M.Sc. in Civil Engineering Thesis

Development of Integrated Process of Electrocoagulation and Filtration in Textile Wastewater Treatment

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July 2025

Development of Integrated Process of Electrocoagulation and Filtration in Textile Wastewater Treatment

A dissertation submitted to the Department of Civil and Environmental Engineering (CEE) in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE (M.Sc.) IN CIVIL ENGINEERING

by

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July 2025

Recommendation of the Board of Examiners

The thesis titled "**Development of Integrated Process of Electrocoagulation and Filtration in Textile Wastewater Treatment**" submitted by Tahmeed Ahmed, Student ID: 211051017 of Academic Year 2021-2022 has been found as satisfactory and accepted as partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering.

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Dedication

I dedicate this work to my parents, teachers, and friends, whose constant support and motivation have been the foundation of my strength throughout this academic journey.

I am profoundly grateful to my supervisor, Associate Professor Dr. Amimul Ahsan, for his expert guidance, endless patience, knowledge sharing, and mentorship that made this research possible.

This thesis stands as a heartfelt acknowledgment of everyone who supported me, provided inspiration, and had faith in my capabilities as I worked toward achieving this milestone.

Acknowledgements

All praise and glory belong to Almighty Allah, who blessed me with the strength, determination, and resilience to complete this M.Sc. thesis. Indeed, all power comes from Allah alone. This academic journey has been enriched by the contributions of many remarkable individuals who have played vital roles in the accomplishments documented in this work.

I wish to convey my sincere gratitude to my thesis supervisor, Associate Professor Dr. Amimul Ahsan, who served as my mentor throughout my M.Sc. program. His supervision opened new research horizons for me, providing consistent support and guidance whenever I strayed from the right path. Dr. Ahsan recognized my potential during moments of self-doubt and provided steadfast encouragement and mentorship that were instrumental in completing this dissertation and its related publications. His research enthusiasm and genuine commitment to student success make him an outstanding academic advisor.

I also express my sincere appreciation to Professor Dr. Jahir Bin Alam, Professor Dr. Md. Rezaul Karim, and Professor Dr. Shakil Mohammad Rifaat, who generously dedicated their time to examine my thesis and offer valuable feedback and insights.

Lastly, I am immensely grateful to my cherished parents, Md. Zahidul Islam and Farzana Afrose, for their endless love, care, and encouragement. Their steadfast support has served as the cornerstone of my resilience throughout this academic pursuit. I extend my heartfelt thanks to my well-wishers, particularly Md. Habibur Rahman Bejoy Khan, Fuad Bin Nazrul, Yasin Khan, Chowdhury Sadid Alam, Mohammad Zunaid Bin Harun, Mohammad Abu Umama, Sadman Sakib, Md. Jahim Uddin Shorif, Niaz Ahmed, Md. Atif Arham, Farhan Anjum Badhon, Sifat Abdul Bari, and Md. Ibrahim Talukdar, whose understanding and affection provided solace and inspiration during the most difficult periods of this journey.

Tahmeed Ahmed
July 2025
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Abstract

The rapid expansion of the textile industry has introduced significant environmental challenges, particularly in wastewater management, where effluents with high levels of chemical oxygen demand (COD), total suspended solids (TSS), turbidity, color, and total organic carbon (TOC) pose serious threats to water resources and regulatory compliance. Conventional treatment methods often struggle to achieve sufficient removal efficiencies while remaining economically feasible, especially for small and medium-sized textile operations. To address these limitations, this study conducts a comprehensive investigation into the development, optimization, and integration of electrocoagulation-based treatment systems for textile wastewater. The research systematically advances from process enhancements, including seawater integration and electrode selection, to the design of advanced multi-stage systems, supported by rigorous multi-criteria decision-making frameworks.

The experimental methodology employed a three-phase approach to systematically evaluate and optimize electrocoagulation (EC) processes for textile wastewater treatment. Initially, the potential of seawater integration in EC processes was investigated using a custom-designed electrolytic reactor, with systematic variation of seawater percentages (0, 5, 10, and 15%) and retention times (45, and 90 min) analyzed through central composite design (CCD) and analysis of variance (ANOVA) using Design-Expert 11 software. Subsequently, comprehensive electrode pair optimization was conducted using thirty-six combinations of six materials including Aluminium (Al), Zinc (Zn), Carbon (C), Copper (Cu), Mild Steel (MS), and Stainless Steel (SS), with performance evaluation through three Multi-Criteria Decision-Making (MCDM) methods: TOPSIS, VIKOR, and PROMETHEE II to identify the optimal electrode configuration. Finally, an integrated system (IS) process was developed and evaluated, incorporating sequential EC, sedimentation (ST), aeration (AT), multimedia filtration (MM), and activated carbon (AC) filtration processes. Twenty-seven distinct IS process configurations were systematically tested by varying EC (20, 40, and 60 min), ST (60, 120, and 180 min), and AT (20, 40, and 60 min) retention times, with optimization achieved through four MCDM methods: TOPSIS, VIKOR, PROMETHEE II, and Analytical Hierarchy Process (AHP) for comprehensive performance assessment.

The seawater integration study demonstrated significant improvements in EC efficiency, achieving maximum removal efficiencies of 99.52% for TSS, 99.30% for turbidity, 98.19% for color, and 47.26% for COD. The integration not only enhanced removal efficiency through

improved coagulation but also provided beneficial dilution effects, reducing overall pollutant concentrations. Power consumption was reduced to 15.769 Am^{-2} with treatment costs approximately 0.20 USD/m^3, making the process economically attractive. The quadratic models developed through CCD showed excellent correlation with experimental data, achieving R^2 values of 0.9121 (COD), 0.9535 (color), 0.9525 (turbidity), and 0.9433 (TSS). The electrode optimization study revealed that while individual electrode pairs achieved varying removal efficiencies with maximum values of 92.09% COD (Al-C pair), 99.66% TSS (Al-Cu pair), 99.17% turbidity (Al-MS pair), and 70.99% TOC (SS-SS pair), no single combination excelled across all pollutant categories. Through comprehensive MCDM analysis, the Al-Zn electrode combination emerged as the optimal balanced solution, delivering consistent high performance with 99.32% TSS, 98.88% turbidity, 68.62% COD, and 57.96% TOC removal efficiencies. The IS process demonstrated exceptional treatment performance, with the optimized configuration (IS process 27) achieving maximum removal efficiencies of 99.69% for TSS, 99.57% for turbidity, 95.23% for COD, and 99.1% for color. The EC stage served as the primary destabilization mechanism, while subsequent ST and AT processes facilitated solid-liquid separation and oxidative degradation. Multimedia and activated carbon filtration provided final polishing, ensuring effluent quality met stringent discharge standards. All four MCDM methods consistently identified IS process 27 as the optimal configuration, validating the robustness of the treatment approach.

This study makes a meaningful contribution to industrial wastewater treatment by developing a systematic framework for enhancing and optimizing the EC process. The novel integration of seawater offers a cost-effective strategy that enhances pollutant removal and presents practical benefits for coastal textile facilities. The comprehensive electrode selection approach provides design flexibility, while the rigorous use of multiple multi-criteria decision-making (MCDM) methods ensures reliable and transparent optimization across complex treatment scenarios. The proposed multi-stage integrated system demonstrates scalable, sustainable performance, consistently achieving high removal efficiencies that meet strict discharge and water reuse standards while remaining economically viable. These findings offer immediate industrial applicability and contribute valuable knowledge to electrochemical water treatment. The study emphasizes the importance of sequential process synergy and optimized retention durations in maximizing treatment performance, offering a practical, adaptable, and high-efficiency solution for textile wastewater management and related industrial applications.

Chapter 1

Introduction

1.1 Background

Industrial growth has advanced global economies but at significant environmental cost, particularly through freshwater contamination by hazardous manufacturing substances (Tripathi et al., 2021). The textile industry generates highly contaminated wastewater (Holkar et al., 2016; Yaseen and Scholz, 2019; Ahmed et al., 2022), responsible for 90% of global dye production and emitting 140,000 tons of wastewater annually (Tripathi et al., 2021; Islam et al., 2023). With production exceeding 100 million tons yearly, it consumes over three trillion gallons of freshwater and releases 2.5 billion liters of effluent daily, ranking as the second-largest water polluter after agriculture (Desore and Narula, 2018; Lellis et al., 2019). Around 33% of global chemical emissions stem from textile processes (Roy et al., 2020).

Untreated textile wastewater depletes oxygen, causes ecotoxic effects, and disrupts aquatic ecosystems through eutrophication (Forgacs et al., 2004; Benkhaya et al., 2020; Desai et al., 2021). Recalcitrant compounds bioaccumulate, posing long-term risks (Robinson et al., 2001; Tkaczyk et al., 2020). Roughly 40% of colorants contain carcinogenic chlorine, linked to allergies and developmental issues (Garg et al., 2020; Uddin et al., 2023).

Conventional treatment methods often fail while maintaining cost efficiency (Un and Aytac, 2013; Garg et al., 2019). Many rely on chemicals causing secondary pollution (Sijan et al., 2023), while biological methods are hindered by dye toxicity (Yaseen and Scholz, 2019; Aljaberi et al., 2023b). These challenges have driven research into integrated treatment systems (Parida et al., 2021).

With rising freshwater scarcity and increasing wastewater pollution, sustainable treatment methods have become essential. Electrochemical technologies, including EC, offer efficient and adaptable wastewater treatment (Mohora et al., 2018; Aljaberi, 2018). EC is noted for its ability to remove various pollutants with simplicity, cost-effectiveness, and low chemical use (Mouedhen et al., 2008; Samsami et al., 2020).

Recognized for eliminating dissolved metals, phenols, tannins, and synthetic dyes, EC applies controlled micro-currents to dissolve sacrificial electrodes, acting as a superior alternative to conventional coagulation (Mao et al., 2023; Al-Jaberi et al., 2023). The process integrates

coagulation, flotation, and electrochemical reactions, offering operational ease, reduced chemical inputs, and minimal sludge generation (Ingelsson et al., 2020; Othmani et al., 2022). EC relies on in situ coagulant generation via electrode dissolution, destabilizing colloids and removing contaminants via sedimentation or flotation (Kobya et al., 2014; Hendaoui et al., 2021). Studies confirm EC's effectiveness in removing color, COD, and TSS from textile effluents, often exceeding 80–90% efficiency (Bayramoglu et al., 2007; Al-Qodah et al., 2020).

In EC, sodium chloride is typically added to regulate pH and conductivity, with chlorine ions needing to comprise at least 20% of total anions for optimal efficiency (Veli et al., 2008; Alkhadra et al., 2022). Seawater, with 3.5% average salt concentration including sodium (11 g kg^{-1}) and chlorine ions (19 g kg^{-1}), can enhance EC efficiency through high conductivity and diverse ion composition (Öztürk, 2013; Andrulionis et al., 2022). The presence of Mg^{2+} and Ca^{2+} promotes hydroxide floc formation, improving coagulation and pollutant removal. However, no global studies have explored seawater's role in textile wastewater treatment using EC. Diverse electrode materials including Aluminum, Iron, Silver, and others offer unique electrochemical properties (Sahu et al., 2014). Polyvalent metals like Aluminum and Iron are preferred for their coagulation capabilities through multivalent ion formation. Advanced materials include graphite, PbO_2, and composite electrodes showing enhanced performance (Guo et al., 2024; Sqalli Houssini et al., 2024), yet optimal electrode selection for textile wastewater remains unexplored.

However, EC alone frequently fails to achieve discharge-compliant water quality standards due to residual turbidity, dissolved organic compounds, refractory substances, and volatile constituents. Operational challenges including sludge generation, energy consumption, and electrode passivation necessitate integrated treatment frameworks (Othmani et al., 2022). To address these limitations, EC is increasingly combined with complementary post-treatment processes through sequential integration of sedimentation tank (ST), aeration tank (AT), and dual filtration, creating a multi-barrier approach for optimal treatment efficiency (Hedeş et al., 2019; Costa et al., 2021; Piras et al., 2022; Udoh et al., 2025).

ST facilitates gravitational settling of destabilized flocs, reducing suspended solids and enhancing water clarity (Gregory, 2005; Ahmad et al., 2020), with retention times of 60-180 minutes governed by Stokes' law (Silva et al., 2015; Shammas, 2005; Wang et al., 2018). AT enhances dissolved oxygen concentrations, supports oxidative degradation of residual organics, and facilitates volatilization of semi-volatile constituents (Skouteris et al., 2020; Pittoors et al., 2014; Awad et al., 2019). The oxygen transfer process follows Henry's law and

two-film theory, promoting biodegradation and chemical oxidation (Lewis and Whitman, 1924; Peng et al., 2020).

Dual filtration comprising multimedia (MM) and activated carbon (AC) filtration provides final polishing. MM filtration uses stratified media of anthracite coal, fine sand, and gravel to maximize particle capture across multiple size ranges (Crittenden et al., 2012; Kawamura, 2000; Verma et al., 2017; Jaeel and Abdulkathum, 2018). AC filtration serves as the terminal barrier, targeting dissolved organics, residual color, and micropollutants through van der Waals forces, π-π interactions, and electrostatic attractions (Hung et al., 2005; Bansal and Goyal, 2005; Zhang et al., 2025; El-Emam et al., 2025; Graese et al., 1987; Aritonang et al., 2025).

This integrated EC-ST-AT-filtration configuration creates synergistic effects exceeding standalone capabilities, ensuring enhanced pollutant removal and regulatory compliance. However, optimal process configuration selection remains challenging due to interdependent operational variables and conflicting objectives regarding removal efficiency, energy use, sludge generation, and sustainability. Multi-criteria decision-making (MCDM) methods including TOPSIS, VIKOR, and PROMETHEE II offer structured frameworks for evaluating treatment alternatives under multiple criteria (Mir et al., 2016). Despite their proven effectiveness, MCDM applications in EC processes remain unexplored globally, yet provide robust approaches for simultaneous consideration of technical, environmental, and economic indicators, supporting transparent decision-making (Ferdous et al., 2024).

1.2 Research Aim with Specific Objectives

This study aims to develop, optimize, and integrate advanced EC-based treatment systems for textile wastewater management through a systematic three-phase approach: seawater integration to enhance EC process efficiency, selection of the best electrode pair from thirty-six electrode combinations, and multistage system integration combining EC with ST, AT, MM filtration, and AC filtration.

The specific objectives of this study are as follows:

1. To investigate the efficiency of multi-pollutant removal from textile wastewater by integrating seawater into the EC process.
2. To obtain the best electrode pair in the EC process to remove multi-pollutant from textile wastewater.

3. To maximize the efficiency of multi-pollutant removal from textile wastewater by integrating EC with ST, AT, MM filtration, and AC filtration process.

1.3 Scope of the Study

This study encompasses the systematic development, optimization, and integration of EC-based treatment systems for textile wastewater through seawater enhancement, electrode material selection, and multi-stage system integration using advanced statistical and multi-criteria decision-making approaches for real-world industrial applications.

I. **Seawater Integration Enhancement**: Evaluation of seawater percentages (0-15%) and retention times (45-90 min) in EC, analyzing key physicochemical parameters using carbon-mild steel electrode configuration.
II. **Electrode Material Optimization**: Testing six electrode materials through thirty-six combinations using MCDM methods (TOPSIS, VIKOR, PROMETHEE II) for optimal pollutant removal selection.
III. **Multi-Stage System Integration**: Development of five-stage treatment system (EC-ST-AT-MM-AC) through twenty-seven configurations using four MCDM methods including AHP.
IV. **Statistical and Analytical Methods**: Implementation of CCD, ANOVA, and MCDM for experimental design and performance evaluation using laboratory-scale setups (600-4000 cm^3).
V. **Performance Evaluation**: Assessment based on technical efficiency, economic viability, environmental sustainability, and industrial scalability across multiple criteria.
VI. **Real-World Application**: Focus on actual textile wastewater treatment with standardized protocols and comparative analysis to establish EC-based treatment benchmarks.

1.4 Layout of the Thesis

This thesis includes five chapters depicting the literature, the adapted method, the analysis and pre-processing, and the result of the study. The references are also listed within this study.

Chapter 1- Introduction: Establishes research foundation by presenting textile wastewater challenges, identifying EC technology gaps, and outlining the three-phase approach with clear research objectives and thesis structure.

Chapter 2- Literature Review: Examines existing knowledge in EC technology, textile wastewater treatment, and multi-criteria decision-making approaches while identifying specific research gaps addressed in this study.

Chapter 3- Methodology: Details systematic experimental frameworks, sample collection, experimental design, MCDM protocols, and statistical analysis methods across all three research phases.

Chapter 4- Results and Discussion: Presents findings from all phases with detailed analysis, statistical validation, and practical implications, concluding with comparative analysis of integrated optimization benefits.

Chapter 5- Conclusions and Recommendations: Synthesizes research contributions, assesses limitations, validates objective achievement, and provides recommendations for future EC technology advancement.

Chapter 2

Literature Review

2.1 General

The rapid expansion of global industrialization has fundamentally transformed the landscape of wastewater generation and treatment, presenting unprecedented challenges for environmental protection and water resource management. Among various industrial sectors, the textile industry stands as one of the most water-intensive and environmentally impactful industries worldwide, generating substantial volumes of highly contaminated effluents that pose significant threats to aquatic ecosystems and human health. This literature review provides a comprehensive examination of existing knowledge across three critical domains: EC technology fundamentals and applications, textile wastewater treatment methodologies, and multi-criteria decision-making approaches in environmental engineering, establishing the theoretical foundation for the systematic three-phase research approach employed in this study.

2.2 Textile Industry and Wastewater Characteristics

2.2.1 Global Textile Industry Overview

The textile industry represents one of the world's largest industrial sectors, requiring over three trillion gallons of fresh water annually and utilizing large amounts of chemicals, dyes, and substances during processing (Desore and Narula, 2018; Yaseen and Scholz, 2019). With global production exceeding 100 million tons annually, the industry discharges approximately 2.5 billion liters of contaminated effluent daily, making it the second-largest water polluter worldwide after agriculture (Kant, 2011; Lellis et al., 2019).

The environmental implications are profound, with the textile industry responsible for one-third of all chemical emissions and significant toxic waste contributions to soil, air, and water (Desore and Narula, 2018; Roy et al., 2020). Approximately 33% of environmental chemical releases are attributed to textile treatment and dyeing processes (Roy et al., 2020). This sector accounts for 90% of global organic dye production, emitting 140,000 tons of wastewater annually containing complex recalcitrant compounds (Tripathi et al., 2021; Islam et al., 2023).

2.2.2 Textile Wastewater Composition and Characteristics

Textile wastewater is characterized by its complex composition and highly variable properties, making it one of the most challenging industrial effluents to treat. The composition varies significantly depending on the manufacturing processes employed, types of fabrics produced, chemicals applied, equipment used, and even seasonal variations in fashion trends (Brik et al., 2006; Kehinde & Aziz, 2014). As noted by Khandare et al. (2013), typical textile wastewater is difficult to define, because the textile application methods, even in the same process, are different from one industry to another.

2.2.2.1 Physical and Chemical Characteristics

Textile effluents are characterized by high levels of key parameters reflecting intensive chemical processing. The discharged effluents contain dyes, metals, and pollutants with high color, pH, suspended solids, COD, BOD, metals, temperature, and salts (Yaseen & Scholz, 2016). Monitoring of TOC, ammonia–nitrogen (NH_4–N), nitrate–nitrogen (NO_3-N), and orthophosphate–phosphorus (PO_4-P) is also required during treatment. Textile wastewater characteristics show considerable variation across studies and sources. pH values range from 6-12, reflecting acidic and alkaline chemical use. COD ranges dramatically from 150-30,000 mg/L, while BOD falls between 80-6,000 mg/L. TSS concentrations vary from 15-8,000 mg/L, and TDS ranges from 1,500-12,000 mg/L. Temperature is typically elevated at 35-45°C, while color intensity varies from 50-2,500 Pt-Co units depending on dyeing processes employed.

2.2.2.2 Process-Specific Pollutant Contributions

Different textile manufacturing processes contribute distinct pollutant profiles through wet processes using considerable potable water and releasing highly contaminated wastewater via sizing, de-sizing, scouring, bleaching, mercerizing, dyeing, printing and finishing techniques (Babu et al., 2007; Liu et al., 2010). The sizing process adds starch, polyvinyl alcohol and carboxymethyl cellulose, contributing BOD from sizes, enzymes, starch and waxes. De-sizing introduces sodium hydroxide, surfactants, soaps, fats, pectin, oils, sizes and waxes. Scouring adds alkali solutions removing oils and waxes, while bleaching contributes hydrogen peroxide, sodium silicate, organic stabilizers, metals, salts, and surfactants. Mercerizing adds concentrated sodium hydroxide and acid solutions, with neutralization agents including acetic acid or formic acid.

2.2.2.3 Dyeing Process and Color Characteristics

The dyeing process is the primary source of color in textile wastewater, adding color to fibers with various chemicals to improve adsorption (Carmen & Daniela, 2012). Dyeing and printing contribute significant color, metals, surfactants, and alkaline/acidic conditions. Dye concentrations vary considerably, ranging from 10-50 mg/L (Laing, 1991) to 60 mg/L for reactive dyes (Shelley, 1994), 100-200 mg/L (Gahr et al., 1994), 600-800 mg/L (Vandevivere et al., 1998), and up to 7,000 mg/L from specific industries (Koprivanac et al., 1993). Synthetic dyes are more widely used than natural dyes due to superior fastness (Khehra et al., 2006), classified by chemical structure (azo, anthraquinone, sulfur, phthalocyanine, triarylmethane) and application mode (reactive, direct, disperse, basic, vat) (Popli & Patel, 2015). Dye intensity ranges between 1000-1500 ADMI units (O'Neill et al., 1999).

2.2.2.4 Heavy Metals and Chemical Additives

Metal contamination occurs from dyes and additives including caustic soda, sodium carbonate and salts. Main environmental challenge metals include chromium, zinc, iron, mercury and lead (Hussein, 2013), while dye chromophores primarily contain cobalt, copper and chromium (Adinew, 2012). Various chemicals including metals, salts, surfactants, organic processing aids, sulfide and formaldehyde are added during dyeing and printing to improve dye-fabric binding. The finishing step adds formaldehyde-based agents for fabric softening, cross-linking and waterproofing (Babu et al., 2007), along with softeners, solvents, resins and waxes that contribute to complex wastewater composition.

2.2.2.5 Variability and Environmental Significance

The composition of textile industry wastewater varies from mill to mill and from country to country, depending on the process, the equipment used in the factory, type of fabric produced, chemicals applied, the weight of the fabric, season, and the trends in fashion (Brik et al., 2006; Kehinde & Aziz, 2014). Real effluent characteristics from different sources demonstrate this variability, with some parameters falling outside typical ranges, indicating the wide spectrum of actual wastewater compositions encountered in practice. This variability presents significant challenges for treatment system design and operation, as treatment technologies must be capable of handling a wide range of pollutant types and concentrations.

2.2.3 Environmental and Health Impacts

The environmental and health implications of untreated or inadequately treated textile wastewater extend far beyond immediate water quality concerns. These contaminants pose significant risks to aquatic biodiversity and human health through bioaccumulation and potential carcinogenic effects (Robinson et al., 2001; Srinivasan and Viraraghavan, 2010; Tkaczyk et al., 2020). Studies have shown that approximately 40% of colorants contain carcinogenic chlorine in an organic bond, which is a proven carcinogen (Garg et al., 2020). Exposure to these chemicals can lead to a range of health issues, from allergies to more serious effects on children and the unborn (Ojha and Tiwary, 2021; Uddin et al., 2023).

2.3 Conventional Textile Wastewater Treatment Technologies

Textile wastewater treatment has been a significant environmental challenge due to the complex nature of textile effluents, which contain high concentrations of dyes, dissolved solids, toxic metals, and organic pollutants (Gosavi & Sharma, 2013). Conventional treatment methods have been widely employed, though each approach presents distinct advantages and limitations.

2.3.1 Physical Treatment Methods

Physical treatment methods mainly target suspended solids and dissolved contaminants. Adsorption, using materials like activated carbon, fly ash, silica, clay, and agricultural wastes, is widely used (Gosavi & Sharma, 2013). Activated carbon is effective for soluble dyes due to its high surface area (Iqbal & Ashiq, 2007; Pereira et al., 2003) but is limited by cost and regeneration needs. Ion exchange offers dye-specific removal but is sensitive to impurities (Robinson et al., 2001; Dajkaa et al., 2003). Irradiation aids decolorization but requires high dissolved oxygen (Robinson et al., 2001), while filtration is mainly used for pretreatment or final polishing.

2.3.2 Chemical Treatment Methods

Chemical treatments involve agents that precipitate, coagulate, or transform pollutants. Coagulation and flocculation are widely used, particularly for insoluble dyes, but are less effective for soluble ones (Kang et al., 2000; Meric et al., 2005). Common coagulants include aluminum sulfate, ferric chloride, and polyaluminum chloride. However, they generate large volumes of sludge and raise disposal costs (Fukushima et al., 2000). Chemical oxidation using agents like chlorine, hydrogen peroxide, and potassium permanganate often results in

incomplete mineralization and toxic by-products. Precipitation methods mainly remove heavy metals via pH adjustment and chemical additives.

2.3.3 Biological Treatment Methods

Biological treatments rely on microorganisms to degrade organic pollutants. Aerobic systems like activated sludge and trickling filters efficiently reduce BOD and COD (Kim et al., 1995) but are less effective at removing synthetic dyes due to their resistance to biodegradation (Lin & Lo, 1997). Anaerobic processes can break azo dyes via reductive cleavage but typically fail to achieve full mineralization (Ledakowicz et al., 2001). The most effective approach combines anaerobic and aerobic stages—anaerobic for azo bond breakdown and aerobic for degrading resulting aromatic compounds (Ledakowicz et al., 2001; Ong et al., 2005). Nonetheless, biological methods are hindered by dye toxicity, long retention times, and vulnerability to load fluctuations.

2.3.4 Limitations of Conventional Treatment Methods

While conventional treatment methods have been extensively used in textile wastewater treatment, they suffer from several inherent limitations:

a) Incomplete Pollutant Removal: Most methods cannot achieve complete removal of all pollutants, particularly recalcitrant dyes and toxic compounds (Banat et al., 1996).

b) Secondary Pollution: Chemical treatments generate secondary pollution through chemical sludge requiring further treatment and disposal (Gosavi & Sharma, 2013).

c) Limited Effectiveness for Specific Pollutants: Biological processes are unsuitable for decolorization of synthetic dyes due to inorganic nature and toxicity, while coagulation techniques are more effective for insoluble than soluble dyes (Gosavi & Sharma, 2013).

d) High Operating Costs: Energy requirements, chemical consumption, and sludge disposal costs make many conventional methods economically challenging (Shaul et al., 1991).

e) Inability to Handle Complex Mixtures: Textile wastewater's complex mixtures of dyes, auxiliary chemicals, and processing aids often require multiple treatment steps, increasing complexity and costs.

These limitations have driven development of advanced treatment technologies, particularly Advanced Oxidation Processes (AOPs), offering potential for complete mineralization without secondary pollutant generation.

2.4 Electrocoagulation Technology: Fundamentals and Mechanisms

2.4.1 Historical Development and Theoretical Background

EC represents an innovative water and wastewater purification methodology that has gained recognition for its effectiveness, environmental compatibility, and economic viability in removing various toxicants including dissolved metals, tannins, phenols, and synthetic dyes from contaminated effluents (Mao et al., 2023). The fundamental principle of EC is based on electrolysis, a concept introduced by Michael Faraday in 1820. As a water treatment technology, EC has a long history, first proposed in London in 1889 and used in a sewage treatment plant for ten years (Boinpally et al., 2023).

The early development of EC technology was primarily focused on producing chlorine for odor reduction and disinfection of sewage effluent through the electrolysis of wastewater mixed with seawater. In 1906, A. E. Dietrich invented and patented the EC technique for treating ship bilge water, while in 1909, a patent was awarded to J.T. Harries in the United States for electrolysis technology utilizing aluminum and iron electrodes for wastewater treatment (Boinpally et al., 2023). However, EC was not widely practiced for water treatment at the time due to the prevailing high cost of power and investment.

2.4.2 EC Process Mechanisms

Figure 2.1 illustrates the schematic representation of the EC cell. The EC process operates by applying controlled micro-electrical currents to eliminate impurities from aqueous solutions, functioning as an advanced alternative to conventional chemical coagulation methods that require external addition of metallic coagulants through electrode electro-dissolution mechanisms. The fundamental mechanism involves the electrolytic dissolution of sacrificial electrodes, which generate coagulant species in situ while facilitating the destabilization of colloidal particles and dissolved contaminants through electrochemical reactions (Kobya et al., 2014; Moussa et al., 2017; Tahreen et al., 2020).

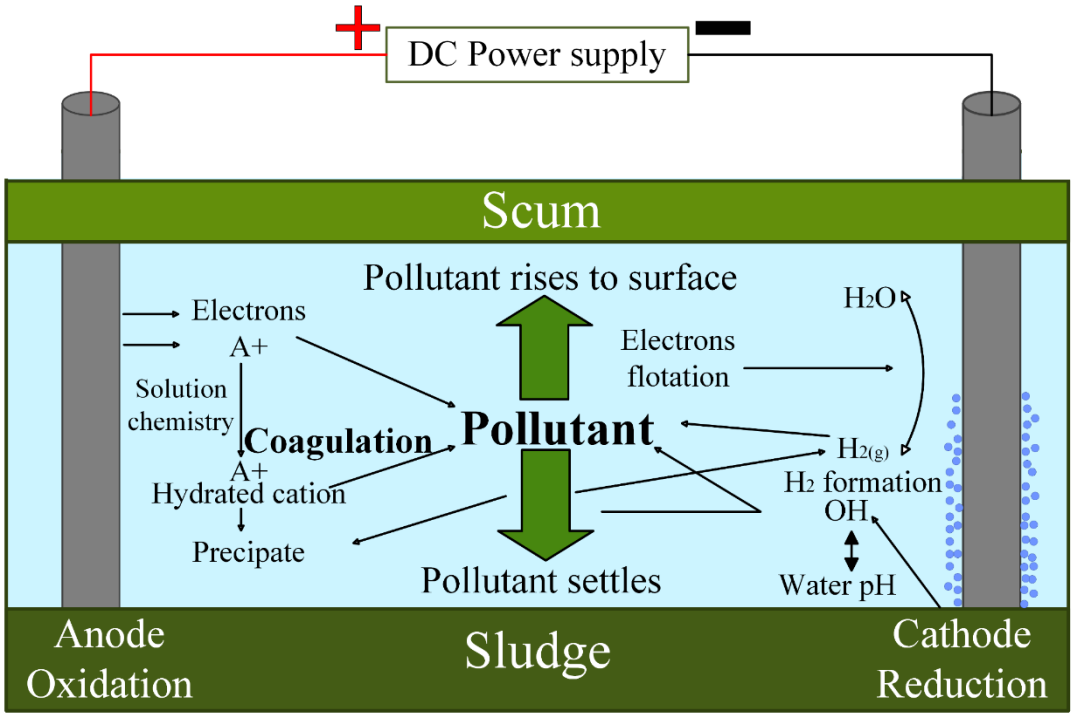

Figure 2.1: Schematic representation of the EC cell.

The EC unit consists of an electrolytic cell with a cathode and an anode connected externally to a power source and immersed in an electrolytic solution. When current is passed through the electrolytic cell, the anode undergoes oxidation, and the metal dissociates into di or trivalent metallic ions, releasing an equal number of electrons. The number of metallic ions generated depends on the applied current density, as determined by Faraday's law (Boinpally et al., 2023). The process of reduction of water on the cathode results in the formation of hydrogen gas and hydroxyl ions, while the metal driven into the anode dissociates into metal ions.

The EC process typically involves chemical equations (Equations. (1)-(4)), that occurs when an electric current passes through electrodes, usually made of Al and Fe (Al Jaberi, 2018; Al Jaberi et al., 2020). The general electrode reactions are as follows (Islam, 2019).

Oxidation at anode:

$$A_{(s)} \rightarrow A_{(aq)}^{n+} + ne^- \quad (1)$$

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \quad (2)$$

Reduction at cathode:

$$2H_2O_{(l)} + 2e^- \rightarrow 2OH_{(aq)}^- + H_{2(g)} \quad (3)$$

$$M_{n+} + nOH^- \rightarrow M(OH)_n \quad (4)$$

2.4.3 Advantages and Limitations of EC

EC has gained increasing attention due to its numerous advantages over conventional treatment methods. It is characterized by operational simplicity, process adaptability, reduced chemical consumption requirements, and diminished sludge production compared to conventional methods (Ingelsson et al., 2020; Almukdad et al., 2021; Othmani et al., 2022). The technology synergistically combines the beneficial aspects of coagulation, flotation, and electrochemical processes into one system, offering significant flexibility and using simple equipment.

One of the key advantages of EC is the minimal usage of chemicals and reduced sludge production compared to conventional chemical coagulation (Dimoglo et al., 2004; Magnisali et al., 2022). The process is considered environmentally friendly as there is no addition of chemical reagents and only minimal utilization of electrode materials due to their abundant availability, non-toxic nature, and inexpensive cost for manufacturing metal coagulants. Additionally, EC equipment can be made portable and can be suitably customized to meet industries' requirements while enabling easy data acquisition for monitoring efficiency.

However, despite these substantial advantages, EC alone frequently proves inadequate for achieving discharge-compliant water quality standards. Residual turbidity, dissolved organic compounds, refractory substances, and volatile constituents commonly persist following EC treatment, necessitating the implementation of additional treatment stages. Furthermore, operational challenges including sludge generation, energy consumption requirements, and electrode passivation during extended operation periods underscore the critical importance of developing integrated treatment frameworks (Othmani et al., 2022).

2.5 EC Applications for Textile Wastewater Treatment

2.5.1 Performance in Textile Industry Applications

EC has emerged as a transformative technology for textile wastewater treatment, demonstrating remarkable efficacy in removing diverse pollutants including TSS, turbidity, COD, TOC, and complex color compounds. Extensive research has validated EC's exceptional performance with removal efficiencies frequently surpassing 80-90% under optimized operational conditions (Bayramoglu et al., 2007; Aoudj et al., 2010; Garcia-Segura et al., 2023).

Table 2.1: Performance of EC process in textile wastewater treatment.

Author	Source	Alone or Hybrid	Electrodes		Experimental condition			Removal efficiencies (%)
			Anode	Cathode	Current density (mA/cm^2)	Time (min)	pH	
Lin and peng (1994)	Textile wastewater	Alone	Fe	Fe	10.00	240	10.00	COD = 51.00
Bayramoglu et al. (2004)	Textile wastewater	Alone	Fe, Al	Fe, Al	20.00	30	6.95	COD = 65.00
Can et al. (2005)	Textile wastewater	Alone	Al	Al	10.00	20	5.50	COD = 50.00
Islam et al. (2011)	Textile wastewater	Alone	Al	Al	-	60	8.50	Turbidity = 79.00
Chackrabartty et al. (2015)	Textile wastewater	Alone	Al	Al	-	60	5.00	COD = 86.50 Color = 93.40
Demirci et al. (2015)	Textile wastewater	Alone	Fe	Fe	10.00	60	9.14	COD = 64.10 Color = 80.00 Turbidity = 84.10
Naje et al. (2015)	Textile wastewater	Alone	Al	Al	-	90	6.00	TSS= 96.4 Turbidity= 96 COD= 92.6 Color= 92.6
Bazrafshan et al. (2016)	Textile wastewater	Hybrid	Al	Al	-	60	-	COD=93.1
Aouni et al. (2017)	Textile wastewater	Hybrid	Al	Al	28.57	120		COD= 98.33 Color= 98.37
Khorram and Fallah (2018)	Textile wastewater	Alone	Al	Al	35.00	60	-	COD = 40.00
Bener et al. (2019)	Textile wastewater	Alone	Al	Al	25.00	120	5.00	COD = 18.60 Color = 90.30 Turbidity = 83.50
GilPavas et al. (2019)	Textile wastewater	Hybrid	Fe	Fe	10.00	60	7.00	COD= 76.00
Núñez et al. (2019)	Textile wastewater	Alone	Fe	Fe	8.00	10	7.1	COD=59.00 Color=86.00 Turbidity= 82.00
De Maman et al. (2022)	Textile wastewater	Alone	Fe	Fe	-	60	7.5	COD= 55.00 Color= 80.00
Gasmi et al. (2022)	Textile wastewater	Alone	Al	Al	-	36.26	9.00	COD= 63.05 Color= 99.07 Turbidity= 96.31

Table 2.1: Performance of EC process in textile wastewater treatment (Continued).

Author	Source	Alone or Hybrid	Electrodes		Experimental condition			Removal efficiencies (%)
			Anode	Cathode	Current density (mA/cm^2)	Time (min)	pH	
Martins et al. (2023)	Textile wastewater	Alone	SS	SS	25.00	50	7.40	COD = 81.00 Turbidity = 74.00
Kalia et al. (2023)	Textile wastewater	Hybrid	Zn-coated Fe	Zn-coated Fe	25.00	-	-	Color= 90.00
Sqalli Houssini et al. (2024)	Textile wastewater	Alone	Bipolar Fe-Al	Bipolar Fe-A	-	-	-	COD= 88.00 Turbidity= 98.5
Arivazhagan (2024)	Textile wastewater	Hybrid	Al	Al	15.00	36	9.36	TSS= 16.04 COD= 76.97 Color= 68.82
Zafar et al. (2024)	Textile wastewater	Hybrid	Al	Al	-	60	7.00-8.00	TSS= 75.00 COD= 79.00 Color= 86.00
Isawi et al. (2024)	Textile wastewater	Hybrid	Fe	Fe	50.00	-	-	COD= 59.1 Color= 94.00
Selvaraj and Arivazhagan (2024)	Textile wastewater	Hybrid	Al	Al	15.00	36	9.36	COD = 76.97 Color = 68.82 TDS = 16.04
Yáñez-Ángeles et al. (2025)	Textile wastewater	Hybrid	IrO_2 Ta_2O_5 |Ti||Ti mesh	IrO_2-Ta_2O_5 |Ti||Ti mesh	10.00	15	7.71	TSS= 96.83 COD= 54.74 TOC= 74.48

The technology has gained widespread acceptance for treating complex industrial wastewaters, particularly from textile manufacturing facilities where traditional approaches face significant limitations due to synthetic dyes' recalcitrant nature. Foundational understanding was established during the 1990s. Lin and Peng (1994) provided earliest evidence achieving 51% COD removal using iron electrodes at 10 mA/cm² for 240 minutes at pH 10. Bayramoglu et al. (2004) achieved enhanced 65% COD removal using iron and aluminum electrodes at 20 mA/cm² over 30 minutes at pH 6.95. Can et al. (2005) refined aluminum electrode performance achieving 50% COD removal at 10 mA/cm² within 20 minutes at pH 5.5, while Islam et al. (2011) demonstrated versatility achieving 79% turbidity removal using aluminum electrodes over 60 minutes at pH 8.5. Significant milestones emerged from Chackrabartty et al. (2015),

who achieved 86.5% COD removal and 93.4% color removal using aluminum electrodes over 60 minutes at pH 5, establishing EC's exceptional effectiveness in color removal. Demirci et al. (2015) provided comprehensive evaluation using iron electrodes, achieving 64.1% COD removal, 80% color removal, and 84.1% turbidity removal at 10 mA/cm² over 60 minutes at pH 9.14. Revolutionary system design emerged from Naje et al. (2015), who introduced alternating monopolar and bipolar aluminum plates achieving exceptional removal efficiencies: 96.4% for TSS, 96% for turbidity, 92.6% for COD, and 92.6% for color under optimized conditions of 0.6 A current, pH 6, NaCl concentration of 0.1 kg/m³, inter-electrode distance of 0.5 cm, rotation speed of 500 rpm, and 90-minute treatment duration. Hybrid approaches began with Bazrafshan et al. (2016), who demonstrated superior potential achieving 93.1% COD removal using EC alone at 60 V, but showed that combining chemical coagulation, EC, and adsorption processes could elevate overall removal efficiency to 98%. Comprehensive validation emerged from Aouni et al. (2017), who investigated EC followed by granular activated carbon adsorption. The EC stage at 28.57 mA/cm² over 120 minutes achieved 62.33% COD and 72.79% color reduction, while integration with GAC at 0.75 g/L dosage enhanced efficiencies to 98.33% for COD and 98.37% for color. Khorram and Fallah (2018) utilized five parallel aluminum plates achieving 40% COD removal and 97% color removal under optimized conditions. Bener et al. (2019) provided detailed evaluation demonstrating 18.6% COD removal, 90.3% color removal, 83.5% turbidity removal, and 42.5% TOC removal using aluminum electrodes at 25 mA/cm², pH 5, and 120-minute treatment. Advanced systems reached new sophistication with GilPavas et al. (2019), who explored progressive enhancement through advanced oxidation process integration. EC alone removed 56% COD, which through hybrid integration with Fenton and photo-Fenton processes achieved 76% COD removal. Núñez et al. (2019) achieved remarkable efficiency documenting 59% COD reduction, 86% color removal, and 82% turbidity removal after only 10 minutes at 8 mA/cm² and pH 7.1. Sophisticated integrated systems reached new heights with Mahmoud et al. (2021), who designed pilot-scale treatment trains combining coagulation-flocculation, filtration, and nanobimetallic iron-copper adsorption, achieving exceptional removal efficiencies of 97% for TSS, 96% for COD, and 82% for color under optimized conditions.

Recent research provided validation with De Maman et al. (2022) achieving 55% COD removal and 80% color removal within 60 minutes using iron electrodes at pH 7.5, while Gasmi et al. (2022) achieved superior performance: 63.05% COD removal, 99.07% color removal, and 96.31% turbidity removal over 36.26 minutes at pH 9. Alternative electrode materials gained

momentum with Martins et al. (2023) investigating 304-grade stainless steel electrodes, achieving 81% COD removal and 74-85% turbidity removal at 25 mA/cm² over 50 minutes at pH 7.4. Kalia et al. (2023) achieved 90% color removal using zinc-coated iron electrodes at 25 mA/cm². Paramita et al. (2023) achieved 71.9% TSS removal using Al6061-T6 aluminum electrodes at 5.5 mA/cm², 15-minute treatment, and 2 cm electrode spacing. Recent advances in 2024 demonstrated enhanced performance with Sqalli Houssini et al. (2024) using bipolar iron-aluminum configurations achieving 88% COD removal and 98.5% turbidity removal. Selvaraj and Arivazhagan (2024) implemented hybrid EC systems achieving 76.97% COD removal, 68.82% color removal, and 16.04% TDS removal at 15 mA/cm² over 36 minutes at pH 9.36. Zafar et al. (2024) demonstrated balanced performance with 75% TSS removal, 79% COD removal, and 86% color removal under conditions of pH 7-8 and 60-minute treatment duration. Advanced hybrid development reached new complexity with Isawi et al. (2024), who implemented combined EC-flotation using iron electrodes followed by SiO_2/PA membrane filtration. At 50 mA/cm², they demonstrated 59.1% COD removal and 94% color removal, with current intensity increases from 50 mA to 600 mA dramatically improving results to 81.5% and 99% respectively. Recent studies continue validating EC's exceptional effectiveness, with researchers reporting removal efficiencies of 76% and 95% for COD and color respectively (Boinpally et al., 2023). Comprehensive electrode material evaluation revealed significant material-specific performance differences. Stainless steel electrodes achieved highest TOC removal efficiency of 70.99% at 20 V over 60 minutes, while aluminum-carbon and stainless steel-mild steel combinations achieved 68.81% and 67.63% respectively. This superior performance significantly exceeded the 42.5% TOC removal reported by Bener et al. (2019), demonstrating critical importance of strategic electrode material selection. The cutting edge of hybrid treatment technology was exemplified by Yáñez-Ángeles et al. (2025), who demonstrated substantial potential using advanced IrO_2-Ta_2O_5|Ti electrode materials in titanium mesh configuration. Operating at 10 mA/cm² for 15 minutes at pH 7.71, they achieved exceptional performance with 96.83% TSS removal, 54.74% COD reduction, and 74.48% TOC removal using laboratory-scale system combining ozonolysis, EC, and electro-oxidation.

The comprehensive body of research establishes EC as highly effective, versatile technology for textile wastewater treatment, with particular strengths in color and turbidity removal consistently demonstrated across diverse operational conditions. The evolutionary progression from simple electrode configurations to sophisticated hybrid systems illustrates continuous

technological advancement driven by systematic understanding of fundamental mechanisms and materials science innovations.

2.5.2 Operational Parameters and Optimization

Figure 2.2 illustrates the key factors influencing EC efficiency. The process can be significantly improved by optimizing parameters such as electrode type, current density, retention time, electrode spacing, pH, and temperature (Zodi et al., 2009; Magnisali et al., 2022). Adjusting current density affects the rate of electrochemical reactions and coagulant production, which directly impacts pollutant removal. Electrode material is another crucial factor, as each metal exhibits distinct electrochemical behavior. Proper retention time ensures sufficient interaction for coagulation and flocculation without excessive energy use. Maintaining an inter-electrode gap between 3–8 mm is typically recommended, though the optimal spacing depends on the electrode material and wastewater composition (Boinpally et al., 2023). pH also plays a vital role, with ideal values varying based on the contaminant and electrode used. Moderate increases in temperature have been shown to improve EC performance by enhancing reaction kinetics and floc stability.

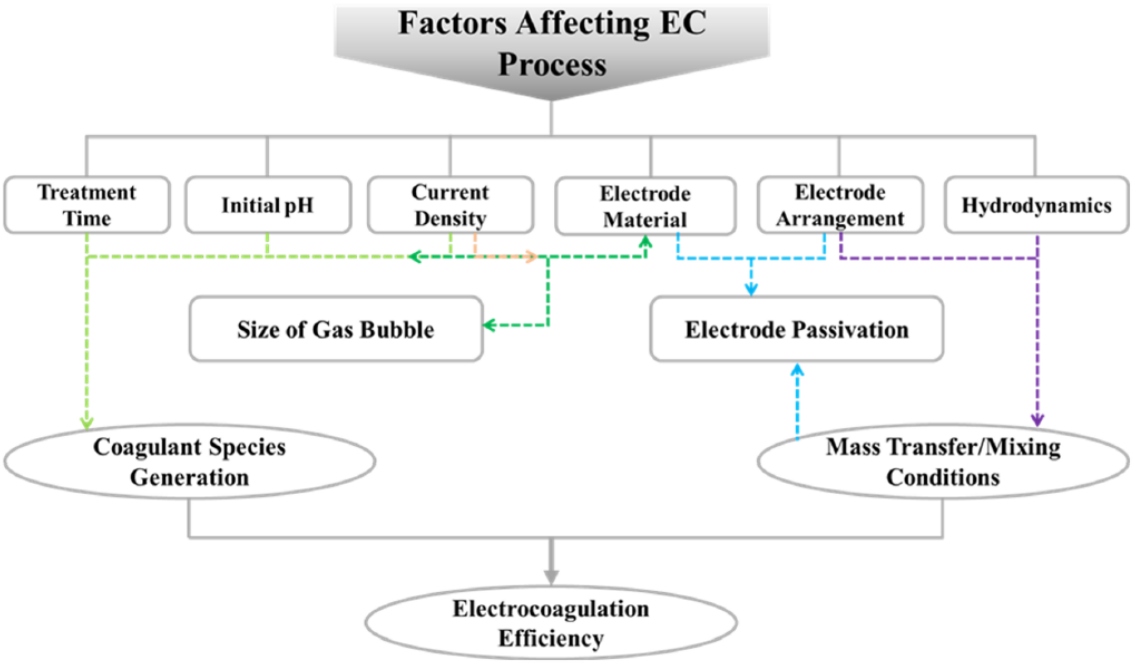

Figure 2.2: Various factors that impact the efficiency of the EC process (Shah et al., 2024).

2.5.2.1 Spacing between the electrodes

The performance of electrolytic cells is notably affected by inter-electrode distance and electrode surface area. Localized concentration gradients near the cathode, caused by ionic migration, can be minimized through solution agitation (Sahu et al., 2014). Gas evolution increases electrical resistance by occupying inter-electrode space, which can be mitigated using corrugated or perforated electrodes for better gas removal (Al-Qodah et al., 2020). High-conductivity effluents benefit from wider electrode spacing, while low-conductivity wastewater requires reduced spacing to lower energy use (Bazrafshan et al., 2015). Very narrow spacing leads to metal hydroxide floc degradation due to excessive collisions, but increasing the gap improves pollutant removal by allowing gradual ion migration and floc agglomeration (Naje & Abbas, 2013). Optimal performance is often achieved at 5 mm spacing (Shahedi et al., 2020), and statistical analyses confirm electrode spacing significantly influences dye removal (Bouguerra et al., 2015; Rahman et al., 2021; Ümmü et al., 2019; Zaied et al., 2020).

