primary clarification using an Imhoff cone, electrocoagulation using different electrode materials, and filtration with natural zeolite. The Imhoff cone removed approximately 50% of total suspended solids (TSS), reducing concentrations from about 1500 mg/L to 370 mg/L, showing effective pre-treatment through simple sedimentation.

Electrocoagulation was carried out using three electrode types: Al–Al, Cu–Al, and Fe–Al. Among them, the Cu–Al electrode achieved the highest organic matter removal, reducing COD from 1789.67 mg/L to 23.2 mg/L and BOD<sub>5</sub> from 614 mg/L to 5.0 mg/L, thus meeting the MNS 6561:2024 Mongolian wastewater discharge standard. The Al–Al electrodes were most efficient for solid removal, while Fe–Al electrodes offered a balanced performance in reducing both organics and solids. In the final stage, natural zeolite filtration was used with 2 mm and 10 mm particle sizes. The 2 mm zeolite provided better COD removal (24.99% after 24 hours), although overall filtration performance was limited and not sufficient as a standalone treatment.

The findings indicate that the combined process, especially Cu–Al electrocoagulation followed by zeolite filtration, is a cost-effective, low-maintenance, and promising method for treating wool scouring wastewater. To confirm scalability and long-term effectiveness, pilot-scale testing in real factory conditions is recommended.

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### List of Abbreviations

<b>Abbreviation</b>	<b>Full Form</b>
BOD <sub>5</sub>	5-Day Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
TSS	Total Suspended Solids
TS	Total Solids
SS	Settleable Solids
EC	Electrocoagulation
EF	Electroflotation
CWTP	Central Wastewater Treatment Plant
pH	Potential of Hydrogen (Acidity/Alkalinity)
MNS	Mongolian National Standard
DVP	Digital Vacuum Pump
FAS	Ferrous Ammonium Sulfate

## 1. Introduction

### 1.1. Background

The wool and cashmere industry is one of Mongolia's most important economic sectors, contributing significantly to employment and export revenue. Mongolia is the second-largest global supplier of raw cashmere, accounting for approximately 25% of the world market, second only to China [2]. However, the processing of wool and cashmere—particularly during the scouring stage—generates large volumes of high-strength wastewater that contain grease, detergents, waxes, dirt, and other organic matter. On average, primary wool and cashmere processing facilities in Mongolia produce over 696,000 m<sup>3</sup> of wastewater annually, with pollutant concentrations often exceeding national standards [4].

The scouring process, which removes impurities from raw wool, is a water-intensive operation that releases wastewater with high chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), and oil and grease [7, 13]. Improperly treated effluent from this process can lead to severe water pollution and environmental degradation. Many factories in Mongolia currently discharge their wastewater into the Central Wastewater Treatment Plant (CWTP) in Ulaanbaatar, which is already operating beyond its capacity [6]. Consequently, the Mongolian government has introduced regulations such as MNS 6561:2024, which require industrial facilities to pre-treat their wastewater before discharge [20].

Traditional treatment methods like chemical coagulation are often costly, require skilled operators, and produce large volumes of chemical sludge. As a result, interest has grown in non-chemical treatment methods, such as electrocoagulation (EC) and natural zeolite filtration, which are simple, cost-effective, and environmentally friendly [29, 56]. EC uses electrical current to destabilize pollutants, forming flocs that can settle or float, while natural zeolite—a porous mineral—adsorbs pollutants through ion exchange and filtration [53, 54].

## 1.2. Objective of the Study

This study aims to design and use non-chemical technologies to treat wastewater from Mongolia's cashmere and wool scouring industry. Specifically, optimizing electrocoagulation and filtration methods, evaluating their efficacy in treating wastewater that meets essential criteria, and comparing the outcomes to the Mongolian effluent discharge standard (MNS 6561:2024). The objectives are as follows:

- Test three different electrode materials and optimize the operating parameters of electrocoagulation for wastewater treatment.
- Identify the ideal conditions for electrocoagulation processes
- Filter wastewater uses natural zeolite with different fraction sizes and analyzes the same four main parameters.
- Evaluate treatment efficiency for four key parameters: BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), TS (Total Solids), and TSS (Total Suspended Solids).
- Compare the treatment results with the Mongolian wastewater effluent standard MNS 6561:2024.

## 1.3. Hypothesis of the Study

- Can electrocoagulation with different electrode materials effectively remove pollutants from wastewater in the wool and cashmere industry?
- How effective is natural zeolite filtration in removing key pollutants, such as BOD, COD, TS, and TSS, from wastewater?
- Can electrocoagulation and filtration methods treat wastewater to meet Mongolian wastewater effluent standards (MNS 6561:2024)?

## 2. State of the Art

### 2.1. Overview of Wool and Cashmere Scouring Industries

Cashmere is a hidden vital driver of Mongolia's economy and ranks as the second-largest export after mining. As the world's second-largest producer, Mongolia supplies over 25% of the global raw cashmere market, second only to China, which dominates with more than 60% of the supply [1]. Figure 1 shows Mongolia's cashmere production was 5.4 thousand tonnes in 2011. Since then, total production has nearly doubled, peaking in 2020 at 10.7 thousand tonnes. However, a slight decline followed, with the Mongolian Statistical Office reporting 9,672 tonnes of raw cashmere production in 2022. Between 2016 and 2022, China's production decreased from 18,800 tonnes to approximately 14,600 tonnes. Over the past decade, Chinese raw cashmere production has steadily declined.

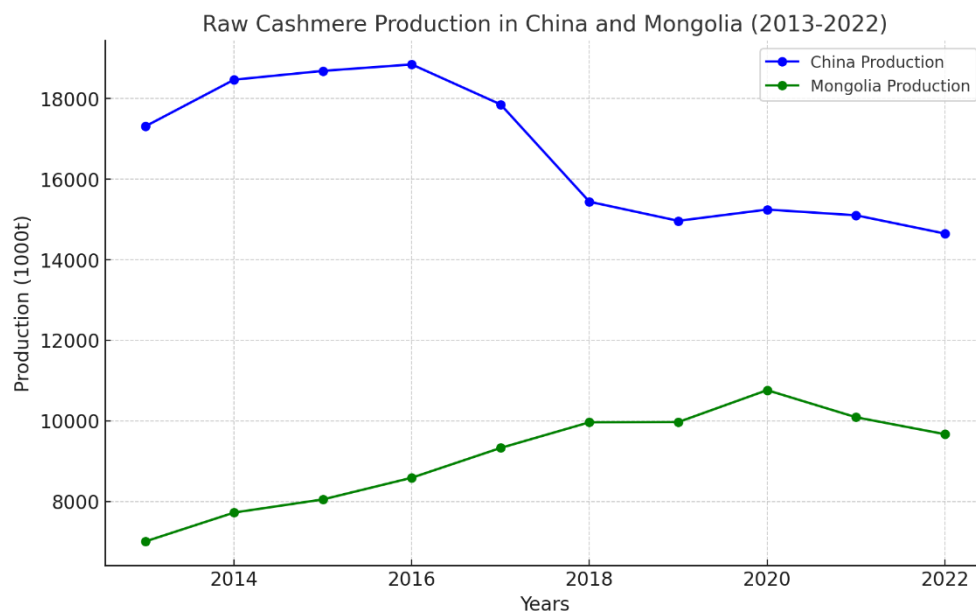


Figure 1. Raw Cashmere Production in China and Mongolia (2013-2022)

These opposing trends—Mongolia's increasing production and China's decline—led to Mongolia's global cashmere production share rising by 10 percentage points, from 26% to 36% [2]. It could be attributed to the quality of Mongolian cashmere. As shown in Fig. 2, 9,672 tons of cashmere intermediates are sourced from different areas (West, Khangai, Central, East, and Ulaanbaatar), and the stream is divided into two main paths: local scouring and export scouring. 2,359 tons are allocated for local scouring with 30% waste, and 7,303 tons undergo export scouring. 6,427 tons of washed cashmere are exported to China for processing.

**"Cashmere Intermediate Processing and Export Flow of Mongolia (2022)**

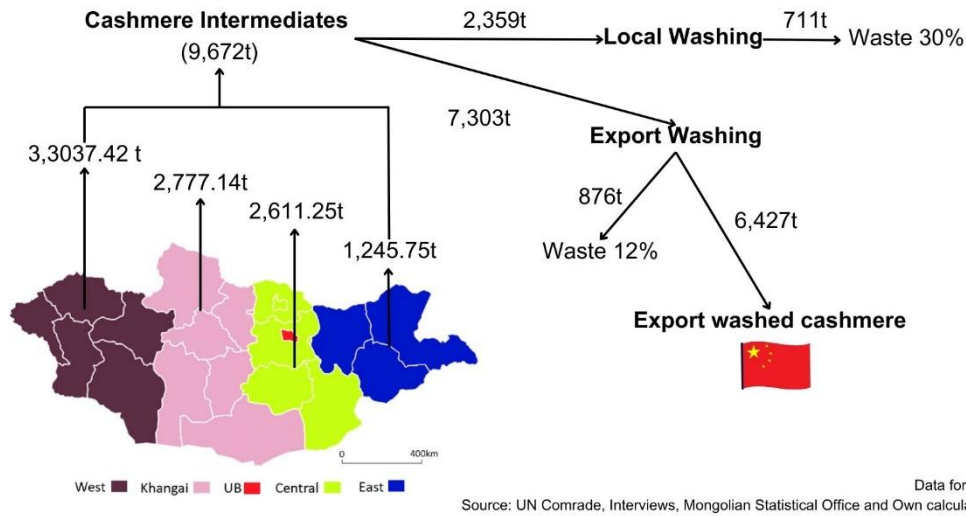


Figure 2. Export Flow of Cashmere in Mongolia (2022)

Chinese cashmere is finer, with an average fiber diameter of 13.5–14.5 microns, while Mongolian cashmere is slightly coarser, averaging 15.5–16.0 microns, as shown in Table 1. However, Mongolian cashmere has longer fibers, measuring 38–43 mm, compared to Chinese cashmere, which ranges from 33–35 mm [3]. This type of cashmere does not yet meet the global cashmere standard, and most of it is either washed or raw and exported to China. As a result, China holds a dominant position in the cashmere market. Meanwhile, with its remaining 24.4%, Mongolia washes its cashmere and supplies the market with value-added products that meet the required standards.

