Mini-Review:

Electrocoagulation for Cattle Slaughterhouse Wastewater Management: A Review of Technologies and Treatment Parameters

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Abstract: *The management of slaughterhouse wastewater presents significant environmental challenges due to its high organic load, fat, oil, and persistent pollutants. Electrocoagulation (EC) is an effective treatment method that utilizes electric currents to generate* in situ *coagulants for pollutant removal. This review examines key operational parameters of EC, including current density, pH, electrode type, and contact time, while comparing its performance with electro-oxidation (EO) and coagulation-flocculation (CF). The findings indicate that EC effectively reduces chemical oxygen demand (COD), biological oxygen demand (BOD), and turbidity with relatively low operational costs. Integrating EC with CF and EO improves treatment efficiency by addressing complex wastewater characteristics. Optimization of parameters, energy consumption reduction, and electrode durability enhancements are recommended for improving EC performance. Bibliometric analysis using VOSviewer highlights the increasing research focus on energy efficiency, electrode materials, and process optimization. EC's role in wastewater treatment highlights its effectiveness, optimization strategies, and integration potential. Future research should focus on scaling up industrial applications and integrating predictive models to enhance efficiency and sustainability in slaughterhouse wastewater management.*

Keywords: *electrocoagulation; operational parameters; slaughterhouses; treatment technology; wastewater treatment*

■ INTRODUCTION

Slaughterhouses, particularly those that process cattle, generate large volumes of wastewater containing a variety of complex pollutants [1]. This wastewater is rich in organic materials such as blood, fat, oil, and tissue residues from animal processing [2]. It also contains inorganic substances like nitrogen, phosphorus, and suspended solids originating from slaughtering activities [3]. The presence of these pollutants makes slaughterhouse wastewater highly contaminated and difficult to treat [4]. High concentrations of chemical oxygen demand (COD) and biological oxygen demand (BOD) are typical features of this wastewater [3,5-6]. If discharged untreated, slaughterhouse wastewater can severely pollute groundwater and surface water bodies [7]. The organic load in the wastewater can deplete dissolved oxygen in aquatic environments, leading to the death of aquatic organisms [8]. Excessive nutrients such as nitrogen and phosphorus can stimulate eutrophication in water bodies, promoting algal blooms [9]. Eutrophication deteriorates water quality, reduces biodiversity, and creates dead zones in aquatic ecosystems [10]. Apart from environmental issues, untreated wastewater can also serve as a vehicle for the spread of pathogens [11]. Pathogenic microorganisms present in the wastewater can cause diseases in humans and animals through direct or indirect contact [12]. Contaminated water used for irrigation poses a risk of transferring pathogens to agricultural products [13]. Pollutants from slaughterhouse effluents can accumulate in the food chain, impacting both human health and wildlife [14]. The strong odors from untreated wastewater can contribute to air pollution and decrease the quality of life in surrounding communities [11].

Proper treatment of slaughterhouse wastewater is essential to protect both environmental and public health, given the high organic and inorganic pollutant loads present in such effluents [15]. In the framework of environmental sustainability, implementing effective wastewater treatment processes plays a critical role in minimizing ecological damage [16]. Recycling treated wastewater can significantly contribute to water conservation efforts by reducing dependency on freshwater resources [17]. Treated slaughterhouse wastewater can potentially be reused for non-potable applications, such as industrial cooling systems and agricultural irrigation [18]. However, achieving safe and acceptable water reuse standards necessitates the deployment of advanced treatment technologies capable of meeting stringent regulations [19].

Electrocoagulation (EC) has emerged as a promising alternative for treating industrial and slaughterhouse wastewater due to its high pollutant removal efficiencies [20]. This technology operates by applying an electric current to metal electrodes, typically aluminum or iron, to produce coagulant species directly within the wastewater [21]. The generated coagulants destabilize suspended pollutants, promoting the aggregation and subsequent removal of contaminants from the water matrix [22]. EC is considered environmentally friendly because it minimizes chemical usage and generates less sludge compared to traditional coagulation-flocculation processes [23]. Moreover, the energy consumption of EC systems can be optimized by adjusting operational parameters, such as current density, electrode spacing, and treatment duration [24].

