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Sustainable Electrochemical Treatment of Textile Effluents Using Recycled Electrode Scrap: A Circular Approach to Wastewater Management

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ABSTRACT
Textile industries, designated as 'Red Category' by India's Ministry of Environment, are significant contributors to water pollution due to effluents rich in dyes, chemicals, and heavy metals. This study explores the reuse of scrap electrodes—copper, mild steel, and aluminium—in Electrochemically Assisted Coagulation (ECAC) for treating final discharge from indigenous textile industries. Lab-scale experiments assessed removal efficiency for Chemical Oxygen Demand (COD), colour, Total Suspended Solids (TSS), and Total Dissolved Solids (TDS) under varying current densities and treatment durations. Results showed maximum COD removal (83.3%), TSS (96.4%), TDS (98.3%), and colour (93.1%) using copper-mild steel electrodes at 60 mA/cm² in 90 minutes. Reusing scrap electrodes significantly reduces treatment costs and environmental burden, aligning with principles of the circular economy and sustainable industrial practices. This eco-innovative method offers a low-cost, scalable alternative for wastewater remediation and supports SDG targets on water quality, sustainable industry, and responsible resource consumption.
Key words: Electrochemically Assisted Coagulation (ECAC), Textile Industry Effluent, Clean Water and Sanitation, Industry Innovation and Infrastructure, Responsible Consumption and Production, Circular Economy in Water Treatment

INTRODUCTION

The textile industry is one of the oldest and most vital sectors of the global economy, providing employment to millions and contributing significantly to industrial development, particularly in countries like India. Second only to agriculture in terms of employment, the Indian textile sector supports over 45 million workers, both skilled and unskilled, and plays a pivotal role in exports and rural livelihood generation.

Despite its socio-economic importance, the textile industry is a major source of environmental degradation. Large volumes of water are consumed during dyeing and finishing operations, resulting in the discharge of highly polluted effluents containing persistent dyes, heavy metals, and chemical additives. These contaminants pose severe ecological and public health risks, including skin disorders, respiratory issues, and toxicity in aquatic systems.

Traditional treatment methods—primarily physico-chemical and biological—have shown limited efficiency in removing complex dye molecules due to their stable aromatic structures. These compounds are engineered to resist breakdown from light, heat, and microbial activity, making them resistant to conventional biodegradation techniques. This highlights the urgent need for efficient, sustainable, and scalable treatment technologies.

Electrochemically Assisted Coagulation (ECAC) offers a promising alternative. In this process, sacrificial electrodes generate coagulant ions in situ under an applied electric current, destabilizing contaminants and facilitating floc formation. However, the cost and consumption of electrode materials remain a concern in large-scale implementation.

This study proposes an innovative and sustainable approach: the reuse of scrap electrode materials—copper, mild steel, and aluminium—in ECAC treatment of final textile effluents. By valorizing industrial scrap and integrating it into a low-energy, chemical-free treatment method, this research contributes to cleaner production practices, reduced operational costs, and advancement toward Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production).

The paper aims to assess the performance of ECAC using different scrap electrodes under varied current densities and treatment durations, focusing on the removal efficiency of COD, colour, and solids in final discharged effluents from indigenous textile units.

EXPERIMENTAL SET-UP AND PROCEDURE

The experimental investigation employed a laboratory-scale Electrochemically Assisted Coagulation (ECAC) reactor system, utilizing recycled scrap electrodes configured in parallel. The reactor, with a total capacity of 1 liter, was operated with a 500 mL sample volume for each trial. Electrodes fabricated from aluminum, mild steel, and copper scraps were tested under varying operational parameters. A digital DC power supply (0–30 V, 3 A) was utilized to apply current densities ranging from 10 to 60 mA/cm², with ambient temperature maintained between 25–27°C throughout the experiments.

Key operational variables included electrode material combinations, current density, and treatment duration. The submerged electrode dimensions were standardized at 40 mm (width) × 30 mm (depth), with a fixed inter-electrode gap of 25 mm. Post-treatment analyses for Chemical Oxygen Demand (COD), colour, Total Suspended Solids (TSS), and Total Dissolved Solids (TDS) were conducted in accordance with Standard Methods for the Examination of Water and Wastewater(APHA & Clesceri, 1995).Figure 1 illustrates the schematic configuration of the lab-scale ECAC system. This methodology aimed to evaluate the efficacy of scrap electrode reuse in pollutant removal while optimizing energy consumption and treatment efficiency under controlled conditions.