2.5.2.2 Effect of electrode material

The choice of electrode material is critical to the performance of EC systems. Numerous materials have been explored such as aluminum, iron, silver, cesium, chromium, magnesium, calcium, and zinc but aluminum and iron remain the most widely used due to their availability, cost-effectiveness, and efficient dissolution (Bouguerra et al., 2015; Ndjomgoue-Yossa et al., 2015). These electrodes can be sourced from commercial metal plates or recycled industrial scraps like shavings and cuttings. Aluminum electrodes are particularly effective in oil removal due to the high adsorption capacity of aluminum oxide formed during EC.

Electrode selection should align with the stoichiometric metal ion needs for neutralizing target pollutants. Iron is often preferred for its affordability, while aluminum is favored for its higher coagulation efficiency. They can be used individually or as hybrid pairs, such as iron-aluminum combinations, which have shown improved performance across various pH levels (Kobya et al., 2020). For wastewater rich in calcium or magnesium, stainless steel or inert cathodes like titanium coated with metal oxides or graphite are recommended to minimize scaling (Sediqi et al., 2021; Naje et al., 2016).

Studies have demonstrated 75–100% arsenic removal using different electrode shapes (plate, mesh, rod, sphere), while aluminum electrodes have outperformed iron in COD reduction. However, no significant difference was found in oil and grease removal between aluminum and mild steel electrodes (Zaied et al., 2020). Maintaining electrode performance requires regular removal of sludge buildup between plates, as accumulated deposits reduce the release of metal ions and hinder treatment efficiency (Sahu et al., 2014).

2.5.2.3 Effects of initial pH

Experimental studies consistently highlight pH as a crucial factor in EC performance. Since pH shifts during treatment, different contaminants require specific pH ranges for optimal removal rather than a single ideal value. The final effluent pH plays a key role in overall removal efficiency (Hanay & Hasar, 2011). For instance, pH 4 is ideal for hexavalent chromium removal (Verma et al., 2013), while treatment of textile wastewater using iron electrodes showed ~90% effectiveness across pH 3–9, though no clear correlation with initial pH was observed (Naje et al., 2016). In contrast, phosphorus removal using aluminum electrodes dropped significantly outside the pH range of 6–8 (Janpoor et al., 2011). Moreover, studies reveal that pH interacts with current density, emphasizing the need to optimize both parameters jointly for effective treatment outcomes.

2.5.2.4 Electrolysis time

Pollutant removal in EC improves with longer electrolysis time, up to an optimal point beyond which efficiency levels off (Abdulrazzaq et al., 2021). As electrolysis continues at constant current density, more metal hydroxides are formed, enhancing floc production and pollutant capture. However, once sufficient flocs are present, extended treatment provides little additional benefit. Studies report optimal durations of 3 hours for standard electrodes and 2 hours for extended surface types (Zhang et al., 2020; Meas, 2021). When comparing power sources DC, AC, and APC all showed similar pollutant removal rates, but APC was favored for its lower energy use, faster processing, and reduced electrode wear. Trials with iron-iron, iron-aluminum, and aluminum-aluminum electrode pairs across varied times (15–60 minutes) and current densities (0.04-0.08 A) confirmed that metal dissolution plays a key role in forming coagulants (Moussa et al., 2017; Chellam & Sari, 2016). Iron-aluminum electrodes proved most efficient, achieving effective treatment at just 0.04 A in 15 minutes, with metal losses of 0.02 g (Fe) and 0.17 g (Al) recorded post-treatment (Kobya et al., 2014).

2.5.2.5 Current Density

Current density, defined as current per unit electrode area, is a key parameter in EC that governs metal ion release, gas bubble formation, and floc characteristics, all of which influence treatment efficiency (Zaied et al., 2020; Gautam et al., 2019). Higher current densities increase anodic dissolution and metal hydroxide generation, enhancing pollutant removal. However, beyond optimal levels, further increases offer minimal benefits as sufficient coagulant is already present for effective sedimentation (Bukhari, 2008). Metal ion release is proportional to current density but also affected by pH, temperature, and flow conditions. EC performance is influenced by the interplay of several factors including current density, treatment time, solution pH, and initial pollutant load (Izadi et al., 2021; Chen et al., 2021). In textile dye removal, raising current density from 5 to 10 mA/cm² improved removal efficiency from 67% to 96% within 6 minutes, but performance declined at 20 mA/cm² due to heat-induced floc destabilization (Chezeau et al., 2020). Since higher current increases energy costs, optimizing current density is essential to balance treatment efficiency with economic viability (Maitlo et al., 2019; Ilhan et al., 2019; Nasrullah et al., 2020).

2.5.2.6 Electrode arrangement

Figure 2.3 illustrates Different configurations of the electrode arrangement in the EC process. EC represents a crucial factor influencing EC system performance.

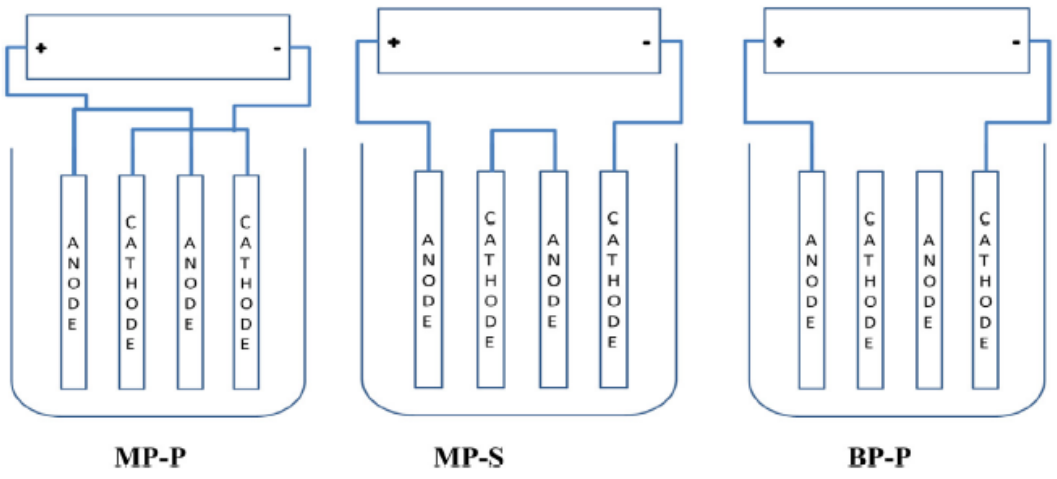

Figure 2.3: Different configurations of the electrode arrangement (Boinpally et al., 2023).

EC setups primarily use two connection types: monopolar and bipolar. In monopolar-parallel (MP-P) configurations, all anodes and cathodes are directly powered, and current distribution

depends on individual cell resistance. Monopolar-series (MP-S) connections link electrode pairs internally, with external electrodes connected to the power supply, creating additive voltages across the cell. Bipolar-parallel (BP-P) setups connect only external electrodes to the power source; internal electrodes become polarized, generating opposite surface charges (Moussa et al., 2017; Sahu et al., 2014; Zaied et al., 2020; Kobya & Demirbas, 2015). Comparative studies using aluminum electrodes in MP-P, MP-S, and BP-P setups found MP-P to be the most efficient (Demirci et al., 2015). Cost analysis for arsenic removal also identified MP-P as the most economical choice for both iron and aluminum electrodes (Kobya et al., 2011). While monopolar systems are generally more cost-effective, bipolar arrangements may offer higher removal efficiency (Naje et al., 2016).

The performance of EC also depends on wastewater characteristics. For example, trinitrophenol (TNP) removal remained consistently high (80–85%) across a wide pH range (5-11) and improved with increased current density (Shen et al., 2022). In contrast, textile wastewater showed better COD removal at 14 mA/cm² than at 20 mA/cm², indicating performance decline at higher currents (Tyagi et al., 2014). Overall, achieving optimal removal efficiency requires careful adjustment of operational parameters tailored to each effluent type.

2.6 Multi-Criteria Decision-Making in Environmental Engineering

2.6.1 MCDM Fundamentals and Applications

In complex environmental engineering applications, particularly those involving multiple operational configurations and competing performance indicators, relying on a single evaluation parameter is often insufficient. Multi-criteria decision-making methods offer a structured and systematic approach for evaluating, ranking, and prioritizing alternatives based on multiple and often conflicting criteria (Huang et al., 2011; Stojčić et al., 2019). MCDM encompasses a range of methods that have gained significant attention in environmental decision-making scenarios due to their ability to address complex trade-offs between multiple performance indicators.

Widely recognized MCDM methods include the Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), VIšekriterijumsko KOmpromisno Rangiranje (VIKOR), Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), as well as Analytic Network Process (ANP),

Elimination et Choix Traduisant la REalité (ELECTRE), Multi-Attribute Utility Theory (MAUT), and MULTIMOORA (Hwang and Masud, 2012; Mardani et al., 2015).

2.6.2 MCDM in Water Treatment Applications

MCDM methods have gained prominence in water and wastewater treatment due to their ability to assess complex systems using both qualitative and quantitative criteria (Kalbar et al., 2012). These tools aid in transparent, evidence-based decision-making by comparing alternatives based on weighted factors, helping balance environmental and economic objectives. Studies highlight MCDM's effectiveness in selecting and optimizing wastewater treatment systems, including municipal solid waste models and treatment alternatives (Mir et al., 2016). However, its application in optimizing electrochemical treatments remains limited, particularly in evaluating trade-offs among efficiency, cost, energy use, and sustainability.

2.6.3 Methodological Approaches and Selection Criteria

The selection of appropriate MCDM methods depends on various factors including the nature of the decision problem, the type and amount of available information, the number of alternatives and criteria, and the decision-maker's preferences. TOPSIS is valued for its geometric perspective, identifying the best alternative as the one nearest to the ideal solution and furthest from the anti-ideal, making it particularly suitable for environmental systems where decision-makers must balance competing goals (Opricovic and Tzeng, 2004; Behzadian et al., 2012).

VIKOR emphasizes compromise solutions, aiming to identify alternatives that achieve the closest proximity to the ideal solution while minimizing individual regret, making it highly suitable in scenarios requiring conflict resolution among objectives (Chang and Hsu, 2009; Mardani et al., 2016). PROMETHEE II, an outranking method, uses pairwise comparisons based on preference functions and delivers complete ranking of alternatives while allowing incorporation of qualitative and quantitative criteria (Figueira et al., 2005; Goswami, 2020).
AHP provides a structured framework for determining the relative importance of criteria through pairwise comparisons, offering a systematic approach to weight determination that can be integrated with other MCDM methods (Aziz and Mahmud, 2016; Darko et al., 2019). The integration of multiple MCDM techniques enables methodological triangulation and enhances the robustness of decision-making frameworks, providing comprehensive cross-validated evaluation of treatment alternatives.

Chapter 3

Methodology

3.1 General

This chapter outlines the comprehensive methodology adopted in this study to develop, optimize, and integrate EC -based treatment systems for textile wastewater management. It details the experimental approaches across three sequential phases: seawater integration enhancement, electrode optimization through multi-criteria evaluation, and integrated multi-stage system development. The methodology encompasses sample collection and characterization procedures, physicochemical analysis protocols, systematic experimental design frameworks, and multi-criteria decision-making approaches for performance optimization. The study further describes the selection and evaluation of treatment performance parameters, the use of statistical and analytical tools for process optimization, and the assessment of treatment configurations across different operational conditions. The methodology ensures a systematic investigation of EC mechanisms and their synergistic integration, enabling robust performance enhancement and identification of optimal treatment strategies for sustainable industrial wastewater management.

3.2 Study Area and Sample Collection

Figure 3.1 shows the location of the wastewater sampling site, which is positioned approximately 300 meters away from the Central Effluent Treatment Plant (CETP). The wastewater used in this study was sourced from an influent drain that predominantly received industrial effluents originating from textile factories affiliated with Apex Holdings Ltd. The operational sites of both the textile division and the Common Effluent Treatment Plant (CETP) are situated in the Shafipur area of Kaliakoir Upazila, which is located in the Gazipur District of Bangladesh. Apex Holdings Ltd. demonstrated the early adoption of environmental principles by incorporating an effluent treatment facility, making them one of the pioneering textile composite enterprises to undertake such an endeavor. The primary biological effluent treatment plant (ETP) located in Chandra, Kaliakoir, Gazipur, Bangladesh was specifically engineered to handle a maximum volume of 8 million liters of wastewater per day. Additionally, it has been documented that the plant operates

with a total hydraulic retention time (HRT) of 100 hours and the CETP has established a treatment capacity of 350 m3/hour. The seawater used in this study was obtained from the bank of Saint Martin Island (Latitude: 20°37'22.86″ N and Longitude: 92°19'12.76″ E) and transported to the lab.

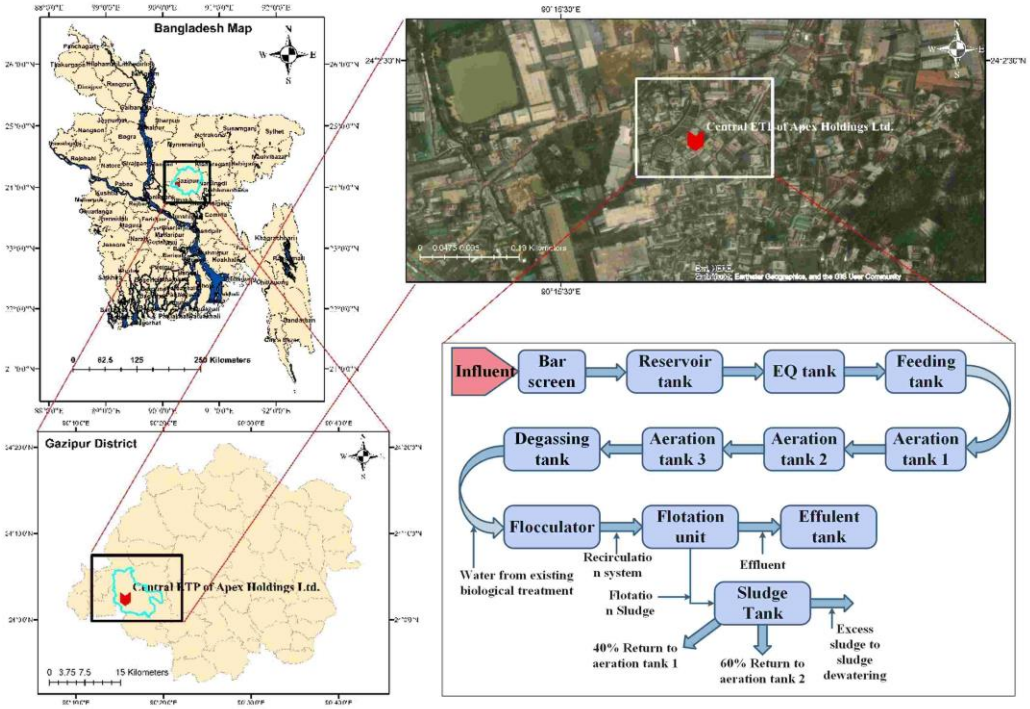

Figure 3.1: Textile wastewater sample collection site in Gazipur, Bangladesh.

3.3 Physicochemical Analysis

Table 3.1 summarizes the physicochemical parameters analyzed in the raw wastewater samples along with their corresponding permissible discharge limits according to Bangladesh Environmental Conservation Rules (ECR, 2023) and the analytical instrumentation employed for each parameter determination. Comprehensive physicochemical characterization was conducted for all wastewater samples to establish baseline conditions and evaluate treatment performance. The analysis focused on key parameters including pH, electrical conductivity, DO, TSS, turbidity, COD, color, TOC, and TDS. All measurements could be performed following standard methodologies as outlined in Standard Methods for the Examination of Water and Wastewater (Rice, 2012). In this study high-precision analytical instruments from reputable manufacturers were used, with the specific equipment detailed in Table 3.1. For each parameter, duplicate

measurements were performed, and the arithmetic mean was reported to ensure accuracy and reproducibility.

Table 3.1: Characterization of raw wastewater.

Parameter	Unit	Raw wastewater	Permissible level* (ECR, 2023)	Apparatus name	Model No.	Country
pH	-	8.16-8.62	6–9	HACH Sension+ PH31 Advanced GLP pH & ORP meter	PH31	USA
Electrical conductivity	µS/cm	1140.0-2033.0	1200	HACH HQ40D Portable Dual Input Multi-Parameter meter	HQ40D	USA
DO	mg/L	0.14-0.35	≥ 1	HACH HQ40D Portable Dual Input Multi-Parameter meter	HQ40D	USA
TSS	mg/L	210.0-332.0	100	HACH DR3900 Benchtop Spectrophotometer	DR3900	USA
Turbidity	NTU	1.66-393.0	10	HACH 2100Q Portable Turbidimeter	2100Q	USA
COD	mg/L	291.0-378.0	200	HACH DR3900 Benchtop Spectrophotometer	DR3900	USA
Color	Pt-Co	13.0-1896.0	150	HACH DR2800 Spectrophotometer	DR2800	USA
TOC	ppm	20.36-39.4	-	Sievers InnovOx ES Laboratory TOC Analyzer	InnovOx ES	USA
TDS	mg/L	1035.0-1160.0	2100	HACH HQ40D Portable Dual Input Multi-Parameter meter	HQ40D	USA

*Industrial effluent discharge standards to inland water in Bangladesh.

For each parameter, duplicate measurements were performed, and the arithmetic mean was reported to ensure accuracy and reproducibility. The measured values were compared against permissible discharge limits as defined in the Environmental Conservation Rules (ECR, 2023) of Bangladesh to assess pollution levels relative to regulatory standards.

The analytical results revealed that several parameters exceeded the established discharge standards. Electrical conductivity, TSS, turbidity, COD, and color measurements surpassed their respective permissible limits, indicating significant pollution loading in the raw wastewater. DO levels were critically below the minimum required standards, suggesting high organic content and potential environmental impact. pH remained within acceptable ranges according to regulatory guidelines. This comprehensive analytical approach provided a thorough assessment of wastewater quality relative to environmental discharge standards.

3.4 Removal Efficiency

Treatment performance all three studies of this thesis was evaluated using removal efficiency as the primary metric. To determine the removal efficacy, represented as Y (%), Equation 1 was utilized.

$$Y = \frac{C_o - C_t}{C_o} \times 100\ \% \quad (5)$$

Where Y is the removal efficacy response; C_o and C_t are the initial and final amount of pollutant (Back et al., 2023). This standardized approach enabled consistent performance comparison across all treatment configurations and provided reliable metrics for optimization and decision-making processes.

3.5 Multi-Criteria Decision-Making (MCDM) Methods

In complex environmental engineering applications, particularly those involving multiple operational configurations and competing performance indicators, relying on a single evaluation parameter is often insufficient. To address this issue, MCDM methods offer a structured and systematic approach for evaluating, ranking, and prioritizing alternatives based on multiple and often conflicting criteria. MCDM is the process of selecting the best alternative from a set of alternatives based on multiple criteria. It is a powerful tool that can be used to solve a wide range of problems in various fields, including engineering, management, economics, and environmental

science. These techniques enable informed and balanced decision making, especially in integrated water and wastewater treatment systems, where technical, economic, and environmental factors must be optimized concurrently. Thus, MCDM has become an essential tool in water treatment research to facilitate the selection of optimal process configurations.

There are many different types of MCDM models, each of which has its own strengths and limitations. Widely recognized MCDM methods include the AHP, TOPSIS, VIKOR, PROMETHEE, ANP, ELECTRE, MAUT, and MULTIMOORA (Hwang and Masud, 2012; Mardani et al., 2015; Bhole and Deshmukh, 2018).

In this comprehensive study, four widely recognized and robust MCDM techniques TOPSIS, VIKOR, PROMETHEE II, and AHP were employed to assess and rank the performance across different phases of the research. For the electrode optimization study, TOPSIS, VIKOR, and PROMETHEE II techniques were specifically used to assess the best electrode combination in the EC process for textile wastewater treatment. For the integrated system evaluation, all four methods (TOPSIS, VIKOR, PROMETHEE II, and AHP) were utilized to assess and rank the performance of 27 integrated system processes for textile wastewater treatment. These methods were selected because of their extensive validation in environmental decision-making scenarios and their capacity to address complex trade-offs between multiple performance indicators such as removal efficiencies for TSS, COD, turbidity, and color. Their transparent frameworks and ease of application make them particularly suitable for evaluating water treatment system performance (Triantaphyllou and Triantaphyllou, 2000).

The decision to utilize these specific MCDM methods was aligned with the study's goals of identifying the most efficient electrode configurations and integrated treatment configurations. These methods were chosen for their complementarity in interpreting complex, multi-criteria environmental datasets, and their ability to offer balanced recommendations based on different decision logic paradigms. The selection was influenced by the aim and context of the study, which focused on determining optimal configurations for EC-based textile wastewater treatment. These methods were chosen because they are applicable and robust in dealing with the decision-making problems presented in the research. The goal was to find a balance between comprehensibility, computational efficiency, and the ability to effectively manage conflicting criteria, for which these methods are well-suited.

TOPSIS is valued for its geometric perspective, identifying the best alternative as the one nearest to the ideal solution and furthest from the anti-ideal. This is particularly relevant for environmental systems where decision-makers must strike a balance among competing goals such as pollutant removal efficiency, energy use, and system complexity (Opricovic and Tzeng, 2004; Behzadian et al., 2012). TOPSIS is known for its straightforwardness and clarity in facilitating the ranking of alternatives based on their proximity to an ideal solution, making it particularly suitable for the comparative analysis of electrode pairs and integrated system configurations in the study.

VIKOR, on the other hand, emphasizes compromise solutions, aiming to identify the alternative that achieves the closest proximity to the ideal solution while minimizing individual regret. It is highly suitable in scenarios requiring conflict resolution among objectives (Chang and Hsu, 2009; Mardani et al., 2016). VIKOR was selected for its proficiency in identifying a compromise solution, which was crucial as no single electrode pair proved superior across all pollutants, and similarly for integrated system configurations where trade-offs between different performance criteria were necessary.

PROMETHEE II, an outranking method, uses pairwise comparisons based on preference functions and delivers a complete ranking of the alternatives. It allows the incorporation of qualitative and quantitative criteria, and is known for its adaptability and transparency, making it suitable for practical wastewater management applications (Figueira et al., 2005; Goswami, 2020). The selection of PROMETHEE II was justified by its flexibility in accommodating both qualitative and quantitative criteria without the need to elicit criterion weights, a process that can be complex and subjective (Chang and Hsu, 2009; Nikolić et al., 2009; Mir et al., 2016).

The AHP was used to determine the relative importance (weights) of the selected evaluation criteria through pairwise comparisons (Aziz and Mahmud, 2016; Darko et al., 2019). These weights were then incorporated into the other MCDM models to ensure methodological rigor and consistency in evaluating alternatives across the integrated system study.

Although other MCDM methods such as the Analytic Network Process (ANP), ELECTRE, and MULTIMOORA possess unique strengths, they were not selected for this study because of their limited applicability in this context. ANP, an advanced extension of AHP, involves complex interdependencies and feedback loops that significantly increase computational intensity without offering proportional benefits for this treatment configuration study (Asadabadi et al., 2019). MULTIMOORA requires the use of multiple ratios, which can make the decision matrix and

interpretation of results more complex, which is not ideal for the straightforward assessment of electrode materials' performance and integrated system configurations. ELECTRE is better suited for filtering or eliminating less favorable alternatives than delivering full rankings (Govindan and Jepsen, 2016). Although methodologically comprehensive, MULTIMOORA lacks the intuitive clarity and environmental validation necessary for comparative analysis of treatment processes (Hafezalkotob et al., 2019). Furthermore, while AHP was included in the integrated system study for weight determination, its heavy reliance on pairwise comparisons and subjective judgments of experts to determine the weights of criteria made it less suitable as a standalone ranking method for the electrode optimization phase, where this study aimed to minimize reliance on subjectivity. Additionally, AHP can be burdensome in scenarios with many alternatives, such as the electrode study which examined thirty-six different electrode pair combinations (Hafezalkotob et al., 2019; Daneshfar and Ardjmand, 2020).

The integration of multiple MCDM techniques in this study allows methodological triangulation and enhances the robustness of the decision-making framework. This combination enabled a comprehensive, cross-validated evaluation of all treatment configurations, ensuring that the selected optimal configurations were consistently identified under diverse decision-making logic. The application of multiple MCDM methods provides a more comprehensive and robust understanding of the optimization problems, allowing for confident selection of the best electrode combinations and integrated treatment strategies for EC-based textile wastewater treatment. The use of these methods supports confident selection of the most effective and scalable treatment strategies based on multiple performance criteria.

3.5.1 VIKOR Method

The VIKOR method is an MCDM technique that identifies mutually agreeable solutions by measuring each alternative's closeness to the ideal solution using the Lp-metric aggregating function (Zeleny, 1982).The development of the method for each function started with the following form of Lp-metric:

$$L_{p,j} = \left\{\sum_{i=1}^{n}\left[w_i(F_i^+ - F_{ij})/(F_i^+ - F_i^-)\right]^p\right\}^{\frac{1}{p}},\ 1 \le p \le \infty;\ j = 1, 2, \ldots, J.$$

The VIKOR approach establishes a ranking list representing a compromise solution by minimizing group utility (Sj) as shown in Equation 2 and individual regret (Rj) as illustrated in Equation 3,

identifying the solution closest to the ideal while considering stakeholder trade-offs (Opricovic, 1998):

(a) Determine the best F_i^+ and worst F_i^- values where i = 1, 2, 3, …n of all the criterion functions as:

$F_i^+ = \max(F_{ij})$ and $F_i^- = \min(F_{ij})$

(b) Normalization of S_j and R_j where j = 1, 2, 3, …n is computed with Equations 6 and 7.

$$S_j = \sum_{i=1}^{n} \left[\frac{w_i(F_i^+ - F_{ij})}{F_i^+ - F_i^-}\right] \quad (6)$$

$$R_j = Max \left[\frac{w_i(F_i^+ - F_{ij})}{F_i^+ - F_i^-}\right] \quad (7)$$

(c) Calculation of the value of Q_j where j = 1, 2, 3, …n is illustrated in Equation 8.

$$Q_j = \frac{v\,(S_j - S^+)}{(S^- - S^+)} + (1 - v)\left(\frac{R_j - R^+}{R^- - R^+}\right) \quad (8)$$

where, S^+= min S_j, S^-= max S_j, R^+=min R_j, R^-= max R_j and v is the weight of the majority of criteria or the maximum group utility, here v = 0.25.

(d) The ranking of the alternatives is done after sorting the S, R and Q values in decreasing order, which gives three ranking lists.

(e) Analyzing the compromising function by the generated best rank alternative (a_2) by measuring the minimum Q through two cases, which are:

Case 1: $Q(a_2) - Q(a_1) \geq DQ$

where, a_2 is the second-place alternative in the ranking list sorted by *Q; DQ = 1/(J-1)*; *J* is the number of alternatives.

Case 2: The compromising function is chosen with a random decision-making process, where Q_j is chosen as the best choice from *S* and/or *R* with $v \geq 0.25$.

The VIKOR method selects the best electrode pair based on the lowest Q value, providing a compromise solution for multi-criteria decision-making with conflicting objectives (Opricovic, 1998; Opricovic and Tzeng, 2004).

3.5.2 TOPSIS Method

TOPSIS is an MCDM technique that selects the best alternative by calculating distances to ideal and anti-ideal solutions, choosing the alternative closest to the ideal solution (Hwang and Yoon,

1981; Chen and Hwang, 1992). The computation technique of TOPSIS has the following steps (Chen and Hwang, 1992):

(a) Computation of the normalized decision matrix r_{ij} is done as follows.

$r_{ij} = \frac{f_{ij}}{\sqrt{\sum_{j=1}^{J} f_{ij}^2}}$, j = 1, 2, …. , J; i = 1, 2, ……, n.

(b) Computation of the weighted normalized decision matrix v_{ij} is done as

$v_{ij} = w_i r_{ij}$, j = 1, 2, …. , J; i = 1, 2, ……, n.

where, w_i is the weight of the i^{th} criteria, and

$$\sum_{i=1}^{n} w_i = 1$$

(c) Establish the positive and the negative ideal solutions.

$A^* = \{v_1^*, \ldots., v_n^*\}$

$= \{(max v_{ij} | i \in I'), (min v_{ij} | i \in I')\}$,

$A^- = \{v_1^-, \ldots., v_n^-\}$

,

$= \{(min v_{ij} | i \in I'), (max v_{ij} | i \in I')\}$

where, I' represent benefit criteria and I'' represent cost criteria.

(d) Computation of the division measures, utilizing the Euclidean distance technique. The division of each alternative from the positive ideal solution is represented as

$D_j^* = \sqrt{\sum_{i=1}^{n} (v_{ij} - v_i^*)^2}$, j = 1, 2, …, J. (9)

Similarly, the negative ideal solution is represented as

$D_j^- = \sqrt{\sum_{i=1}^{n} (v_{ij} - v_i^-)^2}$, j = 1, 2, …, J. (10)

(e) Computation of the relative nearness to the ideal solution. The relative nearness of the alternative a_j as to A^* is represented as

$C_j^* = \frac{D_j^-}{(D_j^* + D_j^-)}$, j=1, 2, …, J. (11)

(f) Lastly, the ranking of the alternatives is done.

TOPSIS selects the best alternative by minimizing distance to the positive ideal solution and maximizing distance to the negative ideal solution through systematic evaluation involving

decision matrix construction, normalization, weighted assessment, and Euclidean distance calculations using Equation 11 (Chen and Hwang, 1992; Çelikbilek and Tüysüz, 2020; Opricovic and Tzeng, 2004).

3.5.3 PROMETHEE II Method

PROMETHEE II is a sophisticated MCDM outranking method that ranks alternatives based on net preference flows calculated through pairwise comparisons using customized preference functions and weighted criteria (Athawale and Chakraborty, 2010). The computation technique of PROMETHEE II has the following steps (Doumpos and Zopounidis, 2004; Hajkowicz and Higgins, 2008):

(a) Computation of the normalized decision matrix is done as

$$R_{ij} = \frac{[X_{ij} - \min(X_{ij})]}{[\max(X_{ij}) - \min(X_{ij})]}, \text{ i = 1, 2, …., n ; j = 1, 2, …, m} \quad (12)$$

where, X_{ij} measures the performance of i^{th} alternative as to j^{th} criterion. In the case of non-beneficial criteria, Equation 12 can be represented as

$$R_{ij} = \frac{[\max(X_{ij}) - X_{ij}]}{[\max(X_{ij}) - \min(X_{ij})]}$$

(b) Computation of the assessment differences of i^{th} alternative as to other alternatives. In this step, the differences in criteria values of the pair-wise alternatives are computed.

(c) Computation of the preference function, $P_j(i, i')$ is done. The linear preference function is used in this study, which is represented as Equation 13 and 14.

$$P_j(i, i') = 0 \; if \; R_{ij} \leq R_{i'j} \quad (13)$$

$$P_j(i, i') = \left(R_{ij} - R_{i'j}\right) if \; R_{ij} > R_{i'j} \quad (14)$$

(d) Computation of the aggregated preference function is done considering the criteria weights, as illustrated in Equation 15.

$$\pi\,(i, i') = \frac{\left[\sum_{j=1}^{m} w_j \times P_j(i, i')\right]}{\sum_{j=1}^{m} w_j} \quad (15)$$

Where, w_j is the relative weight of the j^{th} criterion.

(e) Computation of the positive and negative outranking flows, which are represented Equation 16 and 17.

$$\text{Positive flow, } \varphi^{+}(i) = \frac{1}{n-1}\sum_{i'=1}^{n} \pi\,(i, i') \qquad (i \neq i') \quad (16)$$

$$\text{Negative flow, } \varphi^{-}(i) = \frac{1}{n-1}\sum_{i'=1}^{n} \pi\,(i', i) \qquad (i \neq i') \quad (17)$$

where, n is the total number of alternatives.

(f) Computation of the total outranking flow for each alternative is done with Equation 18.

$$\varphi(i) = \varphi^{+}(i) - \varphi^{-}(i) \quad (18)$$

(g) Lastly, the ranking of the alternatives considering the values of *φ(i)* is calculated. The bigger *φ(i)* represents the better alternatives. Thus, the biggest *φ(i)* is the best alternative among the other alternatives.

PROMETHEE II calculates positive and negative outranking flows to derive a comprehensive ranking based on net outranking flow, providing complete ordering of alternatives unlike PROMETHEE I (Behzadian et al., 2010).

3.5.4 AHP Method

The Analytic Hierarchy Process (AHP), introduced by Saaty (1980), is a systematic hierarchical MCDM approach that structures decision problems into multiple levels and incorporates expert judgments through pairwise comparisons to derive relative weights of criteria, integrating both qualitative and quantitative data (Saaty, 1994; Forman and Gass, 2001). These steps are outlined as follows:

a) Hierarchy Development:

The initial step involves breaking down the decision problem into a structured hierarchy, defining the overarching goal, criteria, and alternatives (Saaty, 1980).

b) Formation of Pairwise Comparison and Judgment Matrix:

To evaluate criterion significance, AHP employs pairwise comparisons where decision-makers assess relative importance using a 1-9 scale to express preference intensity (Saaty, 1990). These comparisons are organized into judgment matrix *A*, where each element a_{ij} represents the assessed importance of criterion i relative to criterion j.

$$a_{ij} = \frac{1}{a_{ji}} \; and \; a_{ii} = 1 \; for \; all \; i,j \quad (19)$$

c) Normalization and Derivation of the Priority Vector:

This step involves normalizing the judgment matrix by dividing each element by its column sum, then computing the average of normalized values across each row to obtain the relative weight vector reflecting criterion importance (Vaidya and Kumar, 2006):

$$W_i = \frac{1}{n}\sum_{j=1}^{n} \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \quad (20)$$

d) Consistency Verification:

The AHP framework incorporates a Consistency Index (CI) mechanism to assess judgment coherence during pairwise comparisons, calculated as:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (21)$$

The Consistency Ratio (CR) is computed using equation 22, and CR ≤ 0.10 indicates acceptable consistency in pairwise comparisons (Saaty, 1990).

$$CR = \frac{CI}{RI} \quad (22)$$

If CR is greater than this critical value, then the comparisons must be reviewed again.

e) Derivation of Weighted Scores for Alternatives:

Each alternative is evaluated using pairwise comparison and normalization, with final weighted scores obtained by multiplying criterion priority vectors with normalized alternative performance scores (Equation X) (Saaty, 1990; Vaidya & Kumar, 2006).

f) Aggregation of scores and ranking:

Each alternative's final score is obtained by summing its weighted scores across all criteria. Alternatives are then ranked based on these total scores to identify the most suitable option.

$$Score_{Alternative\ j} = \sum_{i=1}^{n} (W_i \times Priority\ Score_{ij}) \quad (23)$$

Alternatives are ranked by total scores, with AHP providing a structured framework combining qualitative judgments with quantitative analysis for systematic multi-criteria evaluation and balanced decision-making.

3.6 Statistical Analysis for Seawater Integration Study

Descriptive statistics were applied to all data sets to calculate the mean and standard deviation. The fitness of the model with the experimental data was evaluated using statistical parameters such as mean, R^2, R^2-(adj), and Std. Dev. The ANOVA test was performed to determine the F-value, p-value, and significance of these models. All these statistical analyses were performed using Microsoft Excel® Version 16.1. software (Microsoft Corporation, Redmond, WA, USA) and Design-Expert® Version 11 (Stat-Ease, Inc., Minneapolis, USA). All tests were considered significant if the p-value < 0.05.

3.7 Methodology Used for Seawater Integration Study

3.7.1 Experimental Setup for Seawater Integration Study

Figure 3.2 shows the experimental setup for seawater integration study, where glass beaker was used as an EC reactor with dimensions of 14.5 cm (height) and 10.5 cm (diameter). Two electrodes were used for simplicity and cost-effectiveness of the EC process, where carbon was used as the anode and mild steel was used as the cathode with an identical dimension of 16 cm (height) and 0.95 cm (diameter). The total effective electrode area was 38 cm2, the spacing between the electrodes was 9 cm, and spacing in between the bottom of the EC reactor and electrodes was 2 cm, maintained throughout the experiment. The electrodes were connected to a digital DC power supply machine (Lodestar LP3005D; 0-30 V, 0-5 A). All the experiments were performed maintaining an initial room temperature of 25°C. Prior to each experiment, wastewater was filtered using a screen filter (1.18mm) to remove large, suspended solids. Before starting the EC process physicochemical parameters such as pH, TSS (mg/L), electrical conductivity (μS/cm), DO (mg/L), turbidity (NTU), COD (mg/L), and color (Pt-Co), of the raw textile wastewater were measured according to Standard Methods for the Examination of Water and Wastewater (Rice, 2012). This was done to compare with the physicochemical parameters after the EC process incorporating different proportions of seawater. In each experiment, 600 cm^3 of textile wastewater, collected from an influent drain primarily fed by industrial effluents from textile factories, was poured into the glass beaker used as an EC reactor. Seawater, at concentration of 0%, 5%, 10%, and 15% of the 600 cm^3 of textile wastewater was added to the EC reactor along with the raw textile wastewater. These specific concentrations were chosen to examine the incremental impact of seawater integration on the efficiency of the EC process in treating textile wastewater, specifically on key wastewater parameters such as pH, electrical conductivity, dissolved oxygen, and pollutant removal. This methodical approach aimed to evaluate the baseline efficiency of the EC process, the incremental impact on quality parameters, operational feasibility, and optimization of treatment efficiency, thereby providing a comprehensive insight into the efficacy of seawater in enhancing treatment outcomes. Throughout the experimentation, the current density was maintained at a predefined value with the voltage set at 20V. After each 90 min of EC, the total electrode current consumption was 0.82 A. Two separate retention timeframes of 45 and 90 min were set to conduct

the EC processes to see how well different retention times of EC treatment could remove pollutants from textile wastewater mixed with seawater.

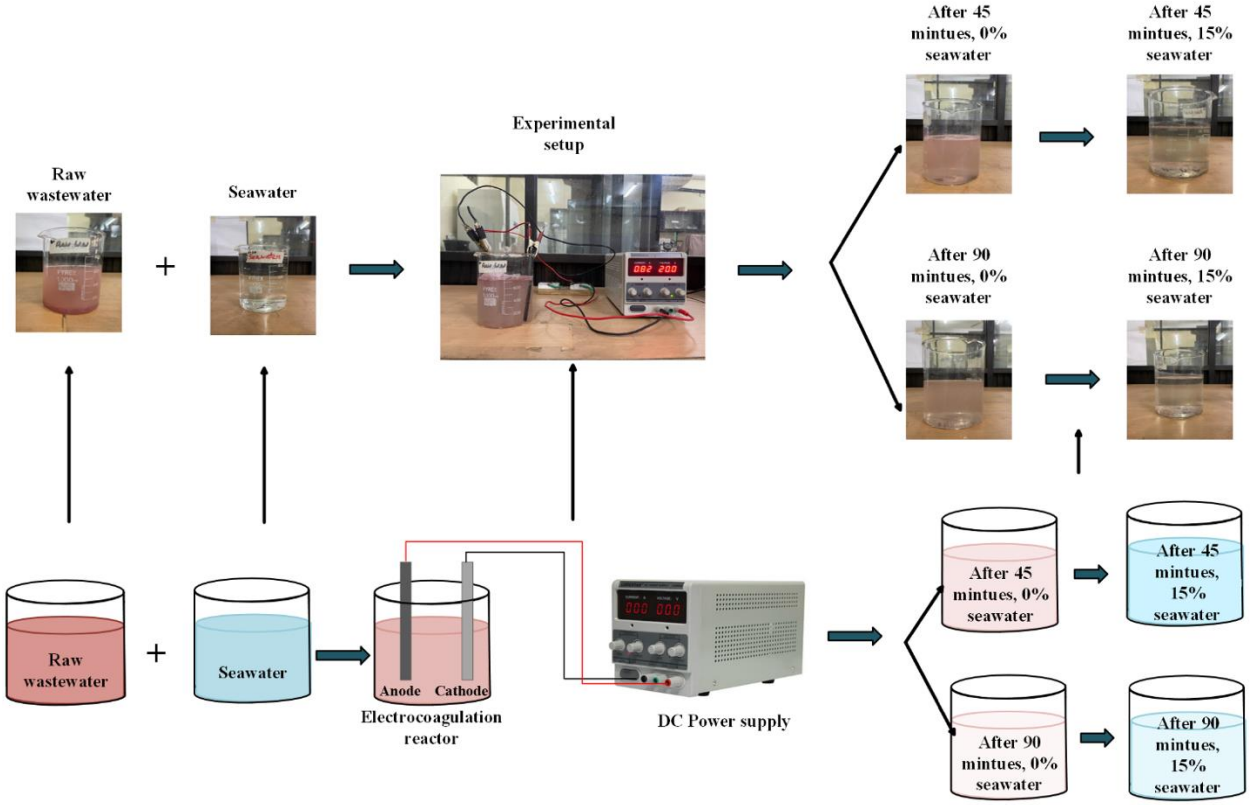

Figure 3.2: Schematic of experimental setup for seawater integration study.

These durations were chosen to compare the effects of shorter and longer treatment times on water quality and identify the optimal conditions for effective wastewater treatment of pollutant removal and the practical considerations of applying EC in real-world scenarios, optimizing the process for maximum efficiency and practicality. After each EC process of 45 and 90 min intervals, both the electrodes underwent a thorough cleansing procedure using mechanical brushing and distilled water to complete the removal of any potential residual solid deposits and impurities from the surfaces of both mild steel and carbon electrodes. Stojek (2010) followed a similar approach in EC process. Furthermore, the electrodes were dried at room temperature and reweighed in order to be reused for the following EC process. At the beginning of the experiment, the weight of the carbon anode was 15.47 g, and the mild steel cathode was 51.58 g. After the EC process, the carbon anode loses its weight between 0.031 and 0.047 g, and the mild steel cathode gains weight between 0.024 and 0.032 g. The electrodes may be replaced by new ones after 10 runs of 90 min. Then the scum

was removed very carefully from the top of the EC reactor with the help of a laboratory spatula. The sludge removal in EC involves allowing the coagulated particles to settle after the treatment, followed by decanting the clear water from the top, which will go for further physicochemical analysis. To prevent increases in turbidity and TSS, careful handling of decanting clear water was applied to ensure the settled sludge does not resuspend into the treated water. Following the EC procedure, physicochemical parameters assessments were conducted after 45 and 90 min of retention time, with varying percentages of seawater, as was done before the EC process.

3.7.2 Cost Analysis

Table 3.2. illustrates the total estimated operating cost of the EC process for seawater integration study. based on the Bangladesh's local market price of 2023. This approach can be tailored to achieve desired treatment levels, also flexible to make the process applicable for textile factories of different sizes and operational scales.

Table 3.2: Total estimated operating cost of the EC process for seawater integration study.

Item	Cost ($)
DC power supply equipment	90.00
EC reactor	5.00
Electricity (kW.h)*	0.23
Electrode (Anode per piece)	1.10
Electrode (Cathode per piece)	1.00
Total	97.33

Note: *Equipment capacity is 1 kW (assumed), runs for 90 min (1.5 h), so 1.5 kW.h electricity is used. Unit electricity cost is about 7 Tk/kW.h (estimated), and daily demand charge is about 12.5 Tk (estimated), so total cost is about 23 Tk = 0.23 USD ($).

3.8 Methodology for Electrode Pair Evaluation Study

3.8.1 Experimental Setup for Electrode Pair Evaluation

Figure 3.3 illustrates the experimental setup for electrode pair evaluation study, where a glass beaker was used as an EC reactor with the dimensions of 15 cm in height and 12 cm in diameter. A total of six unique electrode materials were evaluated in order to determine their effectiveness in the EC process for the treatment of textile wastewater. To ensure a thorough investigation, a diverse range of electrode materials, including common metals like Aluminium (Al), Carbon (C),

Copper (Cu), Zinc (Zn), Mild Steel (MS), and Stainless Steel (SS) were used in this study. Thirty-six distinct combinations of electrode pairs were applied from the selected materials to compare their performances as depicted in Figure 3.4.

The selection was made with the objective of conducting a thorough evaluation of the performance of different electrode materials and their combinations in the EC process for treating textile wastewater. This selection was based on a systematic review of the literature, which indicated that the use of different electrode materials could greatly affect the removal efficiencies of pollutants such as TSS, turbidity, COD, and TOC (Sahu et al., 2014). These combinations were subsequently evaluated to identify the best electrode pair that exhibited the highest efficacy for eliminating pollutants during EC. This diversity allowed the study to explore the efficacy of each material and combination in the EC process. This robust comparison and identification of the most effective electrode pairs for pollutant removal was made possible. Both the anode and cathode electrodes were rod-shaped and consistently measured to have dimensions of 16 cm in height and 0.95 cm in diameter. The total effective electrode area was 42 cm^2, and the spacing between the electrodes was 10 cm. The electrodes were connected to a digital direct current (DC) power supply device (Lodestar LP3005D; 0-30 V, 0-5 A).

All the experiments were performed at an initial room temperature of about 25°C. Throughout the experiment, 1000 cm^3 of wastewater was poured into the electrolytic cell, and one gram of table salt was properly mixed to ensure consistent conditions for each trial. The current density was consistently and deliberately controlled at a predetermined value, while the voltage (V) was set at 20 V in all experiments. The initial current passed through each experiment was 0.9 A, and the initial current density was 15.0 A/m^2. A retention period of 60 min was used to conduct the EC processes.

This specific time frame was selected to ensure uniformity in all tests, enabling easier comparison of electrode performance under standardized conditions. It also strikes a balance between efficiency and practicality, taking into account that certain electrode materials and their reaction dynamics may require longer duration to reach their maximum potential in pollutants removal.

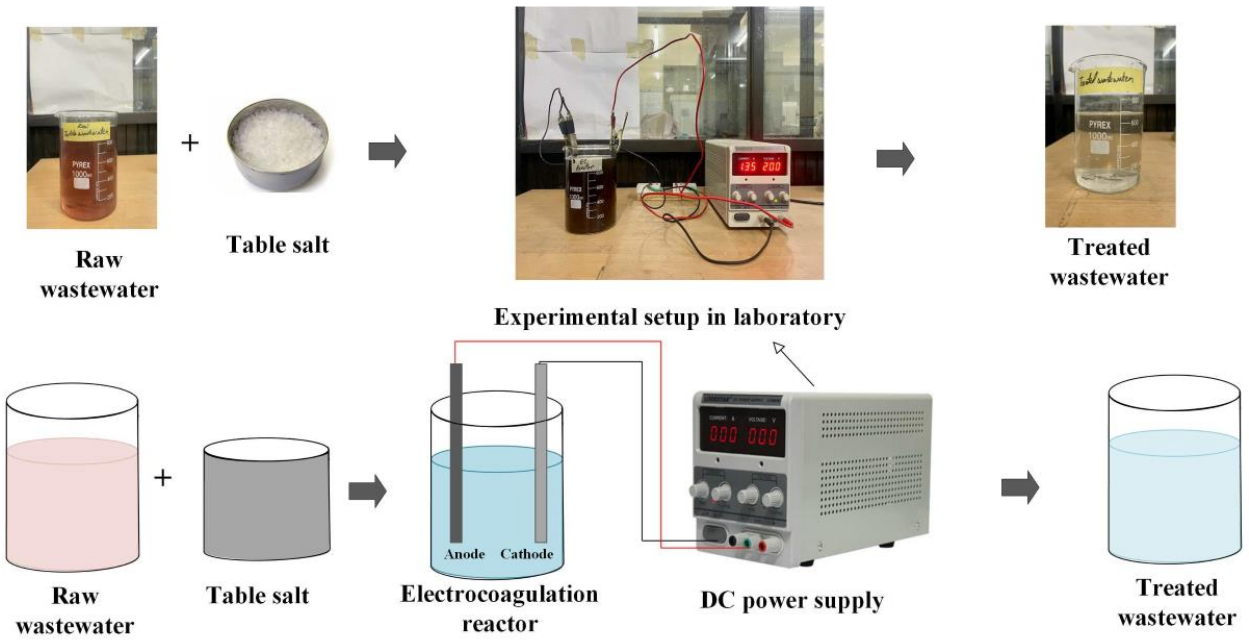

Figure 3.3: Schematic of experimental setup for electrode pair evaluation study.