The removal efficiency of COD, BOD, turbidity, and heavy metals by EC has been reported to be very high in slaughterhouse wastewater treatment [25]. EC also has the ability to inactivate a wide range of pathogenic microorganisms in wastewater [26]. Integration of EC with other technologies, such as electrooxidation, can further enhance treatment performance [27]. The major challenges in treating slaughterhouse wastewater include high organic content, stringent environmental regulations, and the need for cost-effective, scalable treatment solutions. Addressing these challenges requires innovative approaches such as EC. One of the challenges in EC is electrode passivation, which can reduce treatment efficiency over time [28]. Periodic electrode cleaning or using reversible polarity techniques can mitigate electrode fouling issues [29]. The choice of electrode material significantly influences the overall treatment efficiency and operational cost [30]. Aluminum electrodes are often preferred for their high removal efficiency, but iron electrodes are also widely used for certain types of wastewater [31]. Pilot-scale studies have shown that EC can be successfully scaled up for industrial slaughterhouse wastewater treatment [32]. Future research should focus on optimizing EC systems for energy efficiency, cost reduction, and integration with renewable energy sources.

The purpose of this review is to provide a comprehensive overview of the application of EC technology in treating wastewater from cattle slaughterhouses. This review will cover the theoretical background of EC, operational parameters affecting its performance, and case studies illustrating the effectiveness of this technology in reducing key pollutant levels. Additionally, the article will discuss challenges and future prospects for the development of EC technology to support environmental sustainability and industrial efficiency.

CHARACTERISTICS OF SLAUGHTERHOUSE WASTEWATER

Wastewater generated by slaughterhouses has complex and challenging characteristics, requiring an integrated and efficient treatment approach [33-34]. One of the main characteristics is the high COD, which indicates the amount of oxygen required to oxidize organic and inorganic matter in the waste. Wastewater generated from cattle slaughterhouses is characterized by a high COD load, primarily due to the presence of organic matter such as blood, fat, and proteins. EC using aluminum electrodes has been shown to reduce COD levels by up to 95% under optimized conditions [35]. This poses a major challenge in treatment, as it requires technology capable of significantly reducing COD to meet environmental quality standards. Slaughterhouse wastewater also has a high BOD reaching 2,000–3,000 mg/L, indicating that the waste is rich in easily degradable organic matter [18]. This high organic load can trigger excessive microbial growth in receiving waters if not properly treated [36-37].

The turbidity of slaughterhouse wastewater is also a serious concern, caused by suspended solids such as meat particles, blood, and fat, with turbidity levels often exceeding 500 Nephelometric Turbidity Units (NTU) [38]. This high turbidity can obstruct light penetration and disrupt photosynthesis processes in water bodies, making turbidity reduction necessary at the initial stages of treatment [39]. Additionally, the oil and fat content in slaughterhouse wastewater is considerable, originating from slaughtering and meat-washing processes [40]. Oil and fat can form a layer on the water surface, inhibiting oxygen exchange and accelerating water quality degradation [41]. Specialized treatments, such as grease traps or EC technology, are required to ensure effective removal.

Slaughterhouse wastewater also contains significant amounts of nitrogen and phosphorus, originating from blood and feed residues [42]. These high levels of nitrogen and phosphorus can lead to eutrophication, causing excessive algae growth in receiving waters, which ultimately disrupts aquatic ecosystems. Advanced treatment is often necessary to effectively reduce these compounds [43]. Additionally, slaughterhouse wastewater may contain pathogenic microbes such as *Escherichia coli* and *Salmonella*, posing health risks if not properly treated [44]. The characteristics of slaughterhouse wastewater reflect the complexity of its treatment, which requires a combination of effective physical, chemical, and biological methods. Technologies such as EC and electro-oxidation (EO) can provide optimal solutions for addressing the organic, inorganic, and microbiological pollutants in the wastewater.

EC TECHNOLOGY FOR WASTEWATER TREATMENT

EC is a water and wastewater treatment method that uses electric currents to generate coagulants from electrodes *in situ* [45]. The EC process is designed to bind and precipitate various pollutants—including suspended solids, heavy metals, organic compounds, and microorganisms—thereby improving water quality. As illustrated in Fig. 1, during EC treatment, metal ions released from the sacrificial anode undergo hydrolysis to form metal hydroxides, which destabilize and aggregate suspended particles. These aggregates, or flocs, subsequently float to the surface or settle at the bottom as sludge [46]. In the EC process, an electric current passes through electrodes (usually aluminum or iron) submerged in water or wastewater. These electrodes undergo oxidation, releasing metal ions (such as Al^{3+} or Fe^{2+}) that act as coagulants. These metal ions interact with charged pollutants, forming large flocs that can be easily separated from the water through flotation or sedimentation [47].