Table 1. Comparison of Fiber Quality: Chinese vs. Mongolian Cashmere

	Average size of microns	Length (mm)
Chinese cashmere	13.5-14.5	33-35
Mongolian cashmere	15.5-16.0	38-43

The growing demand for cashmere products has led to an increase in the number of factories in Mongolia. Currently, the cashmere processing industry in the country consists of 261 factories, including two carpet manufacturing, four weaving, nine spinning, one nonwoven fabric production, 28 scouring, 23 dehairing, 56 knitting, 16 felt product, one wool-based fertilizer, and 120 felting factories [4]. Despite this expansion, Mongolia is not fully utilizing its capacity to wash raw cashmere. While the country has the potential to wash 60% of its raw cashmere, the actual utilization is much lower. The domestic

capacity for dehairing is approximately 4,100 tons, for spinning is 1,400 tons, and for knitting is 2.8 million pieces [5].

Wool and cashmere processing requires significant amounts of water, depending on the capacity of the equipment, operational scale, and product types. The wastewater generated during the process contains contaminants such as detergents, dirt, and grease, which are discharged into the Central Wastewater Treatment Plant (CWTP) in Ulaanbaatar. Due to the concentrated operations of wool scouring factories in Ulaanbaatar, the city's domestic, industrial, and service water consumption has been steadily increasing recently. As a result, the volume of wastewater discharged into the sewage network has grown, exceeding the CWTP's capacity by 10-20%. Additionally, the pollutant levels in wastewater often exceed the standard limits by 2-4 times, depending on the season [6]. To solve this problem, the Mongolian government and authorities have introduced policies to move wool scouring factories from Ulaanbaatar to rural areas and build new factories in the countryside. These actions have helped speed up industrial development in rural areas, created more job opportunities, and supported the production of value-added raw materials. Currently, 14 wool scouring factories are operating in 13 provinces, helping to reduce the concentration of industrial activities in Ulaanbaatar and alleviate the load on the CWTP [4].

Mongolian wool scouring industries generate about 700,000 cubic meters of wastewater annually, the highest among all large and small cashmere and wool processing industries, as shown in Table 2 [1].

*Table 2. Annual Wastewater Production by Cashmere and Wool Processing Industries*

<b>Types of industries</b>	<b>Produced Wastewater (<math>m^3</math>/year)</b>
Finishing industries	525163
Primary processing and wool scouring industries	696522
Small-sized companies	24145
Felt fabric processing industries	15600
Small knitting companies	22032
<b>Total</b>	<b>1283462</b>

## 2.2. Wastewater Characteristics of Wool and Cashmere Scouring Industries

The textile industry is one of the highest water consumers. It generates wastewater with various contaminants such as dyes, organic chemicals, detergents, stabilizers, desizing agents, inorganic salts, and heavy metals [7]. The amount and quality of wastewater vary considerably depending on the material and processes used. Cashmere and wool processing wastewater in Mongolia is handled as a mixed effluent. Raw wool rich in natural dirt by weight is typically treated by scouring, the first step in textile production. Scouring is a water-consuming process that produces intensely concentrated effluent with high oxygen demand, and it is one of the main reasons for water shortages and pollution [8]. During scouring, impurities such as dirt, waxes, and oil are removed from raw materials and discharged to the wastewater stream. Raw wool can contain up to 50% of its weight in impurities, including grease, sand, vegetable matter, and dirt [9]. Scouring is a necessary step to get rid of these impurities. It has been researched that 70% of water pollution in these industries is caused by impurities in raw wool, along with chemicals and detergents used during scouring [1]. Wool scouring involves the use of both non-ionic and anionic detergents along with alkaline agents. In Mongolia, the most used detergents in the wool scouring process are sulfuric acid monododecyl ether sodium salt ( $R-O-SO_3-Na$ ), known as Monogen, and polyoxyethylene alkyl ether ( $R-O(C_2H_4O)_nH$ ), referred to as Noigen ET127. These detergents effectively remove natural impurities and grease from wool, aiding in the cleaning process [10]. Sulfuric acid monododecyl ether sodium salt is widely used as a foaming agent in many industries due to its low cost and good foaming properties [11]. Polyoxyethylene alkyl ether is a nonionic surfactant commonly used in all detergents. It decreases surface tension and allows the detergent to spread and penetrate more easily to clean. [12]. These surfactants are the causative agents for high COD and BOD of wastewater. [13].

The textile manufacturing process involves various methods of generating wastewater of multiple types. The methods include sizing, desizing, scouring, bleaching, mercerisation, dyeing, printing, and finishing, generating wastewater charged with pollutants like oils, fats, detergents, heavy metals, and organic chemicals, all with high BOD (biochemical oxygen demand) and COD (chemical oxygen demand). Scouring wastewater is typically dominated by high BOD (30% total), pH, and temperature (70-80°C), with black color, and thus is challenging to treat. Concentrated in nature, scouring wastewater has a colossal impact on textile industry wastewater quality overall and ought to be afforded serious consideration to be managed appropriately [14].

Table 3. Major characterizations of textile wastewater studied by various researchers

pH	COD (mg/L)	BOD <sub>5</sub> (mg/L)	TSS (mg/L)	TDS (mg/L)	Color	Turbidity (NTU)	Ref
8.8-9.4	595±131	379±110	276±76	-	-	-	[15]
5-10	1100-4600	110-180	-	50	1450- 1475 (ADMI)	-	[16]
6.5-8.5	550-1000	-	100-400	-	7.5- 25.5	15-200	[17]
8.32- 9.5	278-736	137	85-354	1715- 6106	-	-	[18]
8.7±0.2	17900±100	5500±100	23900±50	1200±50	-	-	[19]

As shown in Table 3, the pH of wool scouring wastewater is typically between 6 and 8. The significant parameters, COD and BOD, are incredibly high, indicating severe organic pollution. The solids content in total suspended solids (TSS) and total dissolved solids (TDS) is likewise high and contributes to the total pollution load. The wastewater's color is typically dark, further complicating the treatment process.

Table 4. Wastewater Discharge and Characteristics of Wool and Cashmere Scouring Factories in Mongolia

Factories	Daily Wastewater Discharge (m <sup>3</sup> /day)	Daily Wastewater Max Discharge (m <sup>3</sup> /day)	Total Solids (mg/L)	COD (mg/L)	BOD (mg/L)
Centralized Sewer System MNS6561:2024	Q	Qmax	700/100	1200/200	2500/300
Tuya	24.0	31.2	800.0	1551	1190
Mon-Italy	35.0	45.5	250.0	1081	308
Goyo	36.0	46.8	50.0	768	222
Loro Piana	33.0	42.9	240.0	5021	1775
Altai Cashmere	54.5	70.9	80.0	6941	3010
Gobi	68.2	88.7	55.0	3101	850
Mogul Wool	25.5	33.2	151.6	3544	1180

Factories	Daily Wastewater Discharge (m <sup>3</sup> /day)	Daily Wastewater Max Discharge (m <sup>3</sup> /day)	Total Solids (mg/L)	COD (mg/L)	BOD (mg/L)
Wool Future	-	145.0	5021	1270	3.95
<b>Average</b>	39.5	51.3	221.5	3379	1226

Mongolia's wastewater COD and BOD levels are four times and 25 times higher than those of the Centralized Sewer System standard, respectively [10]. This confirms that scouring wastewater is a major contributor to high COD and BOD levels, making it a serious source of pollution in the textile production process. As shown in Table 4, factories discharge an average of 39.5 m<sup>3</sup>/day of wastewater, with peak discharges reaching up to 51.3 m<sup>3</sup>/day. This wastewater typically contains 221.5 mg/L of total solids, 3379 mg/L of COD, and 1226 mg/L of BOD.

For example, the "Tuya" industry processes up to 2.7 tons of raw cashmere annually, generating about 13 liters of wastewater per kilogram during the scouring stage. In this process, the cashmere passes through four scouring tanks, each using different cleaning agents. The first tank contains a slightly alkaline solution with sodium carbonate, a detergent builder. The second tank uses Monogen and Noigen ET127 detergents to remove wax, oils, and dirt from the cashmere. The final two tanks rinse the material using only hot water. As a result, the wastewater produced during scouring is highly contaminated, with high levels of COD and TSS, and significant BOD due to the detergents and organic materials released from the cashmere itself.

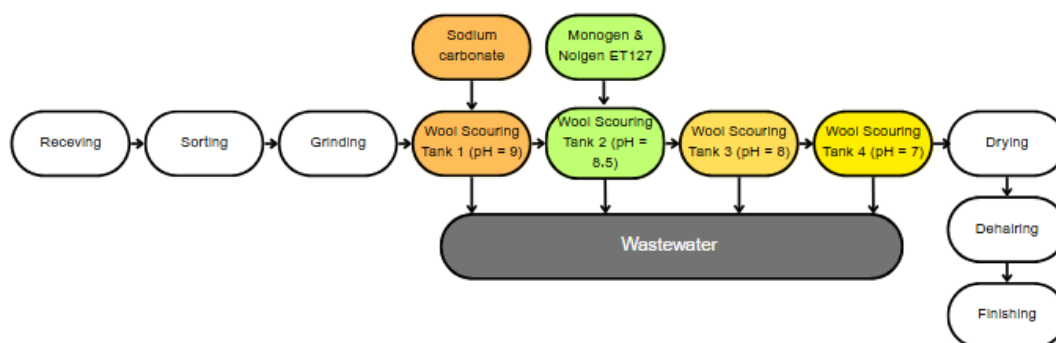


Figure 3. "Tuya" LLC cashmere processing flowsheet

MNS6561:2015 was a significant challenge for relatively strict industries and was poorly implemented. So Mongolian authorities have specified the need for wastewater management improvement, as indicated in Mongolian Government Resolution No. 53. According to this regulation, industrial wastewater must be pre-treated before discharge into centralized treatment facilities to reduce pollutant loads by 2025 [6]. The MNS656:2015 standard has become more flexible and updated in 2024. In compliance with these regulations, Table 5 shows reduction targets for wastewater discharge, such as permissible BOD, COD, and TSS concentrations for scouring wool.