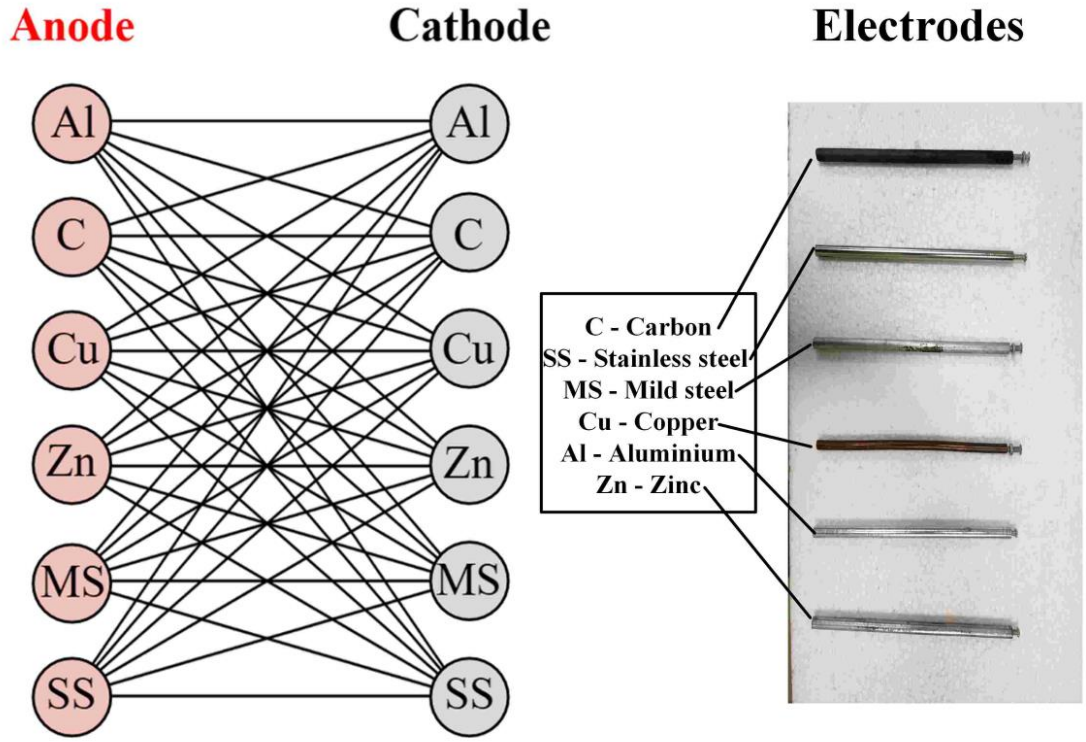

Figure 3.4: Overview of thirty-six electrode pair combinations and materials.

This ensures that electrode materials with slower reaction kinetics have enough time to achieve stability, allowing for a comprehensive evaluation of their performance.

Before the initiation of each experiment, the wastewater was first filtered through a screen filter (1.18mm) to remove large objects such as rags and plastics from wastewater. Then, the wastewater underwent a physiochemical analysis before the EC process began. This analysis involved measuring various physicochemical parameters of the raw and treated textile wastewater, which included pH, TSS (mg/L), TDS (mg/L), electrical conductivity (µS/cm), DO (mg/L), turbidity (NTU), COD (mg/L), and TOC (ppm). These measurements were conducted in accordance with the Standard Methods for the Examination of Water and Wastewater (Rice, 2012).

The purpose of this analysis was to compare the physicochemical parameters for pollutants removal before and after the EC process using different electrode pairs and electrode materials. After 60 min of each EC process, both electrodes underwent a thorough cleansing procedure using distilled water to ensure the total elimination of any remaining solid deposits and contaminants on the electrode surfaces. Moreover, the electrodes were allowed to air dry so that they could be reused in the subsequent EC procedure.

3.9 Methodology for IS Process Study

3.9.1 Experimental Design and Operational Parameters of the IS Processes

Table 3.3 outlines the operational parameters and filtration setups employed in each integrated system treatment process. This structured experimental framework allowed for in-depth analysis of the system's performance, leading to the determination of the most effective IS process for textile wastewater treatment. A comprehensive integrated treatment approach was implemented in this study, aiming to maximize pollutant removal efficiency from textile wastewater. The system was composed of sequential treatment processes, including EC, ST, AT, and dual filtration steps: MM Filtration and AC Filtration. A total of 27 unique IS processes were tested to evaluate the system's performance under varying operational conditions. These configurations systematically varied the retention times for the EC, ST, and AT stages, while the MM, and AC filtration steps remained consistent across all processes.

Table 3.3: Operational parameters and filtration configurations of all IS processes.

Integrated system (IS)	EC (min)	ST (min)	AT (min)	Filter type	Filter type
Process 1	20	60	20	MM filter	AC filter
Process 2	20	60	40	MM filter	AC filter
Process 3	20	60	60	MM filter	AC filter
Process 4	20	120	20	MM filter	AC filter
Process 5	20	120	40	MM filter	AC filter
Process 6	20	120	60	MM filter	AC filter
Process 7	20	180	20	MM filter	AC filter
Process 8	20	180	40	MM filter	AC filter
Process 9	20	180	60	MM filter	AC filter
Process 10	40	60	20	MM filter	AC filter
Process 11	40	60	40	MM filter	AC filter
Process 12	40	60	60	MM filter	AC filter
Process 13	40	120	20	MM filter	AC filter
Process 14	40	120	40	MM filter	AC filter
Process 15	40	120	60	MM filter	AC filter
Process 16	40	180	20	MM filter	AC filter
Process 17	40	180	40	MM filter	AC filter
Process 18	40	180	60	MM filter	AC filter
Process 19	60	60	20	MM filter	AC filter
Process 20	60	60	40	MM filter	AC filter
Process 21	60	60	60	MM filter	AC filter
Process 22	60	120	20	MM filter	AC filter
Process 23	60	120	40	MM filter	AC filter
Process 24	60	120	60	MM filter	AC filter
Process 25	60	180	20	MM filter	AC filter
Process 26	60	180	40	MM filter	AC filter
Process 27	60	180	60	MM filter	AC filter

Note: EC= Electrocoagulation, ST= Sedimentation, AT= Aeration, MM= Multimedia, and AC= Activated Carbon

The EC process was configured with retention times of 20, 40, and 60 min to evaluate its efficiency in destabilizing and aggregating pollutants. Following this, ST was implemented with retention times of 60, 120, and 180 min to allow sufficient time for the settling of coagulated particles. AT was subsequently introduced for durations of 20, 40, or 60 min to improve oxygen transfer, promote the breakdown of organic pollutants, and aid in the elimination of volatile compounds. Finally, the treated effluent passed through a MM filter and an AC filter to ensure the effective removal of remaining suspended solids and dissolved organic pollutants. Each process configuration was identified by a unique combination of retention times across the EC, ST, and

AT stages. For example, IS process 1 featured retention times of 20 min for EC, 60 min for ST, and 20 min for AT, while IS process 27 involved 60 min for EC, 180 min for ST, and 60 min for AT. This systematic approach provided a robust dataset for evaluating the impact of each parameter on the overall treatment efficiency. The integration of filtration steps (MM, and AC filters) across all processes ensured consistency in the final polishing stage, allowing a clear comparison of the effects of varying EC, ST, and AT retention times.

3.9.2 Experimental Setup and Operational Framework of the IS Processes

Figure 3.5 illustrates the schematic of the experimental setup for IS process study, showing the sequential arrangement of each treatment stage. The experimental setup for this study was carefully structured to assess the treatment efficiency of a five-stage IS process for textile wastewater treatment. The IS process sequentially employed EC, ST, AT, MM filtration, and AC filtration to remove key pollutants like TSS, turbidity, COD, and color.

Raw textile wastewater was sourced directly from a local textile industry and stored in laboratory-grade containers under controlled conditions. Prior to treatment, A detailed physicochemical analysis of the raw wastewater was conducted to determine baseline pollutant concentrations, including TSS, turbidity, COD, and color, following standard methods (Rice, 2012). These baseline measurements provided a reference point for evaluating removal efficiencies across the IS process. For each experimental run, 4000 cm^3 of textile wastewater was manually poured into the EC reactor, with 4 g of table salt (NaCl) was thoroughly mixed into the wastewater to enhance conductivity. The EC process operated at a constant voltage of 15 V, and the current density was maintained at a consistent, predetermined value throughout the experiments. Three different retention times 20, 40, and 60 min were evaluated to examine the effect of electrolysis duration on treatment efficacy. Post-EC, sludge and scum were manually separated using a spatula, and 3000 cm^3 of clarified effluent was transferred to the ST tank. The ST stage facilitated gravity-based settling of coagulated flocs over retention periods of 60, 120, and 180 min. After removing the settled sludge, 2500 cm^3 of supernatant was transferred to the AT tank. The AT was conducted for 20, 40, or 60 min using a laboratory air pump to increase dissolved oxygen levels and promote volatilization of organic compounds.

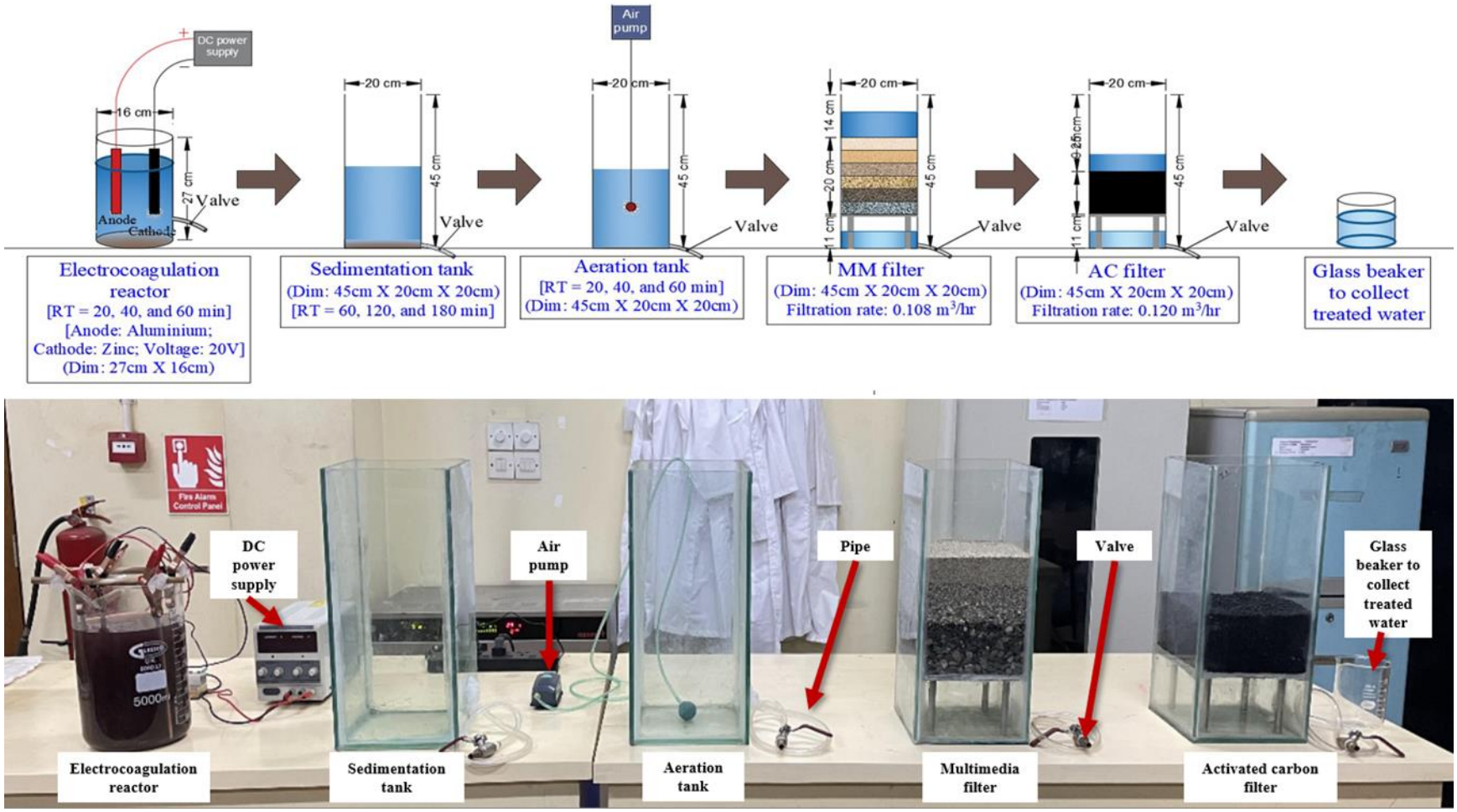

Figure 3.5: Schematic of the experimental setup for IS process study, illustrating the sequential treatment units: EC, ST, AT, MM filter, and AC filter in the integrated system process.

Following AT, the effluent was passed through a dual-filtration setup. The MM filter, consisting of stratified fine sand, coarse sand, and gravel, operated at a flow rate of 0.108 m^3/h and provided mechanical and partial chemical filtration. The final treatment stage involved an AC filter with a flow rate of 0.120 m^3/h, effectively targeting residual color, odor, and organic pollutants through adsorption.

Effluent samples were collected after each stage (EC, ST, AT, MM, and AC) for physicochemical analysis, allowing for stage-wise and overall assessment of removal efficiencies. Post-treatment concentrations were compared to initial values to evaluate performance across all 27 IS configurations, each defined by distinct combinations of EC, ST, and AT retention times. This comprehensive experimental framework enabled systematic evaluation of operational variables and pollutant removal dynamics, ultimately identifying the most effective treatment configuration for real textile wastewater.

3.9.3 EC Reactor Setup

Figure 3.6 demonstrates EC treatment of textile wastewater using a cylindrical glass reactor (5000 cm^3 capacity, 4000 cm^3 working volume, 27 cm height, 16 cm diameter).

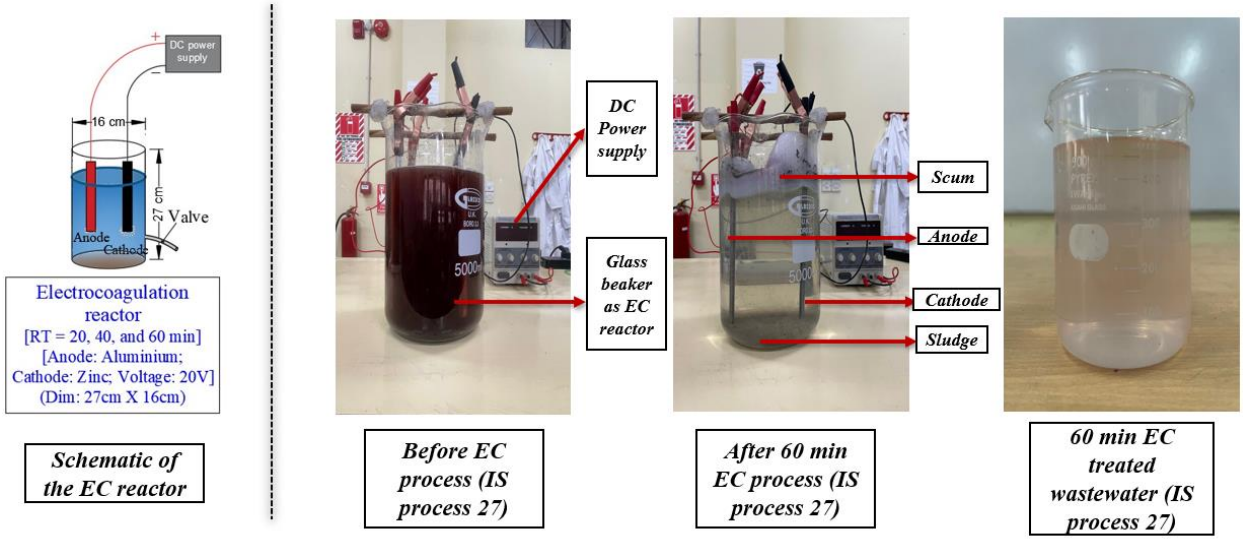

Figure 3.6: EC treatment of textile wastewater: Reactor design, operational setup, and treatment efficiency demonstration over 60-min processing time.

The electrode arrangement followed monopolar parallel (MP-P) configuration, recognized for operational simplicity, energy efficiency, and cost-effectiveness (Khandegar and Saroha, 2013). Two aluminum anodes and two zinc cathodes (19.5 cm height, 25 cm^2 total surface area) were positioned with 11 cm inter-electrode spacing and 2.5 cm clearance above reactor base. A regulated DC power unit supplied consistent 15 V. EC retention times of 20, 40, and 60 minutes were applied across 27 integrated system configurations, with TSS, turbidity, COD, and color parameters analyzed before and after treatment.

3.9.4 ST Tank Setup

Figure 3.7 illustrates the ST tank performance for textile wastewater treatment showing tank design, settling process, and clarification efficiency over 180-min retention time (IS process 27).

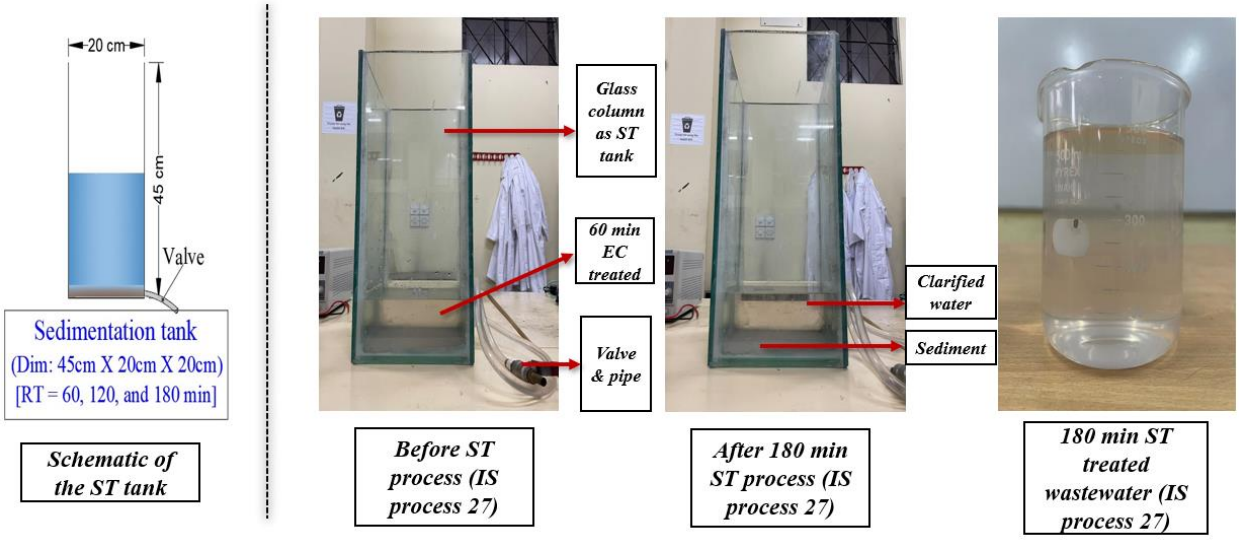

Figure 3.7: ST tank performance for textile wastewater treatment: Tank design, settling process visualization, and clarification efficiency over 180-min retention time.

The ST unit served as second stage, enhancing suspended solids removal through gravitational settling. Following EC treatment, 3000 cm^3 clarified water was transferred into custom-fabricated transparent glass tank (45×20×20 cm). Three retention durations (60, 120, 180 min) were investigated. Performance was assessed through TSS, turbidity, COD, and color measurements, significantly enhancing downstream AT and filtration unit performance.

3.9.5 AT tank setup

Figure 3.8 depicted AT tank treatment performance over 60-min period (IS process 27). The AT system, the third treatment stage, enhanced dissolved oxygen levels and facilitated oxidative breakdown of residual organics. Following ST, 2500 cm^3 clarified effluent was transferred into a custom rectangular glass tank (45×20×20 cm) with aquarium air pump (2.5 W, 180 L/h). Three retention times (20, 40, 60 min) were evaluated. Water samples were collected before/after AT for TSS, turbidity, COD, and color analysis to assess treatment contribution.

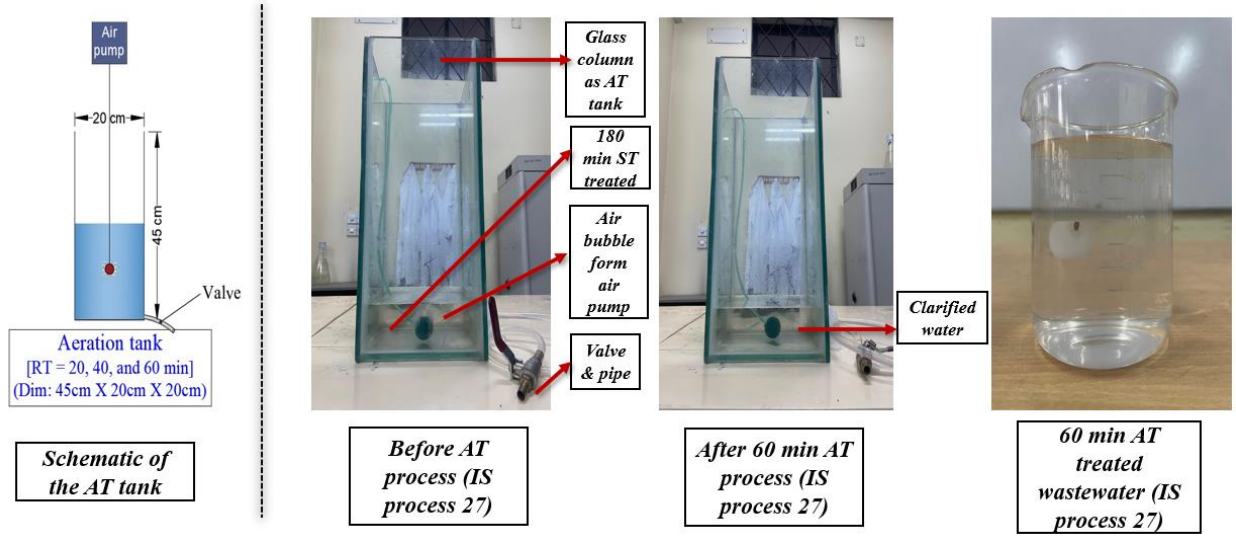

Figure 3.8: AT tank treatment of textile wastewater: Reactor design, air bubble dynamics, and treatment efficiency over 60-min AT period.

3.9.6 MM Filter Setup

Figure 3.9 shows the MM filtration (IS process 27) of textile wastewater for multi-layered filter design, granular media configuration, and filtration efficiency. The MM filtration unit provided advanced physical filtration of residual particulates and enhanced clarity of aerated effluent prior to final adsorption treatment. The system received treated water from the AT tank and was constructed as a custom-fabricated rectangular glass column with internal dimensions of 45 cm height, 20 cm length, and 20 cm width.

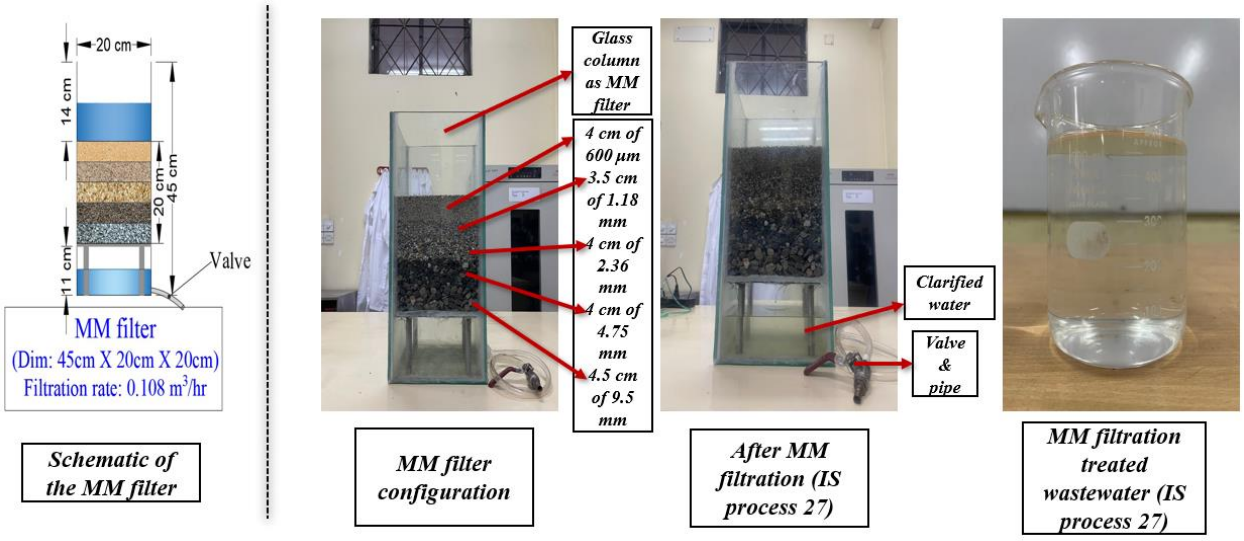

Figure 3.9: MM filtration of textile wastewater: Multi-layered filter design, granular media configuration, and filtration efficiency demonstration.

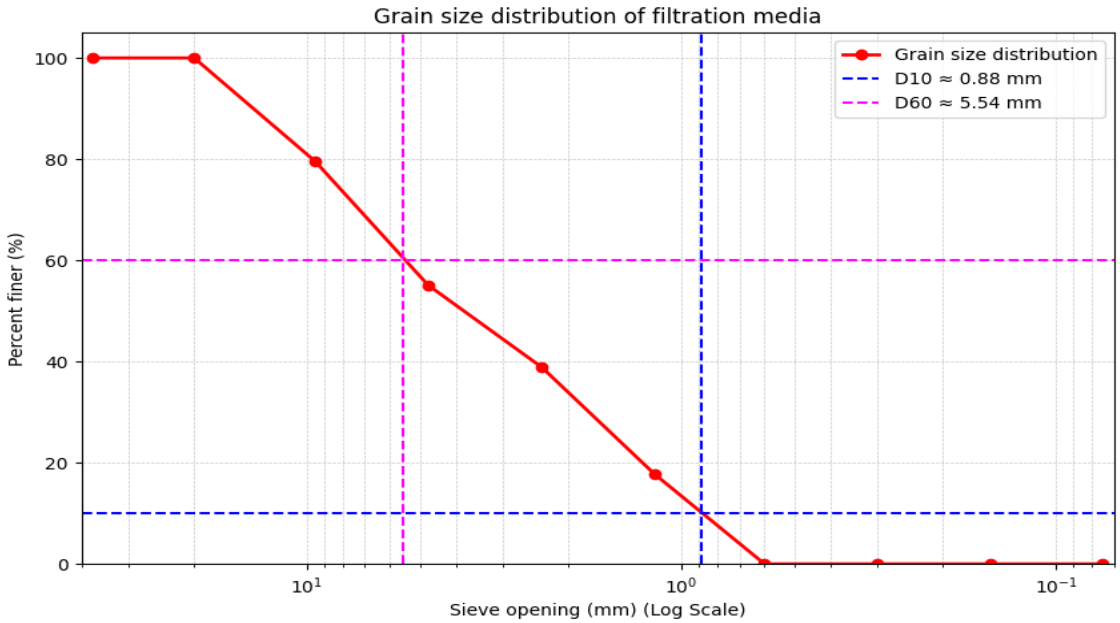

Figure 3.10: Grain size distribution of filtration media.

The filter bed consisted of three distinct layers: 4 cm upper layer of fine sand, 10.5 cm intermediate layer of coarse sand, and 4.5 cm bottom layer of gravel. A storage zone with 11 cm height was incorporated above the outlet valve, positioned 0.5 cm above the base. The filtration rate was measured at 0.108 m³/h. Particle size distribution analysis using ASTM-standard sieves indicated D_{10} of 0.88 mm, D_{50} of 3.89 mm, and D_{60} of 5.54 mm. The uniformity coefficient (C_u) was 6.27, coefficient of gradation (Cc) was 0.71, and fineness modulus (FM) was 4.89, confirming media

met recommended gradation for efficient depth filtration (Bai et al., 2024). Physicochemical parameters TSS, turbidity, COD, and color were measured before and after MM filtration to evaluate individual performance.

3.9.7 AC Filter Setup

Figure 3.11 shows AC filtration (IS process 27) as the final polishing step for removing residual organic matter, dyes, and color pigments after MM filtration. The custom-fabricated glass column (45×20×20 cm) contained a 10 cm GAC bed depth with an 11 cm holding zone above the outlet valve positioned 0.5 cm from base. Operating at constant 0.120 m^3/h flow rate, the system used coconut shell-derived GAC with high iodine number (500-700 mg/g), mechanical hardness exceeding 96%, and 6-50 mesh particle size. Physicochemical parameters (TSS, turbidity, COD, color) were analyzed before and after filtration to assess AC's contribution to overall treatment efficacy.

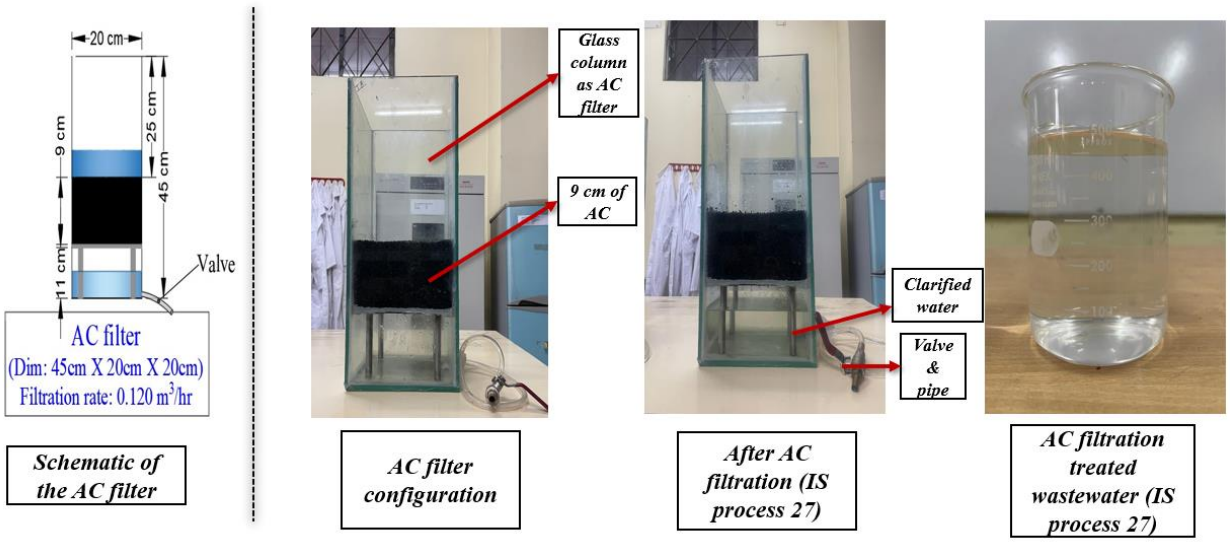

Figure 3.11: AC filtration of textile wastewater: Filter design, carbon bed configuration, and adsorption efficiency demonstration.

Chapter 4

Results and Discussion

4.1 General

This chapter presents a comprehensive analysis of results from three sequential experimental phases designed to systematically develop and optimize EC -based treatment systems for textile wastewater management.

4.2 Seawater Integration study

4.2.1 Physicochemical Analysis

Table 4.1 shows the removal efficiency of physicochemical parameters achieved through the EC process at different seawater concentrations and retention times of 45 and 90 min. The experiment aimed at utilizing the EC process for wastewater treatment employing mild steel and carbon electrodes. Different percentages of seawater were introduced into the wastewater, and the process was tested over two retention times to evaluate the impact of seawater concentration on treatment performance. Different percentages of seawater were introduced into the wastewater, and the process was tested over two retention times, 45, and 90 min, for different percentages of seawater intake. pH, TSS, electrical conductivity, DO, turbidity, COD, and color were subsequently measured to ensure the quality of the treated water to understand the impact of seawater on the treatment process and the summary is provided in the Appendix Table A1.

The EC process demonstrated varying performance levels depending on the seawater percentage and retention time employed. The results indicate distinct patterns in parameter removal efficiency, with some parameters showing enhanced removal with increased seawater concentration while others exhibited optimal performance at specific seawater percentages. The retention time also played a crucial role in determining the overall treatment effectiveness.

Table 4.1: Removal efficiency (%) of different wastewater parameters using EC process varying seawater percentages at different retention times of 45 and 90 min.

Parameter (%)	Retention time (min)							
	45				90			
	0% SW	5% SW	10% SW	15% SW	0% SW	5% SW	10% SW	15% SW
TSS	-	98.1	99.05	98.1	39.52	98.1	99.05	99.52
Turbidity	28.67	99.3	99.15	99.3	38.81	98.79	99.03	98.86
COD	6.51	40.41	30.14	28.77	9.59	28.08	47.26	43.84
Color	1.35	98.2	97.23	96.2	3.67	95.1	96.2	94.97

Note: SW= Seawater

4.2.2 Effect on Parameters

4.2.2.1 Effect on pH

Figure 4.1 shows a trend in which the pH increases as the seawater percentage and retention time increase. The initial pH of the untreated wastewater was 8.16, indicating a slight alkalinity. The underlying principle of these pH shifts is the balance between hydrogen and hydroxyl ions in the solution. During electrolysis, a significant number of hydrogen ions were expelled in the form of H_2 gas. Simultaneously, there was an increase in OH^- ion production at the electrodes, potentially explaining the prevalent alkalinity across the samples (Saleem et al., 2011). At a retention time of 45 min, a positive correlation between the increase in seawater percentage and the addition of pH (9.85-11.04) value was observed. However, at a retention time of 90 min, there was an interesting observation: the pH (10.64-11.60) values initially increased with the introduction of up to 10% seawater but then underwent a decline when 15% seawater was added. A noteworthy aspect to consider is the high initial pH value for this experiment. Kobya et al. (2003) determined optimal removal efficiencies when the initiation pH was under 8. Therefore, it might be recommended that refining the initial pH to values below 8 could enhance the electrolysis procedure (Ahsan et al., 2014). Moreover, the initial pH of the sample wastewater was high and not regulated in this study.

The removal efficiency can be expected to be more optimal if pH levels are controlled with buffer solutions.

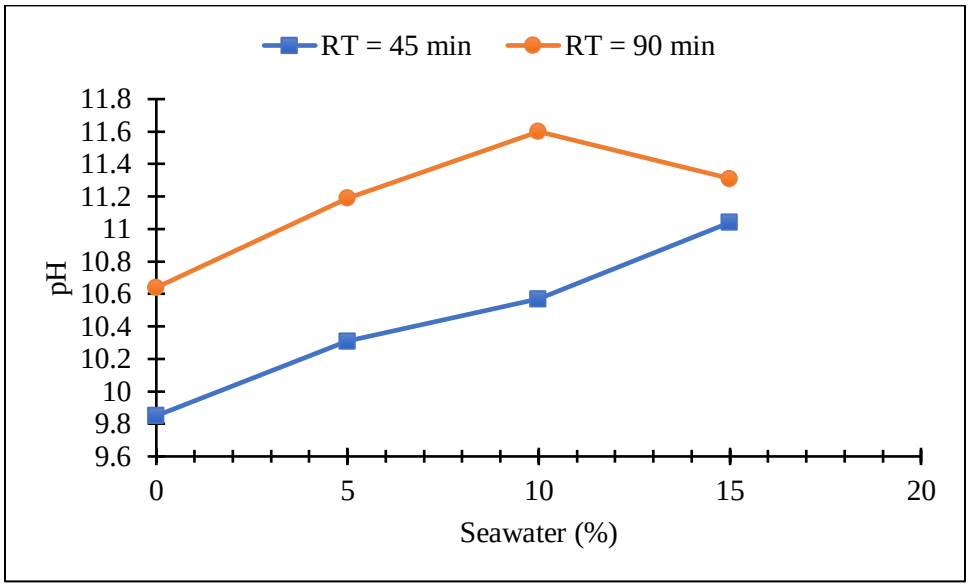

Figure 4.1: Variation of pH for textile wastewater with varying seawater percentage at retention times of 45 and 90 min during EC.

4.2.2.2 Effect on DO

Figure 4.2 shows the impact of seawater addition on the DO levels is clearly depicted for two retention times: 45 and 90 min. For a retention time of 45 min, an initial increase in DO levels was observed when the seawater concentration increased from 0 to 5%. This was followed by a decrease from 5 to 15%. Interestingly, a higher DO concentration was recorded with a 10% seawater addition than a 15% addition. However, for the 90 min retention, a consistent increase in DO levels was noted from 0 to 10% seawater addition. Beyond the 10% mark, a slight drop in DO concentration was observed, up to 15% seawater addition. For a retention time of 45 min, the DO concentration increased from 0.3 mg/L with 0% seawater addition to 7.24 mg/L with 5% seawater addition. This increase is attributed to the addition of seawater, which has a high DO level of 7.91 mg/L, to the textile wastewater that initially had a low DO value of 0.14 mg/L, thereby significantly enhancing the DO concentration in the mixture. The lowest addition of DO was found at 4.77 mg/L for the retention time of 90 min at 0% seawater addition, which is far better than the addition at 45 min retention time, and the highest was 6.69 mg/L at 10% addition of seawater. A peak DO level of 7.24 mg/L was achieved when 5% seawater was added during a 45 min retention

time. The oxygen generation at the anode might have contributed to the DO elevation in the treated wastewater. Based on these trends, it can be inferred that the seawater concentration and retention time are the dominant factors influencing DO addition in the EC process. The effect of DO in EC is studied for the removal of selenium and cadmium (Bae et al., 2022; Xu et al., 2019). However, no study has been conducted combining seawater with EC.

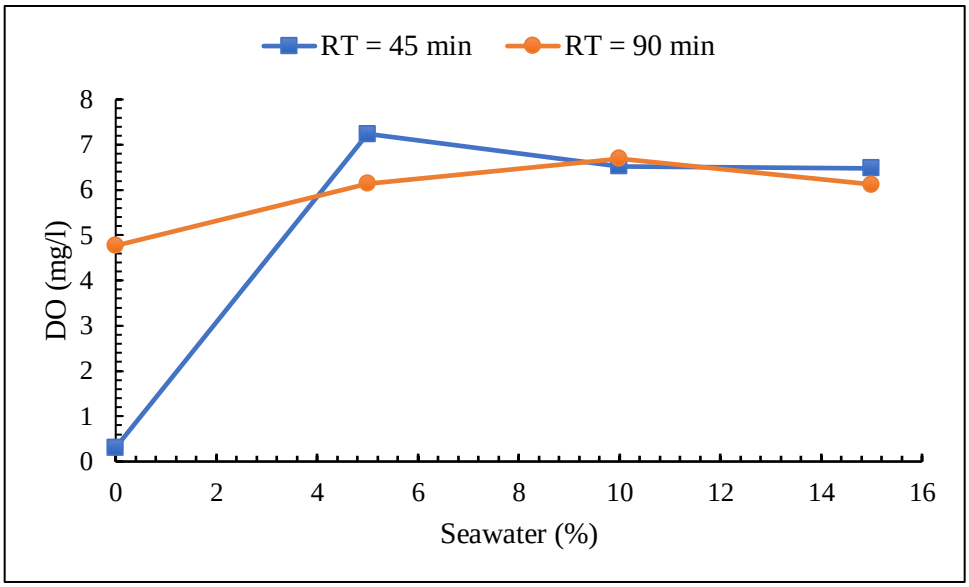

Figure 4.2: Variation of DO for textile wastewater with varying seawater percentages at retention times of 45 and 90 min during EC.

4.2.2.3 Effect on Electrical Conductivity

Figure 4.3 shows the effects of varying seawater concentrations on the electrical conductivity for two retention times: 45 and 90 min. A steady increase in electrical conductivity was observed as the seawater percentage increased across both retention times with no seawater addition, and a minimal level of electrical conductivity addition was detected. The data points for the 45 and 90 min retention times closely follow parallel trajectories, suggesting that while retention time has an influence, it operates in cycles with seawater percentages to affect electrical conductivity levels. As the seawater concentration progressively increased, a consistent upward trend in electrical conductivity was observed, indicative of the enhanced presence of electrical conductivity with increasing seawater percentages. For the retention time of 45 min, the lowest electrical conductivity addition was 2380 µS/cm at 0% seawater addition, and the highest was 9080 µS/cm at 15% seawater addition. The lowest addition of electrical conductivity was found to be 2440

µS/cm for the retention time of 90 min at 0% seawater addition, and the highest was 9690 µS/cm at 15% addition of seawater. Seawater is rich in various salts and minerals that can significantly increase its electrical conductivity. Based on these trends, it can be inferred that seawater concentration is a dominant factor influencing the addition of electrical conductivity, with retention time playing a significant role in modulating this relationship. Also, when the seawater concentration and retention time increase, the electrical conductivity also increases. In a study by Nguyen et al. (2016), it was found that increasing the NaCl solution concentration leads to higher electrical conductivity. This, in turn, improves the removal efficiency of phosphate in a shorter electrolysis time and minimizes the environmental impact. A similar phenomenon was observed in the present study when seawater was added to the EC process.

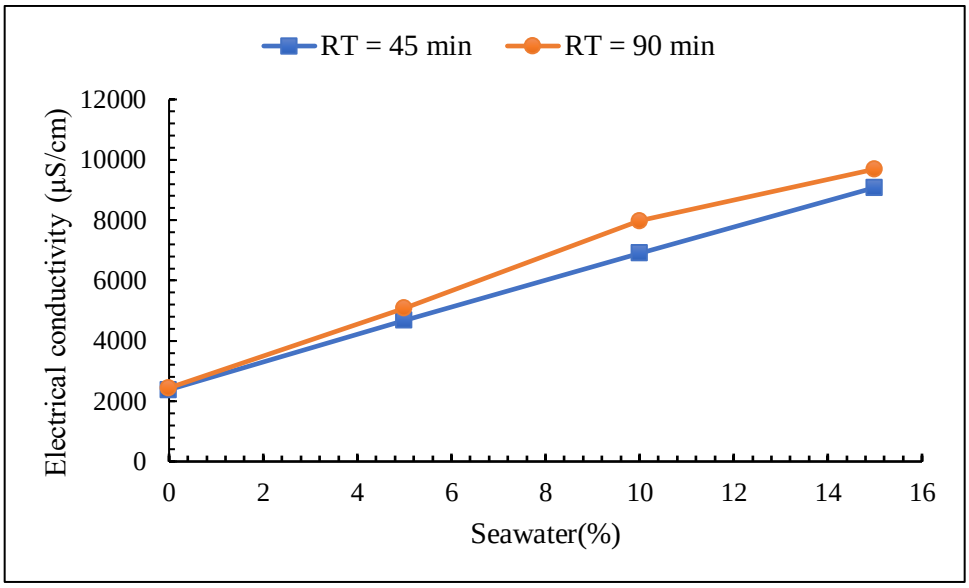

Figure 4.3: Variation of Electrical conductivity (µS/cm) for textile wastewater with varying seawater percentages at retention times of 45 and 90 min during EC.

4.2.2.4 Effect on TSS

Figure 4.4 illustrates the impact of varying seawater percentages on the removal efficiency of TSS at two distinct retention times: 45 and 90 min. At a retention time of 45 min, with no seawater addition, the base removal efficiency of the TSS was observed. A pronounced removal efficiency transition was evident with the introduction of seawater, particularly within the 0 to 5% seawater addition range. This transition manifests as a linear increase, suggesting enhanced removal of TSS with increasing seawater percentage. Beyond 5% seawater addition, the removal efficiency

plateaued, maintaining consistent levels of up to 15% seawater concentration. The results indicated that a 10% addition of seawater demonstrated the highest (99.04%) removal efficiency within the range of 5 to 15% seawater addition in terms of 45 min retention time. In contrast, the 90 min retention time showed a distinct behavior at 0% seawater addition, where appreciable removal of TSS (39.52%) was achieved in the absence of seawater, and the highest removal of TSS (99.52%) was observed with the addition of 15% seawater for 90 min retention time. The removal efficiency of the 5 to 15% seawater addition range mirrors the trend observed at 45 min, indicating comparable removal capacities at both retention times within this concentration window. Previous studies by Bener et al. (2019) found that the removal efficiency of TSS was 64.7%, with optimum conditions at a current density of 25 mA/cm^2, an optimum pH of 5, and 120 min of retention time. In another study, Paramita et al. (2023) found 71.9% removal of TSS using aluminum electrodes (Al6061-T6) under the optimum condition was selected at a time of 15 min, 5.5 mA/cm^2 of current density, and 2 cm of electrode distances. In recent studies, Zafar et al. (2024) found a TSS removal efficiency of 75% under optimum conditions having pH of 7-8, 15 V voltage, 60 min contact time, 2 cm aluminum interelectrode distance, and 20 min settling time. In this study, the highest TSS removal percentage (99.52%) was observed at a retention time of 90 min with the addition of 15% seawater. Therefore, it can be stated that the addition of seawater and a longer retention time resulted in a higher removal of TSS in textile wastewater.

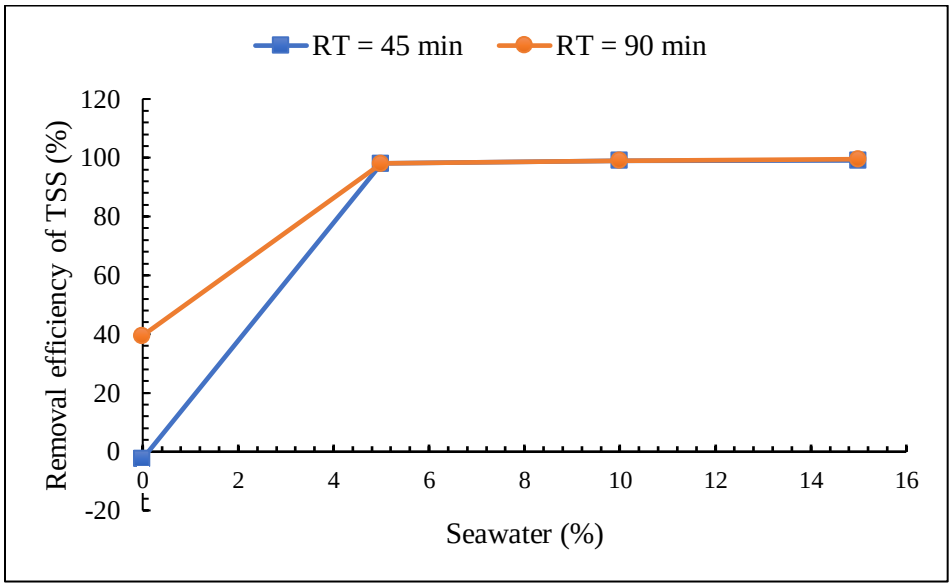

Figure 4.4: Removal efficiency of TSS (%) for textile wastewater with varying seawater percentages at retention times of 45 and 90 min during EC.

4.2.2.5 Effect on Turbidity

Figure 4.5 shows at a retention time of 45 min, an increase of 0 to 5% in seawater (%) can result in significant differences in turbidity removal efficiency (%). The data indicates a consistent trend within the 5 to 15% range for both retention times. The impact of varying seawater concentrations on the turbidity removal efficiency was examined. The results indicated that a 0% addition of seawater resulted in the lowest (28.67%) removal efficiency, while a 5% addition of seawater demonstrated the highest (99.30%) removal efficiency within the range of 5 to 15% seawater addition in terms of 45 min retention time. In the context of retention time, the trend observed for a retention time of 90 min closely resembled that observed for a retention time of 45 min. However, a 0% addition of seawater with 90 min retention time showed the lowest (38.81%) turbidity removal efficiency (%), which is higher than the 0% addition of seawater at a retention time of 45 min, while a 10% addition of seawater demonstrated the highest (99.03%) removal efficiency within the range of 5 to 15% seawater addition for 90 min retention time. Bener et al. (2019) found the removal efficiency of 83.5% turbidity, selecting an optimum condition at a current density of 25 mA/cm^2, an optimum pH of 5, and 120 min of retention time, using Al electrodes. In another study, Núñez et al. (2019) found that 82% turbidity removal was achieved at a retention time of 10 min when the current density was 8 mA/cm^2 and the controlled pH was 7.1. In another study, Martins et al. (2023) found turbidity removal ranging from 74 to85% using 304 stainless steel electrodes in batch mode. In recent studies, Sqalli Houssini et al. (2024) found 98.5% turbidity removal efficiency using bipolar connections of Fe-Al electrodes. In this study, the highest turbidity removal percentage (99.30%) was found at a retention time of 45 min, with the addition of 5% seawater. Therefore, it can be stated that the addition of seawater results in a higher turbidity removal in textile wastewater.