The EC process involves the release of metal ions from electrodes, which play a crucial role in pollutant removal. At the anode, metal oxidation occurs, leading to the dissolution of metal ions into the solution, which subsequently reacts with water to form hydroxides that facilitate coagulation [48]. The general oxidation reaction at the anode is represented as:

$$M \rightarrow M^{n+} + ne^-$$

Additionally, water oxidation can take place at the anode, producing oxygen gas and hydrogen ions.

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

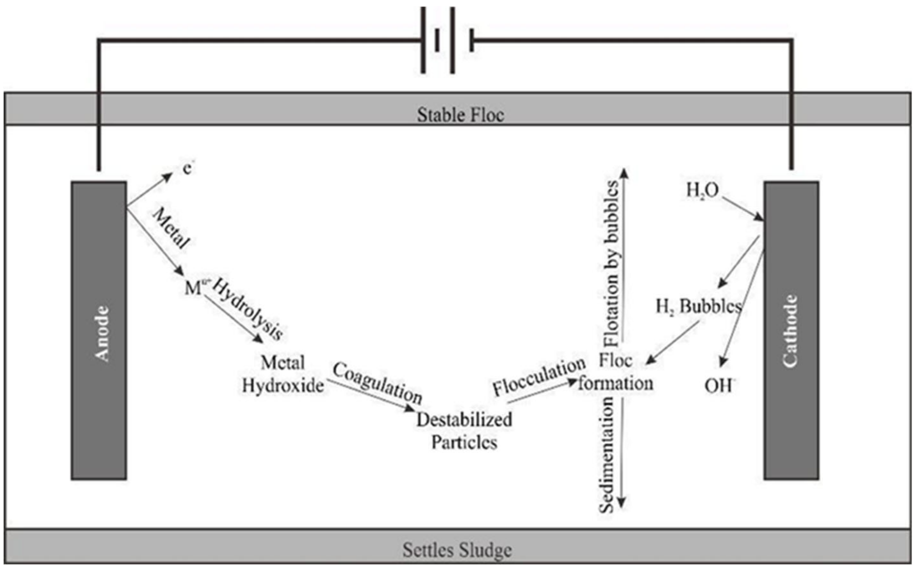

Fig 1. Schematic of EC process showing pollutant removal mechanisms

In the presence of chloride ions, chlorine gas may also evolve, further aiding in contaminant breakdown. Simultaneously, reduction reactions occur at the cathode, resulting in hydrogen gas evolution, which promotes flotation and pollutant separation.

$$2H_2O + 4e^- \rightarrow 2OH^- + H_2$$

Once released into the solution, metal ions react with hydroxide ions to form insoluble metal hydroxides, which aggregate into larger flocs that adsorb and remove pollutants. The formation of these hydroxides is depicted in the following reactions:

$$Fe^{2+} + O_2 + 2H^+ \rightarrow Fe^{3+} + H_2O_2$$

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + HO^{\bullet} + OH^-$$

These hydroxides act as coagulants, effectively removing pollutants through precipitation, adsorption onto metal hydroxides, and electrostatic interactions. The primary removal pathways include precipitation and co-precipitation, adsorption onto floc surfaces, electric double-layer compression, and interparticle bridging due to the polymerization of metal hydroxides. By understanding these chemical reactions and their role in EC, some parameters can be optimized to enhance pollutant removal efficiency while minimizing energy consumption and electrode degradation.

Fig. 2 illustrates the VOSviewer visualization, identifying several primary clusters related to the EC process in treating slaughterhouse wastewater. The key research topics include the EC process, poultry slaughterhouse wastewater, cattle slaughterhouse wastewater, and optimization, emphasizing the focus on wastewater treatment using EC, particularly regarding its efficiency and effectiveness in reducing COD, color, and turbidity levels. Additionally, Fig. 2 highlights the interconnections between EC and other variables such as energy consumption, electrode type (aluminum and iron), and optimal operational conditions that enhance treatment performance. The color-coded clusters indicate distinct research focuses, including fats and