*Table 5. Required Reduction Targets for Industrial Wastewater (MNS6561:2024) [20].*

Industry Category	Daily Wastewater Discharge	BOD (mg/L)	COD (mg/L)	TSS (mg/L)
Wool Scouring	> 240 m <sup>3</sup> /day	1200	2500	700
	< 240 m <sup>3</sup> /day	200	300	100

Physical, chemical, and biological water quality parameters are required to meet the needs of humans and biotic species. For textile factories, total suspended solids (TSS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) are significant parameters of wastewater quality [21]. TSS is a physically visible wastewater parameter composed of organic and inorganic particulate matter. It is required to manage the wastewater treatment processes and determine the permissible limits per the industrial effluent guidelines [22]. TSS can comprise many organic and inorganic particles, including fine clay, silt, nitrates, phosphates, carbonates, and 18 bicarbonates of K, Na, Mg, Ca, and salt in effluents [23].

BOD is a standard parameter for water quality that quantifies the amount of dissolved oxygen required by microorganisms to break down organic matter in wastewater under aerobic conditions [24]. Textile effluent contains high BOD due to suspended solids and fibre residues, which may create regulatory problems and cause the water body to deplete oxygen quickly [25]. Chemical oxygen demand (COD) is the most critical water quality parameter in monitoring textile wastewater effluent and wastewater treatment plants [24]. COD content is high in wastewater that contains much organic material, which consumes dissolved oxygen, leading to anaerobic conditions harmful to aquatic life [26]. The COD of treated water and wastewater is an essential consideration in the design of the electroflotation reactor.

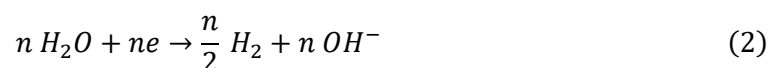
In conclusion, the high COD and BOD contents of scouring wastewater render it an essential source of pollution for the textile industry. Efficient treatment methods are required to achieve regulatory requirements and reduce the environmental effects.

### 2.3. Electrocoagulation Technology for Industrial Wastewater Treatment

The three main electrochemical treatment technologies are electrodeposition, electrocoagulation (EC), and electroflotation (EF) [27]. Heavy metal ions in wastewater are held in place by surface electric charges or hydrogen bonds. When an electric field is applied, these forces are neutralized, causing the pollutants to clump together and separate from the water. The metal particles stick together like tiny magnets, forming larger clumps called sludges or flocs. The flocs made by electrocoagulation (EC) are usually bigger, contain less water, and are more stable than those made by other methods. This makes it easier and cheaper to remove from the water. In contrast, electroflotation (EF) removes pollutants using gas bubbles produced during electrolysis to lift them to the water's surface. [28].

#### 2.3.1. Fundamental Concepts

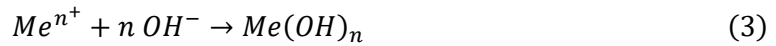
Electrocoagulation (EC) passes a direct electric current through water containing pollutants. This causes chemical reactions at two metal plates called electrodes, which help remove the contaminants from the water. There are three main processes involved: electrooxidation, electroflotation, and electrocoagulation. Electroflotation and electrocoagulation are especially important for cleaning wastewater [29]. During EC, different reactions happen at each electrode. At the cathode (the negative electrode), hydroxide ions ( $\text{OH}^-$ ) and hydrogen gas ( $\text{H}_2$ ) are formed. At the anode (the positive electrode), metal ions like aluminum ( $\text{Al}^{3+}$ ) or iron ( $\text{Fe}^{2+}$ ) are released as the metal slowly dissolves. These metal ions act like natural coagulants and help particles in the water stick together so they can be removed more easily. During EC, different reactions occur at each electrode:



Where:

- Me – anode material
- n – number of electrons involved in the oxidation or reduction reaction.

Then, the metal ions released at the anode react with the hydroxide ions ( $\text{OH}^-$ ) formed at the cathode, forming metal hydroxides, the main coagulants in the electrocoagulation process. This reaction can be expressed as:



Where:

- $\text{Me}^{n+}$  is the metal ion (e.g.,  $\text{Al}^{3+}$  or  $\text{Fe}^{2+}$ )
- $\text{Me}(\text{OH})_n$  is the insoluble metal hydroxide floc.

These insoluble metal hydroxides act as coagulants, binding with suspended and colloidal solids in the water. As a result, the formed flocs either settle at the bottom or float to the surface, making them easier to remove from the treated water [30]. The type of anode material used is essential, as it affects the efficiency of coagulant formation and treatment performance. Different metals produce different quantities and qualities of coagulants, influencing overall results, as shown in Figure 4.

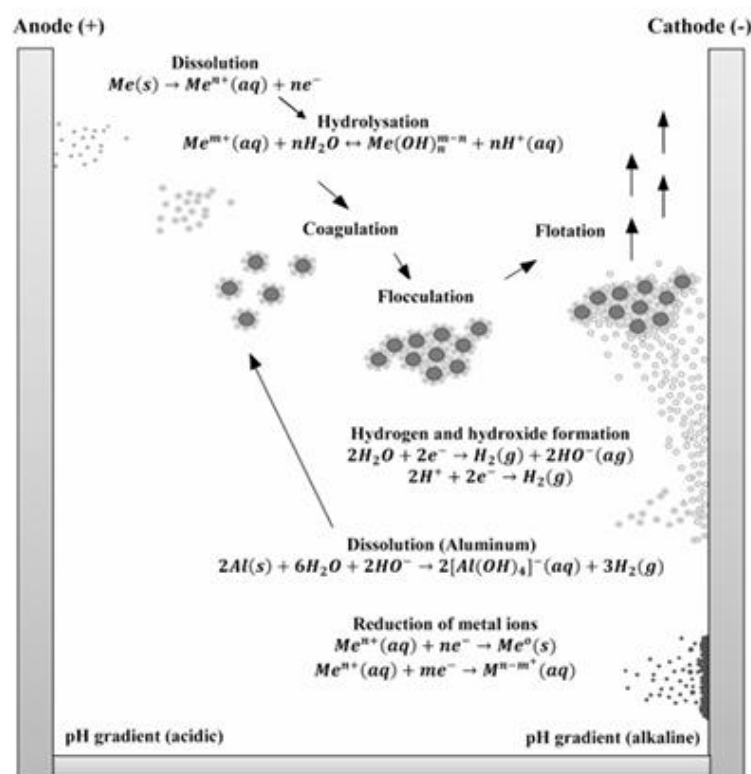


Figure 4. Mechanisms of the Electrocoagulation Process

### 2.3.2. Parameters Affecting Electrocoagulation

As illustrated in Figure 5, electrocoagulation (EC) applications can be divided into six main categories. It is widely used for treating water containing heavy metals by precipitating toxic ions as insoluble hydroxides. EC effectively removes dyes, surfactants, and suspended solids in the textile and industrial sectors. The food industry also benefits from EC treating wastewater rich in fats, oils, and organic matter. EC reduces turbidity, color, and chemical oxygen demand (COD) by removing fibers and other pollutants in the paper industry. Refineries use EC to treat oily wastewater by breaking emulsions and removing hydrocarbons, while in the oil and gas industry, it is applied to treat produced water, eliminating oil, grease, and dissolved contaminants before reuse or discharge [31].

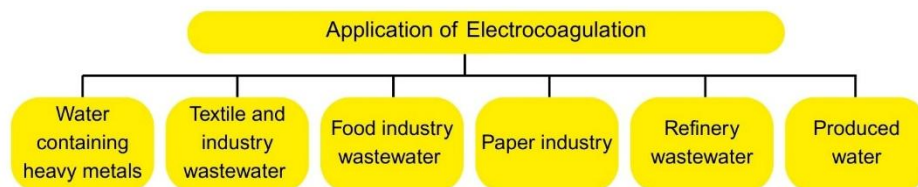


Figure 5. Application of Electrocoagulation [31]

Many factors influence the effectiveness of pollutant removal using the electrocoagulation (EC) method. The most important parameters include the type of electrodes, initial pH, electrolysis time, distance between electrodes, and current density.

#### 2.3.2.1. Electrode material and arrangement

The electrode material significantly impacts the performance, efficiency, and overall cost of the electrocoagulation (EC) process. Table 5 shows that the electrode pairs most used in previous studies are Al–Al, Fe–Fe, and Fe–Al. This is likely because aluminum and iron are nontoxic, have high electrical conductivity, and are cost-effective materials [32]. Many studies have shown that both aluminum (Al) and iron (Fe) can remove similar amounts of COD, but aluminum is usually a bit more effective, while iron uses less energy, making the process cheaper [33]. The best electrode depends on other factors like pH, reaction time, and the type of wastewater. However, several studies have found that using Al–Al electrodes gives the best results for COD removal [34], [35], [36]. Some researchers have also tried using both Al and Fe together, which showed better removal efficiency and lower power use, helping to reduce costs [37], [38], [39].

Table 6. Application of EC Treatment Method for Organic Pollutants

Pollutants	Content (mg/L)	Electrodes	Current	pH	Removal Efficiency [%]	Ref
COD, oil and grease	1019	Cu (anode)	25 A	6.5	95.1, 92.5, 99	[40]
	200	-Al (cathode)				
Phenolic, turbidity & color	-	Al-Al	15 A	5.5	45.7, 99.9, 70.4	[41]
COD	3400-3840	Al-Al	28 V	-	91.9	[42]
Turbidity	728 NTU		-	-	92.3	
Phosphates	4.75	Al-Al	0.2 A	7	99.5 / 96.69	[43]
Organic matter	23		-	-	43.57	
COD	5803	Al-Al	10.75 A	8.7	94.88	[44]
Color	-			8.7	78.65	
COD	1250			8.79	55	
Total Organic Carbon	600	Fe (anode)	1A	8.79	60	[45]
Total Nitrogen	41	-Al (cathode)		8.79	90	
Turbidity	310			8.79	100	

The material and arrangement of the electrodes can affect EC performance. Electrodes can be used in a simple setup (one anode and one cathode) or more complex setups with multiple electrodes. The three common complex types are monopolar parallel (MP-P), monopolar series (MP-S), and bipolar series (BP-S). For example, monopolar connections are often more effective because they provide higher pollutant removal and use less power. On the other hand, bipolar connections may have lower maintenance and operating costs, making them more cost-effective in the long run [37].