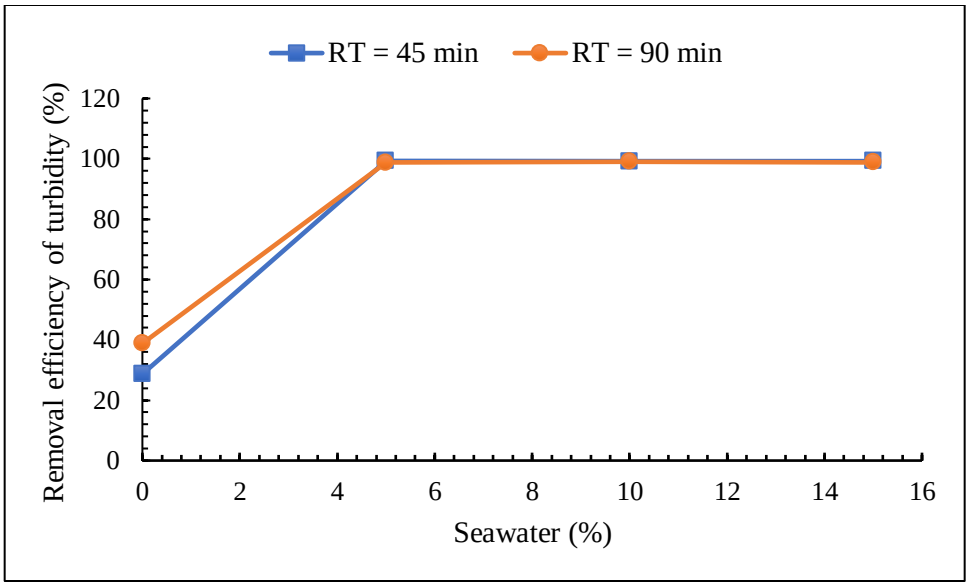

Figure 4.5: Removal efficiency of turbidity (%) for textile wastewater with varying seawater percentages at retention times of 45 and 90 min during EC.

4.2.2.6 Effect on COD

Figure 4.6 illustrates the impact of varying percentages of seawater concentration on COD removal efficiency (%) for textile wastewater at two distinct retention times: 45 and 90 min. Now, at a retention time of 90 min, there was a noticeable upward linear trend in COD removal efficiency (%) from textile wastewater as seawater concentration rose from 0 to 10%. However, for seawater with a 10 to 15% increase, there was a downward linear trend or decrease in the removal efficiency of COD. Moreover, the highest removal efficiency was achieved at a 5% seawater concentration of 40.41 % at 45 min retention time, and the lowest was achieved at a 0% seawater concentration of 6.5%. In contrast, at a retention time of 90 min, there was an increase in the COD removal efficiency with the addition of seawater, ranging from 0 to 5%. However, a sudden decrease in the removal efficiency was observed when seawater addition was increased from 5 to 15%. Increasing the seawater concentration from 5% to 15% in the EC process has resulted in a decrease in COD removal. This could be attributed to several factors, including pollutant dilution, increased electrical conductivity leading to inefficiencies, ion competition affecting coagulation, and pH changes impacting the effectiveness of the treatment. In order to achieve optimal COD reduction, it is crucial to carefully balance the seawater levels. Furthermore, the highest removal efficiency of 47.26% was observed at 10% seawater concentration, and the lowest was observed at 0% seawater concentration of 9.58% at a 90 min retention time. Previous studies conducted in EC

process textile wastewater by Khorram and Fallah (2018) found a 40% removal of COD under optimum conditions of 60 min retention time and current density of (15-35 mA/cm^2). Núñez et al. (2019) found that 59% of COD removal was achieved at 10 min retention time when the current density is 8 mA/cm^2 and the controlled pH was 7.1. Furthermore, Bener et al. (2019) found 18.6% COD removal at a current density of 25 mA/cm^2, an optimum pH of 5, and a retention time of 120 min. In recent studies, Zafar et al. (2024) found COD removal efficiency of 79% under optimum conditions having pH of 7-8, 15 V voltage, 60 min contact time, 2 cm aluminum interelectrode distance, and 20 min settling time. Thus, at a 90 min retention time with 10% seawater addition, 47.26% COD removal was observed in this study without controlling the pH at 20V.

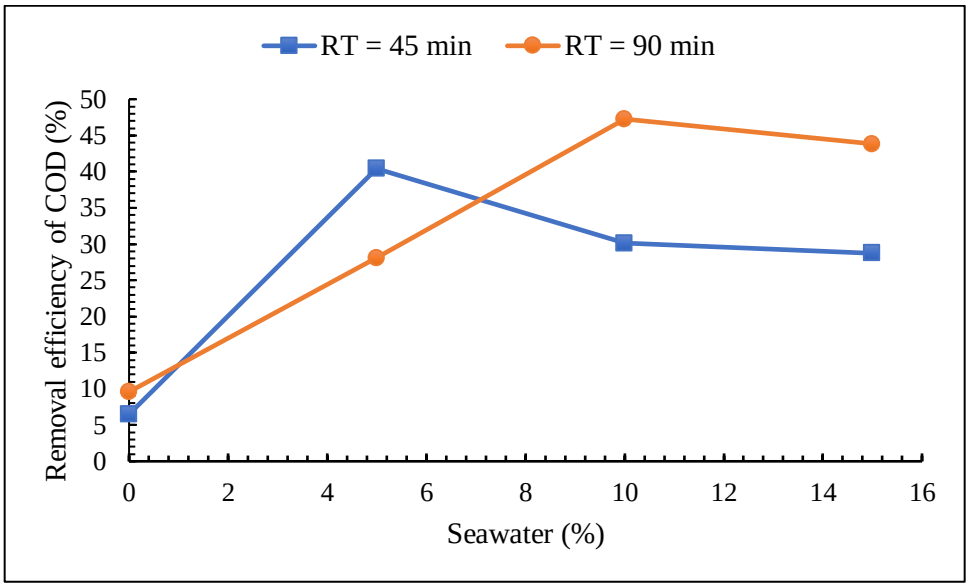

Figure 4.6: Removal efficiency of COD (%) for textile wastewater with varying seawater percentages at retention times of 45 and 90 min during EC.

4.2.2.7 Effect on Color

Figure 4.7 depicted that at a retention time of 90 min, an increase of 0 to 5% in seawater (%) can result in significant differences in the removal efficiency of color (%). The data indicates a consistent trend within the 5 to 15% range. The results indicated that a 0% addition of seawater resulted in the lowest removal efficiency of 1.35%, whereas a 5% addition of seawater demonstrated the highest removal efficiency of 98.19% at 45 min. Moreover, at 90 min retention time, the highest removal efficiency was achieved at a 10% seawater concentration of 96.19 %, and the lowest was 3.67%, achieved at 0% seawater concentration. In terms of retention time, the

observed trend for a retention time of 45 min closely resembles that for a retention time of 90 min. For both retention times, the 10% addition of seawater showed the highest color removal. Previous studies on the textile wastewater EC process by Bener et al. (2019) reported 90.3 to 94.9% color removal using an Al electrode current density of 25 mA/cm^2, an optimum pH of 5, and a retention time of 120 min. Chackrabartty et al. (2015) found color removal of 93.4% by assessing textile wastewater at an initial pH of 5 with 24 V. Núñez et al. (2019) study in textile wastewater found 86% of color removal at a controlled pH of 7.1 with 10 min retention time and 8 mA/cm^2. Furthermore, Khorram and Fallah (2018) found 97% color removal at an initial pH of 5.5 with a retention time of 23 and a current density of 15 mA/cm^2. In recent studies, Kalia et al. (2023) found the best removal of color (90%) from raw textile effluent using a zinc-coated iron electrode at a current density of 25 mA/cm^2 by employing EC followed by partially purified laccase treatment (LT) and activated carbon (AC) polishing at ambient conditions. In another study, Zafar et al. (2024) found a discoloration removal efficiency of 86% under optimum conditions having pH of 7-8, 15 V, 60 min contact time, 2 cm aluminum interelectrode distance, and 20 min settling time. The increase in color removal efficiency from textile wastewater using EC with added seawater is due to enhanced electrical conductivity, improved coagulation dynamics from ionic strength, and effective floc formation. The dilution effect of seawater, with a color value of 13 (Pt-Co), is crucial in the treatment process. As more seawater is added, it dilutes the mixture being treated and lowers the overall color value of the wastewater. These factors work together to improve the removal of color-causing compounds. Seawater's unique composition also promotes the generation of effective coagulants. This highlights the potential of incorporating seawater into EC processes for more efficient color removal. Thus, the results illustrate that color can be removed efficiently at 5% seawater concentration with a 45 min retention time without changing the pH at 20V in the EC process of textile wastewater.

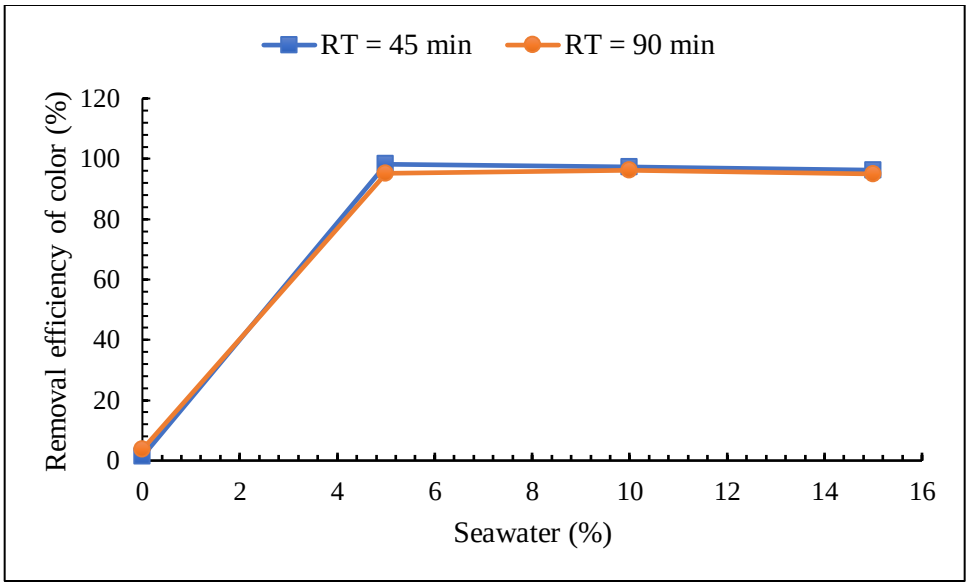

Figure 4.7: Removal efficiency of color (%) for textile wastewater with varying seawater percentages at retention times of 45 and 90 min during EC.

4.2.3 Statistical Analysis Using Design-Expert® (Version 11)

Table 4.2 shows the ANOVA test results for the impact of retention time and seawater percentage on the various water quality parameters. The pH model resulted in an average value of 10.89 with a standard deviation of 0.1456. The coefficient of determination (R^2) is 0.954, and an adjusted R^2 value of 0.921 is noted. A high F-value of 29.16 and a statistically significant p-value of 0.0002 were recorded. The electrical conductivity model exhibited an average of 6059.23 µS/cm with a standard deviation of 201.30. An exceptionally high F-value of 388.81 indicates a very significant model term, corroborated by a p-value of less than 0.0001. The DO model showed a mean value of 5.59 mg/L and a standard deviation of 1.02. The R^2 value was 0.844, with an adjusted R^2 of 0.733. The F-value and p-value are recorded as 7.61 and 0.0095, respectively. The mean value for the TSS removal efficiency model was 80.55%, with a standard deviation of 11.10. The R^2 and adjusted R^2 values are 0.943 and 0.902, respectively. The F-value was 23.29, and the corresponding p-value was 0.0003. The mean removal efficiency of the turbidity model was 83.98%, with a standard deviation of 8.19. The R^2 and adjusted R^2 values are 0.9526 and 0.9186, respectively. An F-value of 28.07 and a significant p-value of 0.0002 were observed. The mean removal efficiency of the COD model was 30.11%, with a standard deviation of 5.33.

Table 4.2: ANOVA test results for the impact of retention time and seawater percentage on various water quality parameters using Design-Expert 11 software.

Parameter	Mean	Std. Dev.	R^2	C.V. %	Analysis of variance (ANOVA)			Prediction model
					F-value	p-value	Significance	
pH	10.89	0.1456	0.9542	1.34	29.16	0.0002	Yes	$Y = 11.08 + 0.3736 \times A + 0.4616 \times B - 0.1057 \times AB - 0.0832 \times A^2 - 0.3272 \times B^2$
Electrical conductivity (µS/cm)	6059.23	201.30	0.9964	3.32	388.81	<0.0001	Yes	$Y = 6275.28 + 268.75 \times A + 3469.14 \times B + 174.75 \times AB - 14.20 \times A^2 - 418.19 \times B^2$
DO (mg/L)	5.59	1.02	0.8446	18.30	7.61	0.0095	Yes	$Y = 6.64 + 0.2940 \times A + 1.74 \times B - 0.9892 \times AB + 0.1021 \times A^2 - 2.28 \times B^2$
Removal efficiency of TSS (%)	80.55	11.10	0.9433	13.77	23.29	0.0003	Yes	$Y = 100.16 + 4.89 \times A + 37.13 \times B - 8.80 \times AB + 2.45 \times A^2 - 42.21 \times B^2$
Removal efficiency of turbidity (%)	83.98	8.19	0.9525	9.76	28.07	0.0002	Yes	$Y = 100.01 + 1.32 \times A + 30.41 \times B - 2.35 \times AB + 1.80 \times A^2 - 34.81 \times B^2$
Removal efficiency of COD (%)	30.11	5.33	0.9121	17.71	14.52	0.0014	Yes	$Y = 37.85 + 2.73 \times A + 13.91 \times B + 4.90 \times AB + 0.2227 \times A^2 - 15.50 \times B^2$
Removal efficiency of color (%)	74.62	11.61	0.9535	15.55	28.72	0.0002	Yes	$Y = 97.67 - 0.3101 \times A + 43.31 \times B - 0.6838 \times AB + 3.52 \times A^2 - 50.87 \times B^2$

Note: Y= Parameter; A= Retention time (min); B= Seawater percentage.

Its R^2 value was 0.9121, with an adjusted value of 0.8493. An F-value of 14.52 is observed, with a p-value of 0.0014. Finally, the removal efficiency of the color model showed a mean of 74.62% with a standard deviation of 11.61. The observed R^2 was 0.9535, and the adjusted R^2 was 0.9203. The F-value was 28.72, with a significant p-value of 0.0002. High F-values illustrate the significance of each parameter in the model. Moreover, p-values less than 0.05 generally denote statistical significance, and in this study, all parameters showed p-values below this threshold, confirming the reliability and significance of the findings. Similar observations are reported by other researchers e.g., Rakhmania et al. (2021) and Asfaha et al. (2022).

Figures 4.8 and 4.9 illustrates 3D plots, those were assessed to analyze the interaction between the input factors (retention times of 45, and 90 min. and seawater percentages of 0, 5, 10, and 15%) on the pH, electrical conductivity, DO, and the removal of TSS, turbidity, COD, and color of textile

wastewater in the EC process, respectively. In this study, an ANOVA test using Design-Expert® (Version 11) was performed. It used 13 runs to assess various water quality parameters, with the aim of understanding their relationships and significance with respect to retention time and seawater increase. Based on the ANOVA test, the following observations were made.

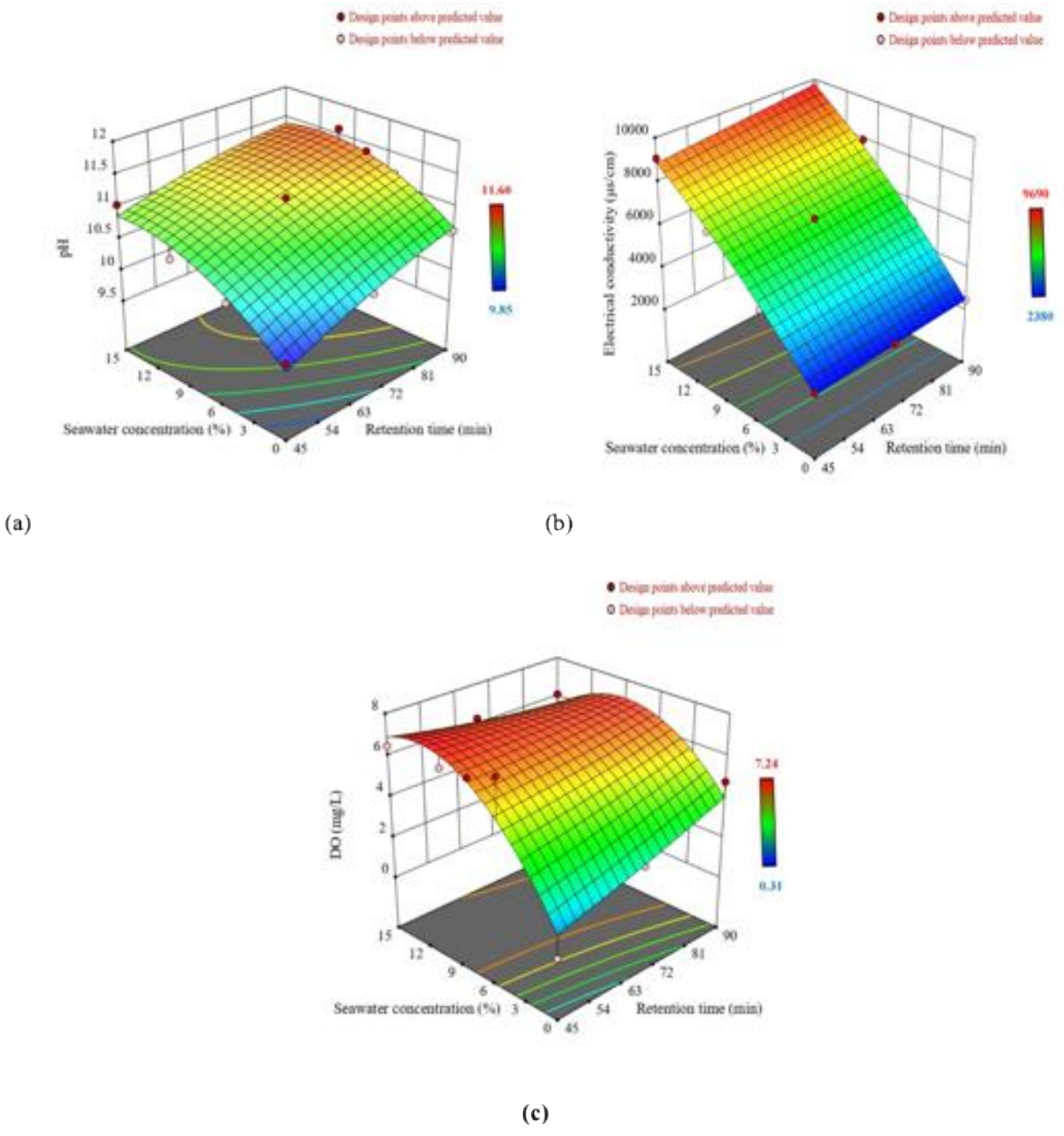

Figure 4.8: 3D plots of the selected parameters with respect to seawater percentage and retention time increase: (a) pH; (b) electrical conductivity and (c) DO.

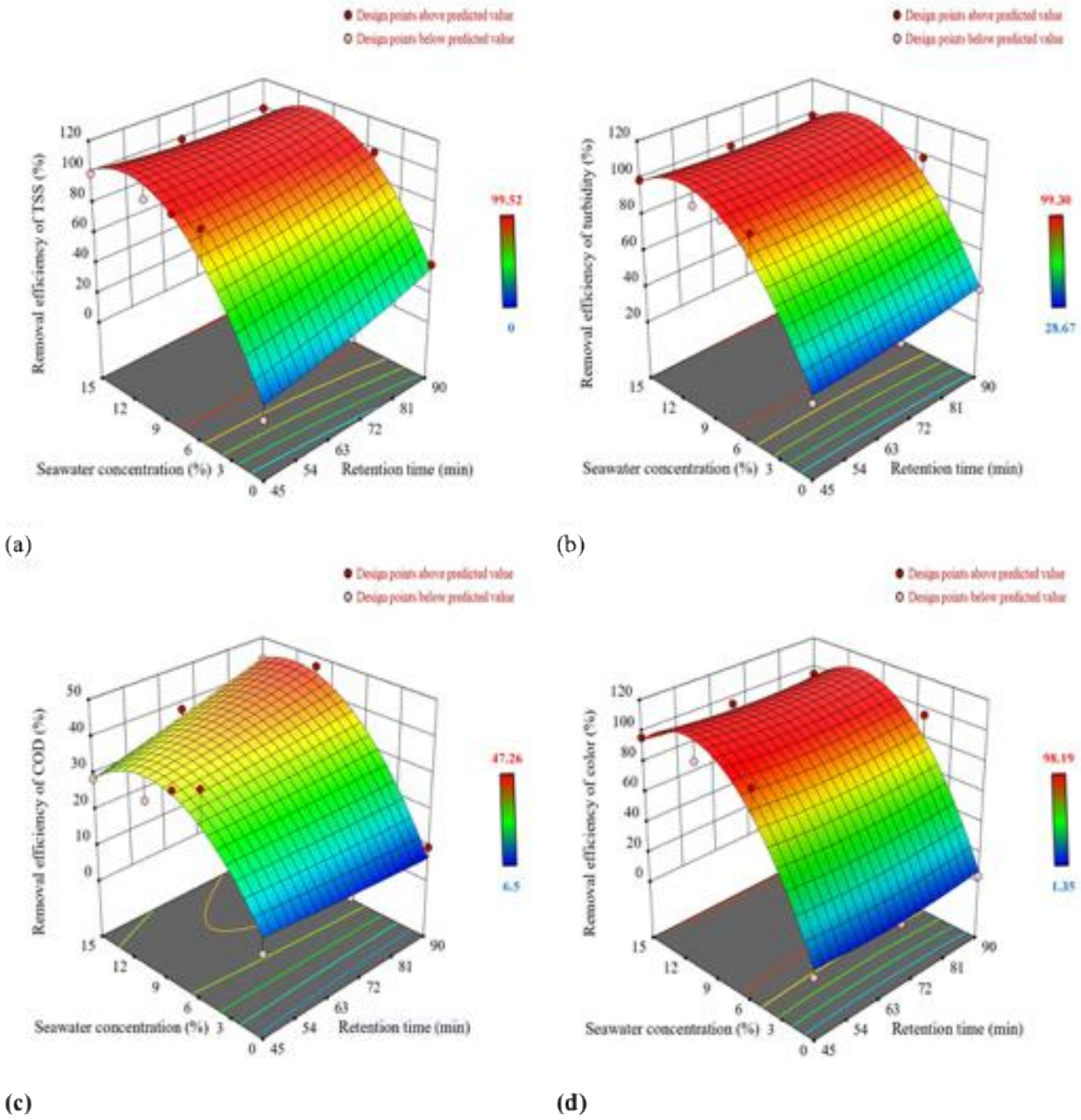

Figure 4.9: 3D plots of removal efficiency of the selected parameters with respect to seawater percentage and retention time increase: (a) TSS; (b) turbidity; (c) COD and (d) color.

4.2.4 Application of the Process

In this study, the integration of seawater into the EC process for textile wastewater treatment is compared with conventional EC process for the treatment of textile wastewater. The process is characterized by its versatility, allowing for adjustments in seawater percentages and retention times, making it suitable for the treatment of various types of textile wastewater with different contaminant profiles. This adaptability is crucial for the textile industry, which often deals with a wide range of dyes and chemicals. It is indicated by the research that higher seawater percentages and extended retention times can significantly enhance pollutant removal for key pollutants such as COD, TSS, turbidity, and color, suggesting that this approach can be tailored to achieve desired treatment levels. It is observed that the integration of seawater in the EC process results in lower electricity consumption, recorded at 15.769 Am^{-2}, as seawater is rich in ionic content seawater is shown to improve the conductivity of wastewater, potentially leading to more efficient coagulation and lower energy requirements. This leads to a low-cost approach for the textile wastewater treatment industry, as the EC process typically requires electricity, which discourages the textile industry from using this system. The incorporation of seawater is found to reduce electricity costs to 0.29 USD/m^3. In previous studies, when aluminum and iron electrodes were used, the operating cost was recorded at 1.5 USD/m^3 (Bener et al., 2019). Similarly, when aluminum was used as an anode and cathode, the operating cost analysis was reported as 0.70 USD/m^3 (Villalobos-Lara et al., 2021). When using copper sheets as electrodes, the cost was reported between 0.803-3.03 USD/m^3 (Shaker et al., 2021). The data indicates that the cost of using seawater in the EC process is much lower than other conventional EC processes. Furthermore, the requirement for additional chemicals in the EC process is eliminated, which reduces the overall cost of the EC process, and allows the treated effluent for reuse applications. This method capitalizes on the natural ionic properties of seawater to significantly enhance the removal efficiencies of pollutants, offering a sustainable and cost-effective solution for textile wastewater management.

The application of the findings from this study in the textile industry offers a promising way for managing wastewater sustainably. Implementing EC technology with seawater integration requires minimal adjustments to existing treatment infrastructures, making it a feasible and cost-effective solution. By utilizing the natural ionic properties of seawater, this approach not only takes advantage of the abundance of seawater but also improves treatment efficiency and reduces

reliance on chemical coagulants and operational costs. The potential of this technique goes beyond the textile industry, making it applicable in coastal regions and highlighting a proactive approach to using natural resources for pollution control. This development signifies a significant shift towards more sustainable industrial processes, demonstrating the practical applicability and potential impact of incorporating seawater into wastewater management strategies.

The variable composition of seawater presents an opportunity for optimizing the treatment process through adaptive monitoring and control systems. The composition of seawater can vary depending on location, season, and environmental factors, which can affect the treatment process. Changes in ionic strength and conductivity may influence the efficiency of the EC process. To address this, treatment facilities need to implement monitoring systems to regularly assess seawater composition and adjust treatment parameters accordingly to maintain consistent removal efficiency. For facilities located in coastal areas, seawater is readily available, making it a viable option for integration into wastewater treatment processes. However, the feasibility of this approach diminishes for inland facilities due to the cost and logistics of transporting seawater. Therefore, geographical location plays a crucial role in the practical application of this treatment method. Developing adaptive control systems that can adjust operational parameters, such as seawater percentage and retention time, in response to real-time data on wastewater and seawater characteristics could enhance the efficiency and consistency of the process. Continuous research and development efforts are also crucial to optimize the process for different wastewater compositions and mitigate adverse effects of seawater variability. The scalability of this innovative process is facilitated by the development of dedicated infrastructure, such as enhanced EC cells and seawater storage solutions, which are investments that pay off through improved treatment efficiencies and reduced reliance on chemical coagulants. The process's flexibility makes it applicable to textile factories of different sizes and operational scales.

Given the inherent variability of effluent characteristics and seawater quality, operators in industrial applications may face significant challenges in maintaining the effectiveness of the EC process for textile wastewater treatment. To address these challenges, it is crucial to implement a dynamic control strategy that can adapt to changing input qualities. This strategy involves continuously monitoring key wastewater quality parameters to enable real-time adjustments to the EC process. By varying the proportion of seawater and adjusting retention times based on real-time data, operators can optimize the removal efficiencies for pollutants despite the variability in

effluent and seawater. Furthermore, leveraging advanced predictive models and machine learning algorithms can enhance the adaptability of the EC process, allowing for predictive adjustments and ensuring consistent treatment outcomes. This approach ensures the robustness and resilience of the wastewater treatment process and aligns with sustainable water management practices by optimizing the use of natural resources and minimizing chemical usage.

Using seawater in the EC process for wastewater treatment offers significant environmental and sustainability benefits, especially in coastal regions. This approach optimizes the use of seawater, a naturally abundant resource, to reduce reliance on freshwater resources, which is crucial in areas with water scarcity. By incorporating seawater, this process reduces the need for chemical coagulants, resulting in lower operational costs and a smaller chemical footprint. Additionally, it enhances energy efficiency by taking advantage of the improved electrical conductivity from seawater. This aligns with the sustainability goals by making better use of renewable resources. Moreover, this method emphasizes environmental stewardship by carefully considering the materials used in the treatment process to resist corrosion and scaling caused by seawater's ionic content. Continuous innovation and research focus on optimizing the seawater EC process, including managing increased salinity and exploring durable materials, to enhance sustainability and efficiency in wastewater treatment.

In essence, the use of seawater in the EC process represents a sustainable, innovative solution for wastewater management that conserves freshwater, reduces chemical usage, and potentially lowers energy requirements, all while maintaining adherence to environmental regulations and standards. This approach not only mitigates the environmental impact of traditional wastewater treatment methods but also offers a practical, cost-effective solution for enhancing water resource management in coastal and water-scarce regions. which is beneficial for the environment and aids in meeting Sustainable Development Goals (SDG).

4.3 Electrode Pair Evaluation Study

4.3.1 Physicochemical Analysis

Table 4.3 illustrates the removal efficiencies of the EC process at a retention time of 60 min.

Table 4.3: Removal efficiency of different textile wastewater parameters using thirty-six different electrode pairs.

Combination number	Anode	Cathode	Removal efficiency (%)			
			TSS	Turbidity	COD	TOC
1	C	C	3.43	27.28	10.47	1.69
2	Cu	Cu	4.46	3.19	16.21	7.09
3	Zn	Zn	6.87	4.41	41.89	6.40
4	Zn	C	0.34	0.81	59.45	7.59
5	C	Cu	1.03	8.30	2.70	1.46
6	Cu	C	2.40	4.21	6.75	11.44
7	Al	Al	80.99	5.81	74.91	54.42
8	Cu	Zn	4.97	1.45	90.72	64.44
9	Al	C	38.00	62.09	92.09	68.81
10	Al	Cu	99.66	98.69	69.79	29.23
11	Al	Zn	99.32	98.88	68.62	57.96
12	Zn	Al	98.98	97.93	69.50	41.09
13	Cu	Al	39.39	19.75	74.37	65.19
14	C	Al	3.030	5.53	65.62	23.51
15	C	Zn	9.84	8.85	19.37	4.48
16	Zn	Cu	67.04	52.91	29.37	47.63
17	SS	SS	90.15	90.98	25.62	70.99
18	SS	MS	92.80	92.57	24.06	67.63
19	MS	SS	93.51	98.98	82.25	7.89
20	C	MS	4.96	5.84	18.06	3.48
21	C	SS	1.90	7.24	8.38	5.96
22	Cu	MS	11.83	25.34	63.87	28.40
23	Cu	SS	13.74	18.10	64.51	12.39
24	Zn	MS	4.19	1.87	83.22	3.69
25	Zn	SS	98.47	97.42	52.88	6.26
26	Al	MS	99.61	99.17	63.73	7.81
27	Al	SS	99.23	98.88	62.38	9.03
28	MS	C	72.52	74.04	51.74	33.41
29	SS	C	44.68	62.47	49.44	36.27
30	MS	Cu	58.97	67.89	59.87	10.68
31	SS	Cu	21.63	13.98	34.48	6.88
32	MS	Zn	79.07	79.50	44.20	46.80
33	SS	Zn	78.36	78.72	52.06	10.73
34	MS	Al	90.07	72.47	47.80	17.33
35	SS	Al	95.03	81.80	48.58	20.90
36	MS	MS	84.75	77.69	60.71	7.14

The EC process for textile wastewater treatment was conducted using six different types of electrode materials to determine the best pair from the thirty-six combinations of electrode pairs, with one electrode serving as the anode and the other as the cathode. TSS, turbidity, COD, and TOC were subsequently measured to assess the quality of the treated wastewater for pollutant removal during the EC process of textile wastewater. The results indicate the effectiveness of different types of electrode materials, such as anodes and cathodes, in textile wastewater treatment using the EC technique.

4.3.2 Effect on Parameters

4.3.2.1 Best Electrode Pair for the Removal of TSS

Figure 4.10 shows the TSS removal efficiency (%) in the EC process using six different electrode materials as both the anode and cathode, resulting in 36 combinations. The initial TSS concentration of the untreated wastewater ranged from 221.00 to 296.00 (mg/L).

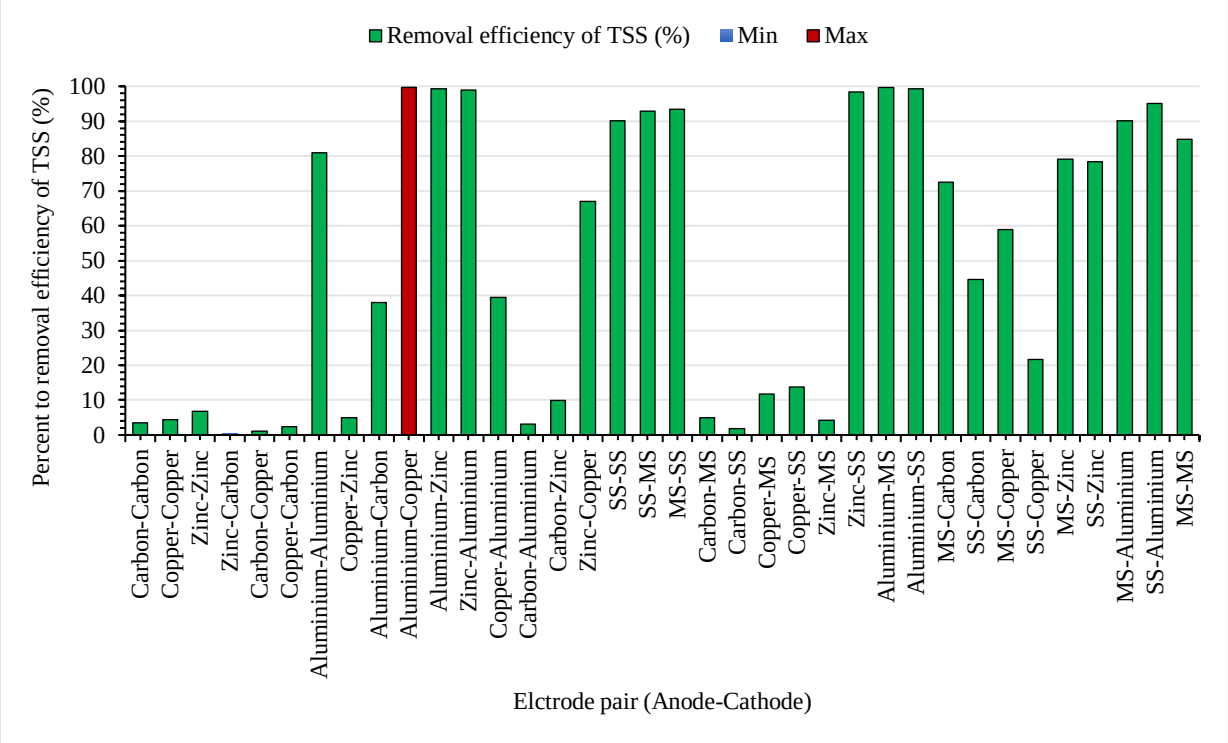

Figure 4.10: Comparison of the TSS removal efficiency (%) of the thirty-six different electrode pairs in the EC process at 20 V and 60 min of retention time.

After the EC process for 60 min, the best-performing electrode pair was found to be Al-Cu, which was set as the anode and cathode, with a removal efficiency of 99.66% (marked in red in Figure

4.10) at 20 V. However, the Al-MS and Al-Zn electrodes used as the anode and cathode performed almost similarly, with removal efficiencies of 99.61% and 99.32%, respectively, at similar retention time and V. On the other hand, the Zn-C electrode set as the anode and cathode performed the worst, with a removal efficiency of 0.34% under similar conditions. Previous studies conducted by Bener et al. (2019) found that the maximum removal efficiency of TSS was 64.7%, using Al and Fe electrodes with optimum conditions at a current density of 25 mA/cm^2, an optimum pH of 5, and a retention time of 120 min. In this study, the highest TSS removal percentage (99.66%) was achieved using Al-Cu as the anode and cathode. Thus, it can be stated that for the removal of TSS from textile wastewater, Al-Cu is the best electrode pair choice among all these combinations.

4.3.2.2 Best Electrode Pair for the Removal of Turbidity

Figure 4.11 illustrates the turbidity removal efficiencies (%) of six different electrode materials used as the anode and cathode in the EC process. The initial turbidity of untreated wastewater ranged from 309.29 to 393.00 (NTU).

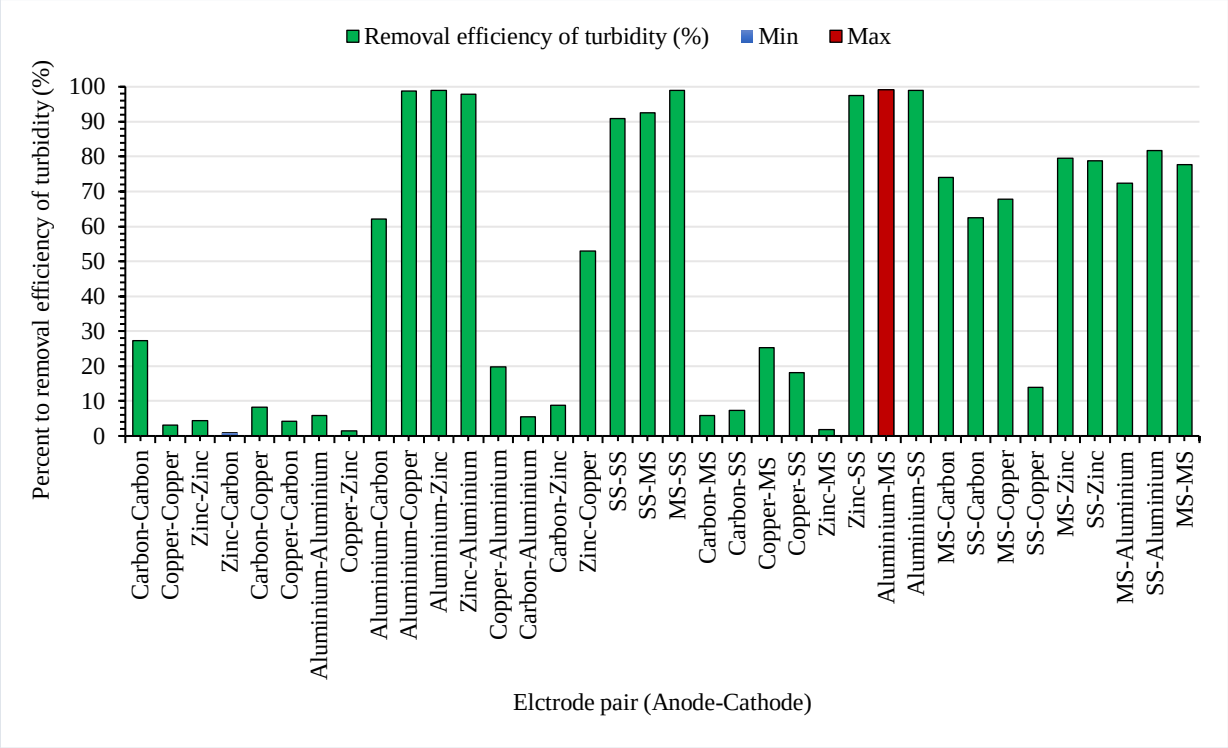

Figure 4.11: Comparison of the turbidity removal efficiency (%) of the thirty-six different electrode pairs in the EC process at 20 V and 60 min of retention time.

After conducting the EC process for 60 min, the best-performing electrode pair was found to be Al-MS, set as the anode and cathode, with a removal efficiency of 99.17% (marked in red in Figure 4.11) at 20 V. However, the MS-SS, Al-SS, and Al-Zn electrode settings as the anode and cathode performed almost similarly with removal efficiencies of 98.98%, 98.88%, and 98.88%, respectively, under the same conditions. On the other hand, the Zn-C electrode set as the anode and cathode performed the worst, with a removal efficiency of 0.81%. Bener et al. (2019), in their study, found a maximum removal efficiency of 83.5% in turbidity by selecting the optimum conditions at a current density of 25 mA/cm^2, an optimum pH of 5, and a retention time of 120 min using Al electrodes. In another study, Núñez et al. (2019) achieved 82% turbidity removal at a retention time of 10 min, a current density of 8 mA/cm^2, and a controlled pH of 7.1. However, in this study, the highest turbidity removal percentage (99.17%) was achieved using Al-MS as the anode and cathode. Thus, to attain the maximum turbidity removal from textile wastewater, the Al-MS electrode combination is the best pair among the other combinations.

4.3.2.3 Best Electrode Pair for the Removal of COD

Figure 4.12 illustrates the removal efficiency of COD (%) in the EC process using six different electrode materials set as the anode and cathode, resulting in 36 combinations. The initial COD of untreated wastewater ranged from 291.00 to 341.00 (mg/L). After the EC process was conducted for 60 min, the best-performing electrode pair was found to be Al-C, set as the anode and cathode, with a removal efficiency of 92.09% (marked in red in Figure 4.12) at 20 V. However, the Cu-Zn, Zn-MS, and MS-SS electrode settings as the anode and cathode performed almost the same with removal efficiencies of 90.72%, 83.22%, and 82.25%, respectively, under similar conditions. However, the C-Cu electrode set as the anode and cathode performed the worst, with a removal efficiency of 2.70%. Previous studies conducted by Khorram and Fallah (2018) using textile wastewater and the EC process found that 40% COD removal can be achieved under optimum conditions of 60 min retention time and a current density of (15-35 mA/cm^2), using 5 pairs of parallel unalloyed Al plate electrodes with dimensions of 2 mm (width), 14.1 cm (height), and 5.6 cm (length). Furthermore, Núñez et al. (2019) found that 59% of COD removal could be achieved at a retention time of 10 min where a pure aluminum sheet (99.9%) was used as the cathode and the anode was made of SAE 1005 steel (95% Fe), at a current density of 8 mA/cm^2 and a controlled pH of 7.1. Furthermore, Bener et al. (2019) found 18.6% COD removal at a current density of 25

mA/cm^2, an optimum pH of 5, and a retention time of 120 min using Al and Fe electrodes. In this study, the maximum COD removal percentage (92.09%) was achieved using Al-C as the anode and cathode. Thus, Al-C is the best electrode pair among all the combinations used to remove COD from textile wastewater.

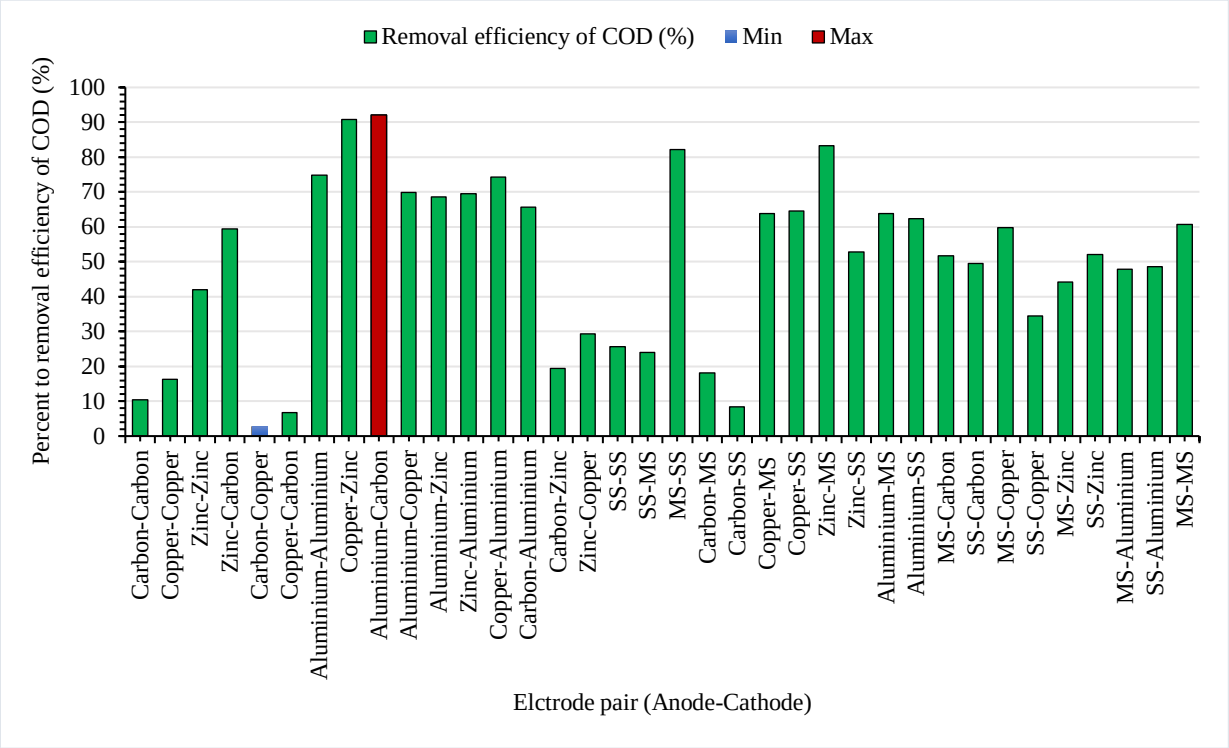

Figure 4.12: Comparison of the COD removal efficiency (%) of the thirty-six different electrode pairs in the EC process at 20 V and 60 min of retention time.

4.3.2.4 Best Electrode Pair for the Removal of TOC

Figure 4.13 shows the removal efficiency of TOC (%) in the EC process of six different electrode materials, forming 36 combinations set as the anode and cathode. The initial TSS concentration of the untreated wastewater ranged from 20.36 to 39.40 (ppm). After conducting the EC process for 60 min the best-performing electrode pair was found to be SS-SS, set as the anode and cathode, with a removal efficiency of 70.99% (marked in red in Figure 4.13) at 20 V. However, the Al-C and SS-MS electrodes used as the anode and cathode performed almost similarly, with removal efficiencies of 68.81% and 67.63%, respectively, at the same conditions. However, the C-Cu electrode set as the anode and cathode performed the worst, with a removal efficiency of 1.46%. Previous studies done by Bener et al. (2019) found that the maximum removal efficiency of TOC

was 42.5%, using Al and Fe electrodes with optimum conditions at a current density of 25 mA/cm^2, an optimum pH of 5, and a retention time of 120 min. However, in this study, the highest TOC removal percentage (70.99%) was achieved using the SS-SS electrode as the anode and cathode, respectively. Thus, the maximum TOC removal efficiency from textile wastewater can be achieved using the SS-SS electrode pair.

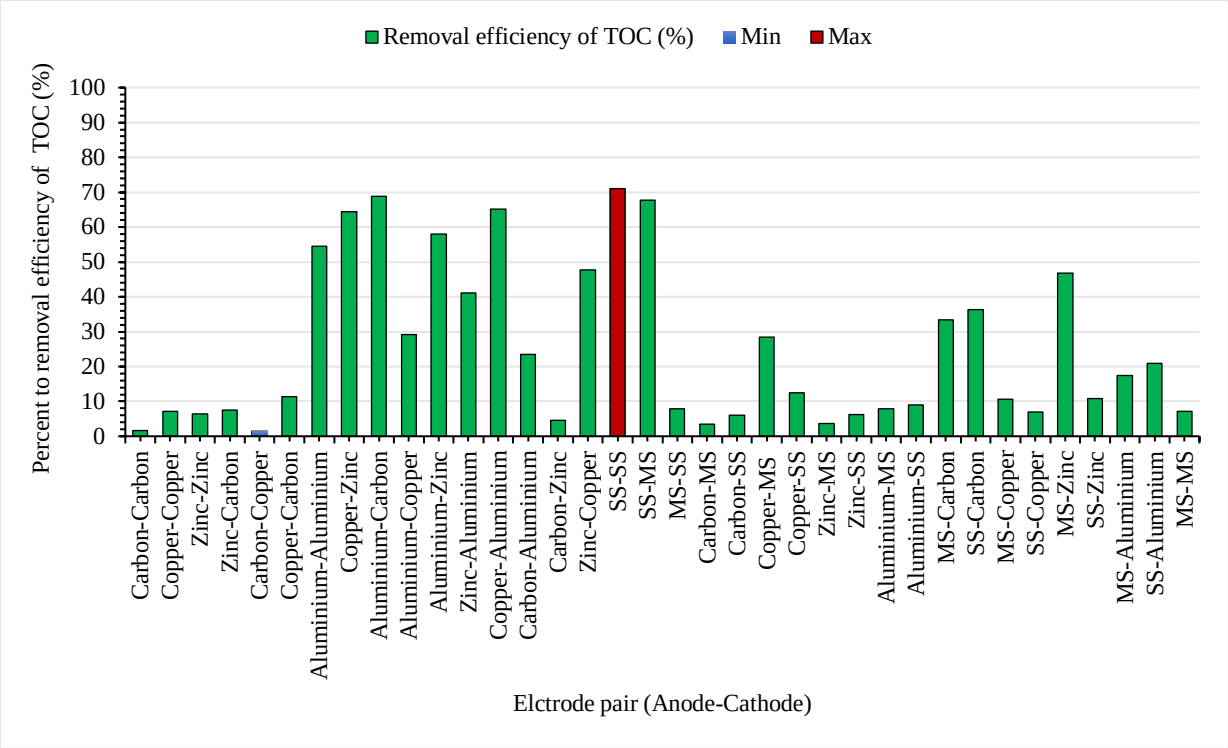

Figure 4.13: Comparison of the TOC removal efficiency (%) of the thirty-six different electrode pairs in the EC process at 20 V and 60 min of retention time.

