Investigation of Electrochemical Treatment for Real Hospital Wastewater and its Future Prospect

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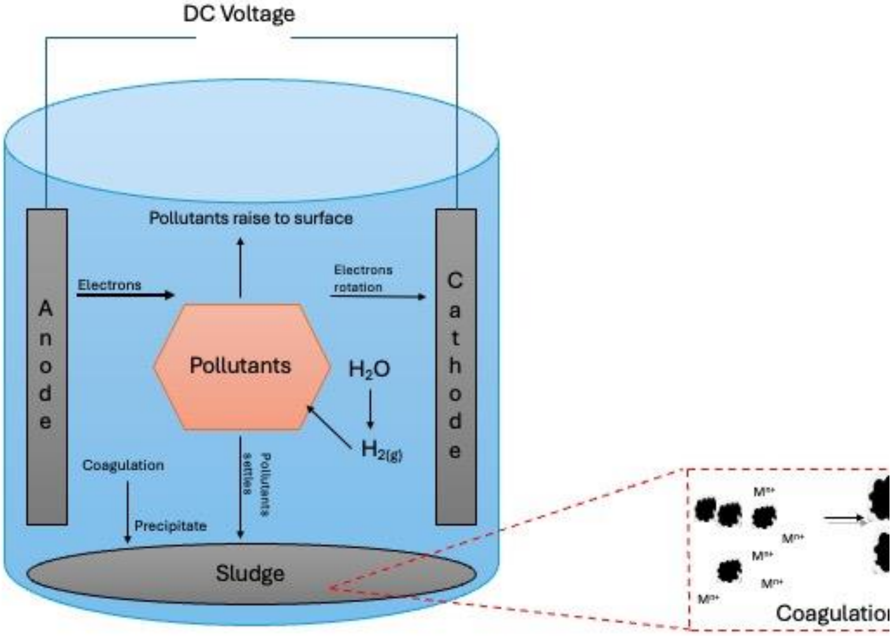
GRAPHICAL ABSTRACT



Abstract

Purpose: This study investigates the efficacy of electrochemical remediation techniques in treating hospital wastewater, focusing on parameters including turbidity, color, BOD, COD, DO, coliform, and E. coli. **Design/Methodology/Approach:** The study conducts a comprehensive analysis of various pollutant parameters, evaluating the impact of contact time on pollutant reduction. Electrochemical methods are explored for their potential in mitigating these parameters.

Conclusions: The findings demonstrate the effectiveness of electrochemical techniques in reducing a range of pollutant parameters, with significant reductions observed in turbidity (up to 99%), color (51%), BOD (99%), COD (60%), and microbial contaminants such as E. coli and coliform (up to 48%). Notably, the study reveals that higher voltage doesn't consistently result in superior performance. **Limitations/Consequences of Research:** While the study showcases promising results, certain limitations and challenges are acknowledged, including the need for further research to address these constraints and optimize electrochemical remediation processes.

Practical Value: The study highlights the practical potential of electrochemical techniques as an effective means of wastewater treatment in hospital settings, offering insights into their application and benefits for environmental sustainability. **Originality and Significance of Results:** This research contributes novel insights into the application of electrochemical methods for hospital wastewater treatment, emphasizing their efficacy in reducing various pollutant parameters and providing a foundation for future research directions in this field.

Keywords: Hospital wastewater; electrochemical treatment; polluted water; electrodisinfection.

1. Introduction

Hospital wastewater poses a multifaceted environmental challenge due to its diverse pollutant composition and the presence of hazardous microorganisms, including Escherichia coli (*E. coli*), which serves as a key indicator of fecal contamination and potential health risks (Majumder et al., 2021). However, beyond E. coli, parameters such as Biological Oxygen Demand (BOD), Carbon Monoxide (CO), turbidity, Dissolved Oxygen (DO), and coliform bacteria also demand attention in wastewater treatment (Chopra, 2011; Loucif et al., 2020). Traditionally, chlorine-based disinfection methods have been employed to address microbial contamination in hospital wastewater (Wibowo et al., 2023b). However, the use of chlorine can lead to the formation of harmful by-products like trihalomethanes, underscoring the need for alternative, environmentally sustainable approaches (Mazhar et al., 2020).

Various treatment methodologies encompassing physical, biological, and chemical processes have been explored for wastewater treatment, including adsorption (Rianjanu et al., 2023; Wibowo et al., 2022a), phytoremediation (Wibowo et al., 2023d), precipitation (Pohl, 2020), filtration (Ates and Uzal, 2018), microbial fuel cells (Kumar et al., 2019), constructed wetlands (Wibowo et al., 2023e), chemical reagents and electrokineticcs (Wang et al., 2005). These methods exhibit efficacy in removing diverse pollutants, including heavy metals (Wibowo et al., 2024), organic dyes (Wibowo et al., 2023c), and microbial contaminants (Kaur et al., 2020). However, their suitability depends on the specific characteristics of the contaminants present in the wastewater.

One promising avenue for hospital wastewater treatment is electrochemical treatment, or electrodisinfection, which utilizes electrochemical processes to eradicate microorganisms. Electrodisinfection offers advantages over traditional chemical methods by minimizing the formation of harmful by-products.

By applying an electric potential to the wastewater, electrodisinfection enables the destruction of microbial contaminants through electrooxidation and electroporation mechanisms (Pi et al., 2022). The efficacy of electrodisinfection is influenced by parameters such as applied potential and contact time between electrodes and wastewater (Vanamo and Bobacka, 2014). Understanding these factors is crucial for optimizing treatment efficiency and ensuring reliable disinfection outcomes. Electrochemical treatment methods offer several advantages for managing hospital wastewater. First and foremost, they are known for their simplicity and adaptability (Yadav and Kamsonlian, 2022), making them suitable for handling varying effluent compositions commonly encountered in hospital settings. These methods can efficiently target and remove a diverse array of pollutants found in hospital wastewater (Ouarda et al., 2019), including heavy metals (Tran et al., 2017), pharmaceuticals (Ouarda et al., 2019), and organic compounds (Poza-Nogueiras et al., 2019). Moreover, the flexibility of electrochemical processes allows for customization to specifically address the unique contaminant profile of a particular wastewater stream. One significant benefit of electrochemical treatment is its minimal reliance on additional chemicals. Unlike some conventional treatment methods that necessitate the use of multiple chemical agents, electrochemical processes often require minimal or even no added chemicals. This not only simplifies the treatment process but also reduces the potential for introducing further pollutants into the wastewater stream, aligning with the goal of sustainable and environmentally friendly wastewater management practices.

Furthermore, electrochemical techniques can offer cost-effective solutions for wastewater treatment in hospital facilities. While initial setup costs may be involved, the long-term operational savings due to reduced chemical usage and simpler treatment processes can make electrochemical methods economically advantageous over time. To fulfil the gap of electrochemical treatment for hospital wastewater, this study investigates the effectiveness of electrodisinfection in treating hospital wastewater contaminated with E. coli, alongside monitoring parameters like BOD, CO, turbidity, DO, and coliform levels. This study is the crucial study to get the holistic information about removal mechanism and performance of electrochemical remediation for treating hospital wastewater. The novelty of this study is analysis of various types of pollutants, this study will fulfil the information from previous study. For example, the previous study using synthetic hospital wastewater with pharmaceutical parameters (Ouarda et al., 2018), other study showed the same pollutants types (Ouarda et al., 2019) This study will give the crucial information due to the unique pollutant parameters. In addition, to the best our knowledge, this study will be the first study that analysis these types of pollutants parameter from hospital wastewater.

By systematically analyzing different applied potentials and contact times, we aim to discern the drivers of electrodisinfection efficiency and contribute to the development of advanced wastewater treatment strategies tailored to healthcare facilities. Through this research, we aspire to advance environmental engineering and public health by exploring innovative approaches to mitigate the complexities associated with hospital wastewater management. Ultimately, our findings can inform the design of sustainable and efficient wastewater treatment systems, promoting environmental stewardship and safeguarding public health against a spectrum of contaminants.