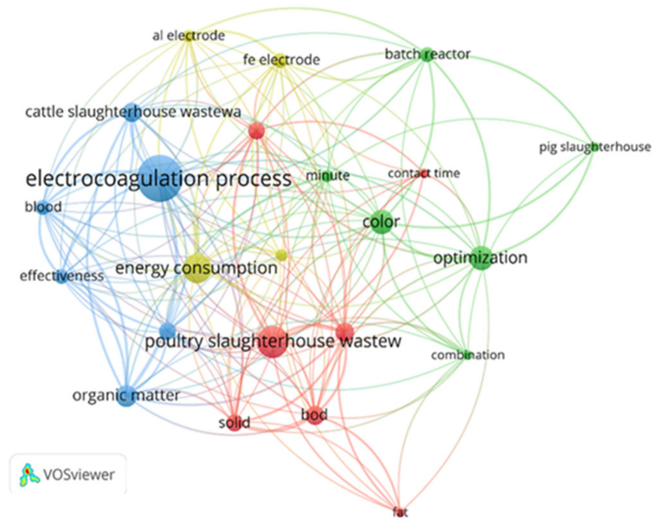

Fig 2. VOSviewer visualization of research on the EC process in slaughterhouse wastewater treatment

blood in poultry and cattle slaughterhouse wastewater and process optimization, considering technical variables like contact time, voltage, and reactor configuration.

To support the publication trend analysis, a bibliometric study was conducted, revealing a notable increase in research on EC for slaughterhouse wastewater treatment over the past decade. A database search in Scopus and Web of Science identified over 80 publications between 2021 and 2024, with a significant rise in studies after 2019, reflecting growing interest in EC as a sustainable treatment method. The VOSviewer clustering further confirms that optimization techniques, energy efficiency, and electrode material improvements are among the most frequently discussed research topics. These findings demonstrate the increasing recognition of EC as a viable wastewater treatment method, with an emphasis on improving its performance and overcoming limitations such as high energy consumption and electrode degradation. The bibliometric data supports the need for further studies on hybrid treatment approaches integrating EC with other advanced treatment technologies.

The main operational parameters in EC include pH, current density, contact time, and the type and concentration of additional electrolytes [49]. The pH significantly influences coagulation efficiency, with optimal conditions typically at a neutral to slightly acidic pH (around pH 6–8), depending on the type of electrode used [50]. At optimal pH, metal hydroxides produced by the electrodes more easily bind with pollutants [51]. Current density determines the rate of ion release from the electrodes and the amount of coagulant produced [29]. Higher current densities can increase pollutant removal efficiency but also raise energy consumption and operational costs [44]. Contact or retention time determines the duration of the EC process, which typically ranges from 10 to 60 min [52]. Extended contact times facilitate the release of more metal ions from the electrodes, enhancing pollutant removal efficiency; however, they also lead to higher energy consumption [45]. To optimize electrical conductivity and reduce energy demand, supporting electrolytes such as sodium chloride (NaCl) are often added to the solution [53].

EC has demonstrated high efficiency in removing various pollutants from slaughterhouse wastewater [54]. EC can achieve COD removal efficiencies of up to 97% from swine slaughterhouse wastewater, with performance significantly influenced by the type of electrode material used—particularly, pure aluminum electrodes yielding the highest removal efficiency [55]. For instance, an iron electrode at 22 mA/cm^2 achieved a COD removal rate of 92.5%, while an aluminum electrode under similar conditions achieved 82.4% [56]. Additionally, the choice of electrode material affects sludge generation, with iron electrodes producing more sludge than aluminum due to higher hydroxide formation [29]. Comparative studies have also shown that EC outperforms coagulation-flocculation (CF) in COD removal efficiency by approximately 20–30% in similar wastewater conditions [57]. These data emphasize the importance of parameter optimization in achieving maximum pollutant removal with minimal resource consumption.

EC also has several drawbacks, one of which is energy consumption at high current densities, which can increase operational costs, and metal electrodes must be replaced periodically due to corrosion during the process [58]. Additionally, the efficiency of EC is highly dependent on operational parameters such as pH, current density, and solution conductivity, so variations in these parameters can reduce pollutant removal performance. This process also generates hydrogen gas, which requires special handling, and produces sludge that needs further treatment to prevent additional pollution.

EO and CF are two wastewater treatment technologies often compared to EC because each has its own advantages and disadvantages in removing various types of pollutants [59]. EO is a process that uses electric current to oxidize organic and inorganic pollutants directly or through the formation of strong oxidants such as ozone, chlorine, or hydroxyl radicals on the electrode surface [59-61]. This technology demonstrates high effectiveness in disinfection and total organic carbon (TOC) removal, including for pollutants that are resistant to biodegradation [62]. The effectiveness of EO is influenced by current density, electrode type, and solution pH, where higher current densities can increase oxidant production but also raise energy consumption [63]. EO can reduce COD by over 90% and can fully disinfect water, making it an excellent choice for removing hard-to-degrade pollutants. However, EO has drawbacks in terms of high energy consumption and the potential increase of compounds such as nitrates during the process, which may require further treatment [64].