4.3.3 Statistical Analysis Using MCDM Methods

4.3.3.1 TOPSIS Method

Figure 4.14 illustrates the evaluation of various electrode pairs for the removal of pollutants from textile wastewater using the TOPSIS method. The Technique for TOPSIS was applied to evaluate and rank the performance of 36 electrode pairs based on multiple criteria, including removal efficiencies for TSS, turbidity, COD, and TOC, to evaluate the best electrode pair for removing pollutants from textile wastewater. The dataset included key metrics such as the positive ideal solution distance (S_i^+), negative ideal solution distance (S_i^-), and the relative closeness coefficient (C_j^*). Higher C_j^*values indicate processes that are closer to the ideal solution and thus more

effective. The ranking provided insights into the overall performance of each electrode pair, considering all removal efficiency indicators.

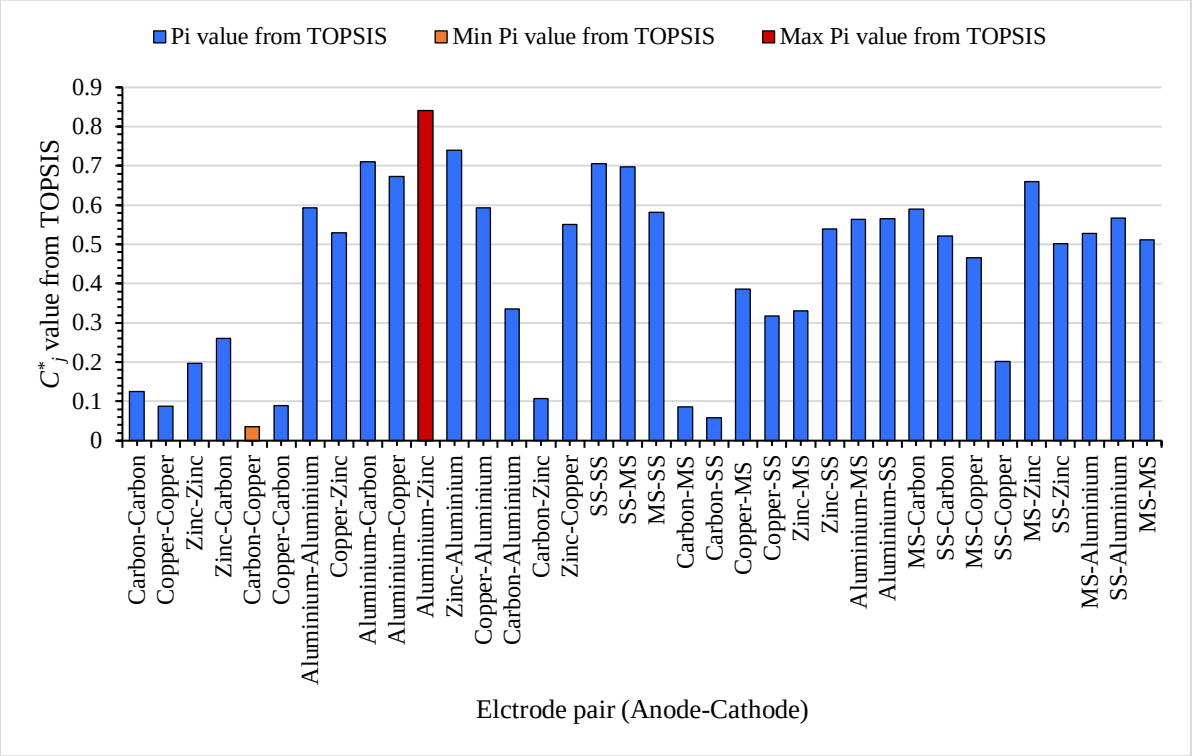

Figure 4.14: Selection of the optimal electrode pair through TOPSIS method analysis.

The x-axis denotes different electrode pairs categorized as anode-cathode combinations, while the y-axis represents the C_j^* values ranging from 0.00 to 0.84 derived from TOPSIS, which indicates the preference measure for each electrode pair. The blue bars represent individual C_j^* values for each electrode pair. The single orange bar indicates the minimum value of C_j^* (0.034) observed across all pairs, which is of particular significance as it denotes the least preferred option based on the TOPSIS assessment, which is the Carbon-Copper set as the anode and cathode. Moreover, the Aluminium-Zinc pair shows the maximum value of C_j^*(0.84), marked as a red bar in the figure, suggesting that it is the most preferred option according to the TOPSIS evaluation. Furthermore, the Zinc-Aluminium electrode pair ranked next, with a C_j^* value of 0.74. The results of this approach demonstrate that using an Aluminium-Zinc electrode pair, with Aluminium serving as the anode and Zinc as the cathode, is the most effective option for achieving optimal TSS, turbidity, COD, and TOC removal efficiencies in textile wastewater. The range of C_j^* values across different

combinations reflects the varying efficacy of each pair, providing a comprehensive insight into their performance. This analysis is pivotal for optimizing electrochemical treatment processes to achieve enhanced pollutant removal efficiency in wastewater treatment applications. Thus, the treatment of wastewater from the textile industry can be carried out with high efficiency and effectiveness by utilizing an electrode pair consisting of Aluminium and Zinc, with one electrode serving as the anode and the other as the cathode.

4.3.3.2 VIKOR Method

Figure 4.15 illustrates the evaluation of various electrode pairs for the removal of pollutants from textile wastewater using the VIKOR method. The Technique for VIKOR was applied to evaluate and rank the performance of 36 electrode pairs based on multiple criteria, including removal efficiencies for TSS, turbidity, COD, and TOC, to evaluate the best electrode pair for removing pollutants from textile wastewater. The dataset included three key parameters: the utility measure (S_J), representing the total deviation from the ideal solution; the regret measure (R_J), indicating the maximum deviation from the ideal solution across criteria; and the compromise ranking index (Q_J), which balances utility and regret to identify the best compromise solution. Processes were ranked according to their Q_J values, with lower values reflecting better overall performance.

The x-axis denotes different electrode pairs categorized as anode-cathode combinations, while the y-axis represents the Q_J values ranging from 0.00 to 1.00, derived from the VIKOR method, which indicates the preference for measuring each electrode pair. Electrode pairs were ranked according to their Q_J values, with lower values reflecting better overall performance. The blue bars represent individual Q_J values for each electrode pair. The single red bar represents the maximum Q_J value (1.00) observed across all the pairs, which is of particular significance as it denotes the least preferred option based on the VIKOR assessment, which uses Carbon-Copper as the anode and cathode. Moreover, the Aluminium-Zinc pair displayed the lowest Q_J value of 0.00, suggesting that it is the most preferred option according to the VIKOR evaluation. The results showed that the Aluminium-Zinc is the best electrode pair for the intended application in textile wastewater treatment, and Zinc-Aluminium electrode pair ranked next with a Q_J value of 0.14. Therefore, setting the Aluminium-Zinc electrode pair as the anode and cathode is the most effective option

for achieving optimal removal efficiencies of TSS, turbidity, COD, and TOC in textile wastewater. The range of Q_J values across different combinations reflects the varying efficacy of each pair, providing comprehensive insight into their performance. This analysis is pivotal for optimizing electrochemical treatment processes to achieve enhanced pollutant removal efficiency in wastewater treatment applications. Thus, the treatment of wastewater from the textile industry can be carried out with high efficiency and effectiveness by utilizing an electrode pair consisting of Aluminium-Zinc, with one electrode serving as the anode and the other as the cathode.

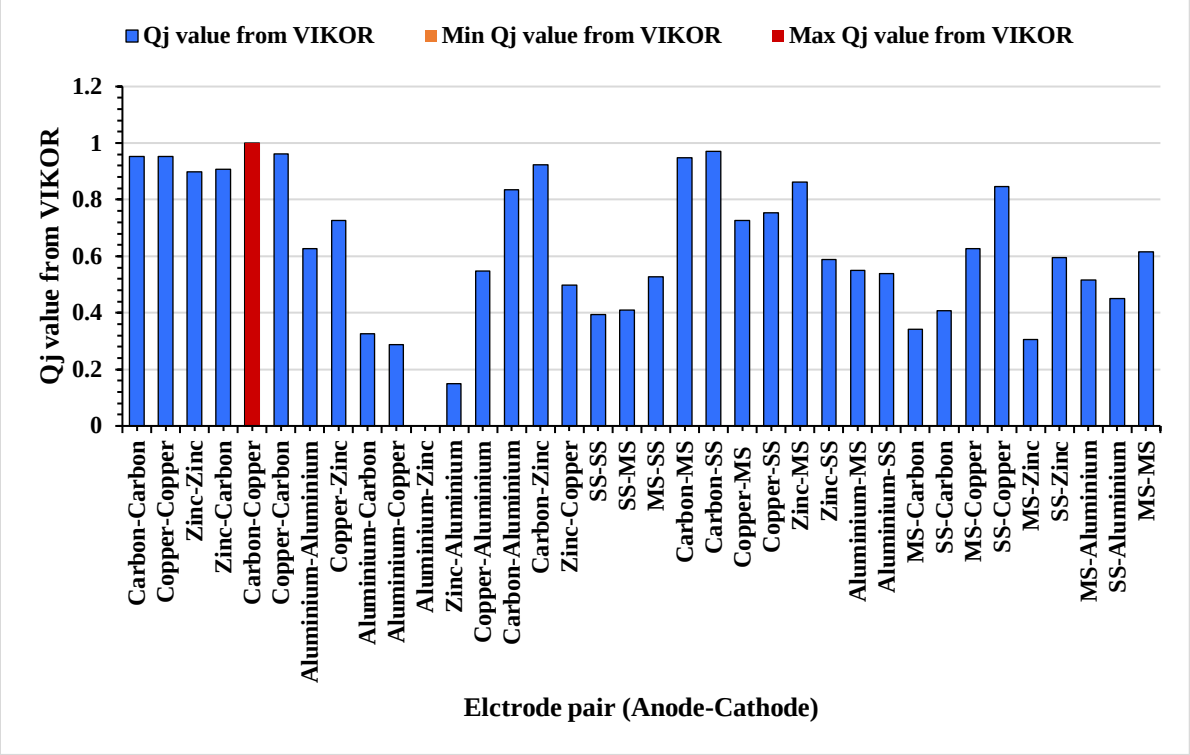

Figure 4.15: Selection of the optimal electrode pair through VIKOR method analysis.

4.3.3.3 PROMETHEE II Method

Figure 4.16 illustrates the evaluation of various electrode pairs for the removal of pollutants from textile wastewater using the PROMETHEE II method. The Technique for PROMETHEE II was applied to evaluate and rank the performance of 36 electrode pairs based on multiple criteria, including removal efficiencies for TSS, turbidity, COD, and TOC, to evaluate the best electrode pair for removing pollutants from textile wastewater. The ranking of the 36 electrode pairs was done using the PROMETHEE II method based on their net preference index ($\varphi(i)$). This net flow,

calculated as the difference between the positive preference flow ($\varphi_{(i)}^{+}$) and the negative preference flow ($\varphi_{(i)}^{-}$), offers a comprehensive measure of an electrode pair's overall dominance or inferiority compared to others across multiple criteria. Higher net $\varphi(i)$ values indicate better performance and stronger dominance in the decision matrix.

As the net outranking flow determines the best electrode pair from other alternatives in this method, the best electrode pair found is Aluminium-Zinc set as the anode and cathode with a $\varphi(i)$ value of 0.42. The next rank is the Zinc-Aluminium electrode pair set as the anode and cathode, with a $\varphi(i)$ value of 0.36. On the other hand, the worst electrode pair was the Carbon-Copper set as the anode and cathode, with a $\varphi(i)$ value of -0.44. The outcome of this method illustrates that to obtain optimum removal efficiencies of TSS, turbidity, COD and TOC in textile wastewater, the Aluminium-Zinc electrode pair set as the anode and cathode can be the best choice. Thus, textile wastewater treatment can be efficiently and effectively done using the Aluminium-Zinc electrode pair set as the anode and cathode.

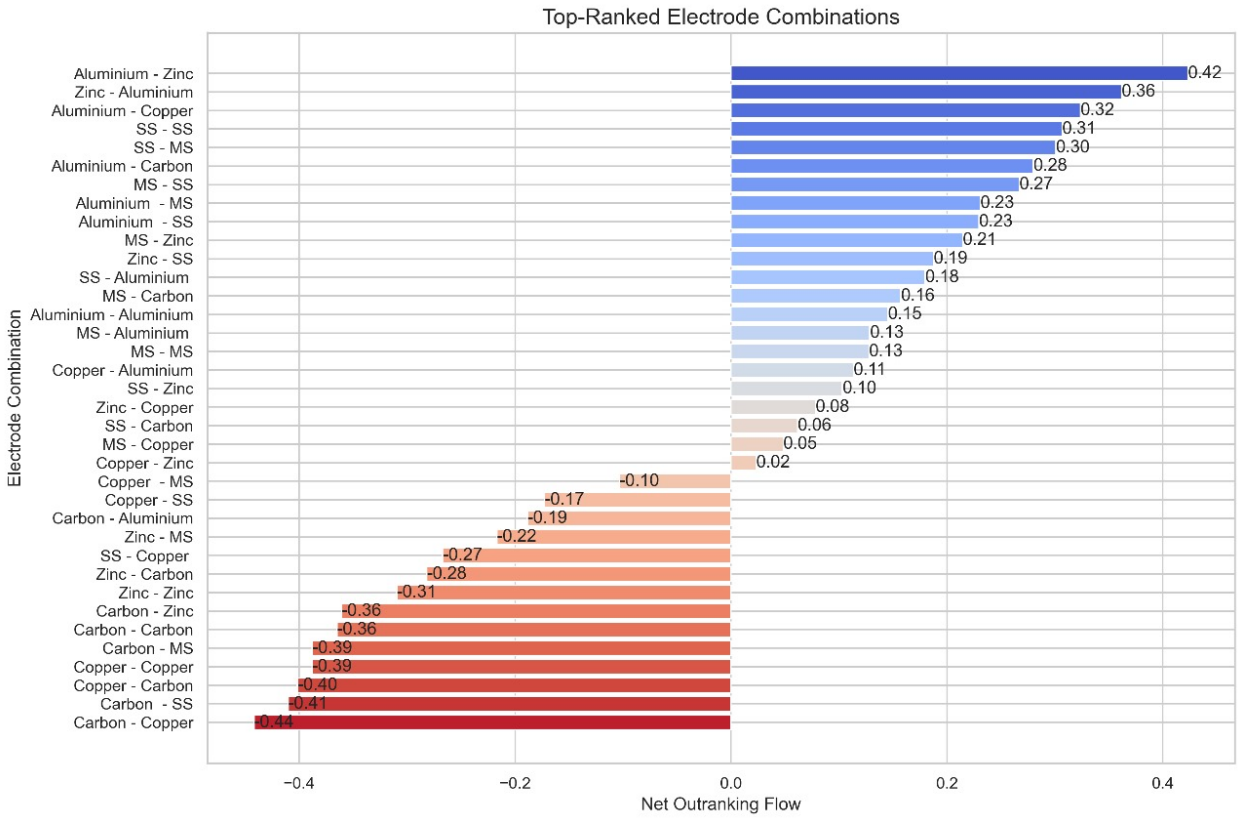

Figure 4.16: Selection of the optimal electrode pair through PROMETHEE II method analysis.

4.3.4 Discussion on Outcome of the MCDM Methods

Table 4.4 shows the output rankings of three MCDM methods, namely VIKOR, PROMETHEE II, and TOPSIS, arranged from the best to the worst alternative. In this study, when applying the MCDM methods of TOPSIS, VIKOR, and PROMETHEE II, the most and least effective electrode pairs were consistently identified as Aluminium-Zinc and Carbon-Copper, respectively. However, there were discrepancies in the intermediate rankings across the three methodologies. These variations are attributed to the inherent differences in the evaluative logic and computational mechanisms of the methods. Each MCDM method uses a different logic to evaluate and compare alternatives. TOPSIS determines the geometric distance from an ideal point, where VIKOR emphasizes a compromise solution that is closest to the ideal and farthest from the anti-ideal, whereas PROMETHEE II relies on pairwise comparisons using a preference function to determine the dominance of one alternative over another. Therefore, each method interprets the data differently and may prioritize different aspects of the alternatives' performance. Table A6 (in Apendix) shows the criteria and normalized decision matrix values of the applied MCDM methods in this study. PROMETHEE II does not use a normalized decision matrix technique as so the preference function $\varphi(i)$ value is shown, which is the criteria value for choosing the best alternative. It is worth noting that some methods are more sensitive to changes in criteria performance than others. For example, a method that heavily penalizes poor performance in one criterion will rank an alternative lower if it underperforms in that specific area, even if it performs well in other areas. On the other hand, a method that seeks a balance may rank an alternative higher if it shows moderately good performance across all criteria. PROMETHEE II is an outranking method that focuses on the extent to which one alternative is preferred over another, while TOPSIS and VIKOR are associated with the pursuit of an ideal solution. This fundamental difference can lead to divergent rankings because outranking methods consider the relative performance of all alternatives against each other, while ideal solution methods focus on the aggregate performance of each alternative individually. Given that the textile wastewater treatment problem involves multiple conflicting and complex criteria, each MCDM method may interpret this complexity differently, resulting in different recommendations for the "best" alternative based on their evaluative frameworks. Some methods may be more sensitive to small variations in data, which can affect the rankings, especially when the performance of alternatives is similar or the differences are not significant.

Table 4.4: Comparative analysis of MCDM methods ranked from the best to the worst alternative for the selection of best electrode pair.

Electrode pair		VIKOR rankth	PROMETHEE II rankth	TOPSIS rankth
Anode	**Cathode**			
Al	Zn	1	1	1
Zn	Al	2	2	2
Al	Cu	3	3	6
MS	Zn	4	10	7
Al	C	5	3	6
MS	C	6	10	13
SS	SS	7	4	4
SS	C	8	19	20
SS	MS	9	5	5
SS	Al	10	12	12
Zn	Cu	11	15	19
MS	Al	12	18	15
MS	SS	13	11	7
Al	SS	14	13	9
Cu	Al	15	9	17
Al	MS	16	14	8
Zn	SS	17	16	11
SS	Zn	18	21	18
MS	MS	19	20	16
Al	Al	20	8	14
MS	Cu	21	22	21
Cu	MS	22	23	23
Cu	Zn	23	17	22
Cu	SS	24	26	24
C	A	25	24	25
SS	Cu	26	28	27
Zn	MS	27	25	26
Zn	Zn	28	29	29
Zn	C	29	27	28
C	Zn	30	31	30
C	MS	31	34	32
Cu	Cu	32	33	33
C	C	33	30	31
Cu	C	34	32	34
C	SS	35	35	35
C	Cu	36	36	36

Lastly, the variation in rankings across different MCDM methods reflects their diverse approaches to handling multiple criteria and trade-offs. This variation is a natural outcome of the complexity involved in MCDM, particularly when dealing with intricate problems

such as textile wastewater treatment. The choice of MCDM method can significantly impact the results, underscoring the importance of selecting a method that aligns with the decision context and goals of the study.

4.3.5 Application of the Process

The EC process investigated in this comprehensive study demonstrates exceptional potential for real-world application in textile wastewater treatment facilities, offering a sustainable and technologically advanced solution for industrial-scale implementation across diverse textile manufacturing operations. The optimal Al-Zn electrode pair configuration identified through rigorous multi-criteria decision-making (MCDM) analysis provides a robust practical foundation that can be effectively scaled from controlled laboratory conditions to large-scale industrial settings, addressing the growing environmental challenges faced by the global textile industry. The meticulously established process parameters, including operating voltage of 20 V, current density of 15.0 A/m², and retention time of 60 min, serve as comprehensive baseline conditions for industrial implementation while maintaining sufficient flexibility for optimization based on specific wastewater characteristics, seasonal variations in textile production, and evolving treatment requirements dictated by increasingly stringent environmental regulations.

The industrial-scale implementation of the EC process presents remarkable versatility in accommodating various reactor designs and configurations, including sophisticated batch systems for smaller facilities, continuous flow reactors for high-volume operations, and innovative hybrid systems that combine the advantages of both approaches depending on the specific operational needs and production schedules of textile manufacturing facilities. The carefully optimized electrode spacing of 10 cm and effective electrode area of 42 cm² per electrode demonstrated in this study can be systematically and proportionally scaled to accommodate substantially larger treatment volumes, with industrial reactors typically employing multiple electrode pairs arranged in carefully designed parallel or series configurations to achieve desired treatment capacity while maintaining optimal current distribution, uniform mass transfer rates, and consistent treatment efficiency across the entire reactor volume. The exceptional removal efficiencies demonstrated in this study 99.32% for TSS, 98.88% for turbidity, 68.62% for COD, and 57.96% for TOC using the Al-Zn electrode pair indicate that the process can consistently and reliably meet or exceed regulatory discharge standards, particularly the Bangladesh Environmental Conservation Rules

(ECR) permissible limits for industrial effluent discharge, while providing substantial safety margins that accommodate normal operational variations and unexpected peak loading conditions.

The remarkable versatility and adaptability of the EC process enables seamless and effective integration into existing textile wastewater treatment systems, functioning either as a highly efficient primary treatment step that prepares wastewater for downstream biological processes or as an advanced polishing unit following conventional biological treatment to achieve superior final effluent quality. When strategically implemented as a pre-treatment step, the EC process can dramatically reduce the organic load, suspended solids content, and toxic compounds entering downstream biological processes, significantly improving their efficiency, stability, and operational lifespan while reducing the frequency of system upsets and maintenance requirements. Alternatively, when deployed as a sophisticated tertiary treatment step, the EC process provides exceptional final polishing capabilities to meet the most stringent discharge standards or prepare high-quality water for various reuse applications within textile facilities, including process water recovery, cooling tower makeup, and non-potable applications. The process demonstrates particular effectiveness in treating high-strength textile wastewaters characterized by complex chemical compositions that may prove challenging or impossible to treat using conventional biological methods due to the presence of recalcitrant synthetic dyes, heavy metals, and organic chemicals that inhibit biological activity. The simultaneous and synergistic removal of multiple pollutant categories in a single treatment step dramatically simplifies the overall treatment train, reduces infrastructure requirements, minimizes operational complexity, and decreases the overall facility footprint while maintaining superior treatment performance.

From a comprehensive environmental sustainability perspective, the EC process contributes significantly to environmental protection and resource conservation through multiple interconnected mechanisms, including substantial reduction in pollutant loads that effectively protect receiving water bodies from contamination, ecosystem disruption, and long-term ecological damage. The process operates entirely without the addition of potentially harmful chemical coagulants, eliminating the risk of secondary pollution from these additives while avoiding the environmental impacts associated with chemical manufacturing, transportation, and storage. The relatively compact treatment units require significantly less land area compared to conventional treatment systems such as clarifiers, lagoons, and extended biological treatment

facilities, making them particularly suitable for urban industrial areas where land constraints severely limit expansion options. The superior treated wastewater quality achieved through the optimized EC process demonstrates exceptional suitability for various beneficial reuse applications within textile facilities, including cooling water systems, equipment cleaning operations, floor washing, landscape irrigation, and even potential integration into certain non-contact process applications following appropriate advanced treatment and disinfection protocols, contributing substantially to water conservation efforts and dramatically reducing demand for increasingly scarce fresh water resources.

The successful industrial implementation of the EC process requires sophisticated monitoring and control systems designed to ensure consistent treatment performance across widely varying operational conditions, influent characteristics, and production schedules typical of dynamic textile manufacturing environments. Critical parameters requiring continuous real-time monitoring include pH levels, electrical conductivity, current density distribution, voltage stability, electrode condition and consumption rates, temperature fluctuations, and various water quality indicators, with advanced automated control systems capable of dynamically adjusting operating parameters in immediate response to variations in influent wastewater characteristics to ensure optimal treatment efficiency and prevent system upsets. Comprehensive electrode maintenance and replacement schedules must be carefully established based on empirically determined electrode consumption rates observed during extended operation under representative conditions, with the detailed findings regarding different electrode materials and their performance characteristics providing valuable guidance for developing sophisticated predictive maintenance programs that minimize unplanned downtime and ensure continuous reliable operation. The exceptional process performance demonstrated throughout this systematic investigation indicates strong potential for meeting or exceeding the most stringent international wastewater discharge standards, with treated effluent quality consistently achieving levels substantially below regulatory limits, providing significant operational safety margins that accommodate typical variations in industrial conditions, seasonal production changes, and unexpected operational challenges.

The implementation of the EC process also presents opportunities for advanced process integration and optimization through the incorporation of complementary technologies such as advanced oxidation processes, membrane filtration, or biological treatment systems to achieve even higher

treatment standards or enable direct potable reuse applications. The modular nature of EC systems allows for phased implementation and expansion as facility needs grow or regulations become more stringent, providing flexibility for operational scaling and technology adaptation. Furthermore, the process generates valuable data on wastewater characteristics and treatment performance that can inform broader facility water management strategies, process optimization efforts, and environmental compliance programs. The multi-electrode material approach demonstrated in this study opens possibilities for customized electrode configurations tailored to specific wastewater characteristics or treatment objectives, allowing facilities to optimize their systems based on predominant pollutant types or seasonal variations in wastewater composition.

The comprehensive documentation and extensive performance data generated through this rigorous systematic evaluation provide the essential technical foundation necessary for regulatory approvals, environmental impact assessments, and permitting processes required for industrial implementation, with the consistent use of standardized testing methods and internationally recognized water quality parameters ensuring ready acceptance by regulatory authorities worldwide and facilitating technology transfer to diverse geographic and regulatory environments. The successful application of three different MCDM methods (TOPSIS, VIKOR, and PROMETHEE II) in optimizing electrode selection demonstrates the robustness of the decision-making framework and provides confidence in the reliability of the Al-Zn electrode pair recommendation for practical implementation. The process represents a significant advancement in sustainable wastewater treatment technology, offering textile facilities an effective solution for meeting environmental compliance requirements while contributing to broader sustainability goals through reduced chemical usage, improved water reuse potential, and enhanced protection of aquatic ecosystems. The scalability and adaptability of the EC process make it particularly well-suited for implementation across the diverse range of textile manufacturing operations, from small specialty producers to large integrated textile complexes, providing a versatile technology platform that can be customized to meet specific facility requirements and regulatory standards in different geographic regions and operational contexts.

4.4 IS Process Study

4.4.1 Physicochemical Analysis

Table 4.5 presents a summary of the removal efficiencies for TSS, turbidity, COD, and color across the twenty-seven integrated system processes.

Table 4.5: Final removal efficiency of different textile wastewater parameters using different IS processes.

Integrated system (IS)	Removal efficiency (%) of the IS processes			
	TSS	Turbidity	COD	Color
Process 1	80.42	76.4	62.95	71.71
Process 2	84.3	81.55	67.83	75.41
Process 3	89.5	87.49	71.9	79.12
Process 4	83.17	82.38	67.12	81.16
Process 5	85.34	84.81	70.4	80.44
Process 6	89.39	89.13	77.64	85.22
Process 7	84.89	84.39	69.25	82.46
Process 8	85.09	82.27	74.08	81.39
Process 9	91.27	90.07	79.89	87.23
Process 10	91.86	89.32	73.81	85.03
Process 11	94.53	91.46	81.28	90.41
Process 12	95.4	93.38	88.51	92.68
Process 13	94.82	94.55	89.77	93.04
Process 14	95.23	92.42	84.77	91.3
Process 15	95.83	94.57	90	93.89
Process 16	93.62	92.71	85.04	90.98
Process 17	96.73	93.76	87.04	92.38
Process 18	96.57	94.73	91	94.72
Process 19	98.19	97.45	91.36	95.53
Process 20	98.63	98.05	92.1	96.01
Process 21	99.01	99.09	93.95	98.57
Process 22	98.38	97.92	92.81	96.91
Process 23	98.9	98.17	93.39	97.06
Process 24	99.24	98.61	94.11	98.65
Process 25	98.65	98.05	93.07	97.14
Process 26	99	98.31	94.08	98.19
Process 27	99.69	99.57	95.23	99.1

The physicochemical analysis of textile wastewater was conducted to evaluate the performance of the integrated treatment system under various operational conditions. The parameters assessed included TSS, turbidity, COD, and color, which are key indicators of wastewater pollution and treatment effectiveness. After treatment through an integrated system comprising EC, ST, AT, MM filtration, and AC filtration, the removal efficiencies of these parameters were determined for each process configuration. Characterization of different textile wastewater parameters after each treatment process are shown in Table A7 (in Appendix).

4.4.2 Sequential Performance Evaluation of IS processes

Table 4.6 presents the removal efficiency (%) after each unit and the overall RE (%) for all the IS processes. The treatment process significantly affects TSS, turbidity, COD, and color, which are critical parameters for assessing water quality. TSS represents solid particles suspended in water, and this process effectively removes them at various stages. The EC step destabilizes, and aggregates suspended particles, which are efficiently separated during the ST stage as they settle to the bottom. As a result, TSS content is substantially reduced, leading to clearer water. Turbidity, a measure of cloudiness caused by suspended particles, is also significantly reduced. The EC process coagulates fine particles, and the ST tank allows them to settle, thereby removing the main contributors to turbidity. Additional reductions occur during the filtration stages, particularly through the MM and AC filters, which eliminate smaller particulates and residual matter. COD, indicating the amount of organic and inorganic pollutants in the water, decreases throughout the treatment. The EC process breaks down complex organic compounds, while ST removes organic matter attached to settled particles. AT further enhances the breakdown of volatile organic compounds, and the filtration stages eliminate dissolved pollutants, ensuring substantial COD reduction. Finally, color, often caused by dyes or organic matter, can be effectively treated through adsorption and coagulation mechanisms. The EC process plays a vital role in destabilizing color-causing compounds, and the AC filter efficiently adsorbs residual color and organic materials, resulting in clear, colorless water. The combined process ensures significant improvements in TSS, turbidity, COD, and color, making the water suitable for reuse or discharge.

Table 4.6: Removal efficiency (%) performance of individual treatment units and overall is processes.

Integrated system (IS)	RE of TSS (%)						RE of Turbidity (%)						RE of COD (%)						RE of Color (%)					
	EC	ST	AT	MM filter	AC filter	Overall IS	EC	ST	AT	MM filter	AC filter	Overall IS	EC	ST	AT	MM filter	AC filter	Overall IS	EC	ST	AT	MM filter	AC filter	Overall IS
Process 1	45.18	22.53	8.51	38.76	17.72	80.42	38.17	21.23	5.44	37.19	18.43	76.41	30.08	14.74	7.48	16.67	19.39	62.95	36.88	15.39	8.72	16.96	30.15	71.72
Process 2	47.10	30.32	14.82	36.96	20.69	84.30	42.72	24.72	15.11	32.02	25.88	81.56	35.97	16.44	12.02	11.18	23.08	67.84	41.73	21.76	10.84	7.76	34.44	75.42
Process 3	48.20	38.61	24.74	41.10	25.58	89.51	43.04	32.81	15.71	45.98	28.26	87.50	36.86	11.01	12.37	17.18	31.11	71.90	42.01	22.76	8.85	20.64	35.56	79.12
Process 4	44.66	39.18	5.77	37.76	14.75	83.17	40.68	37.20	4.73	36.31	22.07	82.38	25.69	26.77	5.58	14.52	25.16	67.13	37.67	33.18	6.86	25.15	35.14	81.17
Process 5	50.18	31.62	5.38	39.77	24.53	85.35	47.03	35.69	6.39	31.84	30.11	84.81	36.78	18.64	3.35	14.45	30.41	70.40	44.75	23.49	4.31	26.42	34.32	80.45
Process 6	48.11	37.96	10.59	43.42	34.88	89.39	46.46	31.80	13.52	37.74	44.76	89.14	41.18	23.00	7.79	21.13	32.14	77.65	44.69	24.06	8.29	33.44	42.38	85.23
Process 7	41.28	43.43	4.04	36.84	25.00	84.90	39.61	39.37	5.65	36.17	29.21	84.39	27.70	24.90	4.59	20.86	25.00	69.25	33.33	31.77	7.14	28.12	42.25	82.47
Process 8	45.75	39.87	7.61	36.47	16.67	85.10	43.18	35.27	10.17	31.84	21.30	82.28	32.11	24.48	9.34	20.61	29.77	74.09	41.63	28.69	7.96	21.40	38.22	81.40
Process 9	44.55	48.32	15.22	46.15	33.33	91.28	42.54	47.54	14.56	38.11	37.75	90.08	37.04	27.73	15.12	23.29	32.14	79.89	39.19	32.78	12.26	31.91	47.73	87.24
Process 10	72.59	26.37	5.97	42.86	25.00	91.87	67.16	23.09	7.83	40.02	23.57	89.33	49.30	12.64	8.18	12.33	26.56	73.82	63.19	18.00	13.26	19.55	28.97	85.04
Process 11	78.50	31.75	18.61	37.14	27.27	94.54	70.64	27.41	19.53	36.07	22.21	91.47	54.09	13.38	11.77	23.33	30.44	81.29	67.86	28.52	9.59	24.64	38.78	90.42
Process 12	78.03	38.81	21.95	40.63	26.32	95.41	72.44	34.75	14.34	38.01	30.76	93.39	55.89	26.71	12.15	34.04	38.71	88.52	70.20	20.17	13.80	33.23	46.61	92.69
Process 13	74.76	41.03	10.87	39.02	36.00	94.82	70.52	33.80	6.37	32.38	55.91	94.55	53.59	20.24	4.48	21.88	63.00	89.78	66.09	25.12	7.73	23.68	61.13	93.05
Process 14	75.09	39.71	9.76	45.95	35.00	95.24	73.59	36.58	5.62	34.35	27.04	92.43	62.07	21.97	6.80	20.83	30.26	84.77	70.93	20.61	8.40	30.28	41.04	91.31
Process 15	81.82	39.58	10.35	38.46	31.25	95.83	80.90	28.47	14.25	38.62	24.60	94.58	54.41	32.26	13.33	34.07	43.33	90.00	73.44	26.44	9.06	37.11	45.36	93.90

Note: EC= Electrocoagulation, ST= Sedimentation, AT= Aeration, MM= Multimedia, AC= Activated Carbon, and RE= Removal Efficiency.

Table 4.6: Removal efficiency (%) performance of individual treatment units and overall is processes (continued).

Integrated system (IS)	RE of TSS (%)						RE of Turbidity (%)						RE of COD (%)						RE of Color (%)					
	EC	ST	AT	MM filter	AC filter	Overall IS	EC	ST	AT	MM filter	AC filter	Overall IS	EC	ST	AT	MM filter	AC filter	Overall IS	EC	ST	AT	MM filter	AC filter	Overall IS
Process 16	72.82	46.91	9.30	41.03	17.39	93.62	68.31	35.27	9.06	40.86	33.98	92.72	57.90	25.66	9.74	14.71	37.93	85.04	67.17	28.50	6.68	23.27	46.33	90.98
Process 17	78.01	45.16	11.77	43.33	41.18	96.73	77.73	37.77	8.16	34.67	25.02	93.76	67.32	16.38	6.19	19.78	36.99	87.04	72.21	20.29	6.30	28.85	48.43	92.38
Process 18	82.56	44.64	12.90	40.74	31.25	96.57	78.32	32.88	14.11	36.90	33.24	94.73	56.61	28.05	16.10	38.38	44.26	91.01	75.37	33.19	11.22	32.85	46.24	94.73
Process 19	91.57	32.14	15.79	43.75	33.33	98.19	87.66	30.47	9.54	49.73	34.72	97.45	72.70	17.35	14.82	20.29	43.64	91.37	81.04	21.45	18.06	32.26	46.03	95.54
Process 20	92.83	38.10	15.39	45.46	33.33	98.64	90.19	33.98	17.52	43.29	35.93	98.06	76.02	17.07	10.29	29.51	37.21	92.11	81.19	32.60	18.78	31.79	43.22	96.01
Process 21	94.75	43.75	22.22	42.86	25.00	99.02	93.14	45.09	28.91	47.88	35.23	99.10	77.04	28.95	27.78	30.77	25.93	93.96	90.64	35.76	29.90	35.29	47.73	98.58
Process 22	92.56	39.13	7.14	38.46	37.50	98.38	89.88	40.07	8.20	43.51	33.99	97.92	80.39	22.54	9.09	18.00	36.59	92.82	85.99	31.20	6.40	38.51	44.44	96.92
Process 23	94.14	43.75	22.22	42.86	25.00	98.90	93.32	32.00	6.66	36.84	31.68	98.17	81.03	22.73	7.84	25.53	34.29	93.39	85.73	27.98	6.86	39.26	49.50	97.06
Process 24	95.08	46.15	14.29	50.00	33.33	99.24	94.30	38.41	12.28	34.35	31.70	98.62	80.88	26.15	10.42	27.91	35.48	94.12	92.06	31.54	10.11	46.25	48.84	98.66
Process 25	92.28	43.48	15.39	45.46	33.33	98.66	91.01	37.06	8.45	43.19	33.88	98.06	82.27	20.31	7.84	19.15	34.21	93.08	86.72	27.00	6.94	42.24	45.16	97.14
Process 26	93.97	47.06	11.11	37.50	40.00	99.01	91.72	42.19	8.29	38.56	37.44	98.31	82.82	24.59	10.87	21.95	34.38	94.09	88.26	31.68	7.97	45.67	55.07	98.20
Process 27	95.33	53.33	14.29	66.67	50.00	99.69	94.88	48.43	17.58	62.46	46.98	99.57	79.89	25.00	14.04	32.65	45.46	95.24	93.04	43.94	16.22	46.77	48.49	99.10

Note: EC= Electrocoagulation, ST= Sedimentation, AT= Aeration, MM= Multimedia, AC= Activated Carbon, and RE= Removal Efficiency.

4.4.2.1 Removal of TSS (%)

Figure 4.17 presents a radar chart comparing the RE (%) of TSS at different treatment stages across 27 IS processes designed for textile wastewater treatment. Each IS process was configured with varying retention times for EC, ST, and AT, followed by sequential treatment using MM and AC filters. The radar plot visualizes stage-wise removal efficiencies, including post-EC RE (%), post-ST RE (%), post-AT RE (%), post-MM Filter RE (%), post-AC Filter RE (%), and cumulative TSS removal (overall IS process RE %), providing an integrated view of treatment performance. The EC retention times were set at 20, 40, and 60 min; ST retention times at 60, 120, and 180 min; and AT retention times at 20, 40, and 60 min, resulting in 27 unique configurations. The overall cumulative TSS removal efficiency (overall IS process RE %) ranged from 80.4% (IS process 1) to 99.69% (IS process 27), demonstrating the high performance of the IS in treating real textile wastewater.

Post-EC RE (%) ranged from 41.28% (IS process 7) to 95.33% (IS process 27), highlighting the significant role of EC retention time (20-60 min) in destabilizing suspended solids. Longer EC durations notably improved the coalescence and aggregation of particulates, facilitating their subsequent separation. Post-ST RE (%) varied from 22.53% (IS process 1) to 53.33% (IS process 27), with the highest values associated with 180-min ST periods, confirming the efficiency of extended settling in removing flocculated matter. The AT contributed modestly to TSS removal, with post-AT RE (%) ranging from 4.04% (IS process 7) to 24.74% (IS process 3), mainly due to enhanced mixing and oxidation at higher retention times. The polishing stages further improved effluent clarity. MM filtration achieved removal efficiencies between 36.47% (IS process 8) and 66.67% (IS process 27), while AC filtration contributed between 14.75% (IS process 4) and 50% (IS process 27), particularly effective in eliminating fine colloidal and residual particulate matter. These sequential processes cumulatively elevated overall TSS removal efficiency across the IS configurations.

IS process 27 exhibited the highest overall TSS removal efficiency of 99.69%, attributable to its configuration employing maximum retention durations (60 min EC, 180 min ST, and 60 min AT), along with effective MM and AC polishing. IS processes 24 (99.24%), 26 (99.01%), 21 (99.02%), and 23 (98.90%) also demonstrated superior performance with slight deviations from the top

configuration. These findings suggest that high-efficiency TSS removal can be systematically achieved through optimization of each treatment stage and retention schedule. Moderate performers, such as IS processes 14 (95.24%) and 12 (95.41%), show that even mid-range configurations can deliver reliable results. In contrast, IS processes 1 (80.42%) and 4 (83.17%) recorded the lowest removal efficiencies due to insufficient residence times and underperforming post-treatment steps.

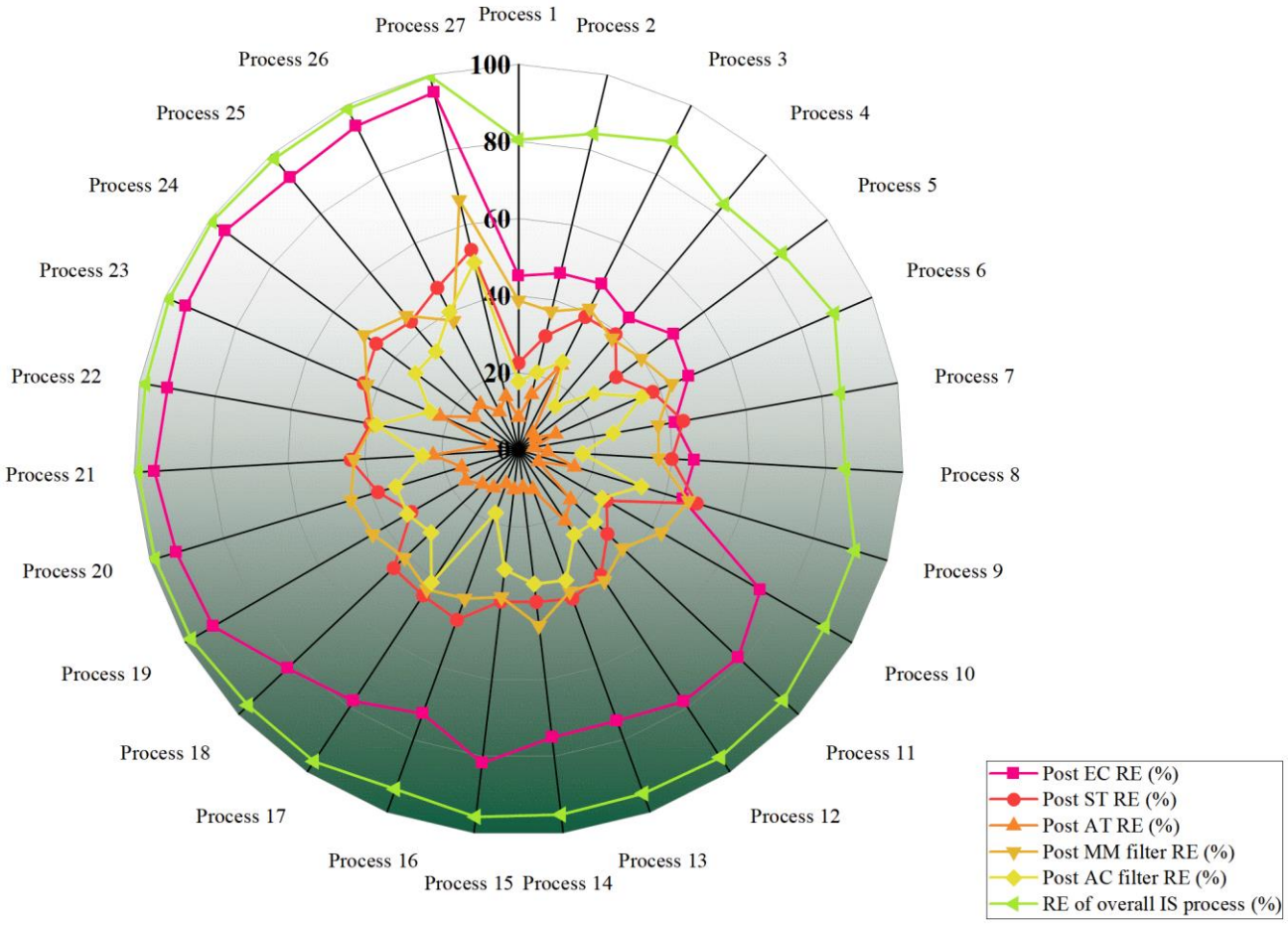

Figure 4.17: Comparative assessment of TSS removal efficiency (%) across 27 different IS processes for textile wastewater treatment.

Previous research has demonstrated varying degrees of TSS removal using EC and hybrid systems under different operational settings. For instance, Naje et al. (2015) reported an efficient EC setup utilizing alternating monopolar and bipolar aluminum plates, achieving 96.4% TSS removal under

optimal conditions: 0.6 A current, pH 6, NaCl concentration of 0.1 kg/m³, an inter-electrode distance (IED) of 0.5 cm, and a rotation speed of 500 rpm over a 90-min treatment period. Bener et al. (2019) observed a lower maximum TSS removal efficiency of 64.7% using aluminum and iron electrodes operated at 25 mA/cm², pH 5, and a retention time of 120 min. Mahmoud et al. (2021) evaluated a complex pilot-scale treatment train combining coagulation-flocculation, filtration, and Fe/Cu-based nanobimetallic adsorption, achieving up to 97% TSS removal from real textile effluent under optimized adsorption conditions (pH 6.0, 0.5 g/L ferric chloride, 1.4 g/L nanomaterial dosage, 80 min contact time, and 250 rpm stirring rate). In another study, Paramita et al. (2023) achieved 71.9% TSS removal using Al6061-T6 aluminum electrodes under optimum conditions of 5.5 mA/cm² current density, 15 min treatment time, and 2 cm electrode spacing. Similarly, Zafar et al. (2024) reported a 75% TSS removal efficiency under conditions of pH 7-8, 15 V applied voltage, 60 min electrolysis, 2 cm electrode gap, and 20 min ST. In more recent advancements, Ahmed et al. (2024a) reported achieving 99.52% TSS removal efficiency by integrating seawater into the EC process, while Ahmed et al. (2024b) demonstrated that an Al–Zn electrode pairing with a 60 min retention period yielded 99.32% TSS removal. Additionally, Yáñez-Ángeles et al. (2025) achieved 96.83% TSS removal using a laboratory-scale system combining ozonolysis, EC, and electro-oxidation.

In comparison, the integrated system presented in this study demonstrates consistently high TSS removal across all treatment stages, particularly under extended retention times, underscoring the effectiveness of a multi-barrier approach for textile wastewater treatment. The radar chart highlights the synergistic roles of the EC, ST, AT, MM, and AC stages, offering a scalable framework for industrial applications. IS process 27, with its full-length retention strategy, not only exceeds the performance of standalone EC setups but also matches or surpasses several advanced hybrid systems reported in the literature. Its 99.69% TSS removal efficiency serves as a benchmark for optimized high-performance integrated treatment solutions.

4.4.2.2 Removal of turbidity (%)

Figure 4.18 presents a radar chart comparing the RE (%) of turbidity at different treatment stages across 27 IS processes developed for textile wastewater treatment. Each IS process included varying retention times for EC, ST, and AT, followed by sequential treatments using MM and AC filters. The radar plot visualizes the stage-wise removal efficiencies: post-EC RE (%), post-ST RE

(%), post-AT RE (%), post-MM Filter RE (%), post-AC Filter RE (%), and cumulative turbidity removal (overall IS process RE %), providing an integrated view of treatment performance. The EC retention times were set at 20, 40, and 60 min; ST retention times at 60, 120, and 180 min; and AT retention times at 20, 40, and 60 min, resulting in 27 unique configurations. The overall cumulative turbidity removal efficiency (overall IS process RE %) ranged from 76.41% (IS Process 1) to 99.57% (IS Process 27), confirming the high effectiveness of the integrated system in treating textile wastewater.

The post-EC RE (%) values ranged from 38.17% (IS Process 1) to 94.88% (IS Process 27), underscoring the critical role of EC in the initial destabilization and aggregation of colloidal particles. Similarly, Post-ST RE (%) increased from 21.23% to 48.43% as ST duration extended, improving the settling of flocs formed during EC. The AT stage exhibited varied performance, with Post-AT RE (%) ranging from 4.73% (IS Process 4) to 28.91% (IS Process 21), attributed to oxidation and microfloc formation during AT.