2. Materials and Methods

2.1 Equipment and Materials

The equipment used in this study includes a set of electrodisinfection apparatus (chamber, aluminum electrode, carbon electrode, wastewater container, DC regulated power supply, and chemical glassware as containers for treated wastewater). Additionally, micropipettes and tips, a Laminar Air Flow (LAF) cabinet, petri dishes, droppers, vials, test tubes, test tube racks, stirring rods, spatulas, Erlenmeyer flasks, and a vortex were utilized. The materials utilized in this research comprise hospital wastewater obtained from one of the hospitals in Lampung, nutrient agar (NA) (Oxoid), distilled water, tissues, wrap, alcohol, gauze, cotton, aluminum foil, paper, rubber bands, and gloves.

2.2 Sampling of Hospital Wastewater

The systematic collection of hospital wastewater followed precise protocols outlined in SNI 8990.2021 for Physical-Chemical Wastewater Sampling (Badan Standarisasi Nasional Republik Indonesia, 2021). Utilizing grab sampling techniques, a weighted bucket was strategically positioned at the hospital wastewater inlet to capture samples accurately (Pabón, 2023). Subsequently, the collected wastewater was carefully transferred into sterilized plastic bottles and promptly transported to the laboratory in insulated cool boxes to preserve its integrity. Prior to undergoing electrodisinfection treatment, thorough analysis for Escherichia coli content was conducted. To mitigate any potential contamination, samples were meticulously collected in sterile containers and stored under optimal conditions to maintain their fidelity during transit to the laboratory. This method ensured that samples were representative of various points within the hospital's wastewater treatment system, facilitating comprehensive analysis and effective treatment protocols

2.3 Treatment of Wastewater Using Electrodisinfection Method

The hospital wastewater obtained was poured into a glass container connected to a hose leading to a chamber containing carbon and aluminum electrodes, which were subjected to electrical current at predetermined potentials and contact times (Abdel-Shafy et al., 2019). In this study, we variate the time contacts and potential of electrochemical method fue to the previous study only provide up to 75 minutes. The wastewater was then subjected to potentials of 5, 10, and 15 volts, with each potential variation having contact times of 30, 60, 90, and 120 minutes, the longer time contacts expected will improve the removal percentage of pollutants. Afterward, the wastewater in the chamber was discharged and collected using chemical glassware. Subsequently, samples were analyzed for each variation.

2.4 Physicochemical and Microbiological Analysis

Basic physicochemical parameters such as pH, temperature, conductivity, and turbidity were promptly assessed onsite using portable meters to ensure real-time monitoring and accurate data collection. For more comprehensive analysis, laboratory procedures were employed to determine parameters including BOD, COD, and DO through established methods such as the Winkler method for DO and spectrophotometric analysis for COD. Microbiological examination involved quantifying Escherichia coli levels as well as coliform bacteria in the hospital wastewater samples, utilizing standard techniques like membrane filtration or the Most Probable Number method for enumeration.

In assessing the efficacy of electrodisinfection treatment in laboratory-scale experiments with various potential voltage and contact time variations, meticulous protocols were followed. All equipment, including tips, test tubes, and petri dishes, underwent thorough sterilization procedures involving autoclaving at 121°C and 1 atm pressure for 15 minutes, followed by drying in an oven at 60°C for 1 hour and sterilization with UV light in a laminar air flow cabinet. Nutrient agar was prepared by dissolving 5.6 grams in 200 mL of distilled water, sterilized in an autoclave, and then utilized for microbial culture. Sample dilutions were meticulously prepared, ranging from 101 to 103, and plated onto petri dishes containing nutrient agar. Following incubation for 24 hours, Escherichia coli bacterial colonies were enumerated and compared between control (untreated wastewater) and treated samples. Colony-forming units per milliliter (CFU/mL) were calculated using Equation 1, facilitating precise quantification and evaluation of treatment efficacy.

2.5 Experimental Setup for Electrodisinfection:

Electrochemical treatment experiments were conducted using a laboratory-scale setup featuring electrodes submerged in hospital wastewater samples. Electrodes, crafted from appropriate materials like stainless steel or titanium, were meticulously chosen to ensure compatibility with the electrochemical process and prevent any potential contamination. A broad spectrum of applied potentials, ranging from 1 V to 10 V, coupled with varied contact times between electrodes and wastewater (spanning minutes to hours), were systematically explored to gauge their impact on electrodisinfection efficiency. Within a reaction vessel equipped with electrodes, hospital wastewater samples were subjected to the electrochemical process initiated by applying the predetermined voltage, thereby instigating an electric field within the wastewater. The duration of electrodisinfection varied according to experimental conditions, with samples methodically collected at specified intervals for subsequent analysis.

Post-treatment, samples underwent meticulous analysis to ascertain residual E. coli levels, coliform counts, and alterations in physicochemical parameters. Microbiological assessment entailed plating samples on selective agar media followed by meticulous colony counting to precisely quantify microbial reduction. Simultaneously, physicochemical parameters were re-evaluated post-treatment to gauge the alterations induced by electrodisinfection.

In preparation, reaction tubes containing 4.5 mL of sterile NaCl solution were first assembled. Samples underwent dilution ranging from 101 to 103, with 500 µL of sample transferred into reaction tube 101 and vortexed. Subsequently, 500 µL of the 101 dilution was transferred into reaction tube 102, homogenized via vortexing. From the 102 dilution, 1 mL was plated onto petri dishes, onto which 15 mL of nutrient agar, in liquid form, was poured. Following solidification, petri dishes were covered with plastic wrap and incubated for 24 hours in an incubator. After this incubation period, the quantity of Escherichia coli bacterial colonies was enumerated and compared between the control (untreated wastewater) and the samples. The calculation of colony-forming units per milliliter (CFU/mL) followed Equation 1, providing a quantitative measure of microbial presence and treatment efficacy.

$$\text{CFU/mL (g)} = \text{Number of Colonies} / \text{Volume of Inoculated Sample} \qquad \text{Eq. 1}$$

2.6 Bibliometric and Recent Trends Analysis

The bibliometric analysis in this study utilized VOSViewer (open source) version 1.6.20 software for mapping purposes. The Scopus database was accessed via https://www.sciencedirect.com, using the search keywords "electrochemical hospital wastewater treatment" to collect relevant literature. The methodology for analysis and screening documents was adapted from the framework established in a previous study by Gusti Wibowo et al., (2024), employing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines of 2020. The process encompassed several key steps, including study selection, data extraction, data synthesis, quality assessment, sensitivity analysis, and reporting, ensuring a comprehensive and systematic approach to the bibliometric investigation.

Result and Discussion

3.1 Time contact effects

Figure 1 showed the outcomes of electrochemical remediation applied to address various pollutants. The findings of this study provide compelling evidence that the duration of contact time significantly influences key parameters including color, turbidity, DO, BOD, coliform, and E. coli levels in hospital wastewater, this crucial parameters not only found in hospital wastewater, in line if the wastewater does not treated it is possible to contaminate water bodies like previous study in Nigeria that the water body was polluted by BOD, DO and impacted in public health issue (Mbah et al., 2017). In terms of color removal, organic dyes pose a significant challenge due to their adverse effects on aquatic ecosystems and human health (Taher et al., 2023). These dyes often persist in water bodies, leading to aesthetic pollution and potential toxicity to aquatic life (Sharma et al., 2021). Additionally, some organic dyes have been linked to carcinogenic properties, dramatics effect and allergic, emphasizing the urgency of their removal from water (Tkaczyk et al., 2020).

Furthermore, electrochemical methods offer distinct advantages over alternative techniques for treating hospital wastewater. Notably, the efficacy of electrochemical remediation in reducing color levels stands out, surpassing conventional treatment methods which often struggle to sufficiently address the complexities associated with organic dye removal. Through the utilization of electrochemical processes such as electrocoagulation or electrooxidation, this study underscores the promising outcomes achieved in mitigating color contamination in hospital wastewater.

In contrast to alternatives like adsorption, which has shown efficacy in treating inorganic pollutants (Budihardjo et al., 2021; Wibowo et al., 2022b), electrochemical approaches demonstrate superiority in addressing color pollutants. Moreover, while phytoremediation has been acknowledged for its potential in managing various pollutant parameters, including those observed in this study, it is accompanied by challenges such as adverse effects on plant health and the logistical hurdles of managing contaminated biomass (Imron et al., 2023). Comparatively, the electrochemical approach emerges as a robust solution with promising results and potentially fewer drawbacks, significantly enhancing the arsenal of wastewater treatment methods available for hospital wastewater remediation.

