Documentary Analysis of the Treatment of Industrial Effluents Using the Electrocoagulation Process

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Abstract

Introduction: Electrocoagulation (EC) has emerged as a promising and versatile technique for the treatment of industrial effluents, offering efficient removal of a wide variety of contaminants such as COD, BOD_5, heavy metals, synthetic dyes, and pharmaceutical compounds. In recent years, interest in EC has grown due to its potential as an environmentally friendly and cost-effective alternative for wastewater treatment.

Methods: This study presents a bibliometric analysis of 50 scientific articles published between 2004 and 2023, using Scopus as the main database. Bibliographic management and analysis tools such as Mendeley and VOSviewer were used to visualize trends in scientific production, identify key countries, collaborative networks, and thematic clusters related to EC. The analysis focused on understanding how research in this field has evolved and which directions are currently most explored.

Results y Conclusions: The results reveal an increase in scientific production since 2015, with India, Turkey, Brazil, China, and the United States being the most active contributors. Research has shifted from basic experimental studies to more integrated approaches involving hybrid technologies such as EC-Fenton, EC-O_3, and the use of biofilters (e.g., algae). There is also a growing focus on sustainability and circular economy principles, including resource recovery and the reuse of sludge as agricultural fertilizer. The findings emphasize EC's role in treating both conventional and emerging contaminants, positioning it as a strategic technology for industrial wastewater management. Future research should expand the bibliometric scope by incorporating additional databases like Google Scholar and exploring the large-scale application of EC systems.

Keywords: Electrocoagulation, treatment, contaminants, wastewater, Scopus, bibliometric analysis.

Introduction

Effluents generated from food processing and other industries pose significant environmental challenges. In particular, these types of wastewater contain a variety of pollutants which, if not properly treated, can have harmful effects on both aquatic and terrestrial ecosystems. These effluents often contain fats, oils, suspended solids, chemicals, and nutrients, among others, compromising the quality of water and soil (Sandoval & Salazar, 2021; Moussa et al., 2017). Wastewater discharged by the meat and dairy industries represents a major source of pollution for water bodies. These industries use large volumes of water in both cleaning and production processes, and this water is later discharged as wastewater. According to Martins et al. (2019), the discharge of industrial wastewater into water resources can have serious consequences for water quality. Moreover, the intensive use of organic compounds in these industries and in agriculture has exacerbated the challenges of adequately treating this wastewater. Hashim et al. (2021) report that the large amounts of organic matter discharged in industrial effluents worsen the pollution of freshwater bodies, thus endangering aquatic ecosystems. Not only the meat and dairy industries, but also other sectors such as the food industry, construction, petroleum refining, pharmaceuticals, and pesticide manufacturing, contribute to the significant concentration of organic pollutants in their effluents (Lapworth et al., 2012; Kryuchkova et al., 2021; Mojiri et al., 2021; Kuzniewski, 2021; Feier et al., 2018; Kushwaha et al., 2010). This increase in pollutant loads in water bodies highlights the urgent need to develop effective strategies for the treatment of industrial wastewater to prevent irreversible damage to water resources and their ecosystems. Therefore, it is essential to emphasize that wastewater from the meat and dairy industries constitutes industrial effluents with notable levels of pollutants, such as organic matter and nutrients like nitrogen and phosphorus, which can cause serious environmental impacts if not properly managed (Rodríguez et al., 2021; Cabrera, 2022; Ghazouani et al., 2019).

On the other hand, effluents from dairy industries, resulting from production and cleaning processes, present significant challenges in terms of pollutant load. According to Magaña et al. (2020), Qasim & Mane (2013), and Valente et al. (2015), these effluents contain a variety of contaminants, including organic matter, fats, proteins, lactose, and other compounds. Similarly, Akyol et al. (2013) and Abdel-Fatah et al. (2019) highlight that these wastes are rich in nutrients that require proper management to avoid eutrophication of receiving water bodies. Therefore, it is imperative to seek strategies that reduce the pollutant load and promote the reuse of this wastewater (Wade, 2005; Anderson, 2006; Rodríguez et al., 2021).