The filtration stages provided essential polishing effects on the effluent. MM filtration achieved removal efficiencies between 31.84% (IS Process 5) and 62.46% (IS Process 27), while AC filtration contributed between 18.43% (IS Process 1) and 55.91% (IS Process 13), demonstrating effectiveness in removing residual fine turbidity-causing particles. These polishing units complemented upstream processes by enhancing clarity and meeting stringent effluent standards.

IS Process 27 emerged as the best-performing configuration, delivering a turbidity removal efficiency of 99.57%. This can be attributed to its maximum retention times across all primary treatment stages (60 min EC, 180 min ST, and 60 min AT), along with high-performance MM and AC filtration. Other high-performing processes included IS Process 24 (98.62%), IS Process 20 (98.06%), IS Process 25 (98.05%), and IS Process 26 (98.31%), all demonstrating that balanced stage durations yield superior outcomes. In contrast, the least efficient process (IS Process 1) achieved only 76.41% overall turbidity removal, limited by short retention times and underutilization of post-treatment stages.

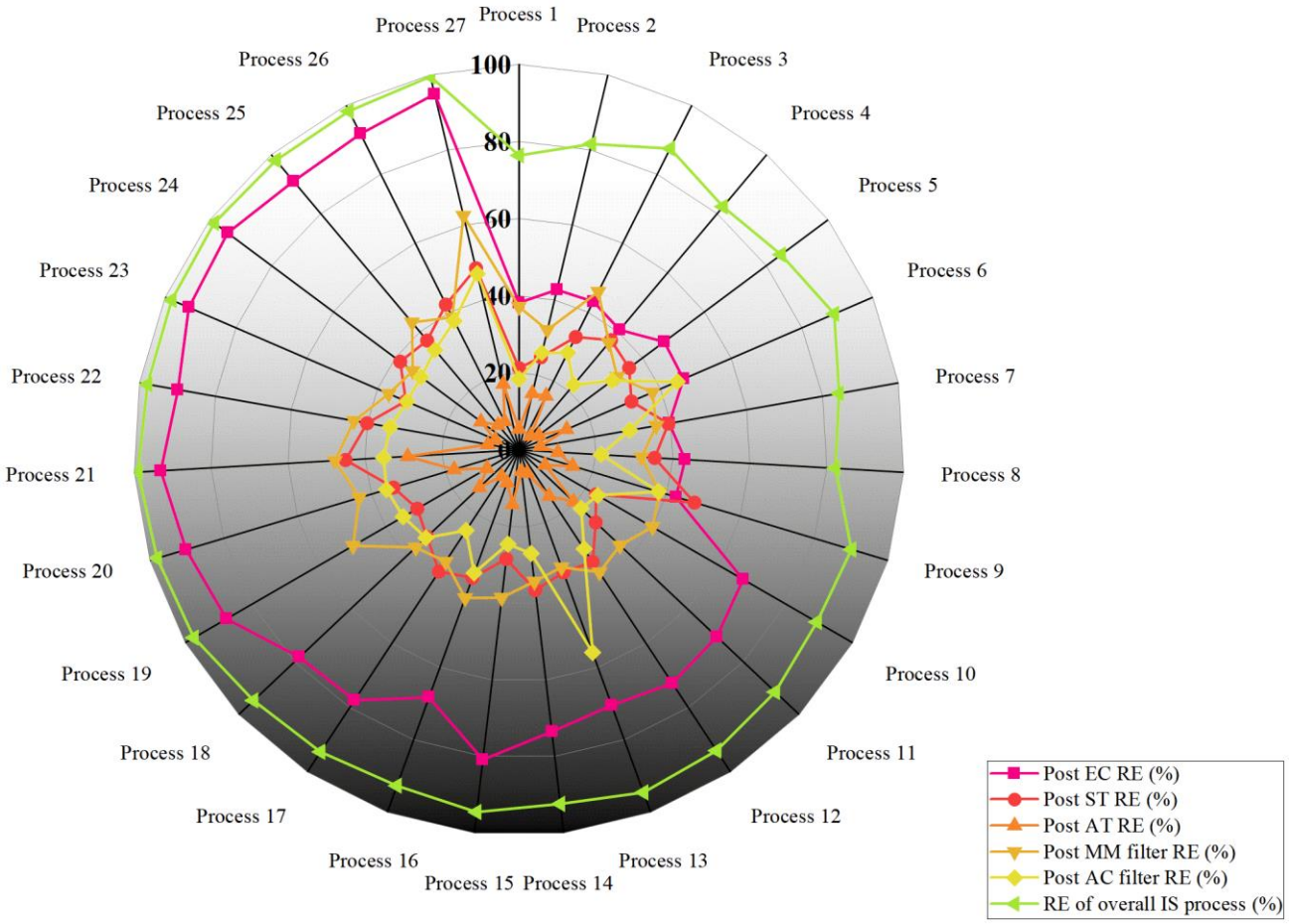

Figure 4.18: Comparative assessment of turbidity removal efficiency (%) across 27 different IS processes for textile wastewater treatment.

Previous investigations into turbidity removal via EC and its hybrid integration have shown a wide range of efficiencies under various operational configurations. Naje et al. (2015) reported a high-performance EC setup employing alternating monopolar and bipolar aluminum plates, which, under optimal conditions (current of 0.6 A, pH 6, NaCl concentration of 0.1 kg/m³, inter-electrode distance of 0.5 cm, and mechanical agitation at 500 rpm for 90 min), achieved a turbidity removal efficiency of 96%. In comparison, Bener et al. (2019) observed a peak turbidity reduction of 83.5% using aluminum and iron electrodes operated at a current density of 25 mA/cm², with an optimal pH of 5 and a retention time of 120 min. Núñez et al. (2019) documented 82% turbidity removal efficiency with a significantly shorter treatment duration of 10 min, maintaining a current density of 8 mA/cm² and a pH of 7.1. De Maman et al. (2022) demonstrated a 91% reduction in turbidity

within 60 min of electrolysis using standard EC protocols. Similarly, Gasmi et al. (2022) achieved 96.31% turbidity removal solely through EC. Martins et al. (2023) utilized 304-grade stainless steel electrodes in batch mode, reporting turbidity removal efficiencies ranging from 74% to 85%. Recently, Sqalli Houssini et al. (2024) demonstrated an enhanced turbidity removal efficiency of 98.5% by applying bipolar Fe-Al electrode configurations. Notably, Ahmed et al. (2024a) achieved up to 99.30% efficiency by incorporating seawater into the EC process, while Ahmed et al. (2024b) achieved a removal rate of 98.88% using the aluminum-zinc electrode pairing with a 60-min treatment time.

In conclusion, the integrated system presented in this study consistently demonstrated high turbidity removal across all treatment stages, particularly with extended retention times. The radar plot effectively reveals the synergistic interactions among EC, ST, AT, MM, and AC, providing a robust framework for industrial scaling. With its 99.57% turbidity removal efficiency, IS Process 27 not only surpasses traditional and standalone EC configurations but also outperforms many advanced and hybrid systems reported in recent literature, setting a new benchmark for comprehensive turbidity control of textile wastewater.

4.4.2.3 Removal of COD (%)

Figure 4.19 presents a radar chart comparing the RE (%) of COD at different treatment stages across the 27 IS processes developed for textile wastewater treatment. Each IS process incorporated varying retention times for EC, ST, and AT, followed by sequential treatments with MM and AC filters. The radar plot visualizes the removal efficiencies at each stage, including post-EC RE (%), post-ST RE (%), post-AT RE (%), post-MM Filter RE (%), post-AC Filter RE (%), and cumulative COD removal (overall IS process RE %), providing an integrated view of treatment performance. The EC retention times were set at 20, 40, and 60 min; ST retention times at 60, 120, and 180 min; and AT retention times at 20, 40, and 60 min, resulting in 27 unique configurations. The overall cumulative COD removal efficiencies ranged from 62.95% (IS process 1) to 95.24% (IS process 27), indicating the system's robust performance in reducing COD levels in textile wastewater.

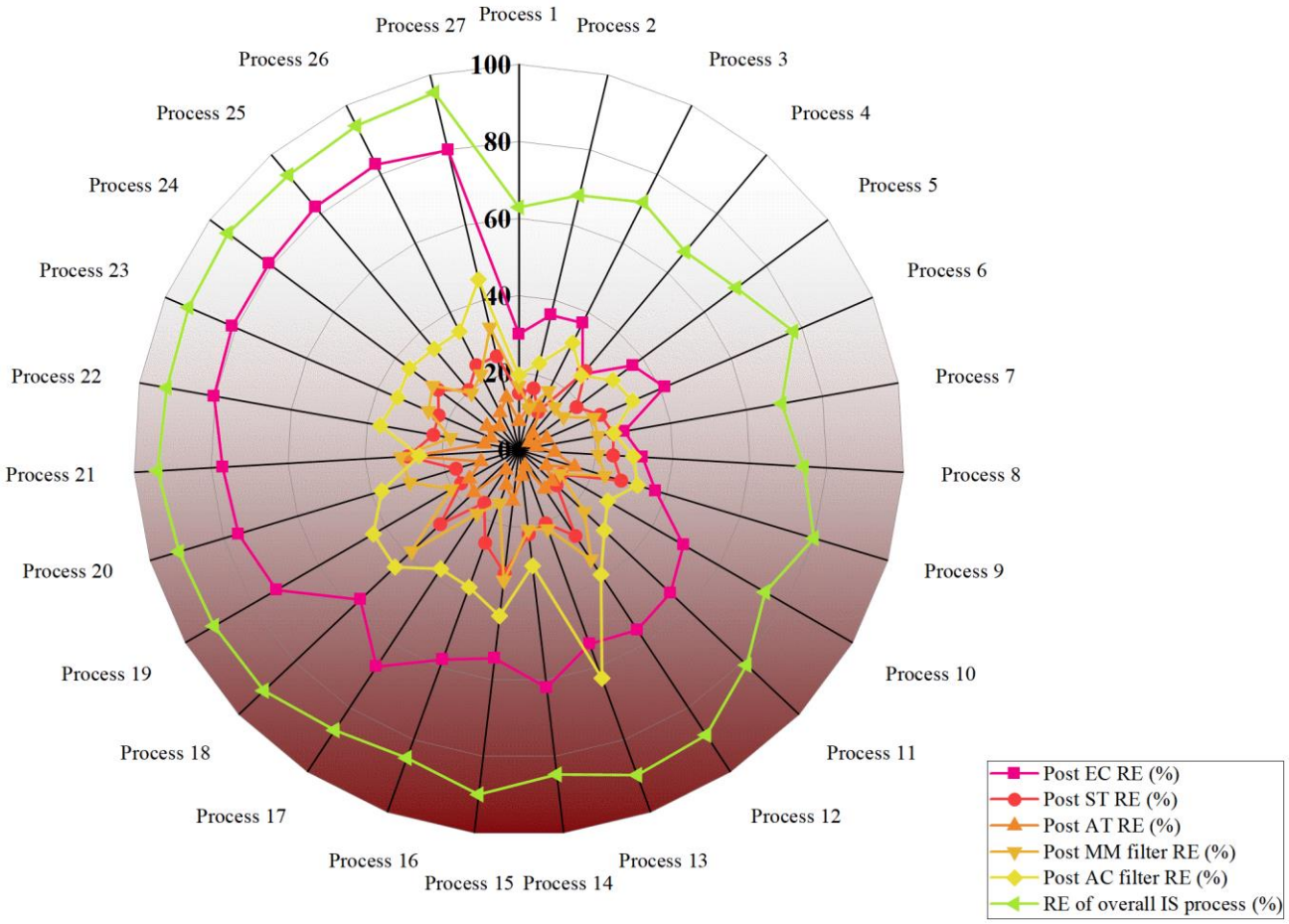

Figure 4.19: Comparative assessment of COD removal efficiency (%) across 27 different IS processes for textile wastewater treatment.

The post-EC RE (%) ranged from 25.69% (IS process 4) to 82.81% (IS process 26), confirming EC's central role in breaking down and aggregating organic contaminants. Longer EC durations (60 min) enhanced destabilization and coagulation mechanisms, contributing significantly to initial COD reduction. The post-ST RE (%) varied between 11.00% (IS process 3) and 32.26% (IS process 15), where prolonged ST periods (180 min) significantly facilitated the settling of coagulated organic matter. AT further supported oxidative degradation, with post-AT RE (%) ranging from 3.35% (IS process 5) to 27.78% (IS process 21), emphasizing its synergistic role when implemented with sufficient retention.

The filtration stages significantly contributed to post-treatment COD polishing. The MM filter RE (%) ranged from 11.18% (IS process 2) to 38.38% (IS process 18), while the AC filter RE (%) varied between 19.39% (IS process 1) and 63.00% (IS process 13). These polishing units effectively removed residual dissolved organic content and fine colloids, especially when preceded by efficient upstream treatments.

The overall COD removal efficiency (overall IS process RE %) ranged from 62.95% (IS process 1) to 95.23% (IS process 27), showing a notable spectrum of performance outcomes. IS process 27, configured with maximum EC (60 min), ST (180 min), and AT (60 min) durations, emerged as the most efficient treatment process. Other top-performing systems included IS processes 24 (94.12%), 26 (94.08%), 23 (93.39%), and 21 (93.96%), indicating that balanced retention schedules combined with effective polishing can yield excellent outcomes. Moderately performing systems such as IS processes 12 (88.52%) and 14 (84.77%) affirmed the viability of the optimized mid-range configurations. In contrast, IS process 1 (62.95%) demonstrated limited performance due to shorter contact times and suboptimal stage integration.

Extensive research has highlighted the diverse performances of EC and integrated treatment systems in removing COD from textile wastewater. For instance, Naje et al. (2015) reported a COD removal efficiency of 92.6% using an alternating monopolar and bipolar aluminum plate configuration under optimal parameters, including a 90-min retention time, pH 6, and NaCl concentration of 0.1 kg/m^3. Similarly, Bazrafshan et al. (2016) demonstrated 93.1% COD removal using EC alone, with an applied voltage of 60 V. Furthermore, when chemical coagulation, EC, and adsorption processes were combined, the overall removal efficiency significantly increased to 98%. Expanding on integrated approaches, Aouni et al. (2017) employed a two-stage treatment involving EC followed by GAC adsorption for dye-rich textile effluent. Their findings revealed that EC alone, optimized at a current density of 28.57 mA/cm^2 and 120 min electrolysis time, led to a 62.33% COD reduction, which was further enhanced to 98.33% upon the addition of GAC 0.75 g/L with a 120-min contact time. In another study, Khorram and Fallah (2018) used five parallel unalloyed aluminum plates and achieved 40% COD removal under optimized conditions of 60-min retention time and current density range of 15–35 mA/cm^2. In contrast, Bener et al. (2019) observed a comparatively lower COD removal of 18.6% using aluminum and iron electrodes at 25 mA/cm^2, pH 5, and 120 min of treatment time. Meanwhile, GilPavas et al. (2019)

explored sequential hybrid systems involving EC, followed by Fenton (F), photo-Fenton (PF), and AC adsorption. Their results showed that EC alone removed 56% of the COD, which increased to 72% and 76% with Fenton and photo-Fenton integration, respectively. Likewise, Núñez et al. (2019) documented a 59% COD reduction after a 10-min EC treatment at 8 mA/cm² and pH 7.1. A more advanced setup was implemented by Mahmoud et al. (2021), who utilized a pilot-scale system incorporating coagulation/flocculation, filtration, and nanobimetallic Fe/Cu adsorption. This configuration achieved up to 96% COD removal under optimal conditions involving 0.5 g/L ferric chloride, 1.4 g/L nanomaterial, pH 6.0, 80-min contact time, and a stirring rate of 250 rpm. Supporting these findings, De Maman et al. (2022) reported a COD removal efficiency of 55% within 60 min of EC, whereas Gasmi et al. (2022) recorded a slightly higher value of 63.05% under comparable treatment durations. More recently, Zafar et al. (2024) recorded a COD removal efficiency of 79% under optimized EC conditions, including pH 7-8, 15 V applied voltage, a 60-min electrolysis duration, 2 cm electrode gap, and a 20-min ST period. Additionally, Isawi et al. (2024) implemented a combined EC-flotation (ECF) approach, followed by SiO_2/PA(TFC) membrane filtration. Their study revealed that increasing the current from 50 mA to 600 mA improved COD removal from 59.1% to 81.5%. In similar research, Ahmed et al. (2024a) investigated the effect of seawater integration into the EC process, achieving a maximum COD removal efficiency of 47.26%. Complementarily, Ahmed et al. (2024b) reported improved performance using an aluminum-zinc electrode pairing over a 60-min retention period, resulting in 68.62% COD removal. Finally, Yáñez-Ángeles et al. (2025) demonstrated a 54.74% COD reduction using a combined lab-scale system of ozonolysis, EC, and electro-oxidation, operating at a near-neutral pH of 7.71.

In summary, this study's IS configurations, particularly IS process 27, not only outperformed standalone EC systems but also matched or exceeded many advanced hybrid treatments reported in the literature. The comprehensive integration of EC, ST, AT, MM, and AC stages under optimized retention conditions reinforces the significance of sequential, multi-barrier designs for COD removal, establishing IS process 27 with a COD removal rate of 95.23% as a high-efficiency benchmark for textile wastewater remediation.

4.4.2.4 Removal of Color (%)

Figure 4.20 presents a radar chart comparing the RE (%) of color at different treatment stages across the 27 IS processes developed for textile wastewater treatment. Each IS process incorporated varying retention times for EC, ST, and AT, followed by sequential treatments using MM and AC filters. The radar plot visualizes the stage-wise removal efficiencies, including post-EC RE (%), post-ST RE (%), post-AT RE (%), post-MM Filter RE (%), post-AC Filter RE (%), and cumulative color removal (RE of the overall IS process %), providing an integrated view of treatment performance. The EC retention times were set at 20, 40, and 60 min; ST retention times at 60, 120, and 180 min; and AT retention times at 20, 40, and 60 min, resulting in 27 unique configurations. The overall cumulative color removal efficiencies ranged from 71.7% (IS process 1) to 99.1% (IS process 27), indicating the system's robust performance in reducing color levels in textile wastewater.

The post-EC RE (%) varied from 33.33% (IS process 7) to 93.04% (IS process 27), highlighting the foundational impact of EC retention time on dye molecule breakdown. Longer EC durations enhanced the destabilization and aggregation of chromophoric compounds, setting the stage for efficient downstream treatment. The post-ST RE (%) ranged from 15.38% to 43.94%, with extended ST times promoting the settling of coagulated color bodies. The contribution from AT was more modest, with post-AT RE (%) ranging from 4.31% (IS process 5) to 29.9% (IS process 21), where increased retention enabled oxidation and partial decolorization of residual organics.

The filtration stages provided critical polishing effects. MM filtration yielded RE values from 7.76% to 46.77%, the latter achieved in IS process 27, which also had the highest overall efficiency. Meanwhile, AC filtration showed performance ranging from 28.97% to 61.13%, with the most effective results in IS process 13, affirming its capacity to adsorb fine, dissolved color compounds not removed earlier. The integration of all stages resulted in synergistic effects, delivering enhanced total RE across most configurations.

IS process 27 achieved the highest total color removal efficiency of 99.10%, attributed to the combined effect of maximum EC, ST, and AT retention times, along with highly efficient MM and AC filtration stages. Other high-performing configurations included IS process 24 (98.66%), IS process 21 (98.57%), IS process 26 (98.20%), and IS process 23 (97.06%), demonstrating that

both retention time optimization and filtration robustness are critical for achieving near-complete color elimination. Moderate performers such as IS process 15 (93.89%) and IS process 13 (93.05%) confirmed that even with mid-range settings, reliable results are possible. In contrast, IS process 1 (71.72%) and IS process 2 (75.42%) reflected the least effectiveness, attributed to lower residence times and suboptimal filtration outcomes.

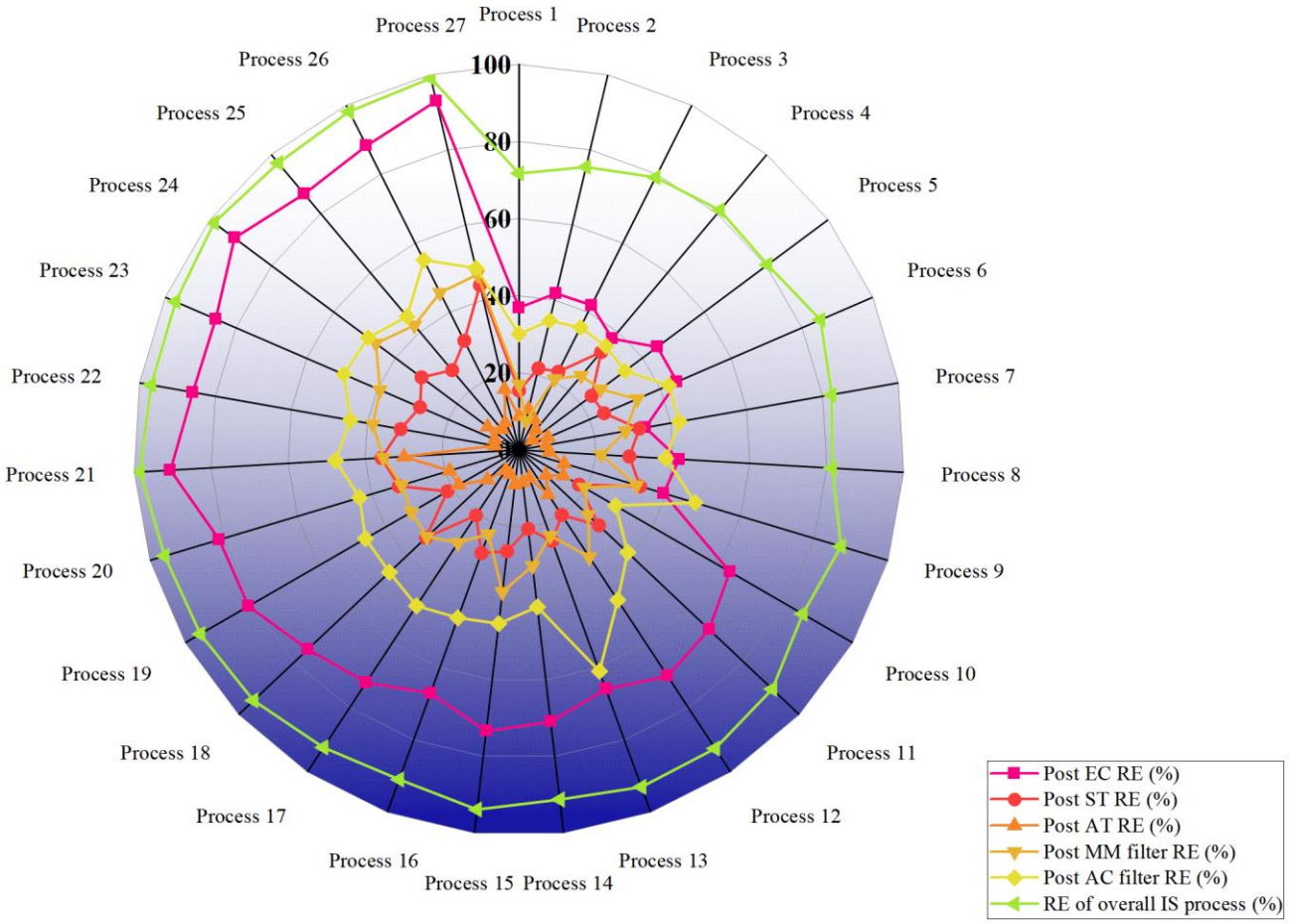

Figure 4.20: Comparative assessment of color removal efficiency (%) across 27 different IS processes for textile wastewater treatment.

Numerous studies have demonstrated the efficacy of EC and its hybrid configurations in removing color from textile wastewater under varied operational conditions. Naje et al. (2015) achieved a color removal efficiency of 92.6% using alternating monopolar and bipolar aluminum electrodes, optimized at a retention time of 90 min, pH 6, and a NaCl concentration of 0.1 kg/m^3. In a similar

timeframe, Chackrabartty et al. (2015) reported a 93.4% color removal efficiency from textile wastewater at an initial pH of 5. Further advancing the treatment framework, Aouni et al. (2017) implemented a two-stage EC–adsorption process targeting highly concentrated dye-laden effluents. The EC component alone, operated at a current density of 28.57 mA/cm² and 120-min electrolysis, yielded 72.79% color reduction, significantly enhanced to 98.37% upon applying GAC at a 0.75 g/L dosage and 120-min contact duration. Likewise, Khorram and Fallah (2018) achieved 97% color removal at an initial pH of 5.5 using a 15 mA/cm² current density over a 23-min treatment period. Supporting these outcomes, Bener et al. (2019) observed color removal efficiencies ranging between 90.3% and 94.9% with aluminum electrodes operated at 25 mA/cm², pH 5, and a 120-min retention time. In another study, Núñez et al. (2019) recorded an 86% color removal rate within a brief 10-min EC treatment at 8 mA/cm² and pH 7.1, emphasizing the potential for rapid treatment cycles under mild conditions. A pilot-scale system developed by Mahmoud et al. (2021), integrating coagulation/flocculation, filtration, and nanobimetallic iron/copper (Fe/Cu) adsorption, achieved an overall color removal efficiency of 82%. The system operated optimally with 0.5 g/L ferric chloride, 1.4 g/L nanomaterial dosage, pH 6.0, 80-min contact time, and a stirring rate of 250 rpm. In parallel, De Maman et al. (2022) reported 80% color removal within 60 min of EC treatment. Gasmi et al. (2022), however, achieved significantly higher efficiency of 99.07% using EC alone, indicating the potential for near-complete color elimination under ideal conditions. In an advanced treatment sequence, Kalia et al. (2023) achieved 90% color removal from raw textile wastewater using a zinc-coated iron electrode at 25 mA/cm², followed by laccase treatment and AC polishing under ambient conditions. Zafar et al. (2024) also reported a high discoloration removal efficiency of 86%, achieved with optimized parameters including pH 7–8, 15 V applied voltage, a 60-min electrolysis duration, 2 cm electrode spacing, and 20 min of settling. Furthermore, Isawi et al. (2024) explored a combined ECF process paired with a SiO_2/PA(TFC) membrane, where increasing the current intensity from 50 to 600 mA improved color removal from 94% to an impressive 99%. Finally, Ahmed et al. (2024a) demonstrated one of the highest color removal efficiencies to date—98.19%—by integrating seawater into the EC process, highlighting the emerging role of saline-assisted electrochemical treatment in advanced wastewater remediation strategies.

In summary, the integrated system processes in this study, particularly IS process 27, exhibited consistently high color removal performance across all stages, reinforcing the importance of a well-structured multistage approach. The radar plot effectively highlights the complementary roles of EC, ST, AT, MM, and AC units in driving performance. The 99.1% removal efficiency of IS process 27 not only validates the design of the integrated treatment chain but also sets a new benchmark for future industrial-scale color remediation strategies.

4.4.3 Statistical analysis using different MCDM methods

4.4.3.1 TOPSIS method

Figure 4.21 illustrates the ranking of IS processes using the TOPSIS method. The Technique for TOPSIS was applied to evaluate and rank the performance of the 27 IS processes based on multiple criteria, including removal efficiencies for TSS, turbidity, COD, and color, to evaluate the optimal IS process for removing pollutants from textile wastewater. The dataset included key metrics such as the positive ideal solution distance (S_i^+), negative ideal solution distance (S_i^-), and the relative closeness coefficient (C_j^*). Higher C_j^* values indicate processes that are closer to the ideal solution and thus more effective. The ranking provided insights into the overall performance of each process, considering all removal efficiency indicators.

The results, depicted in the bar chart, reveal that IS process 27 achieved the highest C_j^* value of 1.0, making it the most effective configuration. This process, with retention times of 60 min for EC, 180 min for ST, and 60 min for AT, achieved outstanding removal efficiencies of 99.69% (TSS), 99.57% (turbidity), 95.23% (COD), and 99.1% (color). Other top-performing processes, such as IS process 24 (C_j^*=0.9689), IS process 21 (C_j^*=0.9684), IS process 26 (C_j^*=0.9608), and IS process 23 (C_j^*=0.9389), also demonstrated high efficiencies, attributed to their optimal retention times. Moderate-performing processes, ranked between 13 and 20, exhibited C_j^* values between 0.5525 and 0.8149, reflecting balanced removal efficiencies with medium retention times. Lower-ranked processes, such as IS process 1 (C_j^*=0), IS process 2 (C_j^*=0.1687), and IS process 3 (C_j^*=0.3423), were characterized by shorter retention times, leading to relatively lower removal efficiencies across all parameters.

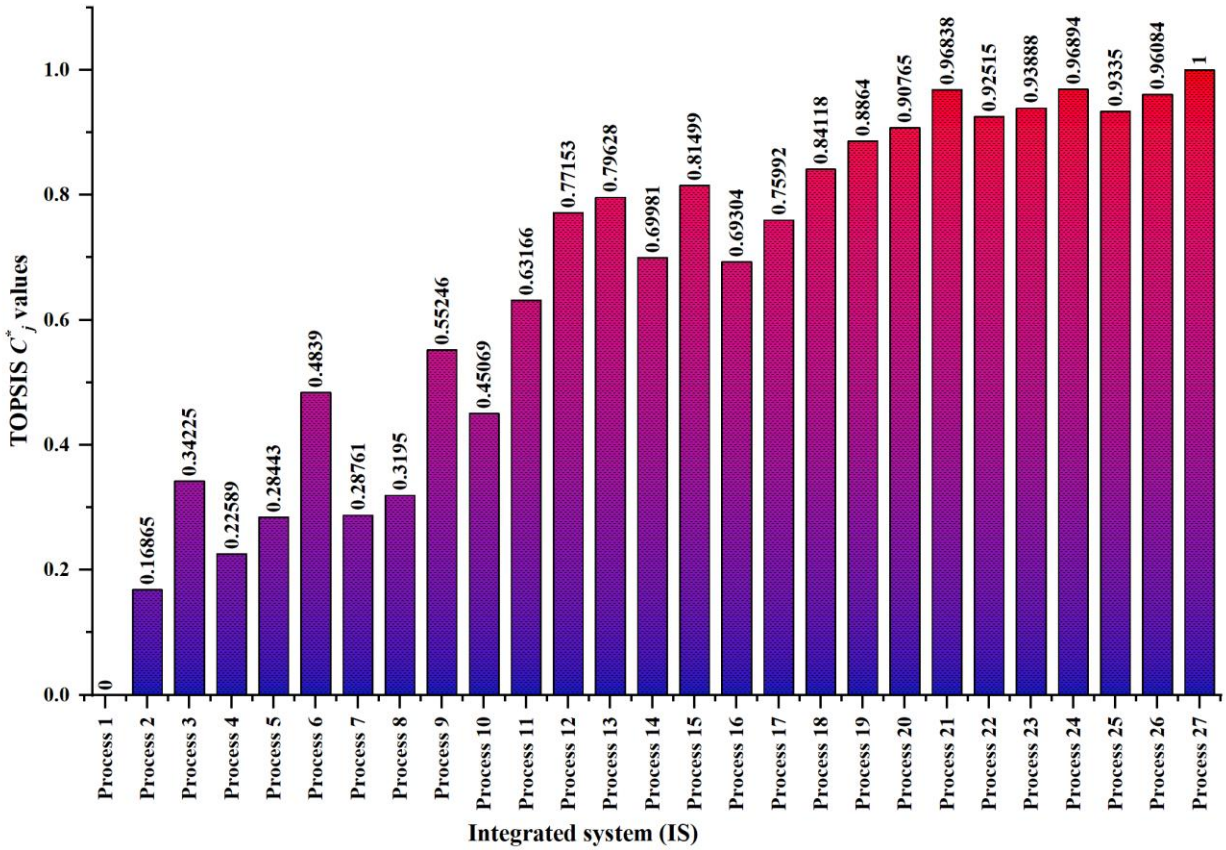

Figure 4.21: Ranking and optimal selection of IS processes based on TOPSIS analysis using $\boldsymbol{C_j^*}$ values.

The TOPSIS results highlight the effectiveness of the method in evaluating multi-criteria environmental systems, providing a clear ranking of the processes based on their overall performance. The analysis emphasizes the importance of longer retention times in achieving superior pollutant removal while demonstrating the trade-offs between different removal efficiency metrics. This approach offers a robust framework for selecting optimal configurations and balancing efficiency and operational feasibility in industrial-scale wastewater treatment applications.

4.4.3.2 VIKOR method

Figure 4.22 presents the ranking of the 27 IS processes using the VIKOR method based on multiple criteria, including removal efficiencies for TSS, turbidity, COD, and color, to evaluate the optimal IS process for removing pollutants from textile wastewater. The dataset included three key

parameters: the utility measure (S_J), representing the total deviation from the ideal solution; the regret measure (R_J), indicating the maximum deviation from the ideal solution across criteria; and the compromise ranking index (Q_J), which balances utility and regret to identify the best compromise solution. Processes were ranked according to their Q_J values, with lower values reflecting better overall performance.

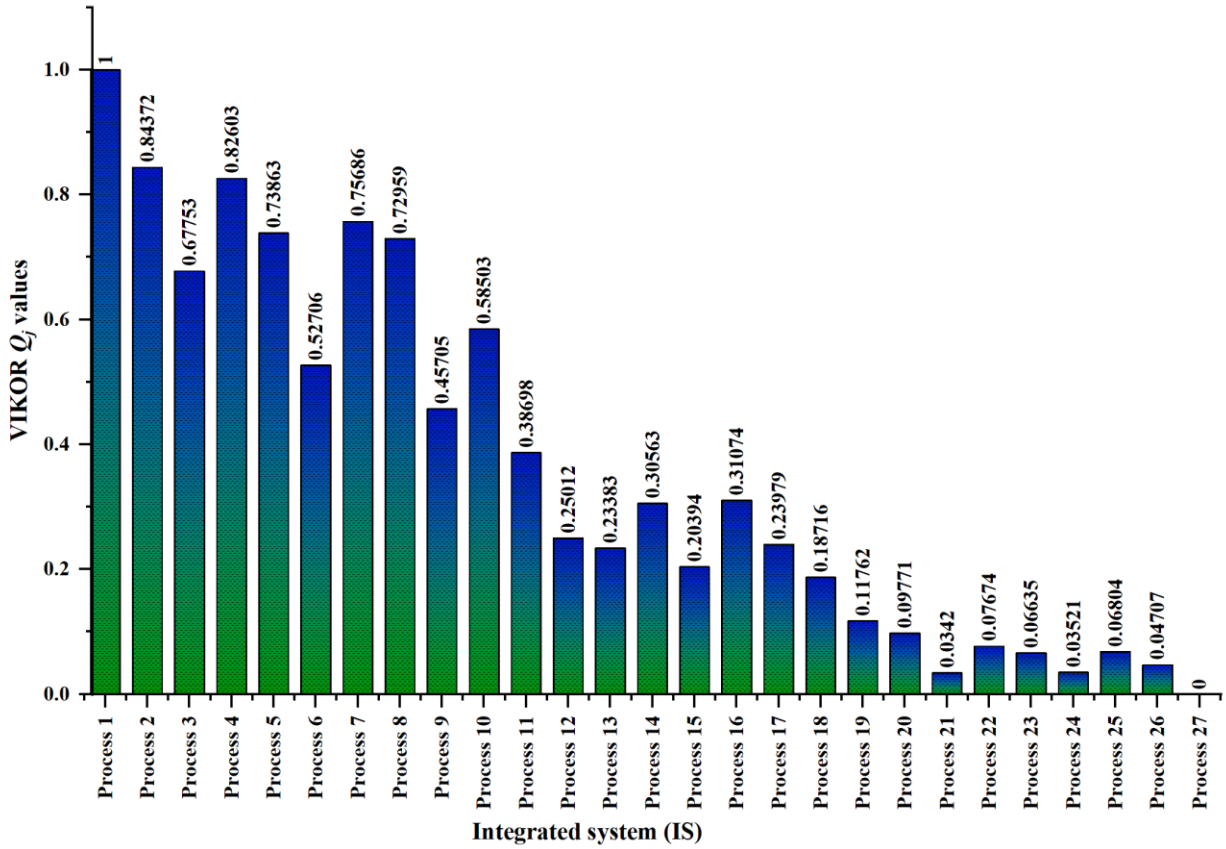

Figure 4.22: Ranking and optimal selection of IS processes based on VIKOR analysis using $\boldsymbol{Q_J}$ values.

The results revealed that IS process 27 achieved the lowest Q_J value of 0.0, making it the most effective configuration with removal efficiencies of 99.69% (TSS), 99.57% (turbidity), 95.23% (COD), and 99.1% (color). This process, employing retention times of 60 min for EC, 180 min for ST, and 60 min for AT, demonstrated superior overall performance. Other top-performing processes included IS process 24 (Q_J=0.0352), IS process 21 (Q_J=0.0342), IS process 26

(Q_J=0.0471), and IS process 23 (Q_J=0.0664), which also showcased high removal efficiencies and balanced performance across all criteria. Moderate-performing processes, such as those ranked between 12 and 18, exhibited Q_J values between 0.1871 and 0.4570, reflecting adequate efficiencies with moderate retention times. Low-performing processes, including IS process 1 (Q_J=1.0), IS process 2 (Q_J=0.8437), and IS process 3 (Q_J=0.6775), were characterized by shorter retention times, resulting in lower removal efficiencies and higher deviations from the ideal solution.

The VIKOR method effectively evaluated the performance of the integrated system by balancing utility and regret measures to identify optimal solutions. Longer retention times were shown to significantly improve removal efficiency, as evidenced by the top-ranking processes. The visualization of Q_J values highlight a clear distinction between low-, moderate-, and high-performing processes, providing insights into the trade-offs between efficiency and deviation from the ideal solution. This comprehensive evaluation demonstrates the value of the VIKOR method in guiding the selection of efficient and practical configurations for industrial-scale wastewater treatment systems.

4.4.3.3 PROMETHEE II method

Figure 4.23 presents the ranking of the 27 IS processes using the PROMETHEE II method based on their net preference index ($\varphi(i)$). This net flow, calculated as the difference between the positive preference flow ($\varphi^{+}_{(i)}$) and the negative preference flow ($\varphi^{-}_{(i)}$), offers a comprehensive measure of a process's overall dominance or inferiority compared to others across multiple criteria. The ranking is grounded in the removal efficiencies of TSS, turbidity, COD, and color, to evaluate the optimal IS process for removing pollutants from textile wastewater. Higher net $\varphi(i)$ values indicate better performance and stronger dominance in the decision matrix.

The results demonstrate that IS process 27 achieved the highest net $\varphi(i)$ value of 5.37, indicating superior performance across all criteria. This process, which utilized 60 min of EC, 180 min of ST, and 60 min of AT, achieved exceptional removal efficiencies of 99.69% (TSS), 99.57% (turbidity), 95.23% (COD), and 99.1% (color). Other top-performing processes, including IS process 21 ($\varphi(i)$ =5.14), IS process 24 ($\varphi(i)$ =5.13), IS process 26 ($\varphi(i)$ =5.05), and IS process

23 ($\varphi(i)$ =4.90), demonstrated similarly high levels of performance due to their optimized retention times and balanced configurations. Moderate performing processes, ranked between 10 and 16, exhibited net ∅ values ranging from 2.92 to 4.04, offering sufficient removal efficiencies but lacking the dominance of the top-ranked configurations. In contrast, low-performing processes, such as IS process 1 ($\varphi(i)$ =−2.63), IS process 2 ($\varphi(i)$ =−1.21), and IS process 3 ($\varphi(i)$ =0.36), were limited by shorter retention times and reduced removal efficiencies, resulting in weaker preference flows.

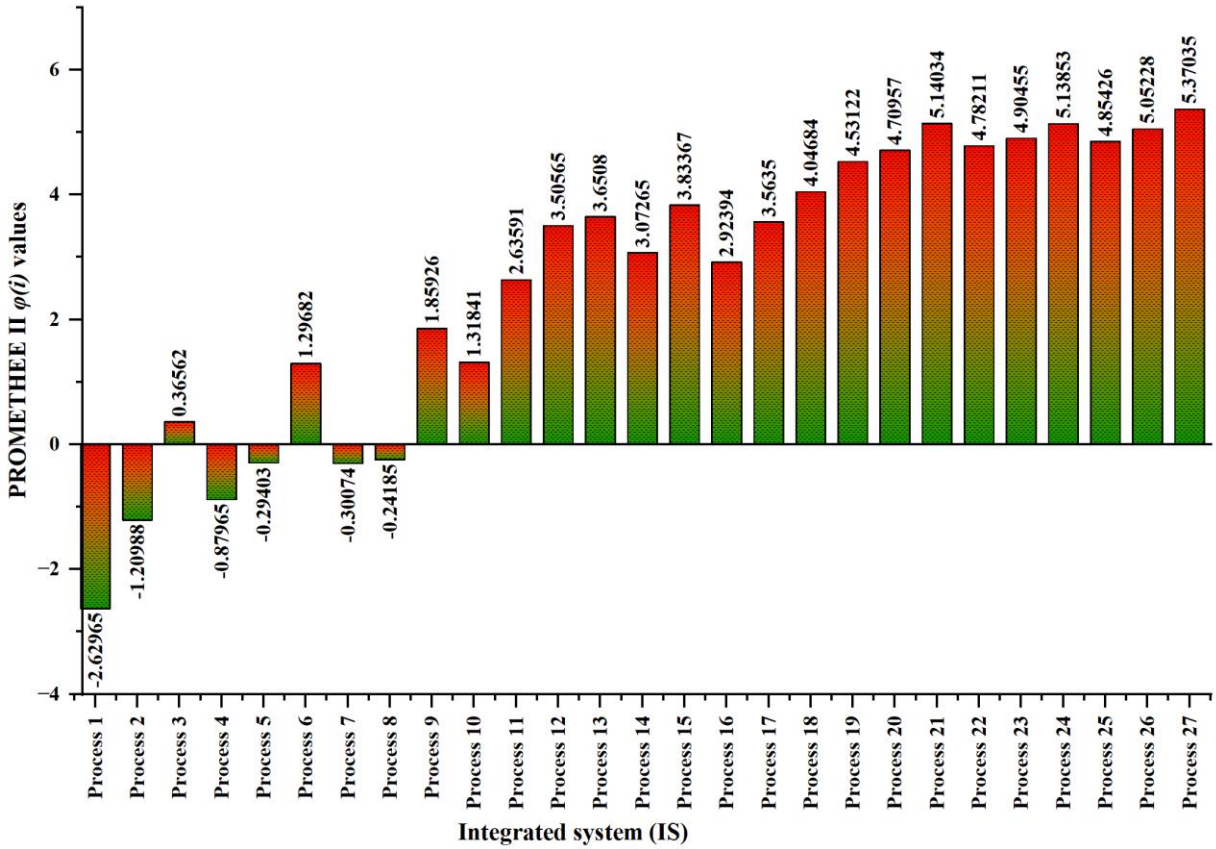

Figure 4.23: Ranking and optimal selection of IS processes based on PROMETHEE II analysis using $\boldsymbol{\varphi(i)}$ values.

The PROMETHEE II method provides a clear and robust ranking of the integrated systems by quantifying the dominance of each process while balancing multiple criteria. The results highlight the critical role of longer retention times in enhancing removal efficiencies and achieving superior performance. The visualization of net $\varphi(i)$ values effectively distinguish between low, moderate,

and high-performing processes, offering valuable insights into the optimization and selection of wastewater treatment configurations. This approach showcases the utility of PROMETHEE II in decision-making for multi-criteria environmental systems, supporting the development of scalable and efficient solutions for wastewater treatment.

4.4.3.4 AHP method

Figure 4.24 illustrates the AHP scoring results for all 27 IS processes, based on a multi-criteria evaluation of pollutant removal performances including TSS, turbidity, COD, and color, to evaluate the optimal IS process for removing pollutants from textile wastewater. Each bar in the graph represents the normalized AHP score of a given process, with higher scores indicating superior overall performance considering all criteria and their relative weights. Each process is assigned an AHP score, reflecting its overall performance across these parameters, with the scores ranked to determine the most effective treatment configurations. The AHP methodology incorporates expert judgment and pairwise comparisons to assign weightages, ensuring that each parameter contributes proportionally to the decision matrix.

The dataset reveals that IS process 27, characterized by an EC time of 60 min, ST time of 180 min, and AT time of 60 min, achieves the highest AHP score of 1, making it the top-performing system. This process's exceptional removal efficiencies for TSS (99.69%), turbidity (99.57%), COD (95.23%), and color (99.1%) position it as the most optimal configuration for wastewater treatment. Similarly, IS processes 24, 21, 26, and 23 rank among the highest, with AHP scores exceeding 0.98, demonstrating their consistent effectiveness across all criteria. These high-ranking systems incorporate extended retention times for EC, ST, and AT, coupled with MM, and AC filtration, which collectively enhance pollutant removal. On the other end of the spectrum, IS process 1 records the lowest AHP score of 0.7396, placing it at the bottom of the ranking (27th). Its comparatively lower removal efficiencies for TSS (80.42%), turbidity (76.4%), COD (62.95%), and color (71.71%) highlight the limitations of shorter retention times and less effective integration of treatment steps. Other lower-ranked processes, such as IS processes 2, 4, and 7, exhibit intermediate AHP scores, emphasizing that shorter retention times and limited optimization in system configurations result in reduced treatment efficiency.

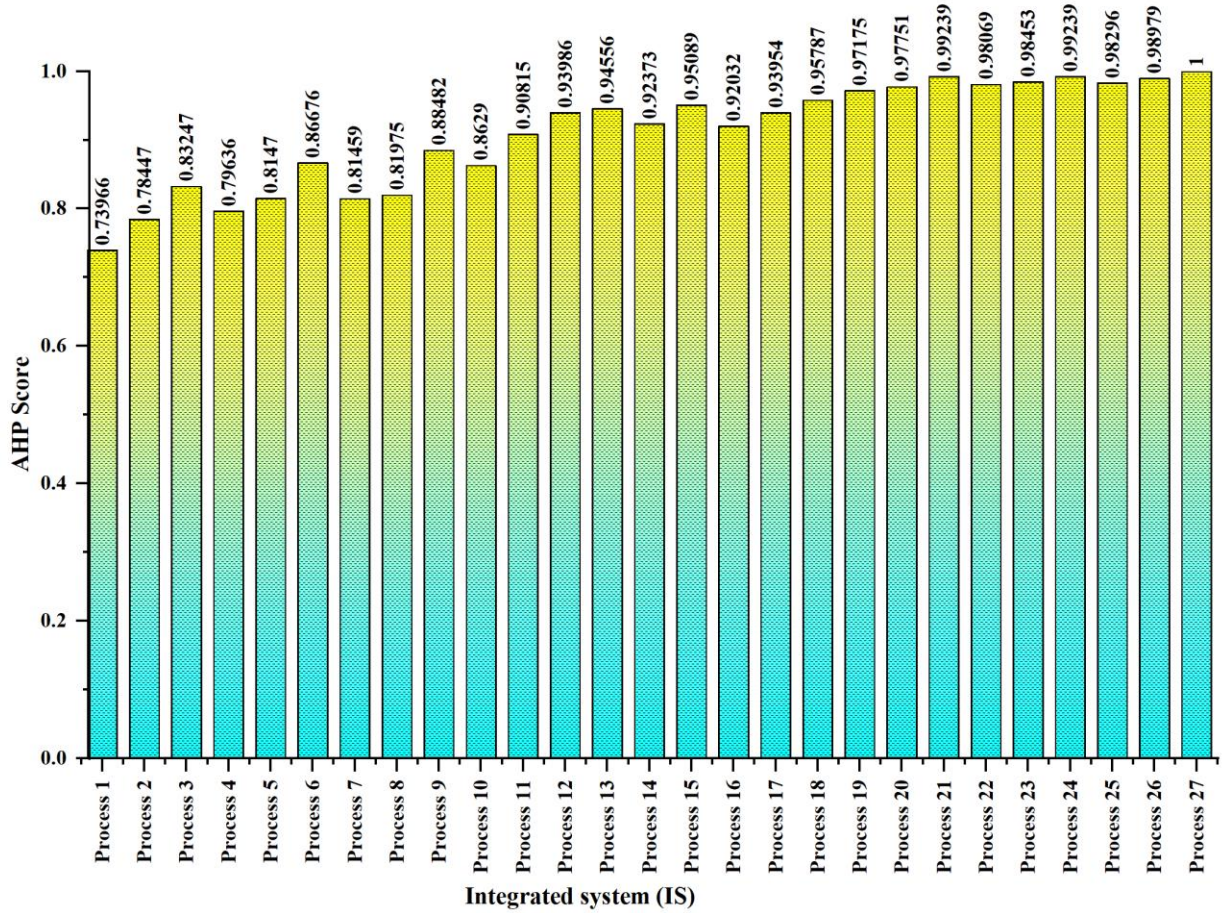

Figure 4.24: Ranking and optimal selection of IS processes based on AHP analysis using AHP Score.