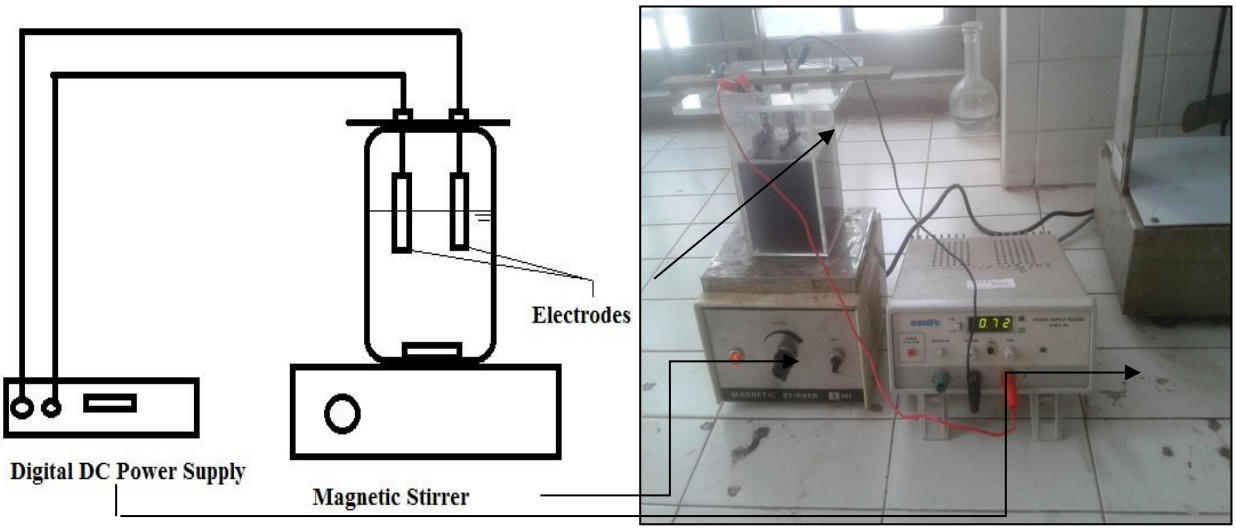

Figure 1 : Lab Scale E.C.A.C. Treatment Set-up

RESULT AND DISCUSSION

3.1 Impact of Electrode Material Composition and Treatment Duration on Pollutant Removal Efficiency

The efficacy of Electrochemically Assisted Coagulation (ECAC) in treating textile effluents was systematically evaluated by analyzing the influence of scrap electrode materials (aluminum, mild steel, copper), applied current density (10–60 mA/cm²), and treatment duration (30–180 minutes). Key performance metrics included Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Total Dissolved Solids (TDS), and colour removal efficiencies.

Impact of Electrode Material Compositioni.e. Mild Steel, Copper, Aluminium and Treatment Duration on Pollutant Removal Efficiency are shown as follows;

Sample Quantity : 500 ml	Thickness of electrodes : 1 mm	Electrode size: 40 mm (width) × 40 mm (depth)
Submerged Area of Electrode: 40 mm (width) × 30 mm (depth)		Distance between Electrodes : 25 mm

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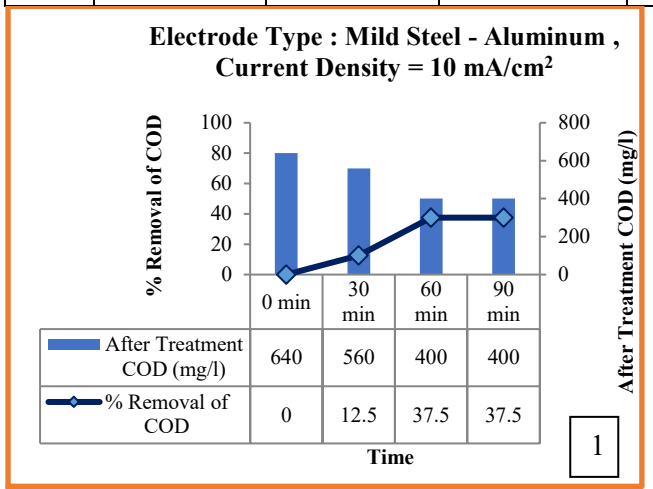
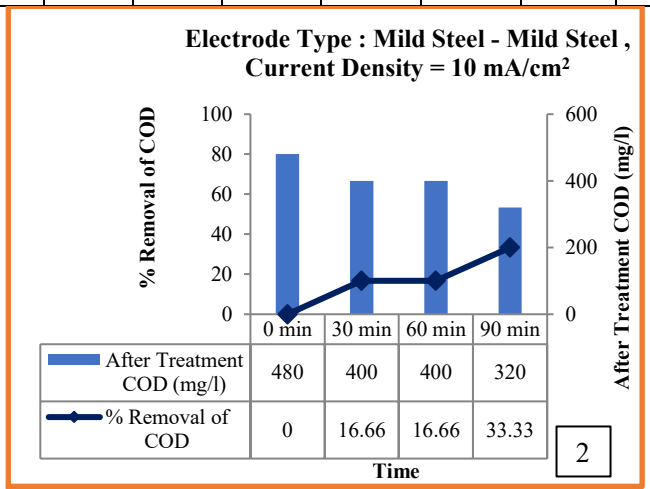
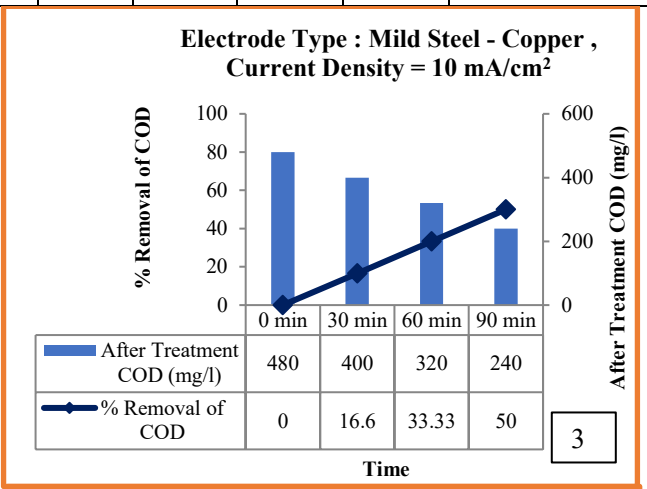
Table 1 Effects of Different Scrap Electrode Materials and Operating Time on Chemical Oxygen Demand