### 2.3.2.2. Initial pH

pH is a very important factor in the electroflotation (EF) process because it affects the formation and size of bubbles and helps control metal hydroxides when using sacrificial anodes. However, it is hard to find a clear connection between pH and how well electroflotation works, because the pH can change during the process. This change depends on the starting pH and the type of electrode used. For this reason, many studies study the effect of pH by adjusting the initial pH of the solution [46]. The pH of the solution

can affect the size of the bubbles made during electroflotation. In this process, bubble sizes usually range from 20 to 70 micrometers ( $\mu\text{m}$ ), smaller than the bubbles in regular flotation systems. These tiny bubbles make electroflotation more effective because they provide more surface area for particles to stick to and help with better mixing in the water [47]. As shown in Table 6, most experiments were conducted under neutral pH conditions (pH 6–8), confirming that this range is the most effective for removing inorganic and other organic pollutants.

#### **2.3.2.3. Reaction time**

Another critical factor that affects pollutant removal and process efficiency in electrocoagulation is electrolysis time. As electrolysis time increases, more metal hydroxides are produced, which improves removal efficiency. However, the removal rate decreases and no longer increases significantly after a certain point.

For example, [48] used the EC process to remove cefazolin and COD from hospital wastewater at 15, 30, and 50 V voltages, and treatment times of 10, 30, and 50 minutes. The best result was achieved at 50 minutes, with over 92% removal efficiency. Similarly, [49] treated dairy effluent to remove COD, TSS, and  $\text{BOD}_5$  using electrocoagulation. Their tests used voltages from 10 to 60 V and times from 15 to 60 minutes. The highest removal rates were at 60 minutes and 60 volts, reaching 98.84% for COD, 97.75% for TSS, and 97.95% for  $\text{BOD}_5$ .

#### **2.3.2.4. Electrode distance**

The distance between electrodes is an essential factor in the electrocoagulation (EC) because it affects the electrostatic field between the anode and cathode. When the electrodes are too close, the electrostatic force becomes very strong, causing metal hydroxide particles, which help form flocs, to break apart due to strong collisions. This reduces EC efficiency [50]. On the other hand, when the electrodes are too far apart, the weaker electrostatic field slows down the formation of flocs [50]. It also leads to higher energy use, as more power is needed to move the ions across the larger gap. Therefore, it's essential to find the optimal electrode spacing. Many studies recommend keeping the minimum electrode distance no less than 10 mm for treating different types of wastewaters, while 20–30 mm spacing has also been used successfully in other research [51], [52], [39].

## **2.4. Filtration Technology for Industrial Wastewater Treatment**

Filtration is a key method in industrial wastewater treatment, mainly as a post-treatment step following processes like electrocoagulation. One of the most effective natural materials used for filtration is natural zeolite, particularly clinoptilolite, due to its high porosity, ion exchange capacity, and adsorption properties. Natural zeolite removes contaminants through a combination of mechanical trapping, adsorption, and cation exchange. As wastewater passes through a zeolite-packed column, suspended solids are physically filtered, while dissolved ions such as ammonium, heavy metals, and organic matter are exchanged or adsorbed onto the zeolite surface. The structure of zeolite consists of negatively charged aluminosilicate frameworks, which attract, and exchange positively charged pollutants in the water. The performance of a zeolite filtration system depends on design parameters such as column depth and particle (fraction) size.

Smaller particles offer higher surface area for adsorption but may reduce water flow, while larger particles allow better flow but with reduced contact efficiency. Several studies have confirmed the effectiveness of natural zeolite in treating various industrial wastewaters. For example, [53] reported up to 95% phosphate removal, and [54] showed successful reductions in BOD, COD, and heavy metals. [55] achieved over 80% removal of COD and ammonium using 2 mm zeolite in a 10 cm column. [56] also found that zeolite works better after electrocoagulation, as the EC process preconditions the wastewater by reducing its organic and colloidal load. These findings support the use of natural zeolite as an affordable, eco-friendly, and efficient filtration medium, particularly suitable for rural industries such as Mongolia's wool and cashmere sector.

## **3. Methodology**

### **3.1. Sample Collection**

The wastewater samples used in this study were collected on September 27th, 2024, from the effluent tank of the "Tuya" primary wool and cashmere processing industry, located in the 32nd khoroo, Songinokhairkhan district, Ulaanbaatar, Mongolia. The facility operates four scouring tanks, and the wastewater generated is discharged into a combined sewage tank within the plant. This experiment collected 25 liters of wastewater after the primary clarifier.

The collected samples were stored in cool conditions, without freezing, to preserve their quality. The laboratory experiments and analyses were carried out on February 3rd, 2025.

### 3.2. Parameters Measured

To determine the water quality parameters, analyses were conducted on the effluent of “Tuya” LLC wool and cashmere processing industry, the influent and effluent of electrocoagulation, and the effluent of filtration using the methods described in the Standard Methods for the Examination of Water and Wastewater [57]. Settleable Solids (SS) were measured using Standard Methods Section 2540 F.1, Total Solids (TS) by Section 2540 B, and Total Suspended Solids (TSS) by Section 2540 D. COD was tested using the closed reflux titration method (Section 5220 C), and oil and grease were measured by the gravimetric method (Section 5520 B). All tests were done three times for accuracy. Odor was checked using a Handheld Odor Meter, and pH was measured with a HANNA pH meter following the device's manuals. BOD<sub>5</sub> was measured using the Lovibond BOD System 600, which records oxygen use over 5 days at 20°C as described in the equipment manual.

#### 3.2.1. Settleable Solids (SS)

1000 mL of unfiltered wastewater was poured into an Imhoff cone to determine the settleable solids. The cone was placed in a stand and left undisturbed for 60 minutes initially, followed by an additional 24 hours at room temperature. After this period, the volume of solids that settled at the bottom of the cone was recorded in milliliters (mL) by the equation.

$$\text{Settleable Solids } \left( \frac{\text{mL}}{\text{L}} \right) = \text{Volume of settled solids after period (mL)} \quad (1)$$

#### 3.2.2. Total Solids (TS)

A well-mixed sample was used to determine the total solids in the wastewater sample. A clean evaporating dish was first heated at 103–105°C for 1 hour in a drying oven. After heating, the dish was cooled in a desiccator and weighed immediately to obtain the initial weight. A measured sample volume was then transferred into the dish and evaporated to dryness. The dish with the dried residue was dried again at 103–105°C for at least 1 hour, cooled in a desiccator, and reweighed. The experiment was repeated three times to ensure the reliability and accuracy of the results. The total solids were calculated using the equation 4.

$$\text{Total Solids } \left( \frac{\text{mg}}{\text{L}} \right) = \frac{(A - B) \times 1000}{V} \quad (4)$$

Where:

A = weight of dried residue + dish (mg)

B = weight of dish (mg)

V = volume of sample used (mL)



Figure 6. Apparatus Used for Total Solids Analysis

### 3.2.3. Total Suspended Solids (TSS)

To measure total suspended solids (TSS), a well-mixed wastewater sample was filtered through a pre-weighed glass fiber filter paper. The filter paper was prepared by drying at 103–105°C for 30 minutes, cooled in a desiccator, and weighed to record the initial mass. A measured volume of the sample was passed through the filter under vacuum. After filtration, the filter paper was again dried at 103–105°C for at least 1 hour, cooled in a desiccator, and reweighed. The total solids were calculated using the equation 5.

$$\text{Total Suspended Solids } \left( \frac{\text{mg}}{\text{L}} \right) = \frac{(A - B) \times 1000}{V} \quad (5)$$

Where:

A = final weight of filter paper with residue (mg)

B = initial weight of filter paper (mg)

V = volume of sample filtered (mL)

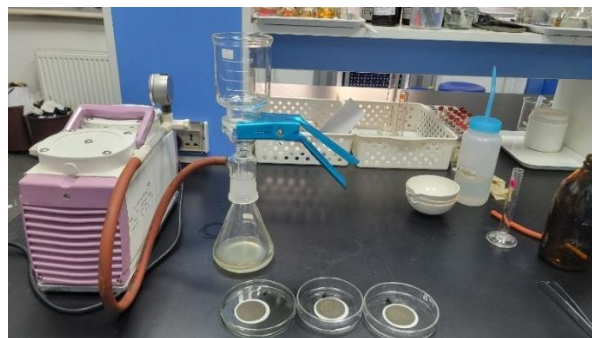


Figure 7. Apparatus Used for Total Suspended Solids Analysis

### 3.2.4. Oil and Grease

The samples were acidified to  $\text{pH} \leq 2$  using 1:1 hydrochloric acid (HCl) to determine the oil and grease concentration. The acidified sample was transferred to a separatory funnel, and the original container was rinsed with 30 mL of n-hexane, which was then added to the funnel. The mixture was shaken vigorously for 2 minutes and left to settle until the layers separated.

The organic (n-hexane) layer was filtered through a solvent-rinsed filter paper containing 10 g of anhydrous sodium sulfate ( $\text{Na}_2\text{SO}_4$ ) into a pre-weighed distillation flask. All extracts were combined in the flask, which was placed in a water bath at  $85^\circ\text{C}$  to evaporate the solvent. Finally, the flask was cooled in a desiccator for 30 minutes and weighed to determine the mass of oil and grease extracted by the equation 6.

$$\text{Oil and Grease } \left( \frac{\text{mg}}{\text{L}} \right) = \frac{(A - B) \times 1000}{V} \quad (6)$$

Where:

A = Final weight of the flask with extract (mg)

B = Initial weight of the empty flask (mg)

V = Volume of the water sample (mL)

### 3.2.5. Odor and pH

The odor of the wastewater samples was evaluated using a Handheld Odor Meter, which provides real-time odor intensity levels. Measurements were taken near the sampling point immediately after collection to ensure accuracy. In addition to the instrument-based evaluation, the researcher conducted a subjective odor sensitivity test. For this test, 50 mL Erlenmeyer flasks were used, each containing 5 mL of the raw wastewater sample diluted with distilled water at ratios of 1:1 to 1:10. The flasks were gently swirled and opened sequentially to assess the detectable odor threshold by smell.



Figure 8. Different Methods of Odor Measurement: A. Personal Smell Sensitivity, B. Odor Meter

The samples' pH was measured using a HANNA pH meter calibrated with standard buffer solutions before use. The probe was rinsed with distilled water between measurements to avoid cross-contamination. All readings were recorded after the values stabilized.

### 3.2.6. Biochemical Oxygen Demand (BOD)

The BOD<sub>5</sub> of the wastewater was determined using the Lovibond BOD system model 600. This instrument measures the amount of dissolved oxygen microorganisms consume over a 5-day incubation period at 20°C in the dark. Samples were selected within the required measurement range, and reagents were used according to the manufacturer's instructions in the equipment manual.