This study further confirms that increasing the voltage does not necessarily lead to better performance in color removal. This observation aligns with the findings regarding turbidity and COD, as these pollutants exhibit more effective reduction at 5 volts compared to 10 and 15 volts. The rationale behind this phenomenon lies in the intricate interplay of electrochemical processes occurring within the remediation system. At higher voltages, there is a risk of overoxidation or excessive generation of reactive species, which may inadvertently lead to the formation of undesirable byproducts or hinder the efficiency of pollutant removal. Additionally, higher voltages can result in increased energy consumption and operational costs without proportional improvements in treatment efficacy. The findings of this study align with previous research indicating that the color parameter can be reduced by up to 35% after 40 minutes of contact time (Shen et al., 2006). Moreover, the study highlights the significant influence of temperature and modifications to the anode and cathode, emphasizing their impact on pollutant reduction (Shen et al., 2006). These additional variables underscore the complexity of the electrochemical process and emphasize the importance of considering various factors to optimize pollutant remediation effectively.

The optimal voltage for electrochemical remediation processes depends on various factors, including the nature of the pollutants, electrode materials, electrolyte composition, and system design (Chen, 2004; Drogui et al., 2007). Therefore, selecting the appropriate voltage is crucial to achieving optimal treatment outcomes while minimizing energy consumption and operational expenses. By demonstrating that lower voltages can yield superior results in terms of color, turbidity, and COD reduction, this study underscores the importance of carefully optimizing electrochemical remediation parameters to maximize treatment efficiency and sustainability. This approach ensures that electrochemical technologies are deployed effectively in addressing water quality challenges while minimizing adverse environmental impacts and resource consumption.

Contrary to the observations regarding color, turbidity, and COD, the study reveals that higher voltages yield the best results in reducing DO levels, BOD, coliform, and E. coli concentrations in hospital wastewater. This divergent outcome can be attributed to the specific electrochemical mechanisms at play for these pollutants. Higher voltages may enhance the generation of reactive species, such as hydroxyl radicals and chlorine species, which are effective in oxidizing organic matter and microbial contaminants (Cheng et al., 2016; Wang et al., 2020). Additionally, elevated voltages can facilitate more efficient electrode reactions, leading to enhanced pollutant degradation and disinfection.

The increased oxidative potential associated with higher voltages likely contributes to the more pronounced reduction in DO, BOD, coliform, and E. coli levels. This phenomenon underscores the versatility of electrochemical remediation techniques in targeting a wide range of pollutants present in complex wastewater streams. However, it is essential to strike a balance between treatment efficacy and energy consumption when determining the optimal voltage for electrochemical remediation processes. While higher voltages may yield superior pollutant removal efficiencies, they also entail greater energy demands and operational costs. Therefore, comprehensive techno-economic analyses are necessary to assess the trade-offs and determine the most cost-effective voltage range for achieving desired treatment objectives. By elucidating the voltage-dependent effects on various water quality parameters, this study provides valuable insights for optimizing electrochemical remediation strategies tailored to the specific characteristics of hospital wastewater. These findings contribute to the ongoing efforts to develop sustainable and efficient solutions for mitigating water pollution and safeguarding public health.

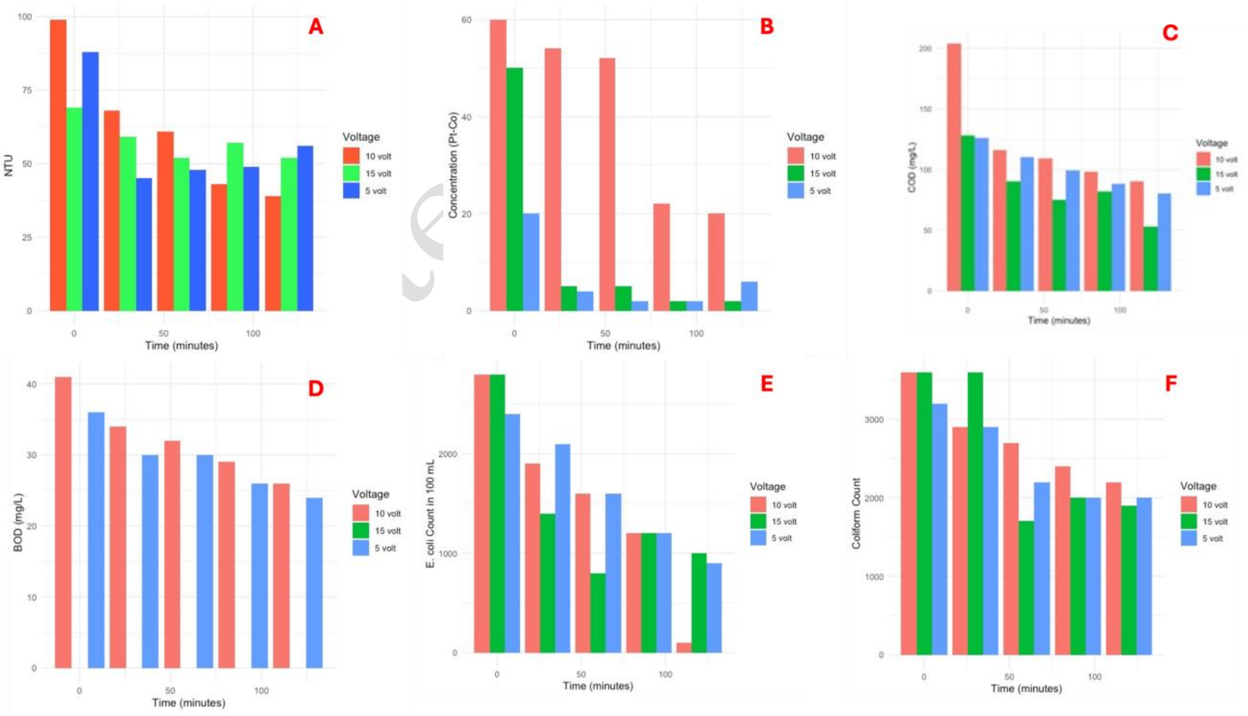


Figure 1. Turbidity (a), color (b), COD (c), BOD (d), *E. Coli* (e) and Coliform(f)

The research findings demonstrate a correlation between contact time and the efficiency of reducing Escherichia coli levels in hospital wastewater (Figure 2). Electrodisinfection processes conducted at 0, 30, 60, 90, and 120 minutes resulted in decreased Escherichia coli counts. Prior to electrodisinfection treatment, the Escherichia coli count was 886 x 103 CFU/mL. Following electrodisinfection treatment, at 5 volts, results showed Escherichia coli counts of 700 x 103 CFU/mL at 30 minutes, 676 x 103 CFU/mL at 60 minutes, 540 x 103 CFU/mL at 90 minutes, and 520 x 103 CFU/mL at 120 minutes. At 10 volts, Escherichia coli counts were 286 x 103 CFU/mL at 30 minutes, 260 x 103 CFU/mL at 60 minutes, 245 x 103 CFU/mL at 90 minutes, and 120 x 103 CFU/mL at 120 minutes. Increasing the voltage during the electrodisinfection process yielded significantly better results. At 15 volts, Escherichia coli counts were 43 x 103 CFU/mL at 30 minutes, 39 x 103 CFU/mL at 60 minutes, 30 x 103 CFU/mL at 90 minutes, and 21 x 103 CFU/mL at 120 minutes. Prolonged electrodisinfection processes resulted in decreased Escherichia coli levels in hospital wastewater. Moreover, increasing the voltage also led to significant reductions in Escherichia coli levels, indicating that the electrodisinfection process can enhance the quality of hospital wastewater.

The growth of Escherichia coli can be observed in Figures 2. Reductions in Escherichia coli growth after the electrolysis process occurred due to the deposition of pollutants present in hospital wastewater along with flocs and electrodes (anode and cathode). The analysis of Escherichia coli counts serves as an indicator to determine the overall quality of the water. Escherichia coli cultures within the range [103 colony-forming units ml-1, CFU/ml] were obtained to observe the presence of these bacteria in hospital wastewater after treatment. Each potential was varied with its respective contact time. The results showed the growth of Escherichia coli at potentials of 5 volts, 10 volts, and 15 volts, as depicted in Figure 2.