The AHP results are visually represented in the accompanying bar chart, which provides a clear and progressive depiction of the scores across the 27 systems. The chart illustrates a distinct separation between the higher-performing systems, clustered at the top with scores near 1, and the lower-performing systems, forming a separate cluster with significantly lower scores. This visualization underscores the impact of extended retention times and comprehensive filtration on the systems' overall performance.

4.4.4 Results of the MCDM methods

Table 4.7 presents the rankings of the 27 IS processes for textile wastewater treatment, evaluated using four prominent MCDM methods: TOPSIS, VIKOR, PROMETHEE II, and AHP. The alternatives are ordered from most to least preferred, providing a comparative assessment of process performance based on selected criteria. These approaches offer a comprehensive

framework to rank the systems based on their effectiveness in removing TSS, turbidity, COD, and color. The consistency in rankings across all methods highlights the robustness of the results, facilitating a clear understanding of each system's relative performance.

All four MCDM methods consistently identify IS process 27 as the best-performing system, ranking it first. This system achieved exceptional removal efficiencies for TSS (99.69%), turbidity (99.57%), COD (95.23%), and color (99.1%), supported by extended retention times of 60 min for EC, 180 min for ST, and 60 min for AT, along with MM and AC filtration. The high rankings across TOPSIS, VIKOR, PROMETHEE II, and AHP confirm the superiority of this process, demonstrating its effectiveness in addressing multiple pollutant removal objectives. Similarly, IS processes 24, 21, 26, and 23 were consistently ranked among the top five by all methods, exhibiting high removal efficiencies for all parameters. These results underscore the importance of optimized retention times and advanced filtration steps (MM and AC filters) in achieving superior performance.

Mid-ranked systems, such as IS processes 12, 13, 15, and 18, displayed moderate performance across all MCDM methods, achieving removal efficiencies between 85% and 94% for TSS, turbidity, COD, and color. These systems incorporate shorter retention times compared to the top-ranked systems, resulting in slightly reduced performance. The rankings for these systems remained consistent across TOPSIS, VIKOR, PROMETHEE II, and AHP, underscoring the reliability of these methods in identifying systems with intermediate effectiveness.

Conversely, the lowest-performing systems, including IS processes 1, 2, 3, and 4, were consistently ranked in the bottom quartile by all MCDM methods. For instance, IS process 1, which involved the shortest retention times (20 min for EC, 60 min for ST, and 20 min for AT), ranked 27th in all methods due to significantly lower removal efficiencies for TSS (80.42%), turbidity (76.4%), COD (62.95%), and color (71.71%). These findings indicate that insufficient retention times and suboptimal integration of treatment processes lead to inadequate pollutant removal.

The comparative analysis of rankings from the four MCDM methods reveals strong consistency. For example, IS processes 9, 19, and 20 were ranked identically (18th, 9th, and 8th, respectively) across all methods, reflecting alignment in the assessment of their overall performance. Minor

variations were observed in a few cases, such as IS process 12, which ranked 13th in TOPSIS and AHP but 14th in VIKOR and PROMETHEE II. These discrepancies are attributed to differences in weighting and normalization approaches inherent to each method but do not significantly impact the overall conclusions.

The rankings from PROMETHEE II and AHP exhibit strong alignment, as both methods rely on detailed pairwise comparisons and weight distributions to evaluate performance. Similarly, the rankings from TOPSIS and VIKOR demonstrate close correspondence due to their focus on the proximity of alternatives to the ideal solution and compromise solutions, respectively. These consistencies enhance confidence in the results and validate the robustness of the analysis.

While the top-ranked (IS Process 27) and bottom-ranked alternatives (IS Process 1) remained consistent across all four MCDM methods, discrepancies were observed in several intermediate rankings. These variations stem from the intrinsic differences in the evaluative logic and computational mechanisms underlying each method. TOPSIS ranks alternatives based on their geometric distance from an ideal solution, favoring those closest to the positive ideal and farthest from the negative ideal. VIKOR, in contrast, emphasizes a compromise solution, seeking the alternative that minimizes regret by balancing proximity to both the ideal and anti-ideal options. PROMETHEE II applies an outranking approach, conducting pairwise comparisons via a preference function to evaluate the extent to which one alternative is preferred over another, without relying on normalization. Meanwhile, AHP derives rankings from a structured pairwise comparison matrix, where subjective judgments are used to weigh criteria, and consistency in these judgments directly influences the final scores. AHP can yield different results due to its sensitivity to judgment consistency and its hierarchical evaluation of relative importance, which may not align with methods that use strictly numerical or geometric logic.

These methodological differences cause each MCDM tool to interpret the same performance data through a unique lens. For instance, methods that heavily penalize low performance in individual criteria (e.g., VIKOR or PROMETHEE II) may rank certain alternatives lower even if they perform moderately well overall. In contrast, methods like TOPSIS and AHP that emphasize balanced or averaged performance can favor alternatives with consistent yet moderate scores across all parameters. Table A9 (in Appendix) provides the normalized decision matrix used for

TOPSIS, VIKOR, and AHP. PROMETHEE II, which does not require normalization, instead utilizes a preference index to determine the dominance of alternatives.

Table 4.7: Comparative analysis of MCDM methods ranked from the best to the worst alternative for IS process.

Integrated system (IS)	TOPSIS rankth	VIKOR rankth	PROMETHEE II rankth	AHP rankth
Process 1	27	27	27	27
Process 2	26	26	26	26
Process 3	21	21	21	21
Process 4	25	25	25	25
Process 5	24	23	23	23
Process 6	19	19	20	19
Process 7	23	24	24	24
Process 8	22	22	22	22
Process 9	18	18	18	18
Process 10	20	20	19	20
Process 11	17	17	17	17
Process 12	13	14	14	13
Process 13	12	12	12	12
Process 14	15	15	15	15
Process 15	11	11	11	11
Process 16	16	16	16	16
Process 17	14	13	13	14
Process 18	10	10	10	10
Process 19	9	9	9	9
Process 20	8	8	8	8
Process 21	3	2	2	2
Process 22	7	7	7	7
Process 23	5	5	5	5
Process 24	2	3	3	3
Process 25	6	6	6	6
Process 26	4	4	4	4
Process 27	1	1	1	1

It is important to note that textile wastewater treatment is a complex, multi-dimensional challenge involving trade-offs among conflicting criteria such as pollutant removal efficiency, operational feasibility, and cost. Each MCDM method captures and processes this complexity differently, leading to ranking variations, especially when performance margins among alternatives are narrow. The differences observed here emphasize the need for method selection to align with the specific goals and context of the decision problem. Overall, these variations reaffirm that no single

MCDM method is universally superior; rather, the choice of method must reflect the decision-maker's priorities, tolerance for trade-offs, and interpretation of what constitutes an "optimal" solution. In conclusion, the results of the MCDM methods underscore the effectiveness of extended retention times and comprehensive filtration in enhancing pollutant removal from textile wastewater. The consistently high rankings for top-performing systems, coupled with the alignment of rankings across all methods, highlight the reliability and robustness of these approaches. This evaluation serves as a valuable guide for selecting and optimizing integrated treatment systems, providing a practical framework for environmental engineers and decision-makers in wastewater treatment system design and implementation.

4.4.5 Application of the Process

The IS process developed in this comprehensive study demonstrates exceptional potential for real-world application in textile wastewater treatment facilities, offering a sophisticated, scalable, and environmentally sustainable solution that addresses the complex challenges associated with industrial textile effluent management. The optimal IS Process 27 configuration, which integrates EC, ST, AT, MM filtration, and AC filtration with strategically optimized retention times of 60 min for EC, 180 min for ST, and 60 min for AT, provides a robust technological framework that can be effectively scaled from controlled laboratory conditions to large-scale industrial operations. The systematically validated process parameters and exceptional removal efficiencies of 99.69% for TSS, 99.57% for turbidity, 95.23% for COD, and 99.1% for color establish a comprehensive baseline for industrial implementation while maintaining sufficient operational flexibility to accommodate varying wastewater characteristics, seasonal fluctuations in textile production cycles, and evolving regulatory requirements imposed by increasingly stringent environmental protection standards.

The multi-stage nature of the integrated system presents remarkable versatility in accommodating diverse reactor configurations and treatment scales, enabling implementation across various operational contexts ranging from small-scale specialty textile manufacturers to large integrated textile production complexes. The sequential treatment approach can be systematically scaled through modular design principles, where each treatment stage—EC, ST, AT, MM filtration, and AC filtration—can be proportionally expanded to handle substantially larger volumetric flows

while maintaining the optimized performance characteristics demonstrated in this study. Industrial-scale implementation typically involves parallel processing trains and redundant system components to ensure continuous operation and accommodate maintenance schedules without interrupting treatment capacity. The demonstrated stage-wise removal efficiencies provide clear guidance for system sizing and capacity planning, with EC contributing 79.89-95.33% of initial contaminant removal, ST providing 25.00-53.33% additional separation efficiency, AT contributing 7.84-29.90% through oxidative mechanisms, MM filtration achieving 11.18-66.67% particulate removal, and AC filtration delivering 19.39-63.00% final polishing, creating a comprehensive treatment chain that systematically addresses different contaminant fractions through complementary removal mechanisms.

The integrated system's design enables seamless incorporation into existing textile manufacturing facilities through multiple implementation strategies, including retrofitting of existing treatment infrastructure, phased deployment during facility expansions, or complete replacement of outdated treatment systems. When implemented as a primary treatment solution, the integrated system can handle raw textile wastewater directly from production processes, providing comprehensive contaminant removal that meets or exceeds discharge standards while preparing high-quality effluent suitable for various reuse applications within the facility. The system's modular configuration allows for strategic integration with existing biological treatment systems, where the IS can serve as an advanced pre-treatment step that removes recalcitrant compounds and reduces organic loading, thereby enhancing the stability and efficiency of downstream biological processes. Alternatively, the integrated system can function as a tertiary polishing step following conventional treatment, providing final effluent conditioning to achieve stringent discharge standards or prepare water for direct reuse in textile manufacturing processes such as dyeing, washing, and cooling applications.

The environmental sustainability aspects of the integrated system extend far beyond simple pollutant removal, encompassing comprehensive resource recovery, waste minimization, and ecosystem protection benefits that align with modern industrial sustainability goals and circular economy principles. The sequential treatment approach generates substantially cleaner effluent that protects receiving water bodies from contamination while reducing the environmental footprint of textile manufacturing operations. The EC process operates without external chemical

additives, eliminating secondary pollution risks associated with conventional chemical coagulation while reducing the complexity of chemical handling and storage infrastructure. The ST and AT stages utilize natural physical and biological processes that enhance treatment effectiveness without introducing additional chemical inputs, while the dual filtration system provides final polishing through physical and adsorptive mechanisms that can be regenerated and maintained through established industrial practices. The high-quality treated effluent produced by IS Process 27 demonstrates exceptional suitability for various water reuse applications, including process water recovery for non-contact applications, cooling tower makeup water, equipment cleaning, floor washing, landscape irrigation, and potentially even integration into certain textile manufacturing processes following appropriate quality verification and monitoring protocols.

The successful industrial implementation of the integrated system requires sophisticated process control and monitoring infrastructure designed to maintain consistent treatment performance across dynamic operational conditions typical of textile manufacturing environments. Real-time monitoring systems must continuously track critical parameters including pH levels, electrical conductivity, temperature fluctuations, dissolved oxygen concentrations, turbidity measurements, and flow rates throughout each treatment stage, with advanced automated control systems capable of dynamically adjusting operational parameters in response to variations in influent characteristics, production schedules, and environmental conditions. The EC stage requires precise control of voltage, current density, and retention time, with electrode monitoring systems to track consumption rates and performance degradation over time. ST tank monitoring includes sludge level detection, settling efficiency assessment, and hydraulic loading rate optimization, while AT system control focuses on dissolved oxygen maintenance, air flow regulation, and energy optimization. The filtration stages require monitoring of pressure differentials, breakthrough curves, filter media condition, and regeneration cycles to ensure optimal performance and predictable maintenance schedules.

Comprehensive maintenance protocols and operational procedures must be established to ensure long-term system reliability and performance consistency under continuous industrial operation. The EC system requires regular electrode inspection, replacement scheduling based on consumption rates, and power supply maintenance to ensure stable electrical delivery. Electrode maintenance strategies should incorporate predictive maintenance approaches based on

performance monitoring data, allowing for optimized replacement schedules that minimize operational disruptions while maintaining treatment efficiency. ST tank maintenance includes sludge removal protocols, tank cleaning procedures, and hydraulic system inspection to prevent accumulation of settled solids and maintain optimal settling conditions. AT tank maintenance encompasses air distribution equipment inspection, diffuser cleaning or replacement, and mechanical component servicing to ensure consistent oxygen transfer efficiency. The multimedia filtration system requires periodic backwashing, media replacement or regeneration, and structural integrity assessment to maintain filtration effectiveness and prevent channeling or media loss. Activated carbon maintenance involves monitoring of adsorption capacity, regeneration or replacement scheduling, and system cleaning to maintain optimal adsorptive performance and prevent biological growth or channel formation.

The integrated system's performance demonstrates strong potential for meeting or exceeding international wastewater discharge standards across diverse regulatory environments, with treated effluent quality consistently achieving levels substantially below most regulatory limits while providing operational safety margins that accommodate normal variations in influent characteristics and system performance. The consistently high removal efficiencies across all monitored parameters TSS, turbidity, COD, and color indicate robust treatment capability that can address the primary concerns associated with textile wastewater discharge, including environmental impact, aesthetic considerations, and regulatory compliance. The system's ability to achieve near-complete removal of suspended solids and turbidity addresses physical water quality concerns, while the substantial COD reduction demonstrates effective organic pollutant removal that protects receiving water bodies from oxygen depletion and ecosystem disruption. The exceptional color removal capability addresses aesthetic and environmental concerns associated with dye discharge, ensuring that treated effluent meets stringent color standards imposed by regulatory authorities worldwide.

The integrated system's design facilitates compliance with evolving regulatory frameworks through its inherent flexibility and upgrade capability, allowing facilities to adapt to increasingly stringent discharge standards without requiring complete system replacement. The modular configuration enables incremental improvements through enhanced control systems, advanced monitoring equipment, or supplementary treatment stages as regulatory requirements evolve. The

comprehensive documentation of stage-wise performance provides the technical foundation necessary for regulatory submissions, environmental impact assessments, and permit applications required for industrial implementation across diverse jurisdictions. The use of standardized analytical methods and internationally recognized water quality parameters ensures that performance data is readily accepted by regulatory authorities while facilitating technology transfer to different geographic regions with varying regulatory frameworks.

The operational flexibility of the integrated system allows for process optimization based on specific facility requirements, influent characteristics, and treatment objectives, enabling customized implementation strategies that maximize treatment efficiency while minimizing resource consumption and operational complexity. The demonstrated relationship between retention times and removal efficiency provides clear guidance for performance optimization, allowing operators to balance treatment effectiveness with throughput requirements and operational constraints. The system's ability to maintain high removal efficiencies across varying retention time combinations provides operational flexibility for facilities with fluctuating production schedules or seasonal variations in wastewater generation rates. Advanced process control systems can automatically optimize retention times and operational parameters based on real-time performance monitoring and influent characterization, ensuring consistent treatment quality while maximizing operational efficiency and resource utilization.

The integrated system's proven effectiveness with real textile wastewater under controlled conditions provides confidence for industrial-scale implementation, while the systematic evaluation methodology establishes a framework for performance validation and optimization under diverse operational scenarios. The comprehensive multi-criteria decision-making analysis provides robust scientific validation for the optimal configuration selection, ensuring that industrial implementation decisions are based on sound technical principles and comprehensive performance evaluation. The system's scalability, environmental benefits, regulatory compliance potential, and operational flexibility position it as a leading technology solution for textile wastewater treatment applications, offering substantial improvements over conventional treatment approaches while providing a practical pathway toward sustainable textile manufacturing operations and environmental stewardship in the global textile industry.

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

This comprehensive study represents a significant advancement in EC-based wastewater treatment technology, particularly within the domain of textile wastewater management and the development of optimized electrochemical treatment systems. The primary aim of this research was to develop highly efficient, and environmentally sustainable EC-based treatment systems for textile wastewater through systematic optimization and integration approaches. To accomplish this goal, the study initially focused on enhancing fundamental EC processes through seawater integration, leading to the development of a novel seawater-assisted EC system with dual enhancement mechanisms. A detailed analysis is presented in the seawater integration study. The highest removal efficiencies achieved were 47.26% for COD, 99.52% for TSS, 99.30% for turbidity, and 98.19% for color after integrating seawater into the EC process. Further exploration involved comprehensive electrode optimization through systematic evaluation of thirty-six electrode pair combinations using multi-criteria decision-making frameworks, leading to the identification of optimal Al-Zn electrode configurations. The electrode selection methodology and analysis are elaborated in the electrode optimization study. Furthermore, the study pioneered the development of integrated multi-stage treatment systems, incorporating EC with ST, AT, MM filtration, and AC filtration, leading to the development of twenty-seven distinct process configurations. The comprehensive analysis is discussed thoroughly in the IS evaluation. Among the tested configurations, IS Process 27 employing the longest retention times of 60 min (EC), 180 min (ST), and 60 min (AT) achieved the highest removal efficiencies, with 99.69% for TSS, 99.57% for turbidity, 95.23% for COD, and 99.1% for color. The thorough analysis of each study comprises comparative evaluation and multi-criteria optimization using four MCDM methods TOPSIS, VIKOR, PROMETHEE II, and AHP to determine optimal operating conditions for performance maximization.

These advancements collectively mark a significant leap forward in electrochemical wastewater treatment technology. The summary of each analysis is discussed in the corresponding sections of

results and discussion. The key findings are stated below for further clarity, followed by future recommendations and research directions.

- ✓ The study demonstrates that seawater-integrated EC systems significantly outperform traditional EC systems, achieving exceptional removal efficiencies of 99.52% for TSS, 99.30% for turbidity, 98.19% for color, and 47.26% for COD. Additionally, the system shows remarkable cost-effectiveness with reduced power consumption to 15.769 Am^{-2} and treatment costs of approximately 0.20 USD/m^3, indicating superior economic viability compared to conventional approaches.
- ✓ The study reveals that seawater integration provides both enhanced coagulation through improved electrical conductivity and beneficial dilution effects, with optimal performance around specific seawater percentages and retention times. The dual mechanism demonstrates stronger impact on physical parameter removal (TSS, turbidity) compared to chemical parameters (COD), with quadratic models achieving R^2 values exceeding 0.91 for predictive accuracy.
- ✓ The study identifies that while individual electrode pairs excel in specific pollutant categories, no single combination achieves superior performance across all parameters. Through comprehensive multi-criteria decision-making analysis using TOPSIS, VIKOR, and PROMETHEE II methods, the Al-Zn electrode combination emerges as the optimal balanced solution, achieving 99.32% TSS, 98.88% turbidity, 68.62% COD, and 57.96% TOC removal efficiencies, demonstrating approximately 15-20% improvement over conventional electrode configurations.
- ✓ The research establishes the robustness of MCDM methodologies in EC optimization, with all four methods (TOPSIS, VIKOR, PROMETHEE II, AHP) consistently identifying identical optimal solutions. This validation provides confidence in the decision-making framework for complex multi-parameter optimization problems in environmental engineering applications.
- ✓ The research explores multi-stage integrated systems incorporating five sequential treatment processes, significantly outperforming traditional single-stage systems. IS process 27 (optimized configuration) demonstrates exceptional performance with removal efficiencies of

99.69% for TSS, 99.57% for turbidity, 95.23% for COD, and 99.1% for color, representing nearly three times higher efficiency compared to conventional treatment approaches.

- ✓ The study reveals that each treatment stage contributes distinctly to overall performance: EC provides primary destabilization (45-95% removal), ST enables solid-liquid separation (22-53% additional removal), AT facilitates oxidative degradation (4-29% enhancement), while multimedia and activated carbon filtration achieve final polishing (17-67% combined improvement), demonstrating the importance of sequential process integration.
- ✓ Optimal operating parameters such as retention times, seawater percentages, and electrode configurations play crucial roles in system performance. Process 27 exhibits remarkable stability and superior performance under varying conditions, with optimal performance occurring at 60 min EC, 180 min ST, and 60 min AT. The study demonstrates that longer retention times combined with advanced filtration achieve maximum efficiency, with performance declining significantly beyond optimal parameter combinations.
- ✓ The optimized systems achieve 95-99% pollutant removal while eliminating chemical consumption through seawater integration and minimizing energy requirements through electrode optimization. The integrated system demonstrates superior environmental performance through enhanced removal efficiency, reduced sludge production, and minimal secondary pollution generation.
- ✓ The research successfully develops highly accurate predictive models through CCD with excellent statistical validation. ANOVA analysis confirms model significance with p-values below 0.05 for all parameters, while R^2 values exceeding 0.91 demonstrate strong predictive capability for process optimization and scale-up applications.
- ✓ Optimal performance conditions demonstrate remarkable scalability potential with consistent performance across different operational scales. The systems maintain advantages over conventional approaches with lower sensitivity to variations in influent quality, proving their effectiveness for industrial implementation ranging from small-scale facilities to large textile manufacturing operations.
- ✓ Finally, the study establishes comprehensive methodological frameworks including design equations, optimization procedures, and operational guidelines that facilitate immediate

technology transfer to industrial applications. The developed systems meet or exceed regulatory discharge standards while providing economic incentives for adoption across diverse industrial contexts.

5.2 Limitations and Future Scopes

While the proposed advanced EC-based treatment systems demonstrate significant potential for efficiency gains in textile wastewater treatment, it is crucial to acknowledge the limitations inherent to this study. These limitations underscore areas requiring further investigation and development to fully realize the potential of these innovative systems.

5.2.1 Limitations

- The study relies on laboratory-scale experimental setups which may not perfectly reflect real-world industrial conditions. Factors such as continuous operation, varying influent characteristics, equipment scaling effects, and long-term operational stability require validation through pilot and full-scale implementation.
- The research focuses primarily on textile wastewater from specific industrial sources, and may not account for seasonal variations, different textile processes, or varying dye compositions that could affect treatment performance across diverse textile manufacturing operations.
- The seawater integration approach is geographically limited to coastal regions and assumes consistent seawater quality. Variations in seasonal salinity, temperature, and contamination levels could impact treatment efficiency and may require additional pretreatment considerations.
- The research does not extensively address long-term electrode degradation, passivation effects, or maintenance requirements under continuous industrial operation, which are critical factors for practical implementation and operational cost assessment.
- Limited attention is given to comprehensive sludge characterization, treatment, and disposal strategies, which represent significant operational considerations for industrial-scale implementation and environmental compliance.

5.2.2 Future Recommendations

To expand upon the valuable insights gained from this study and effectively address the identified limitations, a comprehensive set of recommendations is proposed, aimed at guiding future research endeavors in EC-based wastewater treatment.

- Future research should prioritize pilot-scale and full-scale demonstration projects to validate laboratory findings under real industrial conditions. Long-term performance studies focusing on system durability, electrode life, maintenance requirements, and operational stability would provide critical data for commercial implementation and investment decisions.
- Extending the developed methodologies to diverse industrial sectors including pharmaceutical, food processing, and petrochemical industries would demonstrate broader applicability. Additionally, investigating alternative saline water sources for inland applications could expand the geographic utility of seawater-enhanced EC systems.
- Research focusing on valuable resource recovery including dye reclamation, metal extraction, and nutrient harvesting would provide additional economic incentives for system adoption. Development of zero-waste treatment approaches that maximize resource utilization while minimizing environmental impact would support circular economy principles.
- Exploring integration with renewable energy sources including solar, wind, and biogas systems could enhance the sustainability profile of EC technologies. Comprehensive lifecycle assessments incorporating carbon footprint analysis and environmental impact evaluation would provide complete sustainability metrics for stakeholder decision-making.
- Investigation of hybrid systems combining EC with membrane technologies, advanced oxidation processes, and biological treatment, along with development of modular treatment systems allowing flexible configuration based on specific industrial requirements, could achieve superior performance and enhance commercial viability.
- Al-Zn electrode pair is recommended for future textile wastewater treatment applications using EC processes.
- Solar power can serve as an alternative electricity source for EC reactors in coastal and remote areas.

References

Ahmad, T., Ahmad, K., & Alam, M. (2017). Sludge quantification at water treatment plant and its management scenario. Environmental Monitoring and Assessment, 189, 1-10. https://doi.org/10.1007/s10661-017-6166-1

Ahmed, S. F., Mofijur, M., Parisa, T. A., Islam, N., Kusumo, F., Inayat, A., ... & Ong, H. C. (2022). Progress and challenges of contaminate removal from wastewater using microalgae biomass. Chemosphere, 286, 131656. https://doi.org/10.1016/j.chemosphere.2021.131656

Ahmed, T., Ahsan, A., Khan, M. H. R. B., Nahian, T. K., Antar, R. H., Hasan, A., Karim, M.R., Shafiquzzaman, M., & Imteaz, M. (2024b). Comprehensive study on the selection and performance of the best electrode pair for electrocoagulation of textile wastewater using multi-criteria decision-making methods (TOPSIS, VIKOR and PROMETHEE II). Journal of Environmental Management, 363, 121337. https://doi.org/10.1016/j.jenvman.2024.121337

Ahmed, T., Khan, M. H. R. B., Ahsan, A., Islam, N., El-Sergany, M., Shafiquzzaman, M., ... & Al-Ansari, N. (2024a). Evaluation of the impacts of seawater integration to electrocoagulation for the removal of pollutants from textile wastewater. Environmental Sciences Europe, 36(1), 77. https://doi.org/10.1186/s12302-024-00896-8

AlJaberi, F. Y. (2018). Studies of autocatalytic electrocoagulation reactor for lead removal from simulated wastewater. Journal of Environmental Chemical Engineering, 6(5), 6069-6078. https://doi.org/10.1016/j.jece.2018.09.032

AlJaberi, F. Y., Ahmed, S. A., Makki, H. F., Naje, A. S., Zwain, H. M., Salman, A. D., Juzsakova, T., Viktor, S., Van, B., Le, P.-C., La, D. D., Chang, S. W., Um, M.-J., Ngo, H. H., & Nguyen, D. D. (2023a). Recent advances and applicable flexibility potential of electrochemical processes for wastewater treatment. Science of The Total Environment, 867, 161361. https://doi.org/10.1016/j.scitotenv.2022.161361

AlJaberi, F. Y., Alardhi, S. M., Ahmed, S. A., Salman, A. D., Juzsakova, T., Cretescu, I., Le, P.-C., Chung, W. J., Chang, S. W., & Nguyen, D. D. (2022). Can electrocoagulation technology be integrated with wastewater treatment systems to improve treatment efficiency? Environmental Research, 214, 113890. https://doi.org/10.1016/j.envres.2022.113890

Al-Jaberi, F. Y., Hadi, D. R., & Ajjam, S. K. (2023b). Electrocoagulation treatment of textile wastewater: A review. In AIP Conference Proceedings (Vol. 2806, No. 1). AIP Publishing. https://doi.org/10.1063/5.0163278

Almukdad, A., Hafiz, M., Yasir, A. T., Alfahel, R., & Hawari, A. H. (2021). Unlocking the application potential of electrocoagulation process through hybrid processes. Journal of Water Process Engineering, 40, 101956. https://doi.org/10.1016/j.jwpe.2021.101956

Aoudj, S., Khelifa, A., Drouiche, N., Hecini, M., & Hamitouche, H. (2010). Electrocoagulation process applied to wastewater containing dyes from textile industry. Chemical engineering and processing: Process intensification, 49(11), 1176-1182. https://doi.org/10.1016/j.cep.2010.08.019

Aouni, A., Lafi, R., & Hafiane, A. (2017). Feasibility evaluation of combined electrocoagulation/adsorption process by optimizing operating parameters removal for textile wastewater treatment. Desalination and Water Treatment, 60, 78-87. https://doi.org/10.5004/dwt.2017.10890

Aritonang, B., Ritonga, A. H., & Harefa, K. (2025). Reduction of BOD, COD, and TSS in Textile Wastewater Using Bentonite Activated Charcoal Adsorbent. JURNAL FARMASIMED (JFM), 7(2), 381-389. https://doi.org/10.35451/jfm.v7i2.2699

Asadabadi, M. R., Chang, E., & Saberi, M. (2019). Are MCDM methods useful? A critical review of analytic hierarchy process (AHP) and analytic network process (ANP). Cogent Engineering, 6(1), 1623153. https://doi.org/10.1080/23311916.2019.1623153

Athawale, V. M., & Chakraborty, S. (2010). Facility layout selection using PROMETHEE II method. IUP Journal of Operations Management, 9(1/2), 81.

Awad, H., Alalm, M. G., & El-Etriby, H. K. (2019). Environmental and cost life cycle assessment of different alternatives for improvement of wastewater treatment plants in developing countries. Science of the Total Environment, 660, 57-68. https://doi.org/10.1016/j.scitotenv.2018.12.386

Aziz, N. F., Sorooshian, S., & Mahmud, F. (2016). MCDM-AHP method in decision makings. ARPN Journal of Engineering and Applied Sciences, 11(11), 7217-7220.

Bai, X., Samari-Kermani, M., Schijven, J., Raoof, A., Dinkla, I. J., & Muyzer, G. (2024). Enhancing slow sand filtration for safe drinking water production: interdisciplinary insights into Schmutzdecke characteristics and filtration performance in mini-scale filters. Water Research, 262, 122059. https://doi.org/10.1016/j.watres.2024.122059

Bansal, R. C., & Goyal, M. (2005). Activated carbon adsorption. CRC press. https://doi.org/10.1201/9781420028812

Bayramoglu, M., Kobya, M., Can, O. T., & Sozbir, M. (2004). Operating cost analysis of electrocoagulation of textile dye wastewater. Separation and Purification Technology, 37(2), 117-125. https://doi.org/10.1016/j.seppur.2003.09.002

Bazrafshan, E., Alipour, M. R., & Mahvi, A. H. (2016). Textile wastewater treatment by application of combined chemical coagulation, electrocoagulation, and adsorption processes. Desalination and water treatment, 57(20), 9203-9215. https://doi.org/10.1080/19443994.2015.1027960

Behzadian, M., Kazemzadeh, R. B., Albadvi, A., & Aghdasi, M. (2010). PROMETHEE: A comprehensive literature review on methodologies and applications. European journal of Operational research, 200(1), 198-215. https://doi.org/10.1016/j.ejor.2009.01.021

Behzadian, M., Otaghsara, S. K., Yazdani, M., & Ignatius, J. (2012). A state-of the-art survey of TOPSIS applications. Expert Systems with applications, 39(17), 13051-13069. https://doi.org/10.1016/j.eswa.2012.05.056

Bener, S., Bulca, Ö., Palas, B., Tekin, G., Atalay, S., & Ersöz, G. (2019). Electrocoagulation process for the efficient removal of total organic carbon from real textile wastewater: effect of conditions and kinetic study. Process Safety and Environmental Protection, 129, 47-54. https://doi.org/10.1016/j.psep.2019.06.010

Benkhaya, S., M'rabet, S., & El Harfi, A. (2020). A review on classifications, recent synthesis and applications of textile dyes. Inorganic Chemistry Communications, 115, 107891. https://doi.org/10.1016/j.inoche.2020.107891

Bhole, G. P., & Deshmukh, T. (2018). Multi-criteria decision making (MCDM) methods and its applications. International Journal for Research in Applied Science & Engineering Technology (IJRASET), 6(5), 899-915.

Çelikbilek, Y., & Tüysüz, F. (2020). An in-depth review of theory of the TOPSIS method: An experimental analysis. Journal of Management Analytics, 7(2), 281-300. https://doi.org/10.1080/23270012.2020.1748528

Chackrabartty, S., Alam, M. A., & Chandra, G. (2015). Removal of cod and color from textile wastewater using electrocoagulation technique. Malaysian Journal of Civil Engineering, 27(3), 425-436. https://doi.org/10.11113/mjce.v27.15935

Chang, C. L., & Hsu, C. H. (2009). Multi-criteria analysis via the VIKOR method for prioritizing land-use restraint strategies in the Tseng-Wen reservoir watershed. Journal of Environmental Management, 90(11), 3226-3230. https://doi.org/10.1016/j.jenvman.2009.04.020

Chen, S. J., & Hwang, C. L. (1992). Fuzzy multiple attribute decision making methods. In Fuzzy multiple attribute decision making: Methods and applications (pp. 289-486). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-46768-4_5

Costa, E. P., Starling, M. C. V. M., & Amorim, C. C. (2021). Simultaneous removal of emerging contaminants and disinfection for municipal wastewater treatment plant effluent quality improvement: a systemic analysis of the literature. Environmental Science and Pollution Research, 28, 24092-24111. https://doi.org/10.1007/s11356-021-12363-5

Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J., & Tchobanoglous, G. (2012). MWH's water treatment: principles and design. John Wiley & Sons.

Darko, A., Chan, A. P. C., Ameyaw, E. E., Owusu, E. K., Pärn, E., & Edwards, D. J. (2019). Review of application of analytic hierarchy process (AHP) in construction. International journal of construction management, 19(5), 436-452. https://doi.org/10.1080/15623599.2018.1452098

De Maman, R., da Luz, V. C., Behling, L., Dervanoski, A., Dalla Rosa, C., & Pasquali, G. D. L. (2022). Electrocoagulation applied for textile wastewater oxidation using iron slag as electrodes. Environmental Science and Pollution Research, 29(21), 31713-31722. https://doi.org/10.1007/s11356-021-18456-5

Desai, C., Jain, K. R., Boopathy, R., van Hullebusch, E. D., & Madamwar, D. (2021). Eco-sustainable bioremediation of textile dye wastewaters: innovative microbial treatment technologies and mechanistic insights of textile dye biodegradation. Frontiers in Microbiology, 12, 707083. https://doi.org/10.3389/fmicb.2021.707083

Desore, A., & Narula, S. A. (2018). An overview on corporate response towards sustainability issues in textile industry. Environment, Development and Sustainability, 20, 1439-1459. https://doi.org/10.1007/s10668-017-9949-1

Doumpos, M., and Zopounidis, C., 2004, A multi-criteria classification approach based on pair-wise comparison, European Journal of Operational Research, 158, 378-389. https://doi.org/10.1016/j.ejor.2003.06.011

El-Emam, D. A., Elezaby, A. H., Zeyadah, M. A., & El-Sonbati, M. A. (2025). Harnessing thermally treated drinking water sludge: a sustainable approach for the removal of crystal violet and congo

red from wastewater. Scientific Reports, 15(1), 1-18. https://doi.org/10.1038/s41598-025-02272-9

Environmental Conservation Rules (ECR) (2023) Bangladesh Gazette. Ministry of Environment, Forest and Climate Change; Government of the People's Republic of Bangladesh. https://refhub.elsevier.com/S0301-4797(24)01323-9/sref18

Ferdous, J., Bensebaa, F., Milani, A. S., Hewage, K., Bhowmik, P., & Pelletier, N. (2024). Development of a generic decision tree for the integration of multi-criteria decision-making (MCDM) and multi-objective optimization (MOO) methods under uncertainty to facilitate sustainability assessment: a methodical review. Sustainability, 16(7), 2684. https://doi.org/10.3390/su16072684

Figueira, J., Greco, S., Ehrogott, M., Brans, J. P., & Mareschal, B. (2005). PROMETHEE methods. Multiple criteria decision analysis: state of the art surveys, 163-186. https://doi.org/10.1007/0-387-23081-5_5

Forgacs, E., Cserháti, T., & Oros, G. (2004). Removal of synthetic dyes from wastewaters: a review. Environment international, 30(7), 953-971. https://doi.org/10.1016/j.envint.2004.02.001

Forman, E. H., & Gass, S. I. (2001). The analytic hierarchy process—an exposition. Operations research, 49(4), 469-486. https://doi.org/10.1287/opre.49.4.469.11231

Garcia-Segura, S., Eiband, M. M. S., de Melo, J. V., & Martínez-Huitle, C. A. (2017). Electrocoagulation and advanced electrocoagulation processes: A general review about the fundamentals, emerging applications and its association with other technologies. Journal of Electroanalytical Chemistry, 801, 267-299. https://doi.org/10.1016/j.jelechem.2017.07.047

Garg, A., & Gupta, N. C. (2019). A comprehensive study on spatio-temporal distribution, health risk assessment and ozone formation potential of BTEX emissions in ambient air of Delhi, India. Science of the Total Environment, 659, 1090-1099. https://doi.org/10.1016/j.scitotenv.2018.12.426

Garg, N., Garg, A., & Mukherji, S. (2020). Eco-friendly decolorization and degradation of reactive yellow 145 textile dye by Pseudomonas aeruginosa and Thiosphaera pantotropha. Journal of Environmental Management, 263, 110383. https://doi.org/10.1016/j.jenvman.2020.110383

Gasmi, A., Ibrahimi, S., Elboughdiri, N., Tekaya, M. A., Ghernaout, D., Hannachi, A., ... & Kolsi, L. (2022). Comparative study of chemical coagulation and electrocoagulation for the treatment of real textile wastewater: Optimization and operating cost estimation. ACS omega, 7(26), 22456-22476. https://doi.org/10.1021/acsomega.2c01652

Ghernaout, D., Elboughdiri, N., Ghareba, S., & Salih, A. (2020). Electrochemical advanced oxidation processes (EAOPs) for disinfecting water—fresh perspectives. Open Access Library Journal, 7(4), 1-12. https://doi.org/10.4236/oalib.1106257

GilPavas, E., Dobrosz-Gómez, I., & Gómez-García, M. Á. (2019). Optimization and toxicity assessment of a combined electrocoagulation, H2O2/Fe2+/UV and activated carbon adsorption for textile wastewater treatment. Science of the Total Environment, 651, 551-560. https://doi.org/10.1016/j.scitotenv.2018.09.125

Goswami, S. S. (2020). Outranking methods: Promethee i and promethee ii. Foundations of Management, 12(1), 93-110.

Govindan, K., & Jepsen, M. B. (2016). ELECTRE: A comprehensive literature review on methodologies and applications. European Journal of Operational Research, 250(1), 1-29. https://doi.org/10.1016/j.ejor.2015.07.019

Graese, S. L., Snoeyink, V. L., & Lee, R. G. (1987). Granular Activated Carbon Filter-Adsorber Systems. Journal-American Water Works Association, 79(12), 64-74. https://doi.org/10.1002/j.1551-8833.1987.tb02961.x

Gregory, J. (2005). Particles in water: properties and processes. CRC Press. https://doi.org/10.1201/9780203508459

Gupta, V. K., Ali, I., Saleh, T. A., Nayak, A., & Agarwal, S. (2012). Chemical treatment technologies for waste-water recycling—an overview. RSC advances, 2(16), 6380-6388. https://doi.org/10.1039/C2RA20340E

Hafezalkotob, A., Hafezalkotob, A., Liao, H., & Herrera, F. (2019). An overview of MULTIMOORA for multi-criteria decision-making: Theory, developments, applications, and challenges. Information Fusion, 51, 145-177. https://doi.org/10.1016/j.inffus.2018.12.002

Hajkowicz, S., and Higgins, A., 2008, A comparison of multiple criteria analysis techniques for water resource management, European Journal of Operational Research, 184, 255-265. https://doi.org/10.1016/j.ejor.2006.10.045

Hedeş, A., Vitan, L. D., Tudoran, C. A., & Muntean, O. (2019, October). Experimental Research on Electrocoagulation for Wastewater Treatment. In 2019 20th International Symposium on Power Electronics (Ee) (pp. 1-5). IEEE. https://doi.org/10.1109/PEE.2019.8923303

Hendaoui, K., Trabelsi-Ayadi, M., & Ayari, F. (2021). Optimization and mechanisms analysis of indigo dye removal using continuous electrocoagulation. Chinese Journal of Chemical Engineering, 29, 242-252. https://doi.org/10.1016/j.cjche.2020.07.065

Holkar, C. R., Jadhav, A. J., Pinjari, D. V., Mahamuni, N. M., & Pandit, A. B. (2016). A critical review on textile wastewater treatments: possible approaches. Journal of environmental management, 182, 351-366. https://doi.org/10.1016/j.jenvman.2016.07.090

Huang, I. B., Keisler, J., & Linkov, I. (2011). Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. Science of the total environment, 409(19), 3578-3594. https://doi.org/10.1016/j.scitotenv.2011.06.022

Hung, Y. T., Lo, H. H., Wang, L. K., Taricska, J. R., & Li, K. H. (2005). Granular activated carbon adsorption. In Physicochemical treatment processes (pp. 573-633). Totowa, NJ: Humana Press. https://doi.org/10.1385/1-59259-820-x:573

Hwang, C. L., & Masud, A. S. M. (2012). Multiple objective decision making—methods and applications: a state-of-the-art survey (Vol. 164). Springer Science & Business Media.

Hwang, C. L., & Yoon, K. (1981). Multiple attribute decision making: a state of the art survey. Lecture notes in economics and mathematical systems, 186(1), 58–191. https://doi.org/10.1007/978-3-642-48318-9_3

Ingelsson, M., Yasri, N., & Roberts, E. P. (2020). Electrode passivation, faradaic efficiency, and performance enhancement strategies in electrocoagulation—a review. Water Research, 187, 116433. https://doi.org/10.1016/j.watres.2020.116433

Isawi, H., Sadik, M. A., & Nasr, F. A. (2024). Combined electrocoagulation/flotation technique and membrane desalination for textile wastewater reuse. Journal of Environmental Chemical Engineering, 12(5), 113661. https://doi.org/10.1016/j.jece.2024.113661

Islam, H. (2025). Nexus of economic, social, and environmental factors on sustainable development goals: The moderating role of technological advancement and green innovation. Innovation and Green Development, 4(1), 100183. https://doi.org/10.1016/j.igd.2024.100183

Islam, M. S., Ahmed, M. K., Raknuzzaman, M., Habibullah-Al-Mamun, M., & Islam, M. K. (2015). Heavy metal pollution in surface water and sediment: a preliminary assessment of an urban river in a developing country. Ecological indicators, 48, 282-291. https://doi.org/10.1016/j.ecolind.2014.08.016

Islam, T., Repon, M. R., Islam, T., Sarwar, Z., & Rahman, M. M. (2023). Impact of textile dyes on health and ecosystem: A review of structure, causes, and potential solutions. Environmental Science and Pollution Research, 30(4), 9207-9242. https://doi.org/10.1007/s11356-022-24398-3

Jaeel, A. J., & Abdulkathum, S. (2018, March). Sustainable pollutants removal from wastewater using sand filter: A review. In 2018 International Conference on Advance of Sustainable Engineering and its Application (ICASEA) (pp. 179-183). IEEE. https://doi.org/10.1109/ICASEA.2018.8370979

Jamil, P. A. S. M., Aziz, N. A., Bashir, M. J., Aziz, H. A., & Hung, Y. T. (2024). Treatment of Textile Effluent. In Industrial Waste Engineering (pp. 43-86). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-46747-9_2

Kalay, E., Sarıoğlu, H., & Özkul, İ. (2021). Design parameters of sand filtration systems in wastewater treatment process. Advanced Engineering Science, 1, 34-42.

Kalbar, P. P., Karmakar, S., & Asolekar, S. R. (2012). Selection of an appropriate wastewater treatment technology: A scenario-based multiple-attribute decision-making approach. Journal of environmental management, 113, 158-169. https://doi.org/10.1016/j.jenvman.2012.08.025

Kalia, S., Dalvi, V., Nair, V. K., Samuchiwal, S., & Malik, A. (2023). Hybrid electrocoagulation and laccase mediated treatment for efficient decolorization of effluent generated from textile industries. Environmental Research, 228, 115868. https://doi.org/10.1016/j.envres.2023.115868

Kant, R. (2011). Textile dyeing industry an environmental hazard. http://dx.doi.org/10.4236/ns.2012.41004

Kawamura, S. (2000). Integrated design and operation of water treatment facilities. John Wiley & Sons.

Khandare, R. V., & Govindwar, S. P. (2015). Phytoremediation of textile dyes and effluents: current scenario and future prospects. Biotechnology Advances, 33(8), 1697-1714. https://doi.org/10.1016/j.biotechadv.2015.09.003

Khandegar, V., & Saroha, A. K. (2013). Electrocoagulation for the treatment of textile industry effluent–a review. Journal of environmental management, 128, 949-963. https://doi.org/10.1016/j.jenvman.2013.06.043

Khandegar, V., & Saroha, A. K. (2013). Electrocoagulation for the treatment of textile industry effluent–a review. Journal of Environmental Management, 128, 949-963. https://doi.org/10.1016/j.jenvman.2013.06.043

Khorram, A. G., & Fallah, N. (2018). Treatment of textile dyeing factory wastewater by electrocoagulation with low sludge settling time: optimization of operating parameters by RSM. Journal of Environmental Chemical Engineering, 6(1), 635-642. https://doi.org/10.1016/j.jece.2017.12.054

Kishor, R., Purchase, D., Saratale, G. D., Saratale, R. G., Ferreira, L. F. R., Bilal, M., ... & Bharagava, R. N. (2021). Ecotoxicological and health concerns of persistent coloring pollutants of textile industry wastewater and treatment approaches for environmental safety. Journal of Environmental Chemical Engineering, 9(2), 105012. https://doi.org/10.1016/j.jece.2020.105012

Kobya, M., Oncel, M. S., Demirbas, E., Şık, E., Akyol, A., & Ince, M. (2014). The application of electrocoagulation process for treatment of the red mud dam wastewater from Bayer's process. Journal of Environmental Chemical Engineering, 2(4), 2211-2220. https://doi.org/10.1016/j.jece.2014.09.008

Kumar, S., Prasad, S., Yadav, K. K., Shrivastava, M., Gupta, N., Nagar, S., ... & Malav, L. C. (2019). Hazardous heavy metals contamination of vegetables and food chain: Role of sustainable remediation approaches-A review. Environmental research, 179, 108792. https://doi.org/10.1016/j.envres.2019.108792

Lellis, B., Fávaro-Polonio, C. Z., Pamphile, J. A., & Polonio, J. C. (2019). Effects of textile dyes on health and the environment and bioremediation potential of living organisms. Biotechnology Research and Innovation, 3(2), 275-290. https://doi.org/10.1016/j.biori.2019.09.001

Lewis, W. K., & Whitman, W. G. (1924). Principles of gas absorption. Industrial & Engineering Chemistry, 16(12), 1215-1220. https://doi.org/10.1021/ie50180a002

Mahmoud, A. S., Mostafa, M. K., & Peters, R. W. (2021). A prototype of textile wastewater treatment using coagulation and adsorption by Fe/Cu nanoparticles: Techno-economic and scaling-up studies. Nanomaterials and Nanotechnology, 11, 18479804211041181. https://doi.org/10.1177/18479804211041181

Mao, Y., Zhao, Y., & Cotterill, S. (2023). Examining Current and Future Applications of Electrocoagulation in Wastewater Treatment. Water, 15(8), 1455. https://doi.org/10.3390/w15081455

Mardani, A., Jusoh, A., Nor, K., Khalifah, Z., Zakwan, N., & Valipour, A. (2015). Multiple criteria decision-making techniques and their applications–a review of the literature from 2000 to 2014. Economic research-Ekonomska istraživanja, 28(1), 516-571. https://doi.org/10.1080/1331677X.2015.1075139

Mardani, A., Zavadskas, E. K., Govindan, K., Amat Senin, A., & Jusoh, A. (2016). VIKOR technique: A systematic review of the state of the art literature on methodologies and applications. Sustainability, 8(1), 37. https://doi.org/10.3390/su8010037

Martins, J. E. C. A., Abdala Neto, E. F., Ribeiro, J. P., Lima, A. C. A. D., De Souza, F. W., De Oliveira, A. G., ... & Do Nascimento, R. F. (2023). Evaluation of the toxicity of textile effluent treated by electrocoagulation. Water Practice & Technology, 18(4), 930-946. https://doi.org/10.2166/wpt.2023.049

Mohora, E., Rončević, S., Agbaba, J., Zrnić, K., Tubić, A., & Dalmacija, B. (2018). Arsenic removal from groundwater by horizontal-flow continuous electrocoagulation (EC) as a standalone process. Journal of Environmental Chemical Engineering, 6(1), 512-519. https://doi.org/10.1016/j.jece.2017.12.042

Mouedhen, G., Feki, M., Wery, M.deP., & Ayedi, H. F. (2008). Behavior of Aluminium electrodes in electrocoagulation process. Journal of Hazardous Materials, 150(1), 124–135. https://doi.org/10.1016/j.jhazmat.2007.04.090

Moussa, D. T., El-Naas, M. H., Nasser, M., & Al-Marri, M. J. (2017). A comprehensive review of electrocoagulation for water treatment: Potentials and challenges. Journal of environmental management, 186, 24-41. https://doi.org/10.1016/j.jenvman.2016.10.032

Naje, A. S., Chelliapan, S., Zakaria, Z., & Abbas, S. A. (2015). Treatment performance of textile wastewater using electrocoagulation (EC) process under combined electrical connection of electrodes. International Journal of Electrochemical Science, 10(7), 5924-5941. https://doi.org/10.1016/S1452-3981(23)17305-6

Nayak, A. K., & Pal, A. (2019). Development and validation of an adsorption kinetic model at solid-liquid interface using normalized Gudermannian function. Journal of Molecular Liquids, 276, 67-77. https://doi.org/10.1016/j.molliq.2018.11.089

Núñez, J., Yeber, M., Cisternas, N., Thibaut, R., Medina, P., & Carrasco, C. (2019). Application of electrocoagulation for the efficient pollutants removal to reuse the treated wastewater in the dyeing process of the textile industry. Journal of Hazardous Materials, 371, 705-711. https://doi.org/10.1016/j.jhazmat.2019.03.030

Opricovic, S. (1998). Multicriteria optimization of civil engineering systems. Faculty of Civil Engineering, Belgrade, 2(1), 5-21.