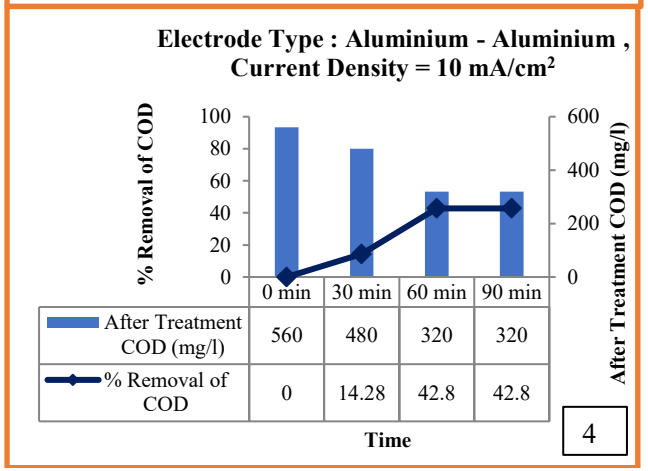
Sr. No.	Electrode Material		COD Analysis												Current Density (mA/cm2)
	Anode	Cathode	Raw COD (mg/l)	After Treatment COD (mg/l)					% Removal of COD						
				30 min	60 min	90 min	120 min	150 min	180 min	30 min	60 min	90 min	120 min	150 min	180 min	
1	Mild Steel	Aluminium	640	560	400	400	--	--	--	12.5	37.5	37.5	--	--	--	10
2	Mild Steel	Mild Steel	480	400	400	320	--	--	--	16.66	16.66	33.33	--	--	--	10
3	Mild Steel	Copper	480	400	320	240	--	--	--	16.6	33.33	50	--	--	--	10
4	Aluminium	Aluminium	560	480	320	320	--	--	--	14.28	42.8	42.8	--	--	--	10
5	Mild Steel	Aluminium	1040	800	640	560	--	--	--	23.07	38.46	46.15	--	--	--	20
6	Mild Steel	Copper	640	560	480	400	240	240	240	12.5	25	37.5	62.5	62.5	62.5	20
7	Copper	Mild Steel	640	480	400	320	160	160	160	25	37.5	50	75	75	75	20
8	Mild Steel	Copper	320	240	160	160	160	160	80	25	50	50	50	50	75	30
9	Copper	Mild Steel	320	240	160	160	160	80	80	25	50	50	50	75	75	30
10	Mild Steel	Copper	480	400	240	160	80	80	80	16.66	50	66.66	83.33	83.33	83.33	40
11	Mild Steel	Mild Steel	320	160	80	80	80	80	80	50	75	75	75	75	75	40
12	Mild Steel	Copper	720	560	480	400	160	80	80	22.22	33.33	44.44	77.77	88.88	88.88	40
13	Mild Steel	Aluminium	1040	800	640	560	--	--	--	23.07	38.46	46.15	--	--	--	40
14	Copper	Mild Steel	400	240	160	160	160	160	80	40	60	60	60	60	80	40
15	Mild Steel	Copper	560	400	320	160	160	80	--	28.6	42.8	71.4	71.4	85.7	--	50

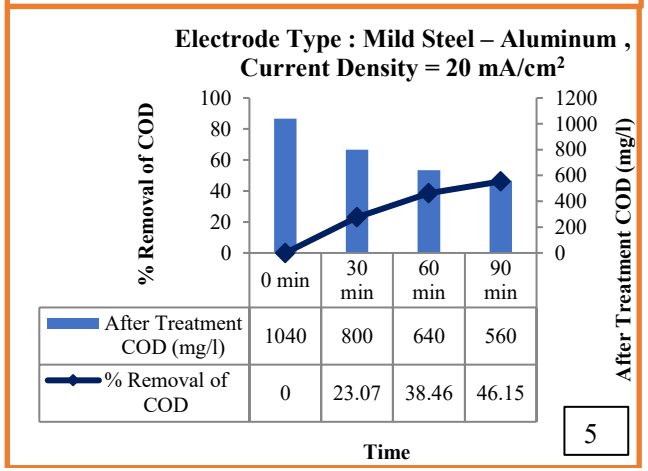
16	Mild Steel	Mild Steel	560	400	320	320	160	80	--	28.6	42.8	42.8	71.4	85.7	--	50
17	Copper	Mild Steel	560	400	240	160	80	80	--	28.6	57.1	71.4	85.7	85.7	--	50
18	Mild Steel	Copper	480	160	80	80	--	--	--	66.6	83.3	83.3	--	--	--	60
19	Mild Steel	Mild Steel	480	240	160	80	--	--	--	50	66.6	83.3	--	--	--	60
20	Copper	Mild Steel	480	160	80	80	--	--	--	66.6	83.3	83.3	--	--	--	60

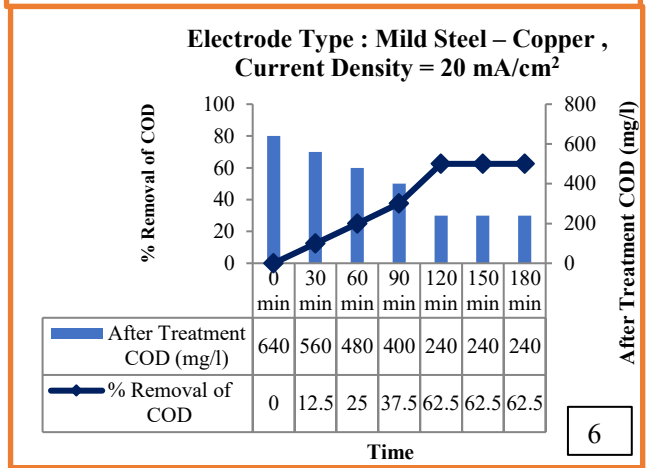












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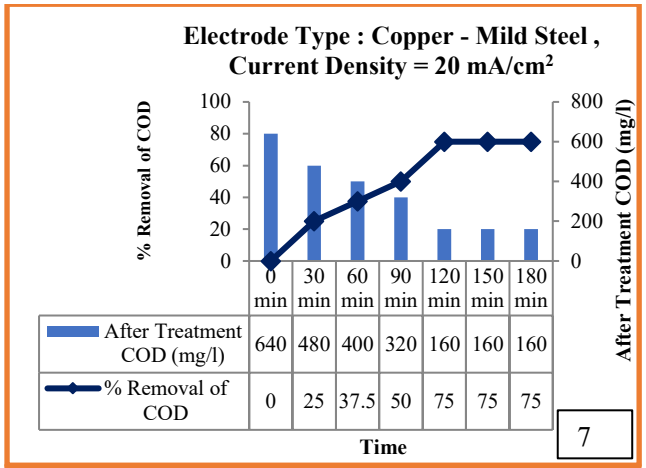