The reduction in Escherichia coli growth can be observed in the media. The inactivation of Escherichia coli bacteria at 5 volts resulted in 21.0% at 30 minutes, 23.7% at 60 minutes, 39.1% at 90 minutes, and 39.5% at 120 minutes. At 10 volts, the percentage of Escherichia coli bacteria inactivation increased with increasing contact time to 67.4%, 70.7%, 72.3%, and 86.0% for 30, 60, 90, and 120 minutes, respectively. The highest potential, 15 volts, showed excellent results, with an inactivation percentage of 95.1% at 30 minutes, surpassing both 5 volts and 10 volts. This percentage continued to increase with longer contact times, reaching an optimum result of 97.6% at 120 minutes

Based on the research findings, it is evident that the electrodisinfection method using carbon and aluminum electrodes can effectively and efficiently eliminate pathogenic bacteria in hospital wastewater. Other researchers have also successfully treated wastewater using the electrodisinfection method who achieved a 99.99% reduction in E. coli pathogens in pig wastewater after 60 minutes of electrodisinfection (Simas et al., 2019). Intensive electrodisinfection systems for ballast water treatment resulted in a 99% reduction in E. coli bacteria (Nanayakkara et al., 2008). The use of electrodisinfection methods in municipal wastewater treatment also yielded a 99% reduction in E. coli bacteria (La Motta et al., 2017). In line with these findings, the research results demonstrate that electrodisinfection is far more effective than chemical disinfection using chlorine, which requires longer exposure times (at least 30 minutes) to achieve a bactericidal performance of 99.94% or higher (A. Hemdan et al., 2020; Hellal et al., 2022)

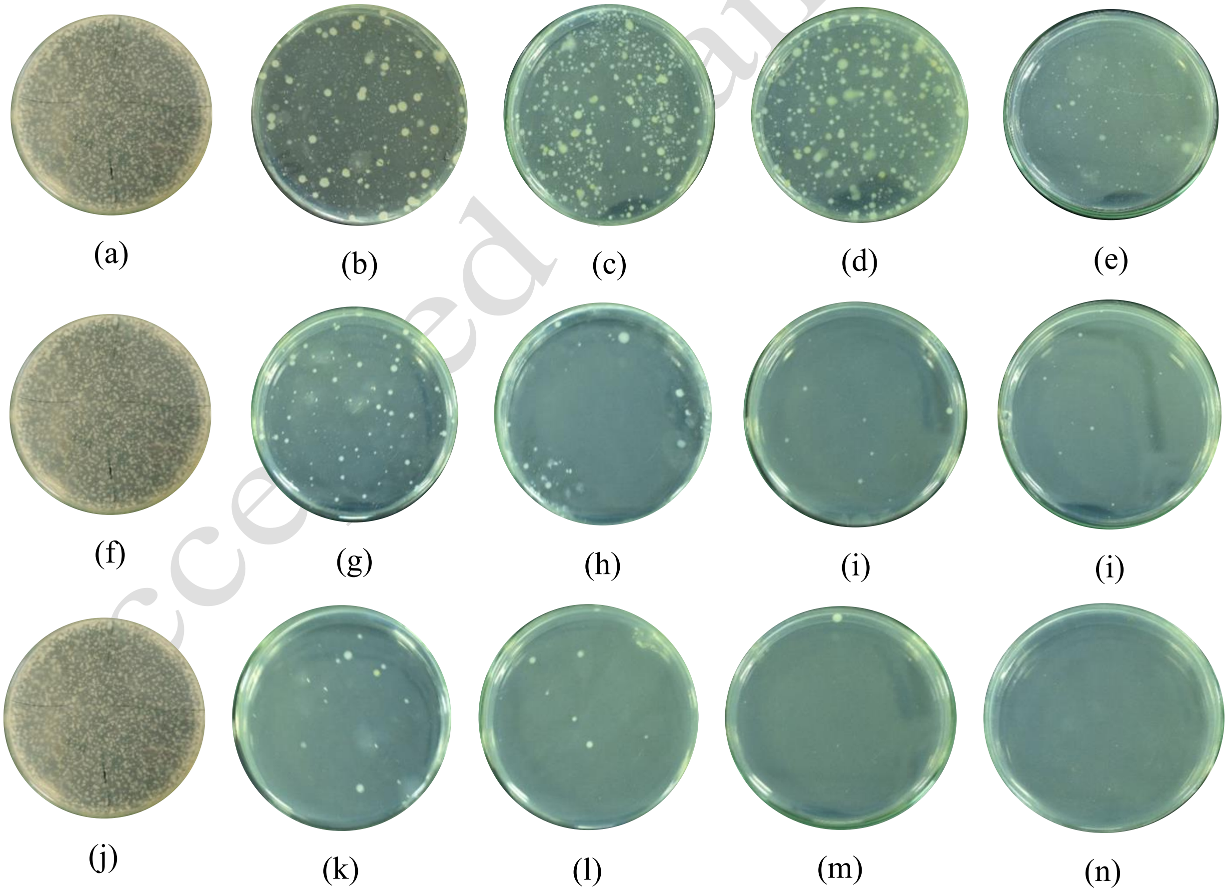


Figure 2. The growth of Escherichia coli at a potential of 10 volts, with variations in time, utilizing the electrodisinfection method at 5 volts for intervals of 0 (a), 30 (b), 60 (c), 90 (d), and

120 minutes (e). Similarly, experiments were conducted at 10 volts at intervals of 0 (f), 30 (g), 60 (h), 90 (i), and 120 minutes (j). and 15 volts, also at intervals of 0 (k), 30 (l), 60 (m), 90 (n), and 120 minutes (o).

3.2 Removal Percentage

Figure 3 presents the removal percentages of various pollutant parameters from hospital wastewater using the electrochemical method. Notably, this method demonstrates exceptional efficacy in turbidity removal, achieving up to 99% removal efficiency. This remarkable performance can be attributed to the electrochemical processes involved, wherein the application of electrical current induces coagulation, flocculation, and subsequent precipitation of suspended particles and colloidal matter. Additionally, electrochemical oxidation or reduction reactions may contribute to the breakdown of organic compounds and other turbidity-causing agents, further enhancing removal efficiency.

The electrochemical method effectively reduces turbidity by promoting the aggregation of suspended particles and facilitating their precipitation, leading to clarified wastewater. This mechanism is particularly advantageous for addressing turbidity, as it offers a rapid and efficient means of achieving substantial removal without the need for extensive pre-treatment or chemical additives. A recent study has provided further evidence of the electrochemical method's effectiveness by demonstrating reductions of up to 97% in various additional pollutants such as carbamazepine, ibuprofen, and estradiol (Ouarda et al., 2018). This crucial finding expands upon previous knowledge, indicating that this method is not only capable of reducing traditional parameters like BOD, COD, DO, turbidity, color, E. coli, and coliform, but also extends its efficacy to a broader range of contaminants. Such comprehensive pollutant removal underscores the versatility and applicability of electrochemical remediation in addressing diverse wastewater compositions and environmental concerns.

In parallel with the turbidity removal, the electrochemical method also demonstrates significant effectiveness in color removal, reflecting the shared underlying mechanisms for the removal of particulate and dissolved constituents contributing to water discoloration.

However, the removal of DO exhibits variability, which is attributed to several factors. The fluctuating DO removal efficiency may result from the complex interplay of electrochemical reactions and mass transport phenomena within the treatment system. Additionally, factors such as electrode configuration, electrolyte composition, and solution pH can influence the kinetics and extent of DO removal.

The optimal treatment conditions for DO removal are observed to be between 20 to 80 minutes at 15 volts, with a continuous increase in removal efficiency until approximately 25 minutes, reaching an equilibrium point thereafter. Conversely, at 10 volts, the optimal treatment time is observed to be 10 minutes, indicating a different kinetic profile compared to the 15-volt condition. Interestingly, at 5 volts, there is no observable DO removal, suggesting that the electrochemical processes at this voltage may not effectively promote oxygen reduction or other mechanisms relevant to DO removal.