CF, on the other hand, is a physico-chemical treatment method that involves the addition of coagulants (such as aluminum or iron salts) to bind charged particles in water, forming large flocs that are easily separated [5]. CF is generally used as an initial treatment stage to reduce turbidity, color, and some organic pollutants before advanced processes. The effectiveness of CF is influenced by pH, coagulant dose, and mixing time [65]. This method effectively removes suspended particles, color, and turbidity, with COD and BOD removal efficiencies reaching up to 50%, making it ideal as an initial stage before further treatment [66]. According to Rezai and Allahkarami [67], CF has advantages in its simple implementation and low operational costs, but its drawback is the large amount of sludge produced, which requires further handling. Additionally, CF is less efficient in removing dissolved pollutants, so it often needs to be combined with other technologies, such as EC or EO, for more optimal results.

In comparison, EO is highly effective for removing hard-to-degrade pollutants and for disinfection, while EC excels in removing COD, heavy metals, and microorganisms. CF is the best choice for reducing turbidity and suspended particles, especially as an initial stage. EO has the highest energy consumption, particularly when using BDD electrodes at high current densities, whereas EC is more economical in energy consumption at lower current densities, and CF does not require electrical energy, making it an energy-efficient option despite needing additional coagulants. CF produces a large amount of sludge due to the use of external coagulants, while EC generates less sludge, and EO does not produce sludge but may increase the concentration of compounds like nitrates that require further treatment. In wastewater treatment, combining CF, EC, and EO is often applied to leverage the strengths of each technology. CF is typically used as a preliminary stage to reduce turbidity and particles, followed by EC or EO for more effective removal of dissolved pollutants.

■ COMPARATIVE ANALYSIS OF CATTLE SLAUGHTERHOUSE WASTEWATER TREATMENT TECHNOLOGIES

Slaughterhouse wastewater typically exhibits complex pollutant characteristics, such as high values of COD and BOD, high turbidity, and significant levels of oil and fat [20,54,59]. Treatment technologies discussed in the literature present various approaches to address these pollutants with varying efficiency, depending on operational conditions, electrode type, and other processing parameters. Each treatment method has distinct advantages and disadvantages in terms of pollutant removal efficiency, energy consumption, and operational costs, which are essential considerations when selecting the most suitable technology for slaughterhouse wastewater treatment.

EC is frequently reviewed due to its high pollutant removal efficiency and relatively low operational costs, especially when using aluminum electrodes. Additionally, EO and anodic oxidation (AO) are known to be effective for disinfection and TOC removal, although both generally require higher energy consumption [68]. CF is commonly used as an initial treatment stage, aimed at reducing turbidity and organic pollutant content before further processing with other methods.

Table 1 provides information on experimental scale, optimal conditions, pollutant removal efficiency, sludge production, energy consumption, operational costs, and the strengths and weaknesses of each reviewed treatment method. The presented data clearly support the evaluation and understanding of the advantages and limitations of various technologies applied in cattle slaughterhouse wastewater treatment studies. Table 1 presents a comparison of cattle slaughterhouse wastewater treatment technologies, covering optimal conditions, pollutant removal efficiency, energy consumption, and

Table 1. Overview of experimental studies and efficiency of EC in treating slaughterhouse wastewater