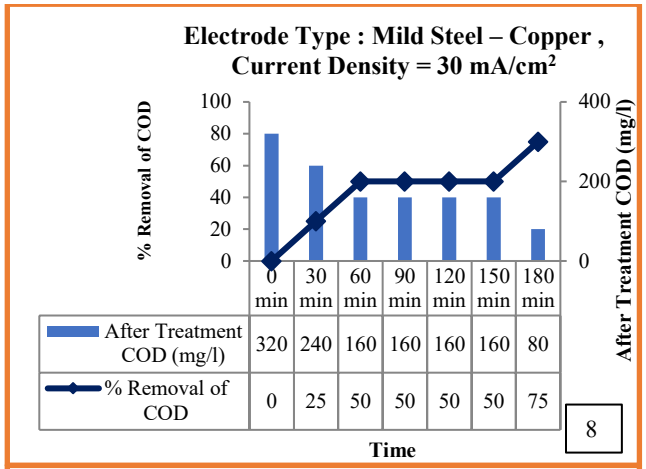

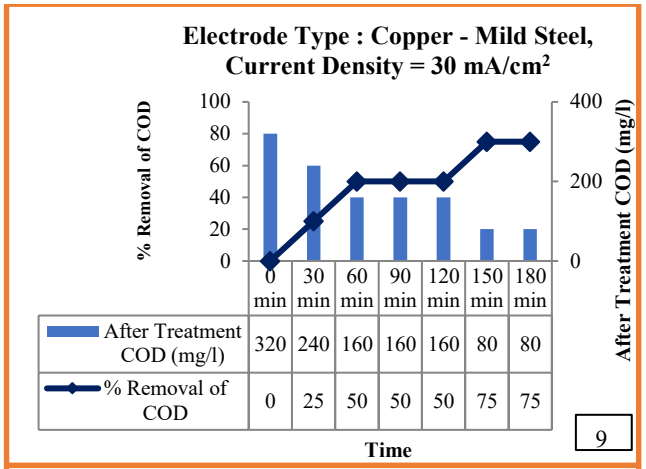

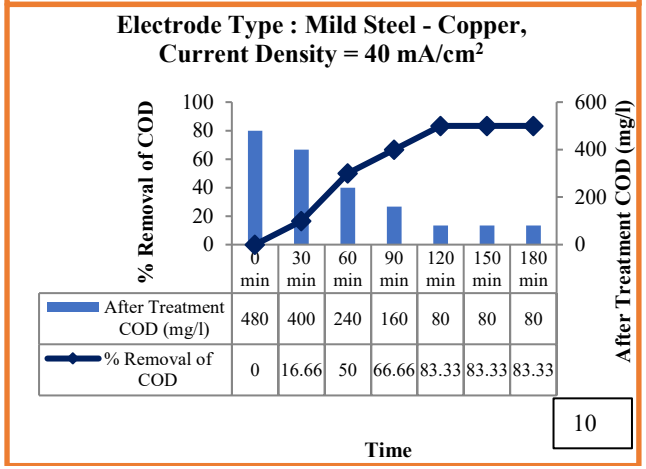

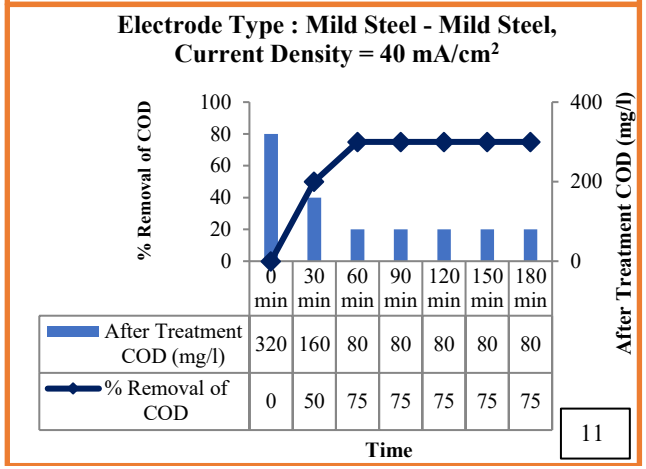

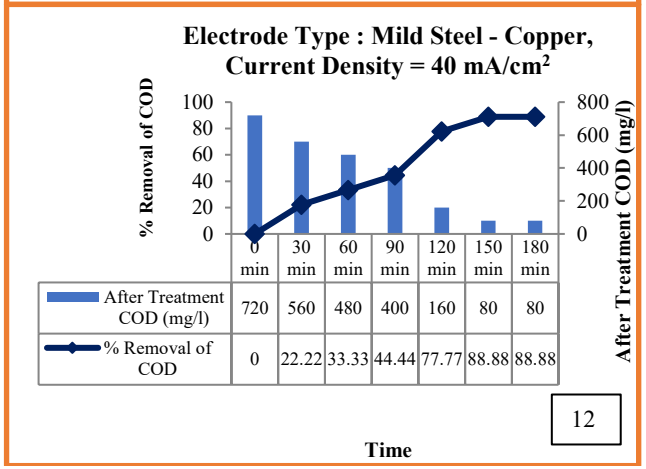

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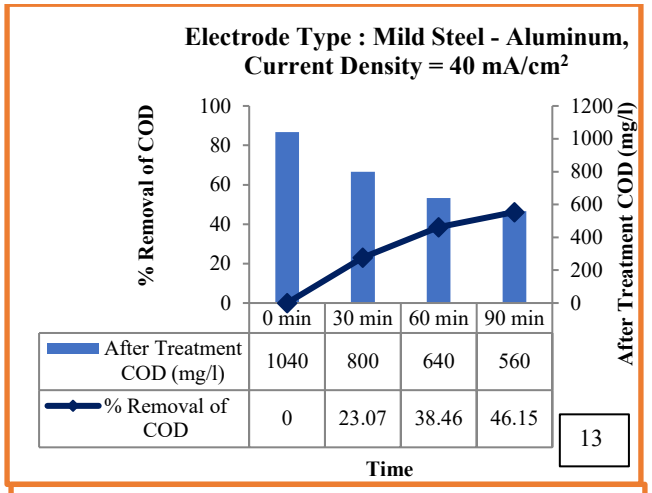