The results for BOD, E. coli, and coliform removal also demonstrate a consistent trend, wherein higher voltages yield better performance in pollutant reduction. This alignment in results can be attributed to the intensified electrochemical processes facilitated by higher voltages. At elevated voltages, increased electrical potential promotes more vigorous electrochemical reactions, leading to enhanced degradation and disinfection of organic matter and microbial contaminants. For BOD removal, higher voltages enable more efficient oxidation of organic pollutants, resulting in greater reduction in BOD levels. The increased oxidative potential of the electrochemical system at higher voltages facilitates the breakdown of complex organic compounds, thereby accelerating BOD removal kinetics.

Similarly, for E. coli and coliform removal, higher voltages promote more effective microbial inactivation through electrochemical processes such as electrooxidation and electrolysis. The elevated electrical potential facilitates the generation of reactive species that exhibit strong biocidal properties, thereby enhancing the disinfection efficacy against pathogenic bacteria like E. coli and coliforms. Overall, the consistent improvement in BOD, E. coli, and coliform removal efficiencies with increasing voltage underscores the role of electrochemical methods as potent tools for the remediation of hospital wastewater. By leveraging higher voltages judiciously, it is possible to achieve robust and reliable treatment outcomes, thereby contributing to the mitigation of waterborne disease risks and the protection of public health.

The findings of this study underscore the electrochemical method as a promising approach for assessing pollutant parameters. Notably, the parameters examined in this investigation surpassed both the US EPA standards and the National Indonesian Standard outlined in Decree of the Minister of Environment of the Republic of Indonesia Number: Kep-58/MENLH/12/1995

(Menteri Negara Lingkungan Hidup Republik Indonesia, 1995). Table 1 provides a comprehensive comparison of international hospital wastewater parameters against these standards.

Table 1. Comparison of the study with international and national standard

Wastewater characteristic	U.S Environmental Protection Agency	Indonesian National Standard (Keputusan Mentreri Negara Lingkungan Hidup Republik Indonesia Nomor :Kep-58/MENLH/12/1995)	This study	Unit
BODs	41	30	21	Mg/L
COD	N/A	80	51	Mg/L
TSS	55.6	30	N/A	Mg/L
pH	6-9	6-9	7	-
Turbidity	N/A	N/A	2	NTU
Color	N/A	N/A	28	Pt/Co
DO	N/A	N/A	2.9	Mg/L
E Coli	N/A	N/A	1,200	CFU/100 mL
Coliform	N/A	N/A	1,700	CFU/100 mL

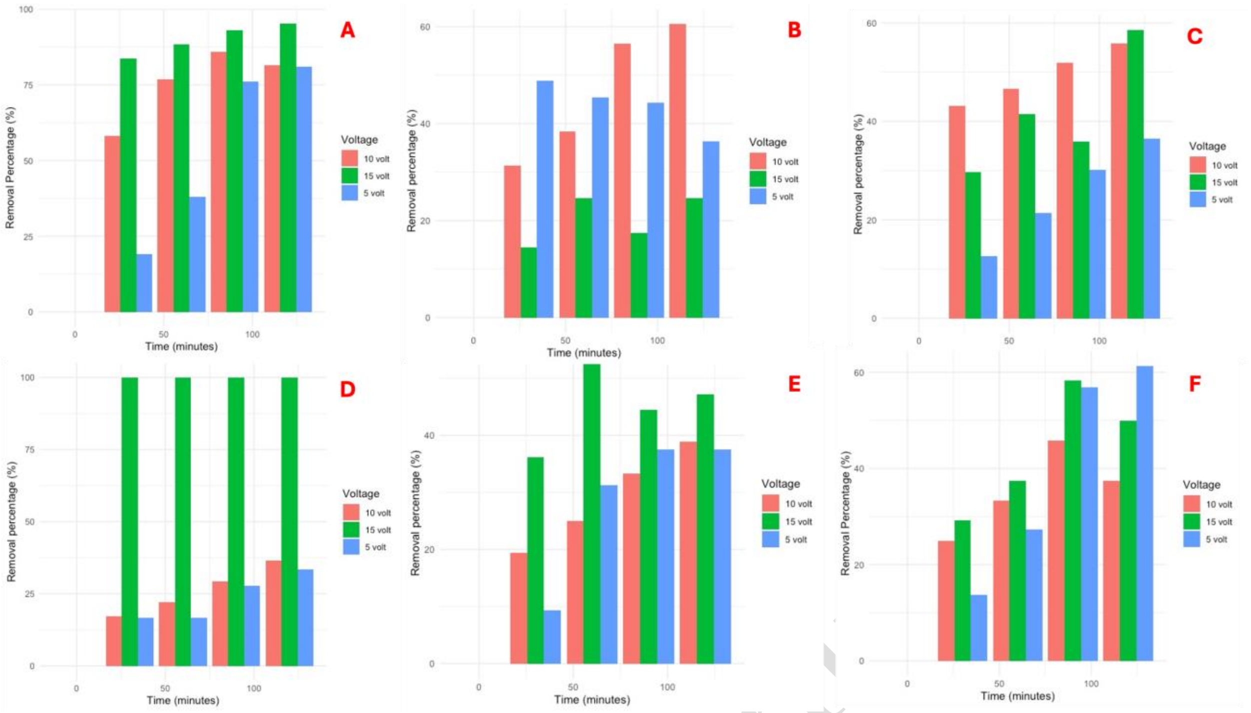


Figure 3. Removal percentage of turbidity (a), color (b), COD (c), BOD (d), Coliform (e) and *E Coli* (f)

3.3 Removal Mechanism

In this comprehensive exploration, this paper embark on a journey through the intricate mechanisms that underpin the removal of diverse pollutants from hospital wastewater utilizing electrochemical methods. The electrochemical remediation process represents a sophisticated interplay of physical, chemical, and electrochemical phenomena, collectively orchestrating the efficient eradication of contaminants. A profound understanding of these mechanisms stands as a cornerstone for refining treatment strategies and optimizing pollutant removal efficiency. Figure 4 showed the mechanism of pollutants removal.

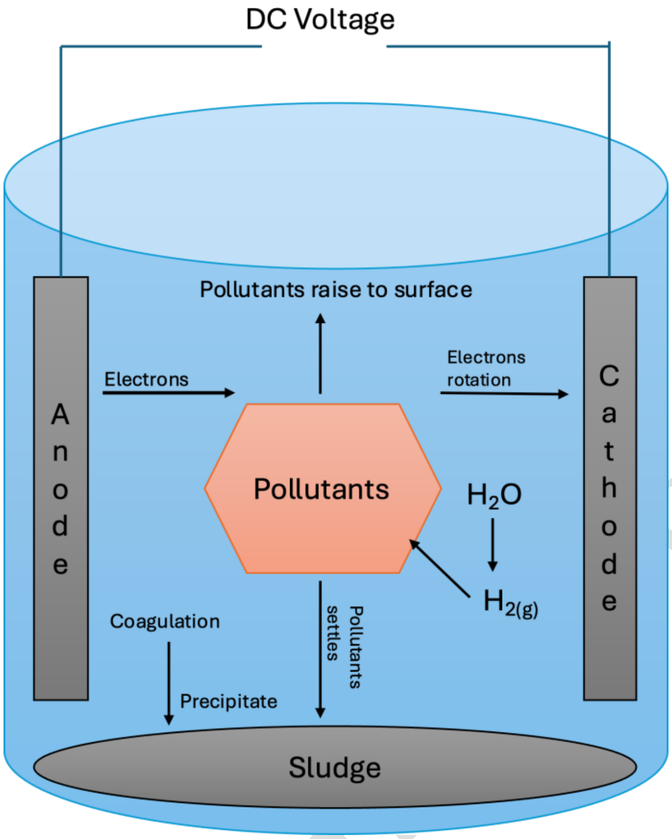


Figure 4. Mechanism removal of pollutants

The extraordinary efficacy of electrochemical methods in turbidity removal finds its roots in several underlying mechanisms. Upon the application of an electric current to the wastewater, electrolysis ensues at the electrodes, giving rise to the generation of reactive species like hydroxyl radicals (OH), chlorine radicals (Cl), and hydrogen peroxide (H_2O_2) (Yin et al., 2021). These reactive entities serve as catalysts in promoting coagulation, flocculation, and precipitation of suspended particles and colloidal matter present in the wastewater milieu.