Title	Experiment Scale	Optimal Conditions	Pollutant Removal Efficiency	Energy Consumption (kWh/m³)	Operational Cost ($/m³)	Advantages	Disadvantages
Investigation removal efficiency of electrocoagulation process as a slaughterhouse wastewater treatment technique: toxicity assessment [54]	Batch	- Fe electrode: pH 9, current density 22 mA/cm², no additional supporting electrolyte - Al Electrode: pH 5, current density 20 mA/cm², no additional supporting electrolyte	- Fe Electrode: COD 92.52% - Al Electrode: COD 82.43%	- Fe Electrode: 48.12 - Al Electrode: 53.56	Not available	- Effective in COD and toxicity reduction. - Uses optimal parameters for pollutant removal efficiency.	- Relatively high energy consumption under certain conditions.
Techno-economic evaluation of electrocoagulation for cattle slaughterhouse wastewater treatment using aluminum electrodes in batch and continuous experiment [35]	Batch & Continuous	pH 7, contact time 75 min, TDS 3,000 mg/L, current density 4 mA/cm²	- COD: 95%	0.87	1.5	- High efficiency in COD, color, turbidity, and BOD removal. - Lower operational cost compared to other conventional methods.	Not available
A design of experiment approach of cattle slaughterhouse wastewater treatment by electrocoagulation method [69]	Batch	- Current density: 32.36 mA/cm² - pH: 4.07 - Flow rate: 1185.12 mL/min - H_2O_2: 0.005 M	- COD: 91.34% - TDS: Not specified - TSS: Not specified	Not available	Not available	- High efficiency in COD removal. - Operational parameters optimized using DoE method.	Not available
Application of copper and aluminium electrode in electro coagulation process for municipal wastewater treatment: A case study at Karachi [56]	Batch	- Voltage: 21 V using Al and Cu electrodes - Duration: 1 h	- COD: 96% - BOD: 38.5% - TSS: 98.14% - Turbidity: 95.7%	Not available	Not available	Effective in removing COD, TSS, and turbidity at higher voltage levels.	Relatively low BOD efficiency.
Electrocoagulation in batch mode for the removal of the chemical oxygen demand of an effluent from slaughterhouse wastewater in Lima Peru: Fe and al electrodes [25]	Batch	- Voltage: 6–10 V - Time: 25 min - Electrodes: Fe and Al	- COD: 53–60% (Al) and 59–60% (Fe) - Turbidity: 99% (Al) and 81.5–88.5% (Fe)	3.07 (Al) and 2.99 (Fe) at 6 V, 25 min	Not available	- Effective in removing COD and turbidity. - Lower voltage option reduces energy consumption.	Moderate COD removal efficiency (maximum around 60%).
Removal of chemical oxygen demand from slaughterhouse wastewater by electrocoagulation in continuous mode: Isothermal, kinetic and adsorption study [25]	Continue	- Voltage: 8 V - Hydraulic retention time: 0.33 h - Electrodes: Al and Fe	- COD: 62.2% (Al) and 51.2% (Fe) - Turbidity: 99.5% (Al) and 94.5% (Fe)	Not available	Not available	- Effective in reducing COD and turbidity. - Continuous mode allows for high-volume treatment.	Moderate COD efficiency (maximum around 62%).
Removal of total organic carbon and color from slaughterhouse wastewaters using electrocoagulation process: central composite design optimization [70]	Batch	- Current density: 22.97 mA/cm² - Electrode gap: 12.03 mm - Reaction time: 78.95 min	- TOC: 94.77% - Color: 99.32%	Not available	2.45 for TOC, 2.57 for color	- High efficiency in TOC and color removal. - Economical parameter optimization.	Not available

Title	Experiment Scale	Optimal Conditions	Pollutant Removal Efficiency	Energy Consumption (kWh/m^3)	Operational Cost ($\$/m^3$)	Advantages	Disadvantages
Electrochemical treatment of cattle wastewater samples [71]	Batch	- EC Current density: 200 A/m^2 - Reaction time: 2 h - Electrodes: Al (EC) and BDD (EO)	- Phosphate: >95% - COD: 25–75% - Nitrate: up to 85% (EC)	Not available	Not available	- EC-EO combination significantly enhances COD and phosphate removal. - Effective for nearly 100% phosphate removal.	EO increases nitrate concentration during the process.
Slaughterhouse wastewater treatment by electrocoagulation process [72]	Batch	- Current density: 1400 mA/dm^2 - Electrodes: 4 anode and 2 cathode configurations	- BOD: 56.4% - TSS: 99.47% - TDS: 20.25%	Not available	Not available	- Highly effective in TSS removal. - Reduces BOD and TDS at high current density.	Relatively low BOD removal efficiency (maximum 56.4%).
Treatment of cattle slaughterhouse wastewater by sequential coagulation-flocculation/electrooxidation process [59]	Continuous	- Coagulant dose: $FeCl_3$ 800 mg/L, pH: 8.5 - EO with BDD electrode, j = 30 mA/cm^2, pH 8.5, 3 g NaCl/L, 0.9 L/h	- COD: 97.2% - Turbidity: 99.9%	91.1	3.50	- Highly effective in reducing COD and turbidity. - Uses EO with BDD for more effective removal.	High energy consumption at high current density

operational costs, as well as the strengths and weaknesses of each method. EC using iron and aluminum electrodes demonstrates varying effectiveness based on electrode type and operational conditions. Reported that an Fe electrode at pH 9 with a current density of 22 mA/cm^2 achieved a COD removal efficiency of 92.52%, while an Al electrode under similar conditions reached 82.43%. However, energy consumption varied, with Fe and Al electrodes consuming 48.12 and 53.56 kWh/m^3, highlighting the need for energy optimization [54].