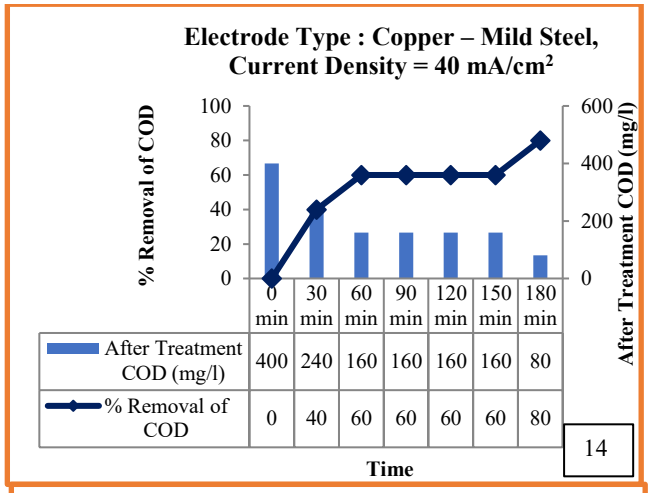

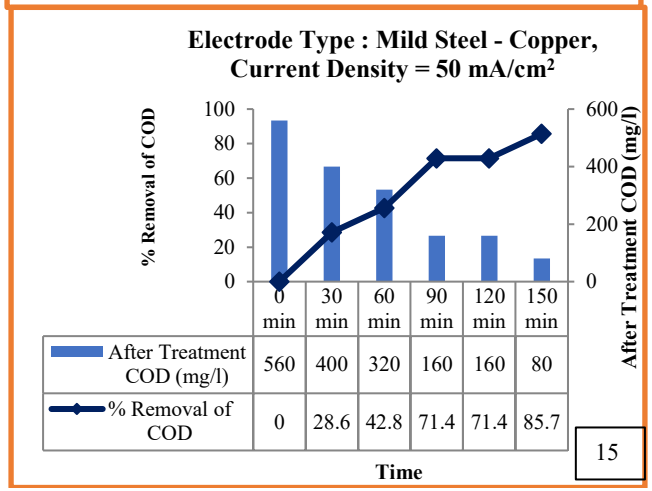

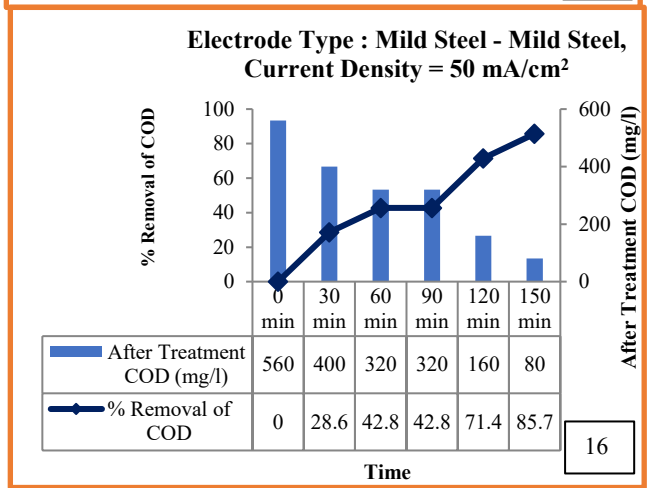

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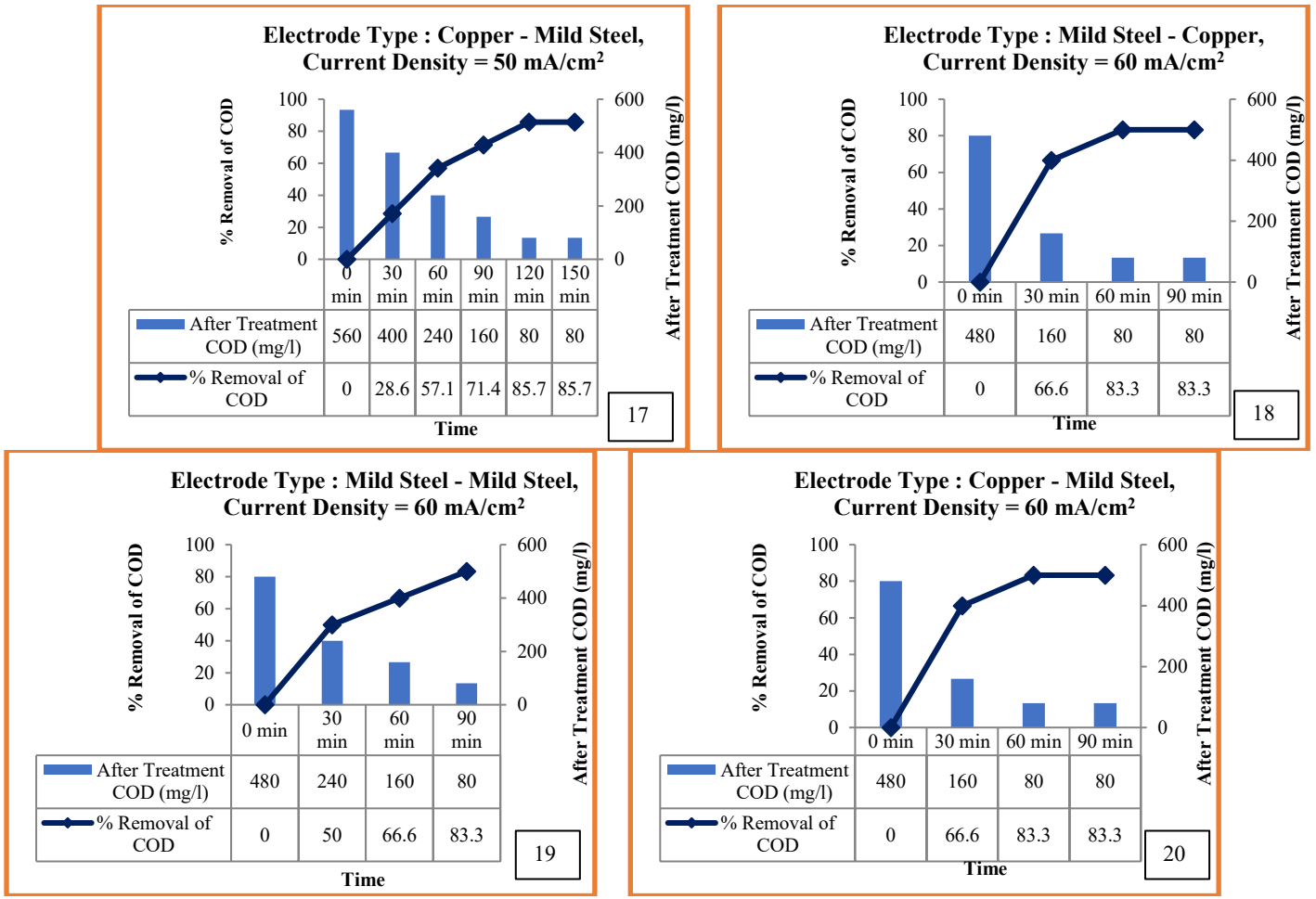


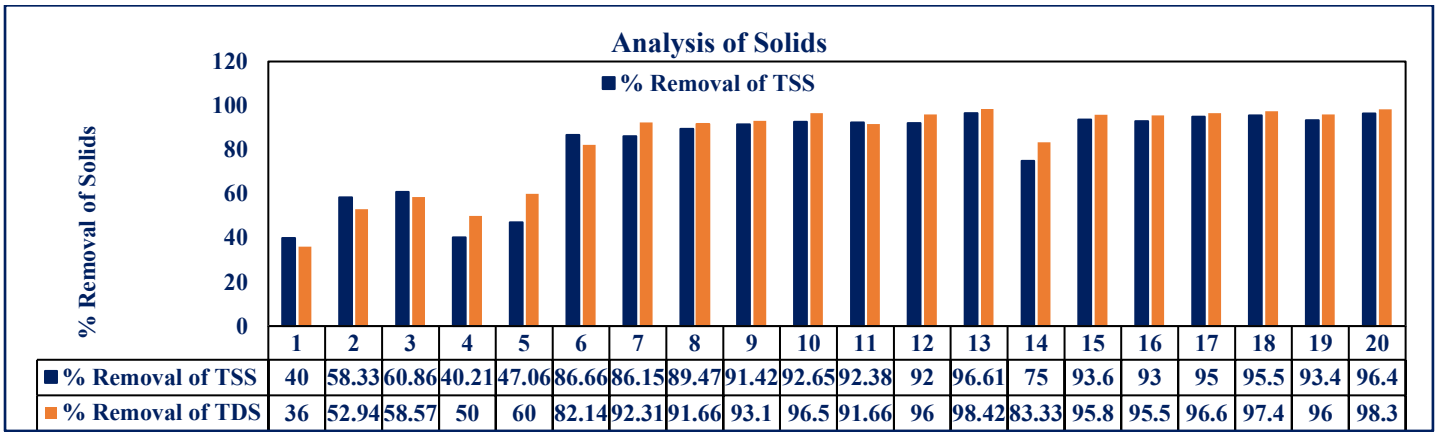
Figure 2 :Effects of Different Scrap Electrode Materials and Operating Time on Chemical Oxygen Demand (1 to 20)

Electrode Material Performance

Experiments revealed significant variations in pollutant removal efficiencies depending on electrode combinations. For instance, mild steel (anode) paired with copper (cathode) demonstrated superior COD removal (83.3%) at 60 mA/cm² after 90 minutes (Table 1, Figure 2). This combination generated reactive ions that destabilized organic pollutants, facilitating effective coagulation and sedimentation. In contrast, aluminum-aluminum electrodes exhibited limited COD reduction (42.85% at 10 mA/cm²), likely due to rapid passivation and reduced ion release.