Central to turbidity removal is the phenomenon of electrocoagulation, which involves the destabilization of colloidal particles through the formation of metal hydroxide flocs at the anode (Tegladza et al., 2021). These flocs act as magnets, adsorbing and entrapping suspended particles, thereby facilitating their aggregation and settling. Furthermore, electrochemical oxidation reactions participate in the breakdown of organic compounds and other turbidity-inducing agents, thereby augmenting turbidity removal efficiency.

The evolution of gas bubbles (e.g., hydrogen and oxygen) at the electrodes during electrolysis further aids in turbidity removal through buoyancy-driven flotation of suspended particles.

Additionally, electrochemical methods wield the power to induce pH alterations in the wastewater, consequently influencing the solubility and precipitation of certain contaminants, thereby expediting their removal process. In summation, the synergistic amalgamation of electrocoagulation, electrooxidation, flotation, and pH adjustment mechanisms culminates in the exceptional turbidity removal efficiency observed in electrochemically treated hospital wastewater.

The removal of color from hospital wastewater via electrochemical methods hinges on akin principles to turbidity removal, albeit with discernible nuances in mechanisms. Organic dyes, prevalent in hospital effluents, are notorious for imparting coloration and posing substantial environmental and health risks (Alsukaibi, 2022). Electrochemical remediation emerges as a promising avenue for mitigating color contamination by fostering the degradation and elimination of dye molecules.

Critical to color removal is the initiation of electrooxidation reactions at the anode surface, orchestrating the breakdown of chromophoric groups inherent in dye molecules. This process culminates in the degradation of intricate organic structures, thereby effectuating the decolorization of the wastewater. Additionally, electrocoagulation mechanisms facilitate the expulsion of colloidal particles and suspended solids that contribute to coloration, thereby further amplifying color removal efficacy.

The genesis of reactive oxidizing species, such as hydroxyl radicals and chlorine radicals during electrolysis, bolsters the oxidative degradation of dye molecules, thereby expediting color removal kinetics. Furthermore, the precipitation of metal hydroxide flocs at the anode surface aids in the adsorption and elimination of dye molecules, thereby contributing to overall color reduction. It is noteworthy that the efficacy of color removal via electrochemical methods may exhibit variance contingent upon factors like dye concentration, molecular structure, solution pH, and electrode material. Nonetheless, by harnessing the synergistic effects of electrooxidation, electrocoagulation, and adsorption mechanisms, electrochemical remediation emerges as a promising solution for tackling color contamination in hospital wastewater.

The eradication of biochemical oxygen demand and microbial contaminants such as *E. coli* and coliform bacteria from hospital wastewater using electrochemical methods entails intricate yet synergistic mechanisms. The electrochemical process instigates oxidative reactions targeting organic pollutants, microbial cells, and extracellular polymeric substances pervading the wastewater matrix.

Under elevated voltages, electrooxidation reactions unfold at the anode, engendering the generation of reactive oxidizing species like hydroxyl radicals and chlorine radicals. These reactive moieties exhibit formidable biocidal attributes, thereby facilitating the inactivation and obliteration of microbial cells, inclusive of pathogenic bacteria like *E. coli* and coliforms.

Concurrently, electrochemical oxidation reactions dismantle organic compounds and organic matter contributing to BOD, thereby effectuating a reduction in BOD levels. The disintegration of complex organic molecules into simpler, more biodegradable intermediates augments the biodegradability of the wastewater, thereby fostering further BOD removal through subsequent biological treatment processes.

In wastewater treatment, electrochemical remediation employs the application of an electric current to electrodes submerged in the water. This electrical energy drives various chemical reactions aimed at removing contaminants. Processes such as electrolysis, electrocoagulation, and electrooxidation occur, targeting specific pollutants. For instance, electrocoagulation induces the formation of metal hydroxide flocs, facilitating the precipitation of suspended particles and contaminants for easier removal (Tegladza et al., 2021). In contrast, physical methods rely on physical properties like size and density to separate contaminants from water (Naswir et al., 2020). Sedimentation (He et al., 2021), filtration (Šostar-Turk et al., 2005), and adsorption (Wibowo et al., 2023a) are common physical processes used in wastewater treatment. Chemical methods, on the other hand, involve the addition of chemicals to initiate reactions that alter the chemical composition of contaminants, making them easier to remove. Coagulation, flocculation, oxidation, and precipitation are typical mechanisms employed in chemical treatment (Rivas et al., 2004). Lastly, biological methods utilize microorganisms to metabolize metals and organic pollutants, breaking them down into simpler, less harmful compounds (Giovanella et al., 2020). While each method has its advantages and limitations, the choice of wastewater treatment depends on factors such as the type of contaminants present, treatment goals, efficiency requirements, and cost considerations. Electrochemical remediation stands out for its ability to target specific pollutants, making it particularly effective for certain types of contaminants or in situations where other methods may be less suitable.

Furthermore, electrocoagulation mechanisms contribute to microbial eradication by fostering the coagulation and precipitation of suspended particles and microbial cells (Ensano et al., 2017). The formation of metal hydroxide flocs at the anode surface facilitates the adsorption and entrapment of microbial contaminants, thereby enhancing their removal efficiency. In essence, the integrated mechanisms of electrooxidation, electrocoagulation, and biocidal action synergistically underpin the efficient removal of BOD, *E. coli*, and coliform bacteria from hospital wastewater, thereby spotlighting the multifaceted capabilities of electrochemical methods in water treatment applications.

3.4 Potential for Field Utilization

The findings presented in this study underscore the significant potential for the field utilization of electrochemical remediation techniques in addressing water quality challenges associated with hospital wastewater. As discussed in earlier sections, electrochemical methods offer several advantages, including high removal efficiency, versatility, and compatibility with various wastewater compositions. This discussion explores the practical implications and considerations for implementing electrochemical remediation technologies in real-world wastewater treatment scenarios.

One key consideration for the field utilization of electrochemical remediation technologies is scalability. While laboratory-scale studies demonstrate promising results (Chen, 2004), scaling up these techniques to treat large volumes of wastewater in field settings presents unique challenges (Garcia-Rodriguez et al., 2022; Sala and Gutiérrez-Bouzán, 2014). Engineering considerations, such as electrode design, reactor configuration, and power supply requirements, must be carefully addressed to ensure the efficient and cost-effective operation of electrochemical treatment systems at scale. Additionally, the adaptability of electrochemical methods to different wastewater characteristics and treatment objectives is essential for addressing the diverse range of pollutants found in hospital effluents.

Effective field utilization of electrochemical remediation technologies necessitates careful attention to operational parameters and maintenance requirements. Continuous monitoring of key performance indicators, such as pH, conductivity, and pollutant concentrations, is essential for optimizing treatment performance and ensuring regulatory compliance (Hand and Cusick, 2021; Sáez et al., 2013). Moreover, routine maintenance activities, including electrode cleaning, electrolyte replenishment, and system calibration, are critical for sustaining long-term treatment efficacy and minimizing downtime.

Cost-effectiveness is a crucial consideration for the widespread adoption of electrochemical remediation technologies in field applications. While electrochemical methods offer several advantages over conventional treatment approaches, such as reduced chemical usage and sludge generation, the initial capital investment and operational expenses must be carefully evaluated against the anticipated benefits. Techno-economic assessments, including life cycle cost analysis and return on investment calculations, can provide valuable insights into the economic viability of electrochemical treatment systems.

Furthermore, sustainability considerations, such as energy consumption, resource utilization, and environmental impact, play a significant role in determining the long-term feasibility of electrochemical remediation technologies. Efforts to minimize energy consumption through process optimization, renewable energy integration, and energy recovery mechanisms are essential for enhancing the sustainability of electrochemical treatment systems. Additionally, the responsible management of electrode materials, electrolytes, and byproducts is critical for mitigating environmental risks and ensuring regulatory compliance.

Meeting regulatory requirements and gaining public acceptance are essential factors influencing the field utilization of electrochemical remediation technologies. Compliance with local, national, and international wastewater discharge standards is paramount to ensuring the protection of human health and the environment. Therefore, it is imperative to conduct comprehensive performance evaluations and validation studies to demonstrate the effectiveness of electrochemical treatment systems in meeting regulatory requirements.