EO with boron-doped diamond (BDD) electrodes, as studied by Akhtar and Kobya [59] and Stylianou et al. [71], demonstrated high efficiency in removing hard-to-degrade pollutants such as phosphate, achieving COD removal up to 97.2%. However, EO requires a current density of 30 mA/cm^2 and $FeCl_3$ at pH 8.5, with an energy consumption of approximately 91.1 kWh/m^3, making it a high-energy-demand process that necessitates further refinement.

Parameter optimization plays a crucial role in enhancing EC performance. Studies have shown that reducing current density to 4 mA/cm^2 while maintaining a pH of 7 can still achieve 95% COD removal at a significantly lower energy cost of 0.87 kWh/m^3 [35]. Additionally, using a design of experiment (DoE) approach, Eryürük et al. [69] identified an optimal current density of 32.36 mA/cm^2 at pH 4.07, achieving 91.34% COD removal. These findings highlight the importance of parameter fine-tuning in minimizing energy consumption while maximizing treatment efficiency.

Further studies investigated the impact of electrode material selection on EC performance. Fe electrodes, due to their ability to release Fe^{2+} and Fe^{3+} ions, tend to enhance flocculation efficiency, leading to higher pollutant removal rates compared to Al electrodes. However, Al electrodes have been shown to produce less sludge, reducing the need for secondary sludge management, which is a key factor in operational cost considerations. The trade-off between higher pollutant removal and sludge generation must be carefully balanced to ensure economic feasibility in large-scale applications.

Another crucial parameter in EC is reaction time. Research indicates that increasing treatment duration from 20 to 60 min can enhance COD removal efficiency by up to 20%, though diminishing returns are observed beyond 60 min [56]. This suggests that an optimal reaction time exists, beyond which additional energy input does not result in proportionate improvements in treatment efficiency. Balancing treatment time with energy consumption is essential to maintaining cost-effective operations.

Combining CF with EO has also proven effective in enhancing COD and turbidity removal. Akhtar and Kobya [59] demonstrated that CF acts as an effective pre-treatment step, improving the efficiency of EO while reducing energy costs. Furthermore, studies optimizing operational conditions through advanced modeling approaches, such as response surface methodology, have further refined energy efficiency, lowering operational expenses while maintaining high pollutant removal rates.

Other process variables such as inter-electrode spacing and electrolyte addition also influence EC efficiency. Increasing inter-electrode distance beyond a certain threshold can reduce treatment efficiency due to increased resistance in the electrochemical process. Conversely, adding supporting electrolytes such as NaCl enhances conductivity and reduces overall energy demand, making the process more viable for industrial applications. These parameters must be carefully controlled to achieve optimal performance in wastewater treatment.

Despite its advantages, EC faces limitations such as high energy consumption and electrode corrosion, which can impact long-term operational stability. One potential solution to mitigate high energy costs is the incorporation of renewable energy sources, such as solar or wind power, to drive the EC process. Studies have explored the feasibility of photovoltaic-powered EC systems, showing promising reductions in operational costs while maintaining treatment efficiency. Another strategy is the optimization of pulsed current or intermittent voltage application, which has been found to reduce energy consumption without significantly compromising pollutant removal efficiency.

Electrode corrosion, particularly for Fe and Al electrodes, remains a major challenge as it leads to electrode degradation and increased maintenance costs. One approach to reducing corrosion is the use of hybrid electrode materials, such as composite electrodes made of conductive polymers or coated electrodes with corrosion-resistant layers. Research indicates that titanium-coated electrodes or mixed-metal oxides can significantly extend electrode lifespan while maintaining effective coagulation performance. Additionally, controlling pH within the optimal range of 6–8 can help minimize excessive electrode dissolution, further enhancing process stability.

EC with Al or Fe electrodes remains a reliable initial treatment for slaughterhouse wastewater, particularly in reducing turbidity and total suspended solids (TSS). Despite its high energy consumption, EO excels in TOC removal and disinfection. CF is also effective in removing turbidity and suspended particles, particularly when integrated with EC or EO. The combination of CF-EO or EC-EO provides superior treatment efficiency and cost-effectiveness for large-scale applications, especially for wastewater with complex pollutants. These findings underscore the necessity of optimizing EC parameters to achieve sustainable and efficient wastewater treatment solutions.