Table 2 :Effects of Different Scrap Electrode Materials on Solids

Sr. No.	Electrode Material		Analysis of Solids						Current Density (mA/cm2)
	Anode	Cathode	Total Suspended Solids (TSS) mg/l			Total Dissolved Solids (TDS) mg/l			
			Raw Effluent	Treated Effluent	% Removal of TSS	Raw Effluent	Treated Effluent	% Removal of TDS	
1	Mild Steel	Aluminium	800	480	40	500	320	36	10
2	Mild Steel	Mild Steel	1200	500	58.33	850	400	52.94	10
3	Mild Steel	Copper	1150	450	60.86	700	290	58.57	10
4	Aluminium	Aluminium	920	550	40.21	600	300	50	10
5	Mild Steel	Aluminium	850	450	47.06	650	260	60	20
6	Mild Steel	Copper	1500	200	86.66	1400	250	82.14	20
7	Copper	Mild Steel	1300	180	86.15	1300	100	92.31	20
8	Copper	Mild Steel	950	100	89.47	1200	100	91.66	30
9	Mild Steel	Copper	1400	120	91.42	1300	90	93.1	30
10	Mild Steel	Copper	1360	100	92.65	2000	70	96.5	40
11	Mild Steel	Mild Steel	1050	80	92.38	1800	150	91.66	40
12	Mild Steel	Copper	1000	80	92	1500	60	96	40
13	Copper	Mild Steel	1180	40	96.61	1900	30	98.42	40
14	Mild Steel	Aluminium	1400	350	75	1500	250	83.33	40
15	Mild Steel	Copper	1400	90	93.6	1900	80	95.8	50
16	Mild Steel	Mild Steel	1430	100	93	2000	90	95.5	50
17	Copper	Mild Steel	1420	70	95	2050	70	96.6	50
18	Mild Steel	Copper	1350	60	95.5	2350	60	97.4	60
19	Mild Steel	Mild Steel	1360	90	93.4	2500	100	96	60
20	Copper	Mild Steel	1380	50	96.4	2400	40	98.3	60



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
% Removal of TSS	40	58.33	60.86	40.21	47.06	86.66	86.15	89.47	91.42	92.65	92.38	92	96.61	75	93.6	93	95	95.5	93.4	96.4
% Removal of TDS	36	52.94	58.57	50	60	82.14	92.31	91.66	93.1	96.5	91.66	96	98.42	83.33	95.8	95.5	96.6	97.4	96	98.3

Figure 3 Effects of Different Scrap Electrode Materials on Solids

Current Density and Treatment Time Optimization

Higher current densities (40–60 mA/cm²) correlated with accelerated pollutant removal. At 60 mA/cm², mild steel-copper electrodes achieved 96.4% TSS and 98.3% TDS removal within 90 minutes (Table 2, Figure 3). Similarly, colour removal efficiency peaked at 93.1% using copper-mild steel electrodes under identical conditions (Table 3, Figure 4). These results suggest that elevated current densities enhance electrochemical reactions, promoting rapid generation of coagulants and destabilization of complex dye molecules.

Treatment duration also played a critical role. While COD removal plateaued after 90 minutes at higher current densities, extended treatment times (>120 minutes) showed diminishing returns, likely due to electrode passivation or saturation of reactive sites. For instance, mild steel-mild steel electrodes achieved 75% COD removal at 40 mA/cm² within 90 minutes, with minimal improvement thereafter.

Table 3:-Effects of Different Scrap Electrode Materials on Colour

Sr. No.	Electrode Material		Analysis of Colour			Current Density (mA/cm2)
	Anode	Cathode	Raw Effluent Colour (Pt.Co)	Treated Effluent (Pt.Co)	% Removal of Colour	
1	Mild Steel	Aluminium	--	Colour Remained	--	10
2	Mild Steel	Mild Steel	--	Colour Remained	--	10
3	Mild Steel	Copper	--	Colour Remained	--	10
4	Aluminium	Aluminium	--	Colour Remained	--	10
5	Mild Steel	Aluminium	--	Colour Remained	--	20
6	Mild Steel	Copper	--	Colour remained	--	20
7	Copper	Mild Steel	710	220	69	20
8	Mild Steel	Copper	764	250	67.27	30
9	Copper	Mild Steel	764	148	80.62	30
10	Mild Steel	Copper	736	217	70.51	40
11	Mild Steel	Mild Steel	786	215	72.64	40
12	Mild Steel	Copper	750	220	70.66	40
13	Mild Steel	Aluminium	--	Colour remained	--	40
14	Copper	Mild Steel	790	80	89.87	40
15	Mild Steel	Copper	720	100	86	50
16	Mild Steel	Mild Steel	700	140	80	50
17	Copper	Mild Steel	740	60	91.9	50
18	Mild Steel	Copper	745	80	89.26	60

19	Mild Steel	Mild Steel	710	120	83.1	60
20	Copper	Mild Steel	730	50	93.1	60

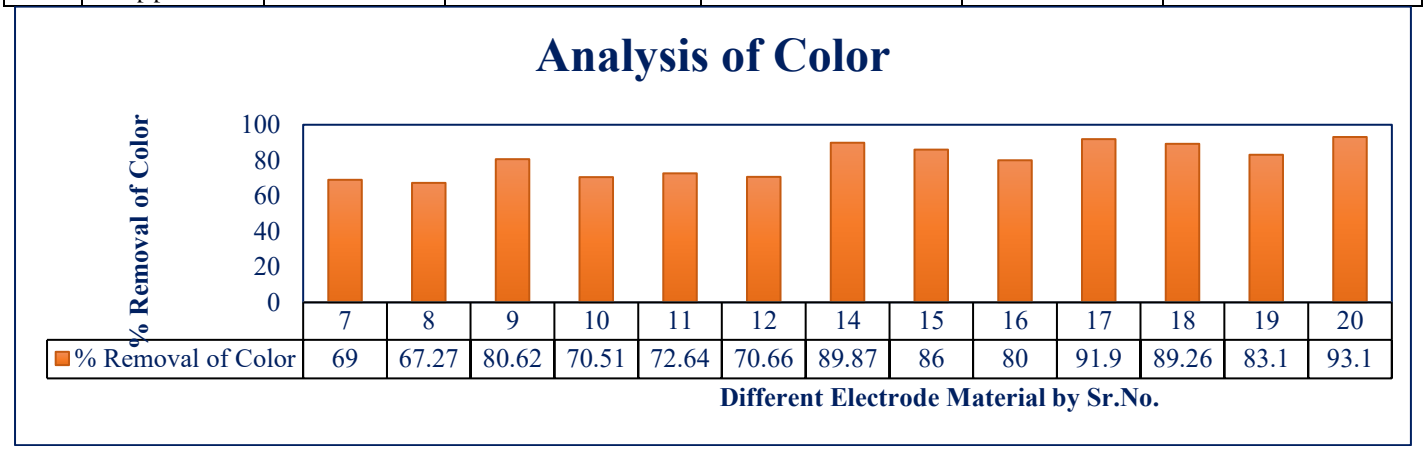


Figure 4 Effects of Different Scrap Electrode Materials on Colour

The effectiveness of Electrochemically Assisted Coagulation (ECAC) in decolourizing textile effluents was critically evaluated under varying electrode combinations and current densities (Table 3, Figure 4). Results demonstrated that colour removal efficiency is highly dependent on both electrode material and operational parameters.