Moreover, proactive stakeholder engagement and public outreach efforts are crucial for building trust and fostering acceptance of electrochemical technologies within the community. Transparent communication regarding the benefits, risks, and limitations of electrochemical treatment approaches can help alleviate concerns and garner support for their implementation in field settings.

Several industrial activities utilize electrochemical methods for treating wastewater. Among these companies are Siemens from Germany, a multinational corporation offering various technological solutions, including electrochemical wastewater treatment. General Electric (GE) from the United States is another multinational technology and infrastructure company providing solutions for wastewater treatment, including electrochemical technology. Suez, based in France, is a multinational company offering water and waste management services worldwide, incorporating electrochemical technology in wastewater treatment processes. Aqua-Chem, Inc., also from the United States, provides various technological solutions for water and wastewater treatment, including electrochemical methods. Hitachi Zosen Corporation, headquartered in Japan, offers a range of solutions for water treatment industries, including electrochemical technology. Veolia, a French multinational specializing in water, waste, and energy management, also employs electrochemical technology in some wastewater treatment solutions. Doosan Heavy Industries & Construction from South Korea provides diverse solutions for energy and environmental industries, including electrochemical methods for wastewater treatment.

In the end, the field utilization of electrochemical remediation technologies holds significant promise for addressing water quality challenges associated with hospital wastewater. By leveraging the advantages of electrochemical methods, such as high removal efficiency, adaptability, and sustainability, it is possible to develop robust and cost-effective solutions for treating complex wastewater streams. However, successful implementation requires careful consideration of scalability, operational factors, cost-effectiveness, regulatory compliance, and stakeholder engagement. Through collaborative efforts between researchers, engineers, policymakers, and stakeholders, electrochemical treatment technologies can play a pivotal role in advancing sustainable wastewater management practices and safeguarding public health and the environment.

3.5 Recent Trends in Electrochemical for Wastewater Treatment

Electrochemical methods have garnered global attention for their effectiveness and efficiency in treating hospital wastewater. The Scopus database reveals that the first published paper on hospital wastewater treatment using electrochemical methods dates back to 2001. This indicates that while electrochemical treatment is promising, it remains relatively underdeveloped compared to established methods like adsorption, which have been documented since as early as 1970 (Gusti Wibowo et al., 2024). Figure 5 illustrates the publication trends extracted from the Scopus database, demonstrating a significant increase in publications from 2016 to 2023, with a continued upward trajectory into 2024

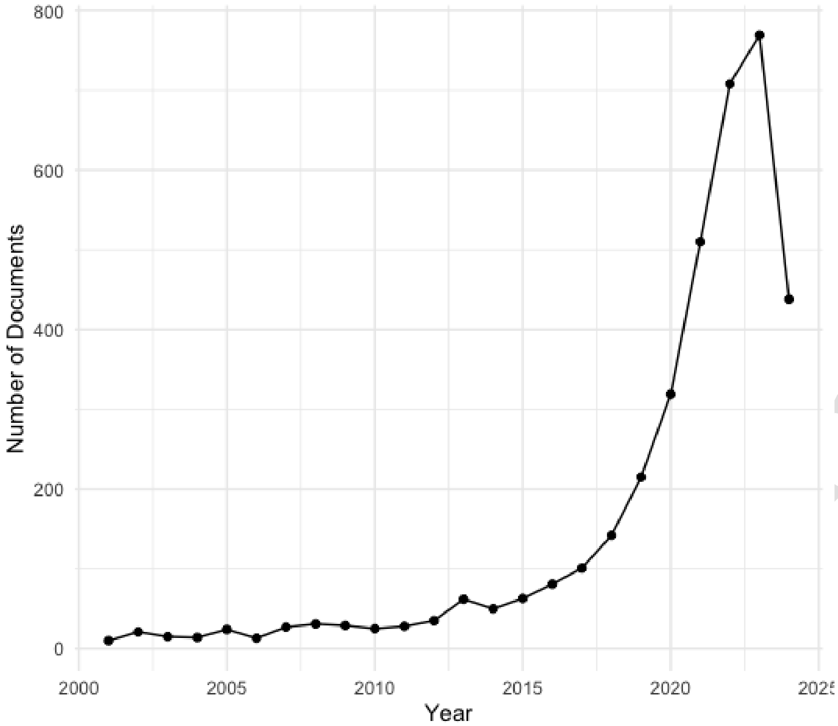


Figure 5. Numbers of documents related electrochemical for hospital wastewater treatment

Furthermore, Figure 6 provides insight into the distribution of document types within the Scopus database concerning this topic. The prevalence of original research articles, totaling nearly 2000 documents, along with reviews and book chapters, underscores the significance of electrochemical methods in this field and the need for further development. Furthermore, the prominence of case studies in hospital wastewater treatment using electrochemical methods is evident. Notably, a significant portion of these studies is published in highly reputable journals such as Chemosphere (271 documents), Chemical Engineering Journal (211 documents), Science of the Total Environment (173 documents), Journal of Environmental and Chemical Engineering (121 documents), Journal of Water Processing Engineering (121 documents), Journal of Hazardous Materials (108 documents), and other esteemed publications. This data confirms the potential of electrochemical treatment methods for hospital wastewater and highlights the importance of continued research and innovation in this area.