In this context, electrocoagulation emerges as an effective alternative for the treatment of industrial effluents, particularly in the food industry (Ghazouani et al., 2019; Hashim et al., 2021; Markou et al., 2017). This process has proven capable of removing a wide range of contaminants, including suspended solids, organic matter, detergents, fats, and oils, and it also improves parameters such as turbidity, hardness, and color (Moreno-Casillas et al., 2007; Shah et al., 2019). According to Chen & Guohua (2004), Jasim & AlJaberi (2023), Delgado-Vargas (2023), Kushwaha et al. (2010), An et al. (2017), and Bayramoglu et al. (2004), electrocoagulation involves inducing changes in suspended, emulsified, or dissolved pollutant particles in an aqueous medium by applying electric current through parallel metal plates, preferably made of iron or aluminum. Furthermore, Sevda et al. (2018), Khan et al. (2023), Yavuz (2018), Holt et al. (2005), and Lu et al. (2021) emphasize that operational conditions, such as current density and type of pollutant, influence the effectiveness of the process.

In summary, a literature review of global studies on electrocoagulation as a complex research field provides a solid foundation for future investigations, enabling the contextualization of the current work, identification of opportunities, and contribution to the advancement of knowledge in this area. For this reason, a bibliometric analysis was carried out using Scopus, a renowned bibliographic database containing abstracts and articles from over 3,000 open-access journals, noted for its continuous updates. This allows the research to be contextualized within the current framework and contributes to the development of sustainable solutions for the treatment of industrial effluents (Martins et al., 2019; Wang et al., 2023; Chandra et al., 2023).

Methodology

Data Collection

This article uses the Scopus database as a reference (https://www.scopus.com/). A bibliographic review was conducted, and a canonical equation was established using ChatGPT based on the keywords macrophytes and greenhouse gases. This approach detected 175 articles related to the topic. The search period was specified (2011-2024), filters were applied to display documents in all languages, and the information was delimited by including keywords in English such as aquatic plants, carbon cycles, carbon sequestration, among others, resulting in 113 documents. The resulting equation was: TITLE-ABS-KEY (macrophytes) AND TITLE-ABS-KEY (greenhouse AND gases) AND PUBYEAR > 2010 AND PUBYEAR < 2024 AND (LIMIT-TO (EXACTKEYWORD , "Macrophyte") OR LIMIT-TO (EXACTKEYWORD , "Greenhouse Gas") OR LIMIT-TO (EXACTKEYWORD , "Greenhouse Gases") OR LIMIT-TO (EXACTKEYWORD , "Wetlands") OR LIMIT-TO (EXACTKEYWORD , "Carbon Dioxide") OR LIMIT-TO (EXACTKEYWORD , "Wetland") OR LIMIT-TO (EXACTKEYWORD , "Climate Change") OR LIMIT-TO (EXACTKEYWORD , "Macrophytes") OR LIMIT-TO (EXACTKEYWORD , "Carbon") OR LIMIT-TO (EXACTKEYWORD , "Organic Carbon") OR LIMIT-TO (EXACTKEYWORD , "Vegetation") OR LIMIT-TO (EXACTKEYWORD , "Biomass") OR LIMIT-TO (EXACTKEYWORD , "Greenhouse Gas Emissions") OR LIMIT-TO (EXACTKEYWORD , "Carbon Sequestration") OR LIMIT-TO (EXACTKEYWORD , "Carbon Cycle") OR LIMIT-TO (EXACTKEYWORD , "Photosynthesis") OR LIMIT-TO (EXACTKEYWORD , "Plants") OR LIMIT-TO (EXACTKEYWORD , "Greenhouse Gas Emission") OR LIMIT-TO (EXACTKEYWORD , "Eichhornia Crassipes") OR LIMIT-TO (EXACTKEYWORD , "Aquatic Macrophytes") OR LIMIT-TO (EXACTKEYWORD , "Aquatic Plant") OR LIMIT-TO (EXACTKEYWORD , "Plant") OR LIMIT-TO (EXACTKEYWORD , "Greenhouses Gas") OR LIMIT-TO (EXACTKEYWORD , "Global Change") OR LIMIT-TO (EXACTKEYWORD , "Gases") OR LIMIT-TO (EXACTKEYWORD , "Climate") OR LIMIT-TO (EXACTKEYWORD , "Aquatic Plants") OR LIMIT-TO (EXACTKEYWORD , "Carbon Cycling") OR LIMIT-TO (EXACTKEYWORD , "Aquatic Ecosystems") OR LIMIT-TO (EXACTKEYWORD , "Aquatic Ecosystem") OR LIMIT-TO (EXACTKEYWORD , "*Azolla*").