Figure 9. Apparatus used for Biochemical Oxygen Demand, BD600

### 3.2.7. Chemical Oxygen Demand (COD)

The closed reflux titrimetric method determined the sample's Chemical Oxygen Demand (COD). First, 2.5 mL of the water sample was carefully pipetted into a COD digestion vial containing a known amount of potassium dichromate ( $K_2Cr_2O_7$ ) and sulfuric acid with silver sulfate as a catalyst. Mercuric sulfate was added to reduce chloride interference. The vial was then tightly sealed and placed into a DRB200 digital reactor block, where the digestion process was conducted at 150°C for two hours. After digestion, the vial was removed and cooled to room temperature. The contents were then transferred into an Erlenmeyer flask for titration.

For the titration, the solution was titrated with ferrous ammonium sulfate (FAS) until the color changed from blue-green to reddish-brown, indicating the endpoint. A blank sample (distilled water with reagents) was also prepared and digested similarly. The volume of FAS used in both the sample and the blank was recorded, and the COD was calculated using the equation 7.

$$\text{COD} \left( \frac{\text{mg } O_2}{\text{L}} \right) = \frac{(A - B) \times N \times 8000}{V} \quad (7)$$

Where:

A = volume of FAS used for blank (mL)

B = volume of FAS used for the sample (mL)

N = normality of FAS (usually 0.1 N)

8000 = equivalent weight of oxygen × 1000

V = Volume of the water sample (mL)

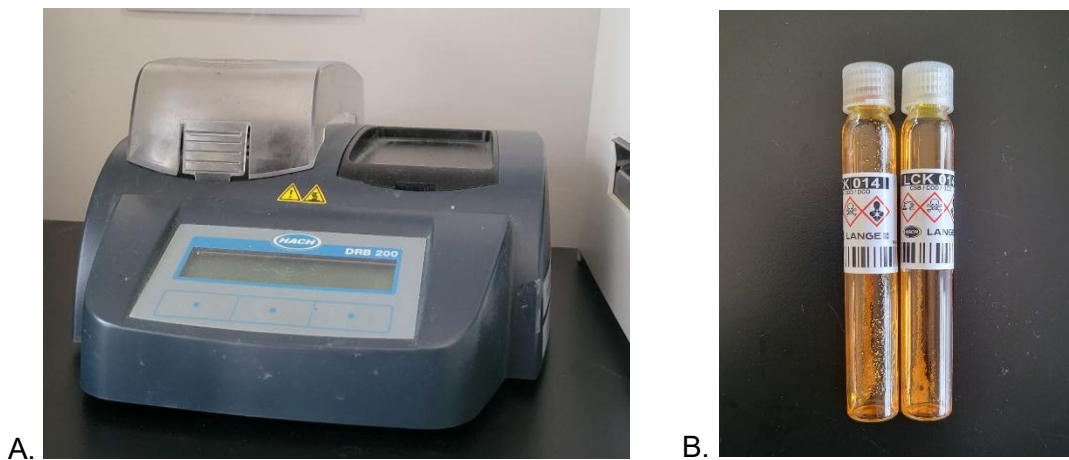


Figure 10. Apparatus Used for COD Determination, A. Hach DRB 200, B. Test tube 10mm x 80mm

### 3.3. Electrocoagulation Setup

The electrocoagulation experiments were carried out in a designed reactor built specifically for treating wastewater using different types of electrodes. Detailed information about the reactor's design, dimensions, and setup is provided in Appendix A. Previous studies found that the Al–Al electrode was the most effective, so the 110 mm × 40 mm × 1 mm electrodes were made to fit the size of the electrocoagulation reactor cell. The treatment time was set to 60 minutes, with an electrode distance of 30 mm, and a voltage of 15V, while currents of 1, 2, 3, 4, and 5 A were used. The pH of the wastewater was neutral, ranging between 6 and 7. To address organic pollution, copper–aluminum (Cu anode, Al cathode), iron–aluminum (Fe anode, Al cathode), and aluminum–aluminum (Al–Al) electrodes were tested, with smaller electrodes (128 mm × 20 mm × 1 mm). In each run, 500 mL of wool scouring effluent is discharged into the reactor for treatment. After each run, treated water samples were collected for further analysis, and the electrodes were cleaned before reuse.

Table 7. Experiment Conditions of Electrocoagulation

Electrode and Arrangement	Dimensions (mm)	Conditions	Applied Current (A)
Al – Al	110 × 40 × 1	Power - 15V, reaction time - 60 min, distance of electrode – 30 mm, pH condition - 7	1, 2,3,4 and 5
Cu – Al (Cu anode, Al cathode)			
Fe – Al (Fe anode, Al cathode)	128 × 20 × 1		5
Al - Al			

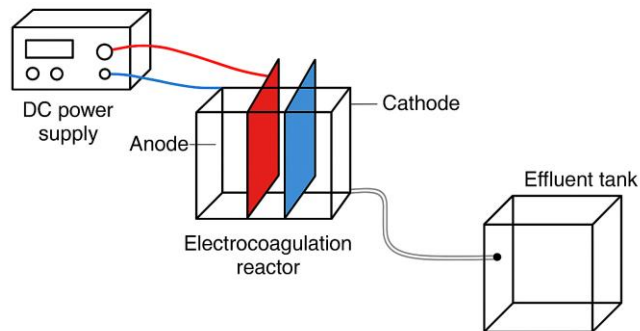


Figure 11. Setup of Electrocoagulation

### 3.4. Filtration Setup

Filtration experiments were conducted using natural zeolite as the filter material. The raw zeolite was first crushed with a jaw crusher, followed by cone and roll crushers to make the particles smaller. The crushed zeolite was then sorted using mesh sizes of 2 mm, 4 mm, 6 mm, 8 mm, and 10 mm to separate it into different particle sizes. For the filtration tests, particles of 2 mm and 10 mm were chosen. The experiments took place in a cylindrical filter column with a diameter of 12 cm and a filter depth of 10 cm. Two 1.5

L samples were used: one was raw wastewater and the other had been treated with electrocoagulation using three electrodes.

The filtration experiments were conducted with two types of samples: the influent of the electrocoagulation sample was filtered for 2 hours, and the effluent of the electrocoagulation was filtered for 24 hours. This setup was used to compare filtration efficiency over different treatment times.

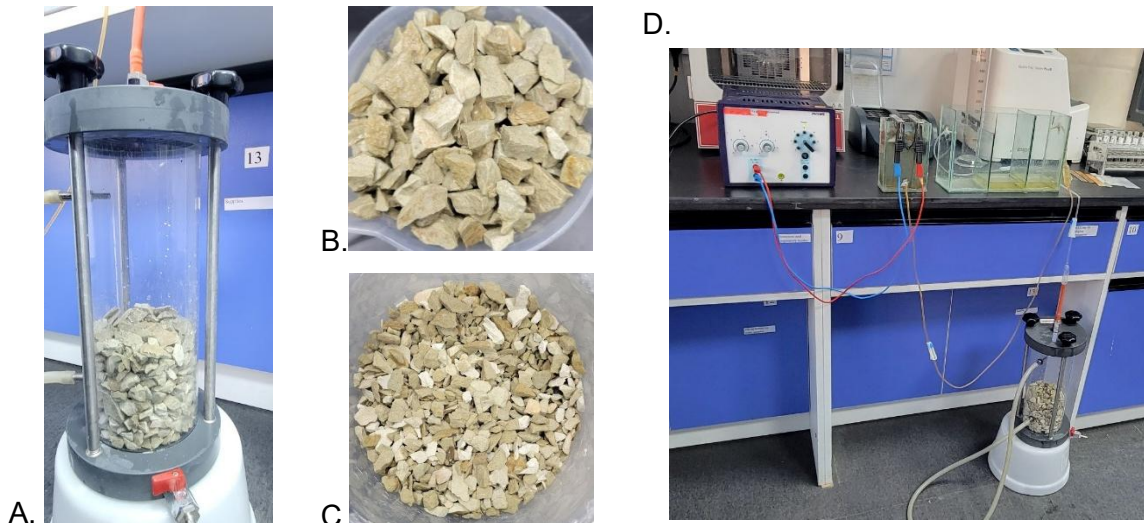


Figure 12. Filtration Setup, A. Filtration cylinder, B. 10 mm fraction size of zeolite, C. 2 mm fraction size of zeolite, D. Constructed Electroflotation and Filtration

Table 8. Experiment Conditions of Filtration

Sample	Condition	Time (hour)
Effluent of EC	Water head = 20 cm	24
	Filter bed height = 10 cm	
	Fraction size = 2, 10mm	

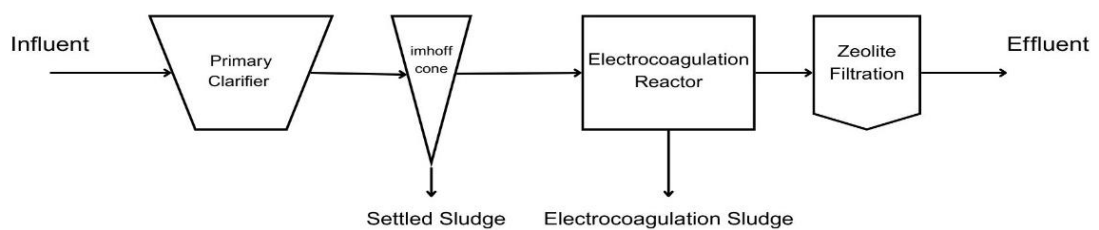


Figure 13. Simplified Flowchart of Experiments

## 4. Results and Discussion

### 4.1. Raw Wastewater Quality Analysis

The effluent from the processing industry had high levels of pollution. In the effluent, total suspended solids (TSS) were between 1400 and 1600 mg/L, and total solids (TS) were between 3300 and 4300 mg/L. After passing through a primary clarifier (Imhoff cone), the wastewater quality improved. TSS dropped to around 370 mg/L, and TS decreased to between 2100 and 3600 mg/L. This shows that the clarifier removed about 50% of the solids.