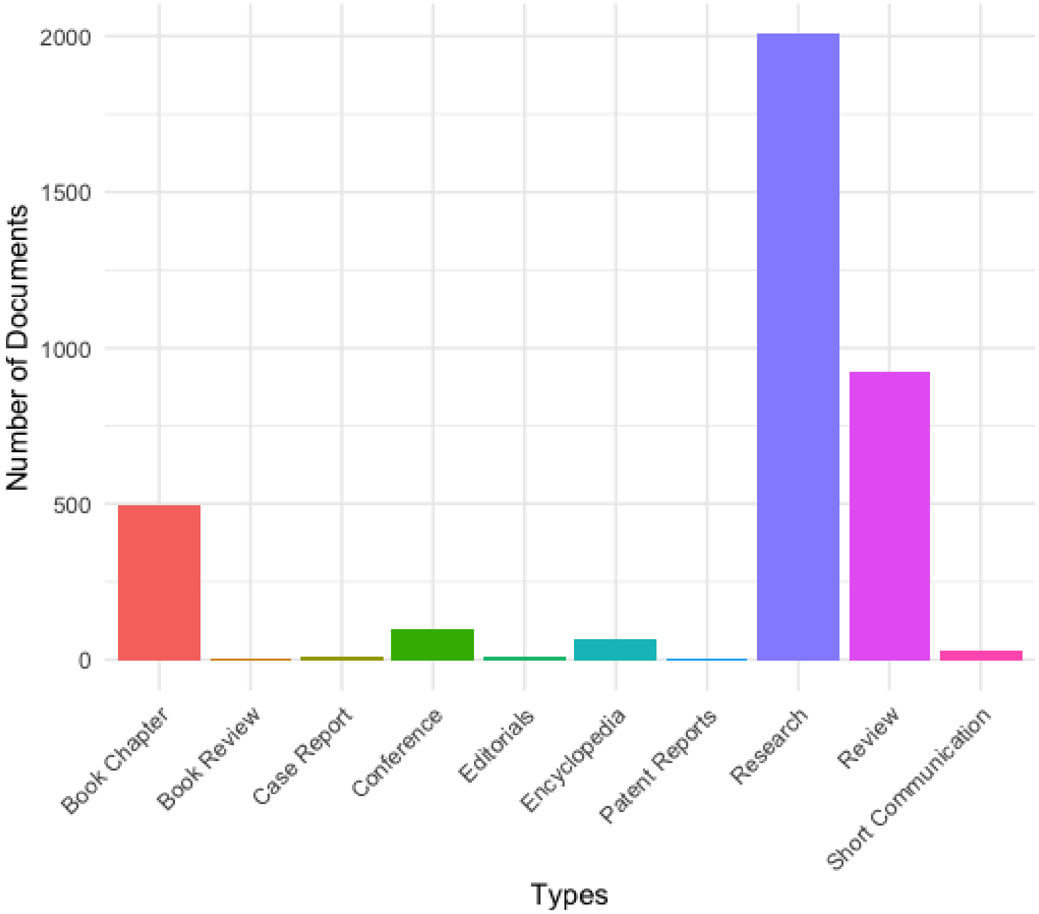


Figure 6. Types of documents by Scopus database

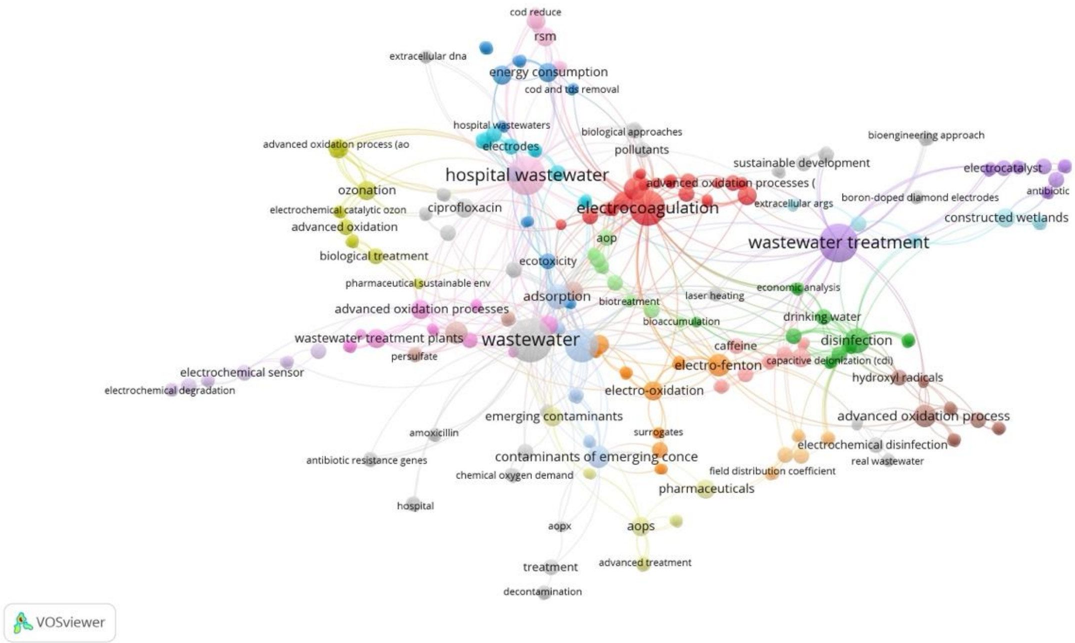


Figure 7. Bibliometric analysis of electrochemical research in treating hospital wastewater

Figure 7 presents a bibliometric analysis of electrochemical utilization for treating hospital wastewater based on all published papers in the Scopus database. The analysis highlights key keywords associated with these publications, represented by varying sizes of balloons.

The largest balloons in the analysis correspond to prominent keywords such as electrocoagulation, wastewater, wastewater treatment, and hospital wastewater. Conversely, smaller balloons represent keywords like electrochemical sensor, graphene oxide, electro-fenton, advanced oxidation, and catalytic activation. This analysis underscores the recent trend in the development of electrochemical remediation techniques, which involves the modification of electrodes with other materials to enhance effectiveness and efficiency. By leveraging innovative materials and techniques, researchers aim to address the complex challenges associated with hospital wastewater treatment more effectively.

3.6 Challenges and Recommendation for Future Research Direction

The transition of electrochemical remediation technologies from laboratory prototypes to practical field applications presents significant challenges, particularly in scalability and integration. Achieving seamless integration into existing wastewater treatment infrastructure while maintaining optimal performance and cost-effectiveness demands meticulous engineering and operational considerations. These efforts are crucial to ensure the smooth operation of electrochemical treatment systems within diverse operational contexts. Electrochemical treatment processes often require substantial energy inputs, especially at higher voltages, posing a persistent challenge in minimizing energy consumption while maximizing treatment efficiency. Innovative approaches, such as developing advanced electrode materials, optimizing reactor designs, and implementing energy management strategies, are necessary to enhance energy utilization and reduce operational costs.

Electrode fouling, resulting from the accumulation of precipitates, organic matter, and microbial biofilms, can significantly impede treatment performance and necessitate frequent maintenance. Overcoming this challenge involves developing fouling-resistant electrode materials and effective cleaning protocols to mitigate fouling-related issues and ensure uninterrupted operation of electrochemical treatment systems. The generation of various byproducts, including disinfection byproducts, metal hydroxide sludges, and volatile gases, poses environmental and regulatory challenges in their management and disposal. Exploring alternative byproduct handling strategies such as resource recovery, recycling, and beneficial reuse can mitigate environmental impacts and enhance the sustainability of electrochemical treatment technologies.

Continued research into advanced electrode materials with enhanced electrocatalytic properties, stability, and durability is crucial for improving the performance and efficiency of electrochemical treatment systems. Exploring novel nanomaterials, composite structures, and surface modifications can facilitate the development of tailored electrodes for specific pollutant removal applications. Comprehensive studies are needed to optimize operating conditions, electrode configurations, and electrolyte compositions to maximize treatment performance while minimizing energy consumption and operational costs. Implementing advanced control strategies such as feedback control algorithms and real-time monitoring systems can enhance process stability, reliability, and efficiency.

Thorough environmental impact assessments are crucial for evaluating the potential implications of electrochemical treatment technologies to ensure long-term sustainability and regulatory compliance. Assessing treatment byproducts' fate and transport, evaluating ecosystem impacts, and quantifying carbon and energy footprints can inform sustainable design and management practices.

Exploring synergies between electrochemical treatment technologies and emerging wastewater treatment approaches, such as membrane filtration and biological treatment, can unlock new opportunities for improving treatment performance and resource recovery. Investigating hybrid treatment systems and integrated process configurations can leverage different technologies' strengths to address complex wastewater challenges effectively.

Conducting large-scale field trials and demonstration projects to validate electrochemical treatment technologies' performance, scalability, and cost-effectiveness under real-world conditions is essential for facilitating their widespread adoption and commercialization. Collaboration with industry partners, utilities, and regulatory agencies in deploying pilot-scale and full-scale electrochemical treatment systems can provide valuable insights into technology deployment challenges and opportunities. By addressing these challenges and pursuing research in the recommended directions, the field of electrochemical wastewater treatment can continue to advance, offering innovative solutions to mitigate water pollution, safeguard public health, and promote sustainable water resource management.

4. Conclusion

The efficiency of electrochemical processes in removing pollutants is evident, as demonstrated by this study's findings on hospital wastewater. Notably, the duration of contact time proved to be a significant factor in reducing pollutant parameters. Interestingly, while high voltage (15 Volts) was effective in removing certain pollutants, others showed greater efficiency at lower voltages (5 Volts). This highlights the nuanced nature of pollutant removal in electrochemical treatment. Additionally, this study demonstrated notable reductions in various pollutant parameters present in hospital wastewater. The method employed successfully achieved removal rates of up to 99% for turbidity, up to 73% for color removal, 54% for BOD, 58% for COD, 61% for E. coli, and 58% for coliform bacteria.

Moreover, the study emphasizes the multifaceted challenges and promising prospects in advancing electrochemical wastewater treatment technologies. From scalability and integration hurdles to energy consumption, electrode fouling, and byproduct management, the field confronts diverse obstacles that demand innovative solutions and collaborative research efforts. Addressing these challenges necessitates a comprehensive approach, integrating material science, engineering design, operational optimization, and environmental stewardship. By prioritizing the development of advanced electrode materials, refining operational parameters, and exploring sustainable byproduct handling strategies, electrochemical treatment systems hold the potential to revolutionize wastewater remediation practices.

Furthermore, collaboration among academia, industry, and regulatory bodies is vital for translating research findings into practical applications. Large-scale field trials and demonstration projects play a crucial role in validating the performance, scalability, and cost-effectiveness of electrochemical treatment technologies under real-world conditions. As efforts to refine and innovate in this field continue, electrochemical wastewater treatment remains a promising avenue for mitigating water pollution, safeguarding public health, and promoting sustainable water resource management. Through sustained research endeavors and interdisciplinary collaboration, we can unlock the full potential of electrochemical technologies to address the pressing challenges of wastewater treatment in the years ahead.

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