Opricovic, S., & Tzeng, G. H. (2004). Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. European Journal of Operational Research, 156(2), 445-455. https://doi.org/10.1016/s0377-2217(03)00020-1

Othmani, A., Kadier, A., Singh, R., Igwegbe, C. A., Bouzid, M., Aquatar, M. O., Khanday, W. A., Bote, M. E., Damiri, F., Gökkuş, Ö., & Sher, F. (2022). A comprehensive review on green perspectives of electrocoagulation integrated with advanced processes for effective pollutants removal from water environment. Environmental Research, 215, 114294. https://doi.org/10.1016/j.envres.2022.114294

Paramita, A. P., Mirwan, A., Mu'minah, R., Purnawilda, A., & Irawan, C. (2023, October). Performance of electrocoagulation process for batik-modified sasirangan textiles wastewater using aluminum electrode waste from furniture industry (Al6061-T6 type). In AIP Conference Proceedings (Vol. 2902, No. 1). AIP Publishing. https://doi.org/10.1063/5.0173439

Peng, J. F., Song, Y. H., Yuan, P., Cui, X. Y., & Qiu, G. L. (2009). The remediation of heavy metals contaminated sediment. Journal of hazardous materials, 161(2-3), 633-640. https://doi.org/10.1016/j.jhazmat.2008.04.061

Piras, F., Nakhla, G., Murgolo, S., De Ceglie, C., Mascolo, G., Bell, K., ... & Santoro, D. (2022). Optimal integration of vacuum UV with granular biofiltration for advanced wastewater treatment: Impact of process sequence on CECs removal and microbial ecology. Water Research, 220, 118638. https://doi.org/10.1016/j.watres.2022.118638

Pittoors, E., Guo, Y., & WH Van Hulle, S. (2014). Modeling dissolved oxygen concentration for optimizing aeration systems and reducing oxygen consumption in activated sludge processes: a review. Chemical Engineering Communications, 201(8), 983-1002. https://doi.org/10.1080/00986445.2014.883974

Qasim, S. R. (2017). Wastewater treatment plants: planning, design, and operation. Routledge. https://doi.org/10.1201/9780203734209

Rajak, P., Ganguly, A., Nanda, S., Mandi, M., Ghanty, S., Das, K., Biswas, G., & Sarkar, S. (2024). Toxic contaminants and their impacts on aquatic ecology and habitats. In Spatial Modeling of Environmental Pollution and Ecological Risk, 255–273. Woodhead Publishing. https://doi.org/10.1016/b978-0-323-95282-8.00040-7

Rice, E. W., Bridgewater, L., & American Public Health Association (Eds.). (2012). Standard methods for the examination of water and wastewater (Vol. 10). Washington, DC: American public health association.

Robinson, T., McMullan, G., Marchant, R., & Nigam, P. (2001). Remediation of dyes in textile effluent: a critical review on current treatment technologies with a proposed alternative. Bioresource technology, 77(3), 247-255. https://doi.org/10.1016/S0960-8524(00)00080-8

Roy, M., Sen, P., & Pal, P. (2020). An integrated green management model to improve environmental performance of textile industry towards sustainability. Journal of Cleaner Production, 271, 122656. https://doi.org/10.1016/j.jclepro.2020.122656

Saaty, T. L. (1980). The analytic hierarchy process (AHP). The Journal of the Operational Research Society, 41(11), 1073-1076.

Saaty, T. L. (1990). How to make a decision: the analytic hierarchy process. European journal of operational research, 48(1), 9-26. https://doi.org/10.1016/0377-2217(90)90057-I

Saaty, T. L. (1994). Highlights and critical points in the theory and application of the analytic hierarchy process. European journal of operational research, 74(3), 426-447. https://doi.org/10.1016/0377-2217(94)90222-4

Samsami, S., Mohamadizaniani, M., Sarrafzadeh, M. H., Rene, E. R., & Firoozbahr, M. (2020). Recent advances in the treatment of dye-containing wastewater from textile industries: Overview and perspectives. Process Safety and Environmental Protection, 143, 138-163. https://doi.org/10.1016/j.psep.2020.05.034

Shah, A. A., Walia, S., & Kazemian, H. (2024). Advancements in combined electrocoagulation processes for sustainable wastewater treatment: A comprehensive review of mechanisms, performance, and emerging applications. *Water research*, *252*, 121248. https://doi.org/10.1016/j.watres.2024.121248

Shammas, N. K. (2005). Coagulation and flocculation. In Physicochemical treatment processes (pp. 103-139). Totowa, NJ: Humana Press. https://doi.org/10.1385/1-59259-820-x:103

Shoukat, S., Bhatti, H. N., Iqbal, M., & Noreen, S. (2017). Mango stone biocomposite preparation and application for crystal violet adsorption: a mechanistic study. Microporous and Mesoporous Materials, 239, 180-189. https://doi.org/10.1016/j.micromeso.2016.10.004

Silva, R., Garcia, F. A., Faia, P. M., & Rasteiro, M. G. (2015). Settling suspensions flow modelling: a review. KONA Powder and Particle Journal, 32, 41-56. https://doi.org/10.14356/kona.2015009

Skouteris, G., Rodriguez-Garcia, G., Reinecke, S. F., & Hampel, U. (2020). The use of pure oxygen for aeration in aerobic wastewater treatment: A review of its potential and limitations. Bioresource technology, 312, 123595. https://doi.org/10.1016/j.biortech.2020.123595

Slama, H. B., Chenari Bouket, A., Pourhassan, Z., Alenezi, F. N., Silini, A., Cherif-Silini, H., ... & Belbahri, L. (2021). Diversity of synthetic dyes from textile industries, discharge impacts and treatment methods. Applied Sciences, 11(14), 6255. https://doi.org/10.3390/app11146255

Sqalli Houssini, N., Elqars, E., Fadili, A., & Essadki, A. H. (2024). Removal of textile pollutants by electrocoagulation using all bipolar and monopolar connection mode of iron and aluminum composite electrodes. International Journal of Environmental Science and Technology, 1-18. https://doi.org/10.1007/s13762-023-05398-3

Srinivasan, A., & Viraraghavan, T. (2010). Decolorization of dye wastewaters by biosorbents: a review. Journal of Environmental Management, 91(10), 1915-1929. https://doi.org/10.1016/j.jenvman.2010.05.003

Stojčić, M., Zavadskas, E. K., Pamučar, D., Stević, Ž., & Mardani, A. (2019). Application of MCDM methods in sustainability engineering: A literature review 2008–2018. Symmetry, 11(3), 350. https://doi.org/10.3390/sym11030350

Tahreen, A., Jami, M. S., & Ali, F. (2020). Role of electrocoagulation in wastewater treatment: A developmental review. Journal of Water Process Engineering, 37, 101440. https://doi.org/10.1016/j.jwpe.2020.101440

Tkaczyk, A., Mitrowska, K., & Posyniak, A. (2020). Synthetic organic dyes as contaminants of the aquatic environment and their implications for ecosystems: A review. Science of the total environment, 717, 137222. https://doi.org/10.1016/j.scitotenv.2020.137222

Triantaphyllou, E., & Triantaphyllou, E. (2000). Multi-criteria decision making methods: A Comparative Study, (pp. 5-21). Springer US. https://doi.org/10.1007/978-1-4757-3157-6_2

Tripathi, S., Sharma, P., Singh, K., Purchase, D., & Chandra, R. (2021). Translocation of heavy metals in medicinally important herbal plants growing on complex organometallic sludge of sugarcane molasses-based distillery waste. Environmental Technology & Innovation, 22, 101434. https://doi.org/10.1016/j.eti.2021.101434

Uddin, M., & Alam, F. B. (2023). Health risk assessment of the heavy metals at wastewater discharge points of textile industries in Tongi, Shitalakkhya, and Dhaleshwari, Bangladesh. Journal of Water and Health, 21(5), 586-600. https://doi.org/10.2166/wh.2023.284

Udoh, E. A., Egba, L. P., Oni-Adimabua, O. N., Zogini, U. C., Abdullahi, S., Donatus, U. D., ... & Ihezie, C. M. (2025). Evaluating the efficiency of combined electrocoagulation and electrooxidation in industrial effluent treatment. European Journal of Sustainable Development Research, 9(2). https://doi.org/10.29333/ejosdr/16290

Un, U. T., & Aytac, E. (2013). Electrocoagulation in a packed bed reactor-complete treatment of color and cod from real textile wastewater. Journal of Environmental Management, 123, 113-119. https://doi.org/10.1016/j.jenvman.2013.03.016

Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. European Journal of Operational Research, 169(1), 1–29. https://doi.org/10.1016/j.ejor.2004.04.028

Verma, A. K., Dash, R. R., & Bhunia, P. (2012). A review on chemical coagulation/flocculation technologies for removal of colour from textile wastewaters. Journal of environmental management, 93(1), 154-168. https://doi.org/10.1016/j.jenvman.2011.09.012

Verma, S., Daverey, A., & Sharma, A. (2017). Slow sand filtration for water and wastewater treatment–a review. Environmental Technology Reviews, 6(1), 47-58. https://doi.org/10.1080/21622515.2016.1278278

Wang, L. K., Hung, Y. T., & Shammas, N. K. (Eds.). (2005). Physicochemical treatment processes (Vol. 3, pp. 3141-3197). Totowa, NJ: Humana Press.

Yáñez-Ángeles, M. J., González-Nava, V. J., Castro-Fernández, J. A., García-Estrada, R., Espejel-Ayala, F., Reyes-Vidal, Y., ... & Bustos, E. (2025). Textile-washing wastewater treatment using ozonolysis, electro-coagulation, and electro-oxidation. Electrochimica Acta, 512, 145473. https://doi.org/10.1016/j.electacta.2024.145473

Yaseen, D. A., & Scholz, M. (2019). Textile dye wastewater characteristics and constituents of synthetic effluents: a critical review. International Journal of Environmental Science and Technology, 16, 1193-1226. https://doi.org/10.1007/s13762-018-2130-z

Yeshiwas, A. G., Bayeh, G. M., Tsega, T. D., Tsega, S. S., Gebeyehu, A. A., Alamrie Asmare, Z., ... & Yenew, C. (2025). Scoping Review on Mitigating the Silent Threat of Toxic Industrial Waste: Eco-Rituals Strategies for Remediation and Ecosystem Restoration. Environmental Health Insights, 19, 11786302251329795. https://doi.org/10.1177/11786302251329795

Zafar, A. M., Naeem, A., Minhas, M. A., Hasan, M. J., Rafique, S., & Ikhlaq, A. (2024). Removal of reactive dyes from textile industrial effluent using electrocoagulation in different parametric

conditions of aluminum electrodes. Total Environment Advances, 9, 200087. https://doi.org/10.1016/j.teadva.2023.200087

Zavadskas, E. K., Pamučar, D., Stević, Ž., & Mardani, A. (2020). Multi-criteria decision-making techniques for improvement sustainability engineering processes. Symmetry, 12(6), 986. https://doi.org/10.3390/sym12060986

Zeleny, M., & Cochrane, J. L. (1982). Multiple criteria decision making McGraw-Hill New York. The Journal of the Operational Research Society, 34, 1011-1013. https://doi.org/10.2307/2580902

Zhang, T., Zheng, L., Yang, X., Demeestere, K., & Van Hulle, S. W. (2025). Integrated spectral based monitoring, optimization and control of the combined ozonation and powdered activated carbon adsorption process to remove organic micropollutants from secondary effluent. Water Research, 268, 122588. https://doi.org/10.1016/j.watres.2024.122588

Appendix A:

Table A1: Characterization of raw textile wastewater and seawater for seawater integration study.

Parameter	Unit	Raw wastewater	Seawater	Permissible level* (ECR, 2023)
pH	-	8.16	8.35	6-9
Electrical conductivity	(μS/cm)	2033	55200	1200
DO	(mg/L)	0.14	7.91	≥ 1
TSS	(mg/L)	210	1	100
Turbidity	(NTU)	286	1.66	10
COD	(mg/L)	292	136	200
Color	(Pt-Co)	1552	13	150
*Industrial effluent discharge standards to inland water in Bangladesh.				

Table A2: Characterization of raw textile wastewater for electrode pair evaluation study.

Parameter	Unit	Raw wastewater	Permissible level* (ECR, 2023)
TSS	(mg/L)	221.00-296.00	100.00
Turbidity	(NTU)	309.29-393.00	10.00
COD	(mg/L)	291.00-341.00	200.00
TOC	(ppm)	20.36-39.40	-
pH	-	8.47-8.62	6-9
TDS	(mg/L)	1035-1160	2100
DO	(mg/L)	0.15-0.35	≥ 1
Electrical conductivity	(μS/cm)	1140-1286	1200
*Industrial effluent discharge standards to inland water in Bangladesh.			

Table A3: Characterization of raw textile wastewater for IS process study.

Parameter	Unit	Raw wastewater	Permissible level* (ECR, 2023)
TSS	(mg/L)	264-332	100.00
Turbidity	(NTU)	351.67-391.24	10.00
COD	(mg/L)	331-378	200.00
Color	(Pt-Co)	1524-1896	150.00
*Industrial effluent discharge standards to inland water in Bangladesh			

Table A4: Characterization of different textile wastewater parameters after EC with varying seawater percentages at different retention times of 45 and 90 min.

Parameter	Unit	Seawater infusion pre-electrocoagulation				45 min				90 min			
		0% SW	5% SW	10% SW	15% SW	0% SW	5% SW	10% SW	15% SW	0% SW	5% SW	10% SW	15% SW
pH	-	8.16	8.18	8.21	8.27	9.85	10.31	10.57	11.04	10.64	11.19	11.6	11.31
Electrical conductivity	(µS/cm)	2033	4568	6726	8892	2380	4680	6900	9080	2440	5080	7980	9690
DO	(mg/L)	0.14	0.76	1.14	1.82	0.31	7.24	6.52	6.48	4.77	6.14	6.69	6.12
TSS	(mg/L)	210	209.72	209.59	209.43	215	4	2	4	127	4	2	1
Turbidity	(NTU)	286	276.11	263.57	253.39	204	1.99	2.43	2.01	175	3.45	2.77	3.25
COD	(mg/L)	292	283	276	271	273	174	204	208	264	210	154	164
Color	(Pt-Co)	1552	1506	1459	1412	1531	28	43	59	1495	76	59	78

*Industrial effluent discharge standards to inland water in Bangladesh
Note: SW= Seawater

Table A5: Characterization of different textile wastewater parameters after EC using thirty-six different electrode pairs.

Combination number	Anode	Cathode	Characterization of different textile wastewater parameters after EC process			
			TSS (mg/L)	Turbidity (NTU)	COD (mg/L)	TOC (ppm)
1	C	C	281	257.34	265	21.48
2	Cu	Cu	278	342.6	248	20.3
3	Zn	Zn	271	338.28	172	20.45
4	Zn	C	290	351	120	20.19
5	C	Cu	288	324.5	288	21.53
6	Cu	C	284	339	276	19.35
7	Al	Al	42	291.3	73	9.28
8	Cu	Zn	210	304.8	27	7.24
9	Al	C	137	117.23	23	6.35
10	Al	Cu	1	5.12	103	27.88
11	Al	Zn	2	4.38	107	16.56
12	Zn	Al	3	8.13	104	23.21
13	Cu	Al	160	294.5	82	11.4
14	C	Al	256	346.7	110	25.05
15	C	Zn	238	334.5	258	31.28
16	Zn	Cu	87	172.8	226	17.15
17	SS	SS	26	33.1	238	9.5
18	SS	MS	19	27.26	243	10.6
19	MS	SS	17	3.66	55	21.92
20	C	MS	249	338	254	22.97
21	C	SS	257	333	284	22.38
22	Cu	MS	231	268	112	17.04
23	Cu	SS	226	294	110	20.85
24	Zn	MS	251	352.28	52	22.92
25	Zn	SS	4	9.25	146.07	22.31
26	Al	MS	1	2.95	112.41	21.94
27	Al	SS	2	3.99	116.6	21.65
28	MS	C	75	97.26	156.83	21.88
29	SS	C	151	140.6	164.31	20.94
30	MS	Cu	112	120.3	130.42	29.35
31	SS	Cu	221	331.6	220.12	36.25
32	MS	Zn	59	79	187.46	20.71
33	SS	Zn	61	82	161.05	34.75
34	MS	Al	28	106.1	175.39	32.18
35	SS	Al	14	70.14	172.76	30.79
36	MS	MS	43	86	132	36.15

Table A6: MCDM ranking results for 36 electrode pairs.

Sl. no.	Electrode materials		TOPSIS			VIKOR			PROMETHEE II		
	Anode	Cathode	S_i^+	S_i^-	C_j^*	S_J	R_J	Q_J	$\varphi_{(i)}^+$	$\varphi_{(i)}^-$	$\varphi(i)$
1	C	C	0.1312	0.0188	0.1254	0.9024	0.2492	0.9534	0.023	0.3879	-0.3649
2	Cu	Cu	0.1318	0.0127	0.0876	0.9256	0.244	0.9526	0.0066	0.3947	-0.3881
3	Zn	Zn	0.124	0.0305	0.1971	0.8471	0.2409	0.8988	0.0258	0.3354	-0.3096
4	Zn	C	0.1232	0.0433	0.2601	0.8192	0.25	0.9075	0.0453	0.327	-0.2818
5	C	Cu	0.14	0.005	0.0348	0.9792	0.25	1	0.0031	0.4448	-0.4418
6	Cu	C	0.1323	0.0129	0.0886	0.939	0.2448	0.9627	0.0099	0.4114	-0.4015
7	Al	Al	0.0682	0.0996	0.5935	0.3919	0.2373	0.6261	0.2778	0.1323	0.1455
8	Cu	Zn	0.0904	0.1016	0.5291	0.5141	0.2484	0.7268	0.2588	0.2355	0.0233
9	Al	C	0.0473	0.1166	0.7113	0.2573	0.1552	0.3256	0.3726	0.0924	0.2802
10	Al	Cu	0.0538	0.1105	0.6725	0.2137	0.1501	0.2867	0.3603	0.0365	0.3237
11	Al	Zn	0.0238	0.1254	0.8407	0.1141	0.0656	0	0.435	0.0116	0.4234
12	Zn	Al	0.0404	0.1151	0.7404	0.1756	0.1075	0.1491	0.386	0.0242	0.3619
13	Cu	Al	0.0679	0.099	0.593	0.424	0.2019	0.5486	0.266	0.1525	0.1135
14	C	Al	0.1081	0.0546	0.3353	0.726	0.2432	0.8353	0.0874	0.2759	-0.1886
15	C	Zn	0.1293	0.0154	0.1066	0.8981	0.2391	0.9236	0.0133	0.374	-0.3607
16	Zn	Cu	0.0667	0.0819	0.551	0.4591	0.1754	0.4971	0.2245	0.1461	0.0784
17	SS	SS	0.0506	0.121	0.705	0.2307	0.1859	0.3935	0.3903	0.0835	0.3068
18	SS	MS	0.0517	0.1194	0.6979	0.2364	0.1903	0.4087	0.3858	0.0848	0.3011
19	MS	SS	0.0777	0.108	0.5816	0.2704	0.2269	0.5276	0.3365	0.0694	0.2671
20	C	MS	0.1329	0.0126	0.0869	0.9254	0.2427	0.9491	0.0066	0.3945	-0.3879
21	C	SS	0.1348	0.0083	0.0578	0.9477	0.2461	0.9711	0.0045	0.4147	-0.4102
22	Cu	MS	0.0944	0.0594	0.3863	0.6408	0.2211	0.726	0.1187	0.222	-0.1033
23	Cu	SS	0.108	0.0505	0.3184	0.7102	0.2163	0.753	0.0814	0.2541	-0.1727
24	Zn	MS	0.1224	0.0606	0.3313	0.7544	0.2473	0.8628	0.0964	0.3134	-0.2169
25	Zn	SS	0.0846	0.0988	0.5387	0.3499	0.2328	0.5895	0.282	0.0944	0.1876
26	Al	MS	0.0802	0.1035	0.5633	0.3066	0.2272	0.5493	0.3069	0.076	0.2309
27	Al	SS	0.0791	0.1029	0.5654	0.3077	0.2228	0.5381	0.3046	0.0748	0.2298
28	MS	C	0.0603	0.0867	0.5899	0.3802	0.1351	0.3422	0.2447	0.0874	0.1573
29	SS	C	0.0687	0.0748	0.5212	0.4758	0.1384	0.4063	0.1957	0.134	0.0617
30	MS	Cu	0.0847	0.0739	0.4658	0.4889	0.2169	0.6267	0.1813	0.1328	0.0485
31	SS	Cu	0.1179	0.0297	0.2015	0.8046	0.2305	0.8462	0.0403	0.3074	-0.2671
32	MS	Zn	0.0503	0.0974	0.6595	0.3227	0.1339	0.3058	0.2901	0.0754	0.2147
33	SS	Zn	0.082	0.0826	0.5018	0.4342	0.2167	0.5946	0.2138	0.1105	0.1033
34	MS	Al	0.076	0.0852	0.5284	0.4088	0.1929	0.5155	0.2306	0.1019	0.1287
35	SS	Al	0.0705	0.0923	0.5669	0.3576	0.1801	0.4511	0.2639	0.084	0.1799
36	MS	MS	0.0835	0.0874	0.5115	0.4095	0.2296	0.6154	0.2304	0.1024	0.128

Table A7: Characterization of different textile wastewater parameters after each treatment process.

Integrated system (IS)	TSS (mg/L)					Turbidity (NTU)					COD (mg/L)					Color (Pt-Co)				
	EC	ST	AT	MM filter	AC filter	EC	ST	AT	MM filter	AC filter	EC	ST	AT	MM filter	AC filter	EC	ST	AT	MM filter	AC filter
Process 1	182	141	129	79	65	236.47	186.27	176.13	110.63	90.24	251	214	198	165	133	962	814	743	617	431
Process 2	155	108	92	58	46	210.93	158.79	134.8	91.64	67.92	219	183	161	143	110	979	766	683	630	413
Process 3	158	97	73	43	32	200.31	134.59	113.45	61.29	43.97	209	186	163	135	93	936	723	659	523	337
Process 4	171	104	98	61	52	231.44	145.34	138.46	88.19	68.73	269	197	186	159	119	1112	743	692	518	336
Process 5	136	93	88	53	40	199.74	128.46	120.25	81.96	57.28	220	179	173	148	103	941	720	689	507	333
Process 6	137	85	76	43	28	188.64	128.66	111.27	69.28	38.27	200	154	142	112	76	906	688	631	420	242
Process 7	175	99	95	60	45	236.28	143.25	135.16	86.27	61.07	261	196	187	148	111	1190	812	754	542	313
Process 8	153	92	85	54	45	210.46	136.23	122.38	83.41	65.64	241	182	165	131	92	1004	716	659	518	320
Process 9	178	92	78	42	28	221.65	116.27	99.34	61.48	38.27	238	172	146	112	76	1153	775	680	463	242
Process 10	91	67	63	36	27	125.62	96.61	89.05	53.41	40.82	182	159	146	128	94	561	460	399	321	228
Process 11	63	43	35	22	16	108.12	78.49	63.16	40.38	31.41	157	136	120	92	64	540	386	349	263	161
Process 12	67	41	32	19	14	96.92	63.24	54.17	33.58	23.25	146	107	94	62	38	481	384	331	221	118
Process 13	78	46	41	25	16	115	76.13	71.28	48.2	21.25	168	134	128	100	37	605	453	418	319	124
Process 14	68	41	37	20	13	99.58	63.15	59.6	39.13	28.55	132	103	96	76	53	495	393	360	251	148
Process 15	48	29	26	16	11	67.29	48.13	41.27	25.33	19.1	155	105	91	60	34	435	320	291	183	100

Note: EC= Electrocoagulation, ST= Sedimentation, AT= Aeration, MM= Multimedia, and AC= Activated Carbon.

Table A8: Characterization of different textile wastewater parameters after each treatment process (continued).

Integrated system (IS)	TSS (mg/L)					Turbidity (NTU)					COD (mg/L)					Color (Pt-Co)				
	EC	ST	AT	MM filter	AC filter	EC	ST	AT	MM filter	AC filter	EC	ST	AT	MM filter	AC filter	EC	ST	AT	MM filter	AC filter
Process 16	81	43	39	23	19	124	80.26	72.99	43.17	28.5	152	113	102	87	54	586	419	391	300	161
Process 17	62	34	30	17	10	82.51	51.35	47.16	30.81	23.1	116	97	91	73	46	478	381	357	254	131
Process 18	56	31	27	16	11	83.62	56.13	48.21	30.42	20.31	164	118	99	61	34	467	312	277	186	100
Process 19	28	19	16	9	6	47.19	32.81	29.68	14.92	9.74	98	81	69	55	31	289	227	186	126	68
Process 20	21	13	11	6	4	36.14	23.86	19.68	11.16	7.15	82	68	61	43	27	316	213	173	118	67
Process 21	16	9	7	4	3	24.13	13.25	9.42	4.91	3.18	76	54	39	27	20	151	97	68	44	23
Process 22	23	14	13	8	5	39.48	23.66	21.72	12.27	8.1	71	55	50	41	26	250	172	161	99	55
Process 23	16	9	7	4	3	25.19	17.13	15.99	10.1	6.9	66	51	47	35	23	243	175	163	99	50
Process 24	13	7	6	3	2	20.1	12.38	10.86	7.13	4.87	65	48	43	31	20	130	89	80	43	22
Process 25	23	13	11	6	4	35.16	22.13	20.26	11.51	7.61	64	51	47	38	25	237	173	161	93	51
Process 26	17	9	8	5	3	30.67	17.73	16.26	9.99	6.25	61	46	41	32	21	202	138	127	69	31
Process 27	15	7	6	2	1	19.74	10.18	8.39	3.15	1.67	76	57	49	33	18	132	74	62	33	17

Note: EC= Electrocoagulation, ST= Sedimentation, AT= Aeration, MM= Multimedia, and AC= Activated Carbon.

Table A9: MCDM ranking results for 27 IS processes.

Integrated system (IS)	TOPSIS			VIKOR			PROMETHEE II			AHP
	S_i^+	S_i^-	C_j^*	S_J	R_J	Q_J	$\varphi_{(i)}^+$	$\varphi_{(i)}^-$	$\varphi(i)$	AHP Score
Process 1	0.028	0.000	0.000	1.000	0.250	1.000	0.000	2.630	-2.630	0.740
Process 2	0.024	0.005	0.169	0.823	0.216	0.844	0.710	1.920	-1.210	0.784
Process 3	0.019	0.010	0.342	0.626	0.182	0.678	1.498	1.132	0.366	0.832
Process 4	0.022	0.007	0.226	0.781	0.218	0.826	0.875	1.755	-0.880	0.796
Process 5	0.020	0.008	0.284	0.708	0.192	0.739	1.168	1.462	-0.294	0.815
Process 6	0.015	0.014	0.484	0.509	0.136	0.527	1.963	0.666	1.297	0.867
Process 7	0.021	0.008	0.288	0.709	0.201	0.757	1.164	1.465	-0.301	0.815
Process 8	0.019	0.009	0.319	0.702	0.189	0.730	1.194	1.436	-0.242	0.820
Process 9	0.013	0.016	0.552	0.439	0.119	0.457	2.244	0.385	1.859	0.885
Process 10	0.016	0.013	0.451	0.506	0.166	0.585	1.974	0.656	1.318	0.863
Process 11	0.011	0.018	0.632	0.342	0.108	0.387	2.633	-0.003	2.636	0.908
Process 12	0.006	0.022	0.772	0.233	0.067	0.250	3.068	-0.438	3.506	0.940
Process 13	0.006	0.023	0.796	0.215	0.063	0.234	3.140	-0.511	3.651	0.946
Process 14	0.009	0.020	0.700	0.287	0.081	0.306	2.851	-0.222	3.073	0.924
Process 15	0.005	0.023	0.815	0.192	0.054	0.204	3.232	-0.602	3.834	0.951
Process 16	0.009	0.020	0.693	0.306	0.079	0.311	2.777	-0.147	2.924	0.920
Process 17	0.007	0.022	0.760	0.226	0.063	0.240	3.097	-0.467	3.564	0.940
Process 18	0.005	0.024	0.841	0.165	0.052	0.187	3.338	-0.709	4.047	0.958
Process 19	0.003	0.025	0.886	0.105	0.033	0.118	3.580	-0.951	4.531	0.972
Process 20	0.003	0.026	0.908	0.083	0.028	0.098	3.670	-1.040	4.710	0.978
Process 21	0.001	0.027	0.968	0.029	0.010	0.034	3.885	-1.255	5.140	0.992
Process 22	0.002	0.026	0.925	0.074	0.020	0.077	3.706	-1.076	4.782	0.981
Process 23	0.002	0.027	0.939	0.058	0.019	0.066	3.767	-1.137	4.905	0.985
Process 24	0.001	0.027	0.969	0.029	0.010	0.035	3.884	-1.254	5.139	0.992
Process 25	0.002	0.026	0.933	0.065	0.018	0.068	3.742	-1.112	4.854	0.983
Process 26	0.001	0.027	0.961	0.04	0.014	0.047	3.841	-1.211	5.052	0.990
Process 27	0.000	0.028	1.000	0.000	0.000	0.000	4.000	-1.370	5.370	1.000

Table A10: ANOVA test results for the impact of retention time and seawater percentage on various water quality parameters using Design-Expert 11 software.

Parameter	Mean	Std. Dev.	R^2	R^2-(adj)	C.V. %	Lack of Fit	df	Mean square	R^2-(predicted)	Analysis of variance (ANOVA)			Efficiency model
										F-value	p-value	Significance	
pH	10.89	0.1456	0.9542	0.9215	1.34	0.1485	6	0.0247	0.7406	29.16	0.0002	Yes	$Y = 11.08 + 0.3736 \times A + 0.4616 \times B - 0.1057 \times AB - 0.0832 \times A^2 - 0.3272 \times B^2$
Electrical conductivity (µS/cm)	6059.23	201.30	0.9964	0.9938	3.32	283,700.0	5	56731.72	0.9839	388.81	<0.0001	Yes	$Y = 6275.28 + 268.75 \times A + 3469.14 \times B + 174.75 \times AB - 14.20 \times A^2 - 418.19 \times B^2$
DO (mg/L)	5.59	1.02	0.8446	0.7337	18.30	7.33	6	1.05	0.2539	7.61	0.0095	Yes	$Y = 6.64 + 0.2940 \times A + 1.74 \times B - 0.9892 \times AB + 0.1021 \times A^2 - 2.28 \times B^2$
Removal efficiency of TSS (%)	80.55	11.10	0.9433	0.9028	13.77	861.71	6	143.62	0.8018	23.29	0.0003	Yes	$Y = 100.16 + 4.89 \times A + 37.13 \times B - 8.80 \times AB + 2.45 \times A^2 - 42.21 \times B^2$
Removal efficiency of turbidity (%)	83.98	8.19	0.9525	0.9186	9.76	470.03	6	78.34	0.8725	28.07	0.0002	Yes	$Y = 100.01 + 1.32 \times A + 30.41 \times B - 2.35 \times AB + 1.80 \times A^2 - 34.81 \times B^2$
Removal efficiency of COD (%)	30.11	5.33	0.9121	0.8493	17.71	198.96	6	33.16	0.7106	14.52	0.0014	Yes	$Y = 37.85 + 2.73 \times A + 13.91 \times B + 4.90 \times AB + 0.2227 \times A^2 - 15.50 \times B^2$
Removal efficiency of color (%)	74.62	11.61	0.9535	0.9203	15.55	943.07	5	188.61	0.8622	28.72	0.0002	Yes	$Y = 97.67 - 0.3101 \times A + 43.31 \times B - 0.6838 \times AB + 3.52 \times A^2 - 50.87 \times B^2$

Note: Y= Parameter, A= Retention time (min), B= Seawater percentage.

Table A11: Expected and predicted value of physicochemical parameters from ANOVA test using Design-Expert 11 software.

Run order	pH		Electrical conductivity (µS/cm)		DO (mg/L)		Removal efficiency of TSS (%)		Removal efficiency of turbidity (%)		Removal efficiency of COD (%)		Removal efficiency of color (%)	
	Expected value	Predicted value	Expected value	Predicted value	Expected value	Predicted value	Expected value	Predicted value	Expected value	Predicted value	Expected value	Predicted value	Expected value	Predicted value
1	10.31	10.40	6340	6275.28	6.30	6.11	99.09	100.00	99.03	95.69	36.47	35.34	96.16	97.67
2	11.15	11.08	9110	93326.22	6.12	5.51	99.05	100.00	98.99	100.00	38.22	36.26	96.16	97.67
3	11.31	11.40	9080	8868.53	6.48	6.90	98.57	100.00	99.30	98.52	40.41	30.62	98.20	81.9
4	9.85	9.73	2380	2279.75	2.54	2.62	98.57	100.00	98.79	89.99	30.14	36.62	96.20	94.63
5	11.19	11.22	2410	2467.75	6.53	6.64	99.05	100.00	28.67	32.99	6.50	10.84	1.35	6.64
6	11.39	11.37	2440	2467.75	6.64	6.45	98.10	77.72	38.81	40.34	8.04	8.44	3.67	7.39
7	11.13	11.22	4680	4847.73	6.41	7.04	19.77	20.82	99.07	100.00	43.83	44.12	94.97	92.64
8	11.04	10.86	7980	7697.99	7.24	5.29	99.52	93.62	33.74	34.87	28.08	32.81	95.65	81.02
9	10.24	10.29	6340.00	6275.28	4.77	4.01	99.31	95.08	99.30	85.78	28.76	28.85	96.16	97.67
10	10.57	10.78	9690.00	9755.53	6.14	6.54	0.000	9.59	98.99	100.00	37.07	37.85	2.51	3.49
11	11.15	11.08	6340.00	6275.28	6.52	7.11	98.09	93.36	99.15	100.00	37.08	37.85	95.63	90.11
12	10.64	10.69	6900.00	7043.99	6.69	7.04	39.52	36.96	99.03	100.00	47.26	45.35	96.20	100.00
13	11.60	11.45	5080.00	5268.73	0.31	1.44	98.57	97.72	98.86	96.46	9.59	6.49	97.23	100.00

Note: Expected values are generated by using Design-Expert 11 software; Predicted values are generated by using equations mentioned in table 4.2.

Appendix B:

Outline of the thesis work

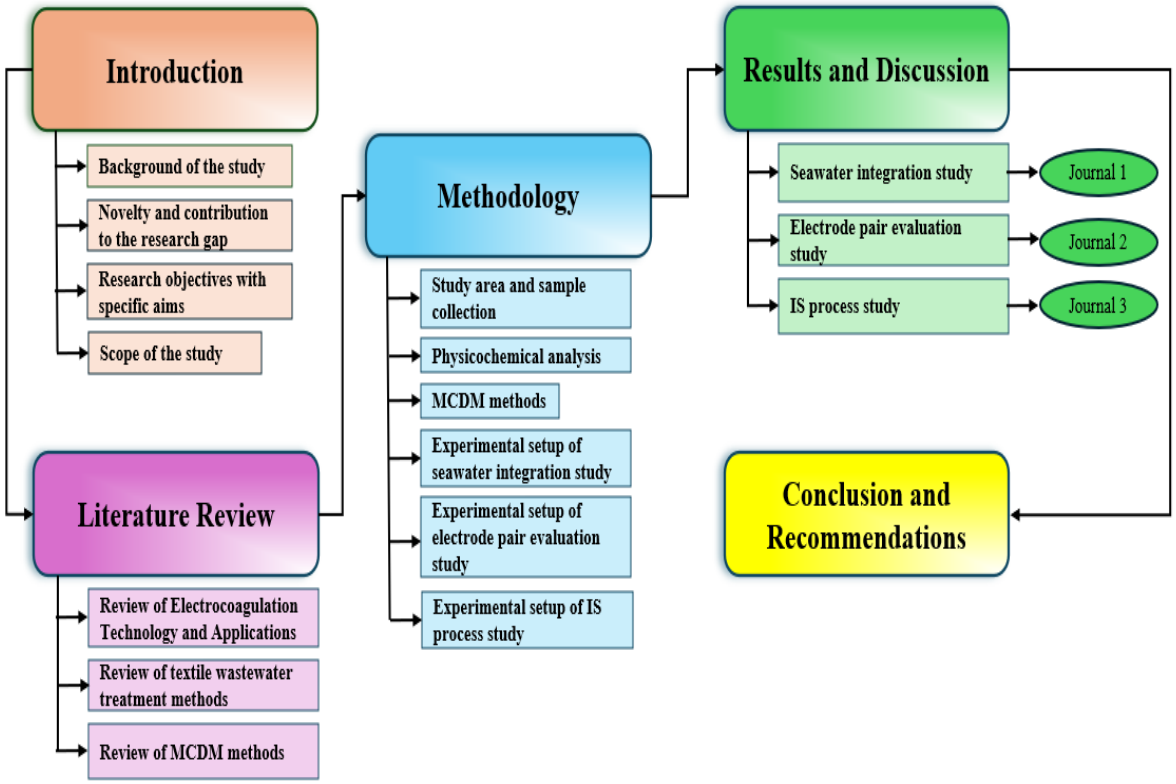

Figure 0.1: Structure and outline of the thesis work.

Novelty and Contribution to The Research Gap

Despite extensive research in EC technology and textile wastewater treatment, several critical knowledge gaps persist that limit the widespread adoption and optimal performance of these systems. This comprehensive study addresses these gaps through innovative approaches and systematic integration, providing significant contributions to the field of electrochemical wastewater treatment.

Research Gap 1: Seawater Integration in EC Processes

Traditional EC systems rely heavily on synthetic chemical additives to enhance conductivity and treatment efficiency, leading to increased operational costs and potential secondary pollution. While seawater's natural ionic content and high conductivity present obvious advantages for

electrochemical processes, no comprehensive study has systematically investigated the integration of seawater into EC systems for textile wastewater treatment. The existing literature lacks fundamental understanding of how seawater's complex ionic composition affects pollutant removal mechanisms, optimal integration ratios, and the dual enhancement effects of conductivity improvement and pollutant dilution.

Novel Contribution

This research pioneers the first comprehensive investigation of seawater-enhanced EC for textile wastewater treatment, establishing the dual enhancement mechanism theory and developing predictive models for optimal seawater integration. The study introduces a novel cost-reduction strategy particularly beneficial for coastal textile manufacturing facilities while eliminating chemical additive requirements.

Research Gap 2: Systematic Electrode Material Optimization Using Multi-Criteria Frameworks

Current electrode selection practices in EC rely primarily on empirical approaches or single-parameter optimization, often resulting in suboptimal performance across multiple pollutant categories. While numerous studies have investigated individual electrode materials, no comprehensive systematic evaluation has been conducted to compare multiple electrode pair combinations using robust multi-criteria decision-making frameworks. The literature lacks guidance for selecting optimal electrode configurations that balance performance across diverse pollutant types while considering practical implementation constraints.

Novel Contribution

This study presents the first systematic evaluation of thirty-six electrode pair combinations using advanced multi-criteria decision-making methodologies (TOPSIS, VIKOR, PROMETHEE II). The research establishes a comprehensive electrode selection framework that identifies the Al-Zn combination as the optimal balanced solution, providing practical guidance for electrode material selection across diverse industrial applications. The integration of multiple MCDM methods ensures robust decision-making and establishes new standards for electrode optimization research.

Research Gap 3: Integrated Multi-Stage Treatment System Development and Optimization

While EC demonstrates excellent performance for primary pollutant removal, achieving discharge-compliant water quality standards requires integration with complementary treatment processes. However, the literature lacks comprehensive studies on systematic integration of EC with sequential treatment stages, particularly the optimization of retention times across multiple treatment units. Existing research typically focuses on individual treatment processes rather than exploring synergistic effects and operational optimization of integrated systems using real industrial wastewater.

Novel Contribution

This research develops the first comprehensive five-stage integrated treatment system combining EC, ST, AT, MM filtration, and AC filtration with systematic optimization of twenty-seven process configurations. The study establishes the sequential treatment synergy theory, demonstrating how each stage contributes distinctly to overall performance. The application of four MCDM methods for system optimization represents a novel approach to integrated treatment system design, providing a replicable framework for industrial implementation.

Research Gap 4: Comprehensive Multi-Criteria Decision-Making Applications in Electrochemical Treatment

Environmental engineering applications increasingly require consideration of multiple competing objectives, yet the application of comprehensive multi-criteria decision-making frameworks in electrochemical treatment optimization remains limited. The literature lacks systematic comparison of different MCDM methodologies for treatment system optimization, particularly in addressing the complex trade-offs between removal efficiency, operational costs, energy consumption, and environmental sustainability.

Novel Contribution

This research establishes the first comprehensive MCDM framework for electrochemical treatment optimization, systematically applying and comparing four distinct methodologies (TOPSIS, VIKOR, PROMETHEE II, AHP) across different optimization scenarios. The study validates the robustness of MCDM approaches through methodological triangulation and provides practical guidelines for decision-makers facing complex optimization challenges in environmental engineering applications.

Overarching Research Contribution

This comprehensive study fills critical knowledge gaps in EC technology through systematic investigation and innovative integration approaches. The research establishes new theoretical frameworks (dual enhancement mechanism, sequential treatment synergy), develops practical optimization tools (predictive models, MCDM frameworks), and demonstrates immediate industrial applicability through real wastewater treatment. The integrated approach transforms conventional EC from a standalone treatment method into a comprehensive, optimized, and sustainable solution for industrial wastewater management.

The novelty of this research lies not only in individual innovations but also in the systematic integration of multiple optimization approaches, creating a comprehensive framework that addresses technical, and environmental considerations simultaneously. This holistic approach represents a paradigm shift in electrochemical treatment research, moving from component-level optimization to system-level integration and providing a replicable methodology for addressing complex environmental engineering challenges. The research outcomes provide immediately implementable solutions for textile industries worldwide, with particular benefits for developing countries seeking cost-effective and sustainable wastewater treatment technologies. The developed frameworks and optimization tools facilitate rapid technology transfer and adaptation across diverse industrial contexts, supporting global efforts toward sustainable industrial development and environmental protection.

Geographical and Industrial Scope

The research focuses on textile wastewater treatment with primary data collection conducted in Bangladesh, specifically targeting effluents from textile manufacturing facilities operated by Apex Holdings Ltd. in the Shafipur area of Kaliakoir Upazila, Gazipur District. The study utilizes real industrial textile wastewater to ensure practical relevance and immediate applicability of findings. Seawater samples for integration studies are sourced from Saint Martin Island coastal waters, representing typical marine water composition for coastal industrial applications.

Technical Scope and Research Phases

Phase 1: Seawater Integration Enhancement (Fundamental Process Innovation)

- Investigation of seawater integration percentages ranging from 0% to 15% in EC processes.
- Systematic evaluation of retention times from 45 to 90 min to optimize treatment duration.
- Assessment of physicochemical parameters including pH, TSS), electrical conductivity, dissolved oxygen (DO), turbidity, COD, and color.
- Development of predictive mathematical models using Central Composite Design (CCD) and ANOVA.
- Economic analysis comparing seawater-enhanced systems with conventional EC approaches.
- Investigation limited to carbon anode and mild steel cathode configuration for focused analysis.

Phase 2: Electrode Material Optimization (Systematic Material Selection)

- Comprehensive evaluation of six electrode materials: Aluminum (Al), Zinc (Zn), Carbon (C), Copper (Cu), Mild Steel (MS), and Stainless Steel (SS).
- Systematic testing of thirty-six electrode pair combinations to identify optimal configurations.
- Pollutant removal assessment for TSS, turbidity, COD, and Total Organic Carbon (TOC).
- Application of three Multi-Criteria Decision-Making (MCDM) methods: TOPSIS, VIKOR, and PROMETHEE II.
- Standardized operating conditions with 60-min retention time and 20V applied voltage.
- Focus on monopolar electrode configuration for practical industrial applicability.

Phase 3: Integrated Multi-Stage System Development (Advanced System Integration)

- Development of five-stage treatment system incorporating EC, ST, AT, MM filter, and AC filter.
- Systematic evaluation of twenty-seven process configurations through retention time optimization.

- EC retention times: 20, 40, and 60 min.
- ST retention times: 60, 120, and 180 min.
- AT retention times: 20, 40, and 60 min.
- Application of four MCDM methods: TOPSIS, VIKOR, PROMETHEE II, and Analytic Hierarchy Process (AHP).
- Utilization of Al-Zn electrode configuration based on Phase 2 optimization results.

Analytical and Methodological Scope

Physicochemical Analysis Parameters:

- Primary pollutants: TSS, turbidity, COD, color, and TOC.
- Supporting parameters: pH, electrical conductivity, dissolved oxygen, total dissolved solids (TDS).
- All measurements conducted according to Standard Methods for the Examination of Water and Wastewater (Rice, 2012).
- Duplicate measurements with arithmetic mean reporting for accuracy and reproducibility

Statistical and Optimization Methods:

- CCD for experimental design and model development.
- ANOVA for statistical validation and significance testing.
- Multi-Criteria Decision-Making (MCDM) methods for complex optimization scenarios.
- Regression analysis for predictive model development.
- Radar chart visualization for comprehensive performance assessment.

Equipment and Instrumentation Scope:

- Laboratory-scale experimental setups ranging from 600 cm^3 to 4000 cm^3 treatment volumes.

- Standardized analytical instruments including HACH spectrophotometers, turbidimeters, and multi-parameter meters.
- Controlled power supply systems (Lodestar LP3005D; 0-30 V, 0-5 A) for consistent electrical conditions.
- Custom-fabricated treatment units for ST, AT, and filtration processes.

Performance Evaluation Scope

Treatment Efficiency Metrics:

- Pollutant removal efficiency calculations using standardized formulas.
- Stage-wise performance assessment for integrated system evaluation.
- Comparative analysis with conventional treatment methods and literature benchmarks.
- Economic performance indicators including power consumption and operational cost analysis.

Optimization Criteria:

- Technical performance: pollutant removal efficiency across multiple parameters.
- Economic viability: operational cost reduction and energy consumption minimization.
- Environmental sustainability: chemical consumption reduction and sludge minimization.
- Practical applicability: scalability potential and industrial implementation feasibility.

Publications From This Thesis

1. Ahmed T, Ahsan A, Khan MH, Nahian TK, Antar RH, Hasan A, Karim MR, Shafiquzzaman M, Imteaz M. Comprehensive study on the selection and performance of the best electrode pair for electrocoagulation of textile wastewater using multi-criteria decision-making methods (TOPSIS, VIKOR and PROMETHEE II). Journal of Environmental Management. 2024 Jul 1; 363:121337. ISSN 0301-4797. Impact factor-8.4, SJR rank- Q1
https://doi.org/10.1016/j.jenvman.2024.121337

2. Ahmed T, Khan MH, Ahsan A, Islam N, El-Sergany M, Shafiquzzaman M, Imteaz M, Al-Ansari N. Evaluation of the impacts of seawater integration to electrocoagulation for the removal of pollutants from textile wastewater. Environmental Sciences Europe. 2024 Apr 16; 36(1):77, ISSN 2190-4707. Impact factor-6.0, SJR rank-Q1
http://dx.doi.org/10.1186/s12302-024-00896-8