Table 9. Measurement Results of Settleable Solids Using a 1000 mL Imhoff Cone

Duration (hours)	Settleable Solid (mL/L)			Mean	Standard Dev	Error	Relative Error	Variance
	Trial 1	Trial 2	Trial 3					
1	0.004	0.005	0.0045	0.0045	0.00041	0.00024	5.24%	$1.67 \times 10^{-7}$
24	0.02	0.02	0.025	0.0217	0.00236	0.00136	6.28%	$5.56 \times 10^{-6}$



Figure 14. Difference in Settleable Solids Over Time Duration: (A) After 2 Hour, (B) After 24 Hours

The influent of electrocoagulation was assumed to have a high COD value. To avoid excessive use of the FAS solution, the sample was diluted 30-50 times. The chemical oxygen demand (COD) ranged from 5360 to 6968 mg/L, and the biological oxygen demand over 5 days ( $BOD_5$ ) ranged from 575 to 688 mg/L. The influent also had a strong bad smell, which is common in scouring processes because of oils, waxes, and dirt.

After the Imhoff cone clarifier, the COD (Chemical Oxygen Demand) dropped to between 1340 and 2144 mg/L due to the removal of organic matter during the clarification process. The Imhoff cone clarifier helps to settle out suspended solids and some of the organic contaminants, which in turn reduces the oxygen demand in the wastewater. The pH of the influent was slightly alkaline to neutral. The pH of the clarified water was slightly alkaline, ranging from 7.09 to 7.16, which is normal for wool scouring industry wastewater. Although solids levels have been lowered, clarifier wastewater still contains high pollution potential, meaning additional treatment must be applied to meet discharge standards. The elevated odor levels in the clarified samples, ranging from 619 to 687, indicate that significant contaminants, likely organic, remain even after the initial clarifying step. In terms of my smell sensitivity, this level could be perceived as strongly high, due to wastewater having been stored for a long time in refrigeration. The odor was eliminated by diluting it 1:8 with water; the odor meter level was similar.

*Table 10. The Influent Characteristic for Electrocoagulation*

Definition	TSS mg/L	TS mg/L	COD (mg O <sub>2</sub> /L)	BOD5 (mg O <sub>2</sub> /L)	Odor	Grease mg/L	pH
Raw sample	1500	4300	5896	688	-	-	-
	1600	3300	6968	575	-	-	-
	1400	4300	5360	579	-	-	-
Mean	1500	3966.67	6075	614	-	-	-
Standard Dev	81.65	471.40	668.51	52.35	-	-	-
Error	47.14	272.17	385.96	30.23	-	-	-
Relative Error	3.1427	6.8613	6.3537	4.9227	-	-	-
Clarifier (Imhoff cone)	370	2100	1340	-	619	20.4	7.16
	370	2400	1876	-	683	23.2	7.09
	370	3600	2144	-	687	21.2	7.09
Mean	370.00	2700.00	1786.67	-	663.00	21.60	7.11
Standard Dev	0.00	648.07	334.25	-	31.16	1.18	0.03
Error	0.00	374.17	192.98	-	17.99	0.68	0.02
Relative Error	0.0000	13.8580	10.8012	-	2.7131	3.1475	0.2678

## 4.2. Electrocoagulation Treatment Efficiency

The effluent characteristics from the electrocoagulation experiment with Al–Al electrodes (110 mm × 40 mm × 1 mm) under varying currents (1, 2, 3, 4, and 5 A) show significant improvements in the quality of the wastewater after treatment, as evidenced by reductions in TSS, TS, COD, and BOD. As indicated by Table 9 and Table 10, the findings show that as the current rises, the efficiency of processes also increases with considerable decreases in parameters like TSS, TS, COD, and BOD.

Table 11. Effluent Characteristics of Electrocoagulation Experiment

Electrode	Current (A)	TSS (mg/L)	TS (mg/L)	COD (mg O <sub>2</sub> /L)	BOD (mg O <sub>2</sub> /L)
Influent (mean value)		370	2700	1789.67	614
Al–Al	1	340	1793.33	278.72	513
	2	290	1500	231.45	488
	3	245.33	1040	178.67	420
	4	156.67	810	113.66	375
	5	66.67	423.33	55.39	73

Table 12. Treatment Efficiency of Electrocoagulation with Al- Al

Current (A)	TSS	TS	COD	BOD
	Removal (%)			
1	8.11	33.58	84.43	16.45
2	21.62	44.44	87.07	20.52
3	33.69	61.48	90.02	31.6
4	57.66	70	93.65	38.93
5	81.98	84.32	96.91	88.11

This study investigated the effect of electric current on the electrocoagulation process using a 500 mL wastewater sample with a pH of 7. Most importantly, the optimal removal rates were obtained under neutral conditions. It may be attributed to pH impacts on bubble sizes, the extent of the soluble electrode's solubility, and the coagulation

mechanism. It can be derived from the findings of other studies that the medium's pH significantly impacts the chemical species of the anode material. At a low pH of 2-3, chemical species such as  $Al(OH)^{2+}$  and  $Al^{3+}$  are developed,  $Al^{3+}$  and  $OH^-$  ions are generated at pHs such as 4-9 and elevated pH (10-14), rates of removal are decreased because a lower percentage of aluminum ions is produced [30][47]. Besides, literature showed that the hydrogen bubble diameter was smallest in a neutral environment devoid of cathode material influence. Still, in the case of an acid medium, the cathode material affects the bubble diameter [58]. Therefore, the optimal start-up pH would be 7.

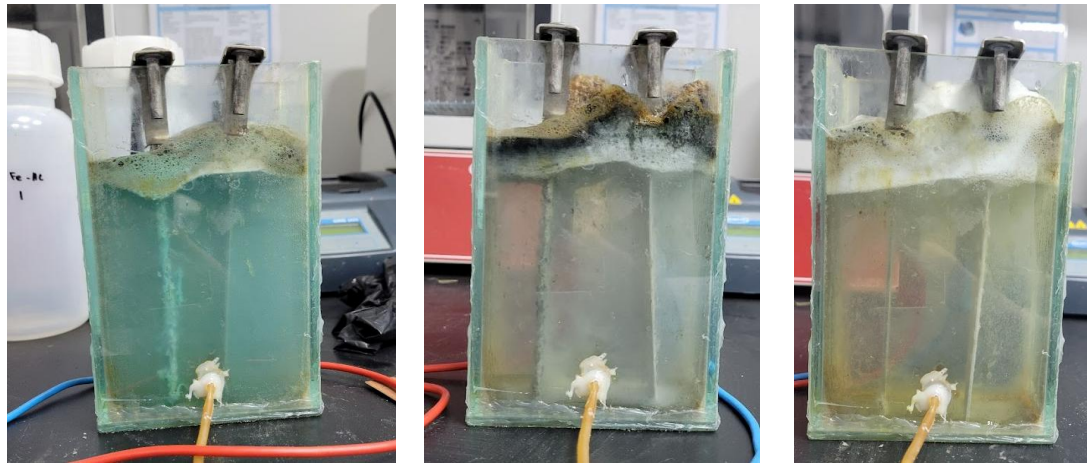
[59], [60] studies found that increasing the current applied leads to greater bubble density with a smaller diameter, improving electrocoagulation efficiency. Further, the increased number of gas bubbles improves the collision between suspended particles and bubbles, enhancing the removal efficiency of the contaminant. As the applied current increased, the removal rates of pollutants—including TSS, TS, COD, and BOD—also improved significantly. This can be attributed to the current's direct impact on key operational factors such as bubble generation rate, bubble size, coagulant dosage, and mass transfer at the electrodes [59].

TSS removal efficiency increased from 8.11% at 1 A to 81.98% at 5 A, indicating that higher current densities enhance floc formation and sedimentation. Similarly, TS removal rose from 33.58% to 84.32%, showing effective reduction in both suspended and dissolved solids. COD removal reached up to 96.91% at 5 A, which demonstrates the high efficiency of electrocoagulation in breaking down complex organic compounds. BOD removal improved from 16.45% to 88.11%, confirming that biodegradable substances were also effectively removed at higher current levels.

The optimized conditions for the electrocoagulation process are 15V, 5A, 30 mm electrode distance, and a treatment time of 1 hour, which results in the most efficient removal of pollutants from wastewater.

Following the optimization of current conditions, three different electrode combinations were operated and tested under the same working conditions. In this study, three different electrode combinations—Cu–Al, Fe–Al, and Al–Al—were tested to compare their effectiveness in electrocoagulation treatment of wastewater. Table 11 showed that all electrode types of significantly reduced pollution levels, but their performance varied by parameter. The Al–Al electrodes achieved the best reduction in total suspended solids (TSS), lowering it from 370 mg/L to 46.7 mg/L, and total solids (TS) from 2700 mg/L to 180 mg/L. This suggests that Al–Al is especially effective for removing solid particles. On the other hand, the Cu–Al electrodes were most efficient in

removing organic pollutants, with chemical oxygen demand (COD) reduced from 1789.67 mg/L to 23.2 mg/L, and biological oxygen demand (BOD<sub>5</sub>) from 614 mg/L to just 5.0 mg/L. The Fe–Al combination also showed good performance, especially in balancing solid and organic removal. All electrode types also helped reduce odor and grease, with Fe–Al showing the lowest grease concentration at 13.2 mg/L. In summary, Cu–Al electrodes are most suitable for organic matter removal, while Al–Al electrodes are best for solid removal, and Fe–Al offers a balanced treatment option.



A. Cu – Al electrodes

B. Fe – Al electrodes

C. Al–Al electrodes

*Figure 15. During the Electrocoagulation Experiment*

As shown in Figure 15, during the electrocoagulation experiment, the color differences in the effluent and the extent of electrode fouling were influenced by the type of electrode materials used. The setup with Cu–Al electrodes produced a greenish effluent, which is attributed to the formation of copper hydroxide or basic copper carbonate as copper oxidized and reacted with hydroxide ions in the solution. This green coloration indicates the presence of copper corrosion products. In the case of Fe–Al electrodes, the effluent appeared dark yellow due to the formation of iron hydroxides such as Fe(OH)<sub>3</sub> and iron oxides, which are typical of iron corrosion and precipitation during electrocoagulation. These compounds tend to form heavier flocs, contributing to both the darker color and more severe electrode fouling. Meanwhile, the Al–Al electrodes resulted in a lighter yellow effluent, indicating the presence of aluminum hydroxide flocs (Al(OH)<sub>3</sub>), which are effective at adsorbing impurities and typically produce a clearer solution. Despite aluminum also undergoing corrosion, the fouling appeared less severe compared to copper and iron. After three trials, all electrodes showed significant fouling and corrosion, requiring thorough cleaning to maintain their performance and ensure consistent treatment efficiency.