Optimizing EC parameters, including pH, current density, electrode material, reaction time, and electrolyte addition, is crucial to maximizing pollutant removal efficiency while minimizing energy and operational costs. Future research should focus on real-scale implementation of optimized EC processes, incorporating machine learning and artificial intelligence-driven models for predictive optimization. Additionally, hybrid technologies integrating EC with other advanced treatment methods, such as membrane filtration and bio-electrochemical systems, could further enhance wastewater treatment performance, ensuring environmental sustainability and economic feasibility.

■ IMPLICATIONS AND DEVELOPMENT RECOMMENDATIONS

Findings from this review indicate that EC technology has significant potential in managing wastewater from slaughterhouses, primarily due to its high capacity for removing organic and inorganic pollutants and its energy efficiency, which can be optimized. One of the main implications of these findings is the importance of optimizing operational parameters such as pH, current density, electrode type, and contact time, which have been shown to greatly impact the removal efficiency of pollutants such as COD, BOD, and turbidity. In this context, further research is recommended to deepen understanding of the interactions between these parameters and to identify optimal conditions that can be applied consistently across various types of slaughterhouse wastewater.

Beyond parameter optimization, industrial-scale implementation is also a crucial step in developing EC technology. Although this technology has proven effective in laboratory settings, larger-scale testing is necessary to understand practical challenges, such as energy requirements, electrode maintenance costs, and efficiency in processing larger volumes of wastewater. Studies have shown that Fe electrode at pH 9 with a current density of 22 mA/cm^2 can achieve a COD removal efficiency of 92.52%, while Al electrode under similar conditions reaches 82.43%. However, the energy consumption varies, with Fe and Al electrodes consuming 48.12 and 53.56 kWh/m^3, necessitating further refinement in energy efficiency strategies [54].

The integration of EC with other treatment methods, such as CF or EO, has shown promising improvements in pollutant removal efficiency. Studies indicate that using CF as a pre-treatment stage before EC enhances turbidity and TSS reduction, while EO as a post-treatment stage increases COD and TOC removal. Akhtar and Kobya [59] demonstrated that a CF-EO combination achieved a COD removal efficiency of 97.2% with an energy consumption of 91.1 kWh/m^3, while Hellal et al. [35] and Eryürük et al. [69] optimized CF-EC combinations using the DoE method, achieving high COD efficiency at a significantly lower energy consumption of 0.87 kWh/m^3 at a current density of 4 mA/cm^2.

To further substantiate the benefits of integrating EC with CF or EO, additional research should focus on determining the most effective operational parameters for each combined system, assessing sludge generation, and quantifying long-term cost savings. Future studies should also explore hybrid models incorporating renewable energy sources, such as solar-powered EC, to address high energy consumption challenges. By leveraging these approaches, the integration of EC with other methods can be fine-tuned to maximize treatment efficiency, lower operational costs, and ensure a sustainable solution for slaughterhouse wastewater management across various scales of application.

■ CONCLUSIONS AND FUTURE DEVELOPMENTS

This review demonstrates that EC technology is a promising method for treating wastewater from slaughterhouses due to its high effectiveness in removing organic and inorganic pollutants such as COD, BOD, turbidity, oil, and fat. Comparative analysis with other technologies, such as EO and CF, highlights that each technology has specific advantages depending on the type of pollutants and desired operational parameters. EC excels in reducing turbidity and suspended particles with relatively low operational costs, particularly when using aluminum electrodes. On the other hand, EO proves highly effective for disinfection and TOC removal, making it the optimal choice for the final treatment stages. CF serves as an advantageous preliminary treatment stage to reduce heavy pollutant loads before further processing with EC or EO. Overall, EC stands out as the most effective and efficient choice for treating slaughterhouse wastewater in terms of multi-pollutant removal with economical costs, especially for large-scale applications with optimized parameters. Combining EC with other technologies such as CF and EO can further enhance treatment efficiency, providing an integrated solution capable of addressing the complex characteristics of slaughterhouse wastewater.

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■ CONFLICT OF INTEREST

The authors declare no conflict of interest.

■ AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript preparation. Each author actively participated in the research process, drafting, and reviewing the article. All authors have read and approved the final version of the manuscript.

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