Electrode Material Synergy

Copper-mild steel electrode pairs exhibited the highest decolourization performance, achieving 93.1% colour removal at 60 mA/cm² within 90 minutes (Table 3, Sr. No. 20). This can be attributed to the synergistic electrochemical activity of copper (anode) and mild steel (cathode), which generated reactive hydroxyl radicals and metallic coagulants (e.g., Fe^{2+}/Fe^{3+} and Cu^{2+} ions). These species effectively destabilized and oxidized complex dye molecules, such as azo dyes, through charge neutralization and flocculation. In contrast, homogeneous electrode pairs (e.g., mild steel-mild steel or aluminium-aluminium) showed lower efficiencies (≤83.3%), likely due to slower ion release rates and reduced redox potential.

Current Density Influence

Colour removal efficiency increased proportionally with current density. At lower densities (10–20 mA/cm²), minimal decolourization (<25%) was observed, as insufficient ionic species were generated to degrade persistent dyes. However, at 60 mA/cm², the enhanced electric field accelerated ion dissolution and electrochemical reactions, breaking down chromophoric groups in dyes. For instance, copper-mild steel electrodes achieved 89.26% colour removal at 60 mA/cm² (Sr. No. 18), compared to only 69% at 20 mA/cm² (Sr. No. 7).

Mechanistic Insights

The superior performance of copper electrodes can be linked to their higher conductivity and corrosion resistance, enabling sustained ion release over extended treatment durations. Mild steel, as a cathode, complemented this process by facilitating hydroxide formation, which adsorbed fragmented dye molecules. Aluminum electrodes, despite their low cost, showed limited efficacy due to rapid passivation and unstable oxide layer formation, which hindered consistent ion generation.

Sustainability and Practical Implications

The use of scrap electrodes not only reduced material costs by 40–60% compared to conventional electrodes but also minimized industrial waste, aligning with circular economy principles. The high colour removal efficiency (93.1%) achieved with scrap copper-mild steel electrodes rivals or exceeds conventional methods like adsorption or ozonation, which often require expensive chemicals or energy-intensive processes. Furthermore, this method effectively addresses non-biodegradable dyes, a critical challenge in textile effluent management.

Recommendations for Industrial Adoption

For optimal colour removal, industries should prioritize copper-mild steel electrode pairs operated at 60 mA/cm² for 90 minutes. However, electrode longevity and energy consumption must be balanced—higher current densities improve efficiency but accelerate electrode wear. Periodic polarity reversal or hybrid

electrode configurations could mitigate passivation issues. Future studies should explore scaling up this system while integrating renewable energy sources to enhance sustainability.
In conclusion, the ECAC process using scrap electrodes offers a robust, cost-effective solution for decolourizing textile effluents, addressing both environmental and economic challenges in wastewater management.

CONCLUSION

This study demonstrates that Electrochemically Assisted Coagulation (ECAC) using scrap metal electrodes is a highly effective and sustainable technique for treating final effluent from indigenous textile industries. Among the tested combinations, copper and mild steel scrap electrodes achieved the highest removal efficiencies—up to 83.3% for COD, 96.4% for Total Suspended Solids (TSS), 98.3% for Total Dissolved Solids (TDS), and 93.1% for colour – at a current density of 60 mA/cm^2 within 90 minutes of treatment.
The reuse of scrap electrodes not only delivers comparable or superior treatment performance to fresh electrodes but also significantly reduces material costs and environmental burden. This aligns with circular economy principles and contributes directly to achieving the United Nations Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production).
By validating scrap-based ECAC treatment at the laboratory level, this research offers a practical and low-cost pathway for pollution control in small- to medium-scale textile units, promoting eco-innovation in wastewater management.

RECOMMENDATION

Based on the findings of this study, the following recommendations are proposed to enhance the practical applicability and sustainability of the ECAC treatment process for textile effluents:
Adopt Recycled Electrode Scrap in Pilot and Full-Scale Operations
The demonstrated efficiency of scrap electrodes—particularly copper and mild steel—supports their use in larger-scale ECAC systems. Industries should explore structured reuse policies for electrode waste to lower operational costs and environmental footprint.
Integrate ECAC as a Post-Biological Treatment Stage
ECAC should be implemented after primary or biological treatment stages to maximize pollutant removal, particularly for persistent contaminants such as dyes, COD, and fine solids that are resistant to biodegradation.
Explore Electrode Material Optimization
Further research should investigate optimal combinations of electrode materials, geometries, and configurations to enhance treatment performance and extend electrode life in long-term operations.
Support Circular Economy and SDG-Aligned Policies
Regulatory agencies and textile clusters should incentivize the adoption of scrap-based ECAC systems through policy frameworks that support circular resource use, in line with SDGs 6, 9, and 12.
Conduct Life Cycle and Cost-Benefit Analysis
Comprehensive techno-economic and life cycle assessments should be carried out to validate the long-term sustainability, cost-effectiveness, and carbon footprint reduction potential of this technology.

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