Table 13. Result of Electrocoagulation with Different Electrodes

Electrode (128 mm × 20 mm × 1 mm).	TSS (mg/L)	TS (mg/L)	COD (mg O <sub>2</sub> /L)	BOD5 (mg O <sub>2</sub> /L)	Odor	Grease mg/L	pH
Influent(mean)	370	2700	1789.67	614	663.00	21.60	7.11
Cu anode, Al cathode	76.7	240.0	23.2	5.0	155.7	15.4	6.95
Fe anode, Al cathode	73.3	186.7	29.7	25.0	218.0	13.2	7.01
(Al–Al)	46.7	180.0	55.4	68.0	196.7	19.3	7.08

Table 14. Treatment Efficiency of Electrocoagulation with Different Electrodes

Electrode	TSS	TS	COD	BOD	Odor	Oil & Grease	Total
Efficient (%)							
Cu -Al	79.27	91.11	98.7	99.19	76.52	28.7	78.92
Fe-Al	80.19	93.09	98.34	95.93	67.12	38.81	78.91
Al-Al	87.38	93.33	96.9	88.93	70.33	10.65	74.59



Figure 16. Visual Difference of Influent and Effluent of Electrocoagulation

Therefore, using the optimized condition, the Cu–Al electrode was the optimum electrode for filtration with natural zeolite during the next filtration experiment.

#### 4.3. Filtration Performance

The effluent from the Cu–Al electrocoagulation process, which showed the highest removal efficiency of COD and BOD, was used as the influent for the filtration experiment. This step aimed to further polish the treated water by removing remaining suspended solids and COD.

Table 15. Removal Efficiency of Electrocoagulation Influent After 2 Hour Filtration

Fraction Size	Parameter	Influent	Effluent	Efficiency (%)
10 mm	COD (mg O <sub>2</sub> /L)	1786.67	1690	5.41
	BOD (mg O <sub>2</sub> /L)	614	575	6.35
	TS (mg/L)	2700	2450	9.26
	TSS (mg/L)	370	360	2.70
2 mm	COD (mg O <sub>2</sub> /L)	1786.67	1680	5.97
	BOD (mg O <sub>2</sub> /L)	614	-	-
	TS (mg/L)	2700	1479	45.22
	TSS (mg/L)	370	296	20

This experiment aimed to compare the filtration performance of influent and effluent of electrocoagulation, using natural zeolite as the filtration medium. To achieve this, both influent and effluent with Cu–Al electrocoagulation was filtered for comparison. The influent was left to settle for 2 hours before filtration, which may have caused partial clarification, but overall, the results were unsatisfactory.

Initially, three zeolite particles, 2 mm, 6 mm, and 10 mm—were selected for testing. However, during the preparation of the 6 mm fraction, it was found that the sample did not reach the required height (10 cm), making it impossible to form a complete filter bed. Therefore, the 6 mm size was excluded, and the study proceeded using only the smallest (2 mm) and largest (10 mm) particle sizes. An important issue encountered was the failure to properly rinse the zeolite before use, which resulted in elevated total solids (TS) in some filtrate samples. This affected the accuracy of the results and made it necessary to repeat the filtration experiments with proper rinsing.

Additionally, BOD measurements were unreliable, often falling outside the instrument's detectable range or showing very low values. Due to this inconsistency, BOD was excluded as a performance parameter in the filtration analysis. Although COD and TSS results showed general improvement, the overall filtration performance was not satisfactory. As shown as Table 13, with 2 mm zeolite, COD removal was 5.97% and TSS removal was 20%, indicating some effectiveness due to mechanical filtration and adsorption. However, the 10 mm fraction showed weaker performance, likely due to lower surface area for interaction and adsorption.

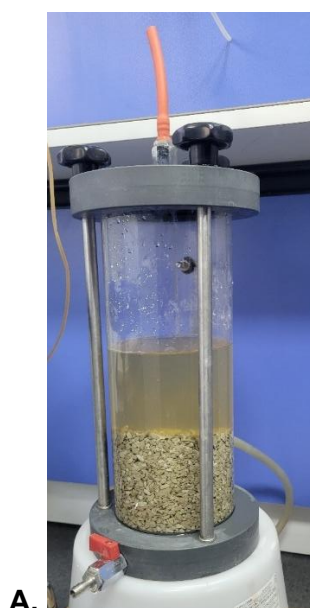
It was observed that longer contact time increases filtration efficiency. Therefore, the next stage of the experiment was to use a fixed 24-hour filtration period to evaluate the effect

of contact time more accurately. Since a strong correlation between COD and TSS was observed, and COD more consistently reflected organic pollutant levels, it was decided to focus exclusively on COD as the main evaluation parameter in further filtration experiments.

*Table 16. Removal Efficiency of Electrocoagulation Effluent After 24-Hour Filtration*

Fraction Size	Parameter	Influent	Effluent	Efficiency (%)
10 mm	COD (mg O <sub>2</sub> /L)	21.44	29.5	-
		18.76	27.3	
		29.48	31.02	
	Mean	23.23	21.43	7.721
2 mm	COD (mg O <sub>2</sub> /L)	21.44	22.3	-
		18.76	20.1	
		29.48	21.9	
	Mean	23.23	17.42	24.986

As shown in Table 14, the COD removal performance of zeolite filtration was evaluated using two different particle sizes: 10 mm and 2 mm, under gravity flow through a 10 cm high column with a 20 cm water head. For the 10 mm fraction, COD concentrations unexpectedly increased in all three samples. The calculated mean COD removal efficiency was 7.72%, suggesting that the coarse zeolite may have contributed to COD release, possibly due to trapped organic matter or insufficient rinsing before use. In contrast, the 2 mm zeolite showed improved performance with COD decreasing, resulting in a mean removal efficiency of 24.99%.



*Figure 17. Visual Difference of Filtration, a. Immediately into filtration, B. After 24 hours of standing post-filtration*

The electrocoagulation effluent flow duration was 3 minutes and 15 seconds for 10 mm zeolite and 5 minutes and 21 seconds for 2 mm. This result reflects the impact of particle size on hydraulic conductivity. The larger 10 mm zeolite created larger pore spaces, allowing water to pass through more quickly. On the other hand, smaller 2 mm particles reduced the flow rate due to higher resistance and tighter packing, which increased the water's retention time within the column. Although longer contact time theoretically enhances treatment through improved adsorption and ion exchange, the results suggest that other factors, such as zeolite preparation, column compaction, and fines release, may significantly influence filtration performance.

## 5. Conclusion

This study investigated the treatment of wastewater from the wool and cashmere processing industry using a combined method of Imhoff cone clarification, electrocoagulation, and natural zeolite filtration. The Imhoff cone clarifier successfully reduced TSS by approximately 50%, significantly lowering the suspended solids and organic load before further treatment.

In the electrocoagulation stage, three electrode types—Al–Al, Cu–Al, and Fe–Al—were tested under optimized conditions (15V, 5A, 30 mm electrode spacing, 1-hour treatment). The results showed that Al–Al electrodes were the most effective in removing solids, reducing TSS and TS to 46.7 mg/L and 180.0 mg/L, respectively. Cu–Al electrodes achieved the highest removal of organic pollutants, with COD decreasing to 23.2 mg/L and BOD<sub>5</sub> to just 5.0 mg/L, representing removal efficiencies of 98.7% and 99.2%, respectively. Meanwhile, Fe–Al electrodes demonstrated a balanced performance, showing good efficiency in both solid and organic removal, including the lowest grease concentration (13.2 mg/L) and COD of 29.7 mg/L. Overall, Cu–Al was selected as the most suitable electrode combination for follow-up filtration due to its excellent COD and BOD reduction. In the final step, zeolite filtration showed better results with 2 mm particles, removing 25% of COD after 24 hours. The 10 mm particles were less effective, and in some cases, COD increased because the zeolite did not rinse well. Overall, the best results came from using Cu–Al electrocoagulation. This simple and low-cost method worked well in the lab and met the MNS 6561:2024 standard, so it is recommended to test this treatment system at real factories to see how it works in real conditions.

In conclusion, the combination of Imhoff clarification, electrocoagulation with Cu–Al electrodes presents a viable, low-cost, and scalable treatment strategy for industrial wastewater in Mongolia’s textile sector. Future research should focus on scaling up, optimizing zeolite columns, and integrating this approach into existing wastewater treatment systems.

## 6. Recommendations

The following areas recommended for additional research are as follows:

- Evaluate the treatment system using an increased volume of wastewater and more regular assessments. This will assess the system's performance on a larger scale and facilitate enhanced data analysis.
- Extend the testing of electrocoagulation, as it was only conducted briefly in the lab. Given its good performance in removing COD and TSS, longer-term and varied condition testing is needed to fully evaluate its effectiveness.
- Consider integrating electrocoagulation with Cu-Al other combinations to evaluate potential enhancements in efficiency of treatment.
- Conduct kinetic investigations of electrocoagulation to ascertain the reaction rates. This can facilitate the design of a larger and more efficient reactor.
- Improve the filtration design by testing different zeolite particle sizes and filtration times to find the best setup.
- Try using other natural or low-cost materials for filtration, such as coal ash, sand, or activated carbon, and compare their performance with zeolite
- Analyze the operational expenses of the system at full capacity and juxtapose them with conventional wastewater treatment techniques to see which is more economical and feasible.

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## 8. Appendix

### Appendix A. Experimental Results and Statistics analysis

Table A 1. Results of Total Solids and Statistics Analysis

No	Definition	Explanation	TS mg/L	Mean	Standard Dev	Error	Relative Error
1	Raw Sample	the primary clarifier of the wool scouring factory	4300  3300 4300	3966.66667	471.404521	272.16553	6.86131581
		After 24 h, the Imhoff cone settled in the laboratory	2100  2400 3600	2700	648.07407	374.16574	13.8579903
2	Clarifier	1A current	1520 1880 1980	1793.33333	197.540432	114.05002	6.35966663
		2A current	1420 1500 1580	1500	65.3197265	37.712362	2.51415744
3	Al-Al (110 mm × 40 mm × 1 mm)	3A current	980 1040 1100	1040	48.9897949	28.284271	2.71964147
		4A current	880 760 790	810	50.9901951	29.439203	3.63446949
4	Cu (anode) -	Voltage -15 V, current -	400 200	240	117.756812	67.986927	28.3278862
		5A current	600 200 470	423.333333	166.599987	96.186547	2.27212316

	Al (cathode)	5A, duration	120				
	Fe (anode)- Al (cathode)	time - 1 h, distance - 3 cm	150 240 170	186.666667	38.586123	22.277709	11.9344867
5							
	Al-Al (128 mm x 20 mm x 1 mm)		180 180 180	180	0	0	0
6							

Table A 2. Experimental Results of Total Solids

No	Definition	Explanation	TSS mg/L	Mean	Standard Dev	Error	Relative Error
1	Raw Sample	the primary clarifier of the wool scouring factory	1500 1600 1400	1500	81.6496581	47.140452	3.14269681
		After 24 h, the Imhoff cone settled in the laboratory	370 370 370	370	1.1603E-12	6.699E-13	1.8106E-13
		1A current	380 330 310	340	29.4392029	16.996732	4.99903874
3	Al-Al (110 mm x 40 mm x 1 mm)	2A current	290 280 300	290	8.16496581	4.7140452	1.62553283
		3A current	260 256 220	245.333333	17.9876501	10.385175	4.23308748
		4A current	150	156.666667	6.23609564	3.6004115	2.298135

			165				
			155				
			40				
	5A current		90	66.6666667	20.5480467	11.86342	1.77951304
			70				
	Cu		70				
4	(anode) - Al (cathode)	Voltage -15 V, current - 5A, duration time - 1 h, distance - 3 cm	80	76.6666667	4.71404521	2.7216553	3.54998513
	Fe		70				
5	(anode)- Al (cathode)		80	73.3333333	4.71404521	2.7216553	3.7113481
	Al-Al (128 mm x 20 mm x 1 mm)		50				
6			40	46.6666667	4.71404521	2.7216553	0.58321184
			50				

Table A 3. Experimental Results of Chemical Oxygen Demand using Closed Reflux, Titrimetric Method

No	Definition	Explanation	COD mg O2/L	Mean	Standard Dev	Error	Relative Error
1	Raw Sample	the primary clarifier of the wool scouring factory	5896 6968 5360	6074.66667	668.509453	385.96411	6.35366735
2	Clarifier	After 24 h, the Imhoff cone settled in the laboratory	1340 1876 2144	1786.66667	334.254727	192.98206	10.8012345
3		1A current	353.76	278.72	54.6614892	31.558825	11.3227703

		225.12				
		257.28				
		226.75				
	2A current	256.94	231.416667	19.2199451	11.09664	4.79509131
		210.56				
	Al-Al	198.32				
	(110 mm	3A current	182.24	178.666667	17.6870976	10.211651
	× 40 mm		155.44			5.71547607
	× 1 mm)		115.09			
		4A current	100.45	113.663333	10.2559425	5.9212711
			125.45			5.20948221
		48.24				
		5A current	64.32	55.3866667	6.68509453	3.8596411
			53.6			0.69685384
	Cu	21.44				
4	(anode) -	18.76	23.2266667	4.5551241	2.6299021	11.3227703
	Al					
	(cathode)	Voltage -15	29.48			
		V, current -				
	Fe	5A,	19.296			
5	(anode)-	duration	48.24	29.6586667	13.1681091	7.6026113
	Al	time - 1 h,	21.44			25.6336922
	(cathode)	distance - 3				
	Al-Al	cm	48.24			
6	(128 mm		64.32	55.3866667	6.68509453	3.8596411
	× 20 mm		53.6			0.69685384
	× 1 mm)					

Table A 4. Experimental Results of Biochemical Oxygen Demand

No	Definition	Explanation	BOD mg O <sub>2</sub> /L
1	Raw Sample	Wastewater collected from the primary clarifier of the wool scouring factory	688 575 579
2		1A current	513

		2A current	488
	Al-Al (110 mm × 40 mm × 1 mm)	3A current	420
		4A current	375
		5A current	73
3	Cu (anode) -Al (cathode)		5
4	Fe (anode)-Al (cathode)	Voltage -15 V, current -5A, duration time - 1 h, distance - 3 cm	25
5	Al-Al (128 mm × 20 mm × 1 mm)		68

Table A 5. Experimental Results of Oil & Grease, pH, and Odor

No	Definitio n	Explanatio n	pH	Odor (level )	Oil and Greas e	Mean	Standar d Dev	Error	Rela tive Error
1	Clarifier	After 24 h, the Imhoff cone settled in the laboratory	7.1 6	619	20.4	21.6	1.17756 8	0.679 869	3.14 7543
			7.0 9	683	23.2				
			7.0 9	687	21.2				
			6.9 8	148	13.7				
2	Cu (anode) -Al (cathod e)	Voltage - 15 V, current - 5A, duration time - 1 h, distance - 3 cm	6.9 2	126	18.6	15.433 33	2.24251 8	1.294 719	8.38 9106
			6.9 5	193	14				
			6.7 9	211	12				
3	Fe (anode)-		6.7 9	211	12	13.166 67	0.90308 1	0.521 394	3.95 9956

Al	6.7	198	13.3				
(cathod	2						
e)	6.8	245	14.2				
Al-Al	7.0	198	19.7				
(128	1						
4 mm x	7.1	178	20.2	19.266	0.98770	0.570	2.95
20 mm	5			67	2	25	9776
x 1 mm)	7.0	214	17.9				
	9						

## Appendix B. Experimental Apparatus and Procedure

This appendix clearly explains the experimental setup utilized within the research and the procedures adopted for conducting the experiments. It details materials, equipment, and setup for electrocoagulation and filtration experiments.

### 1. Biochemical Oxygen Demand (BOD)

The Lovibond BOD 600 system measures the Biochemical Oxygen Demand (BOD). The initial BOD was assumed to be high, with a range of 0-800 mg/L. After the electrocoagulation experiment, the BOD was supposed to decrease, and the range was calculated to be 0-200 mg/L. During BOD measurement, the values were initially below range, and after 1-2 days of incubation, the measurements started on the third day, without the need for bacterial inoculation. The measurements continued for five days. The nitrification inhibitor ATH dosage was applied according to the manual.

### 2. Chemical Oxygen Demand (COD)

The Standard Potassium Dichromate Digestion Solution was made by dissolving 2.4515 g of  $K_2Cr_2O_7$  (primary standard grade, previously dried at 150°C for 2 hours) in 250 mL of distilled water. 83.5 mL of concentrated  $H_2SO_4$  and 16.65 g of  $HgSO_4$  were added, and the solution was diluted to a final volume of 500 mL with distilled water.

The Sulfuric Acid Reagent was made by dissolving 2.75 g of  $Ag_2SO_4$  (technical or reagent grade) powder or crystals in 500 mL of concentrated  $H_2SO_4$ . It was left standing for 1-2 days to dissolve completely. The Ferroin Indicator Solution was obtained by dissolving 1.485 g of 1,10-phenanthroline monohydrate and 695 mg of  $FeSO_4 \cdot 7H_2O$  in 100 mL of distilled water. Finally, the Ferrous Ammonium Sulfate (FAS) Titrant Solution was prepared by dissolving 39.2 g of  $Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$  in distilled water. 20 mL of

concentrated H<sub>2</sub>SO<sub>4</sub> was added, the solution was cooled, and diluted to a final volume of 1000 mL.

The digestion vessels used had a volume of 6 mL. According to Table B1, five digestive vessels were prepared, each containing one sample for titration. A total of 3 titration experiments were performed. The digestion process was performed using the Hach DRB 200 at 150°C for 2 hours. The Hach DRB 200 can run 20 samples simultaneously. It can be used with standard test tubes or digestion vials, usually 16 mm x 100 mm or 25 mL samples. Its temperature range is from 50°C to 170°C, making it suitable for many digestion applications. After digestion, the samples were cooled to room temperature, following the procedure outlined in the instructions. Afterward, titration was performed.



*Figure B. 1. Observation of Color Change During Reaction, A. Before digestion and after digestion, B. Sample before the end point, C. Sample after the end point.*

*Table B. 1. Reagent and Sample Volumes for COD Determination*

Digestion Vessel	Sample (mL)	Digestion Solution (mL)	Sulfuric Acid Reagent (mL)	Total Volume (10mL)
Standard 10mL	2.5	1.5	3.5	7.5
Used a 6 mL test tube	1.5	0.9	2.1	4.5

### 3. Total Solids and Total Suspended Solids

For Total Suspended Solids (TSS) and Total Solids (TS), a 100 mL raw sample was utilized. Glass fiber filter paper with a pore size of 0.6 µm was used to measure TSS. However, owing to the tiny pore size, I had the drawback of clogging the filter paper during the filtration of raw samples. This made it challenging to filter the solids, slowing down the filtration rate and requiring frequent cleaning of the filter paper. Hence, the sample was divided into 10 mL for easy handling and analysis. To facilitate the filtration, the vacuum pump DVP-30B1 was used, which provided a steady rate of filtration.



*Figure B. 2. Filtration Setup and Glass Fiber Filter Paper Used for TSS Measurement*

The odor was relatively high, so the measurements were taken within a BioBase Fume Hood (Model: FH1000(E)). Total solids were measured with a Faithful Water Bath. A 100 mL sample was evaporated for 2 hours until no water remained. The lab drying oven, JK-DO-9240A, was used to dry filter papers and dishes. The filters and dishes were placed in a desiccator to cool and avoid moisture absorption before weighing.

#### 4. Odor

A Handheld Odor Meter (Model XYZ) was used to measure the wastewater samples' odor intensity. The meter ranges from 0-999, expressing odor intensity as the concentration of volatile chemicals in air. In addition to the odor meter usage, subjective odor sensitivity tests were conducted. 50 mL of wastewater sample was measured and diluted by utilizing distilled water in a ratio from 1:1 to 1:10. After dilution, the researcher smelled the sample, and the intensity of the smell detected was compared to the readings from the handheld odor meter. This allowed for comparison of the human sense of smell with meter readings, which made it possible to determine the odor meter reading accuracy against the sense of smell, validating the device's accuracy in detecting odor.

*Table B. 2. Level of Handheld Odor Meter*

<b>Reading (0–999 scale)</b>	<b>Odor Intensity</b>
0–100	Low or negligible odor
101–300	Mild odor
301–600	Noticeable/moderate
601–800	Strong odor
801–999	Very strong odor