Bibliometric Analysis Tools

Once the sample was selected, the abstracts were read and the co-occurrence analysis of keywords available in the preview offered by the Scopus platform was carried out (see Figure 1). Articles were then selected using the appropriate export option, exporting them through BibTeX export. When the “Export document settings” tab is displayed, the Mendeley option is selected, choosing the necessary information to allow for more complete reading and compatibility with programs such as VOSviewer for the generation of bibliometric maps and networks. Subsequently, the Export button was clicked, sending the files directly in RIS format for reading and management through Mendeley, which can even be integrated as a plug-in within a Word document without requiring the full download of the articles. Throughout the process, the introduction, methodology, and conclusions of the texts were re-read carefully to ensure that the selected articles also reflected current trends and were relevant for the analysis in this review. As a result of this work, a total of 50 articles were selected, containing both convergences and divergences among different authors regarding the addressed issue and the following thematic trends: (1) types of effluents, (2) treatment processes, (3) electrocoagulation process, (4) complementary technologies, and (5) sustainability and by-products.

Based on these selected documents, the VOSviewer software was used to generate bibliometric networks based on the co-occurrence of keywords, authors, and co-authorship links, aiming to detect thematic patterns. In this context, the convergent categories gather recurring concepts, techniques, and approaches that reveal consolidated research lines in the treatment of industrial effluents, which typically present a high load of organic matter, fats, proteins, suspended solids, and chemical compounds. This highlights the need for proper treatment to reduce risks to the quality of water and soil in receiving environments. In this regard, techniques such as electrocoagulation stand out for their ability to remove a wide variety of pollutants, microorganisms, and emerging compounds, as well as improve parameters such as turbidity and color. In contrast, divergent categories reveal the existence of different approaches and applications, reflecting the breadth of the field, with research focused on new treatment technologies, classified by type of pollutant or geographic region. This dual categorization not only provides a more stratified reading of the results but also enriches the understanding of the current state of industrial effluent management.

Note. Map created using VOSviewer software based on data extracted from the Scopus database. Own elaboration.

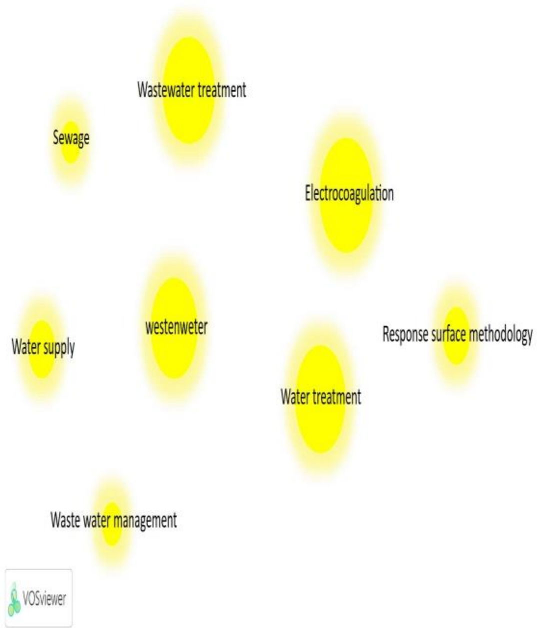

Figure 1. Keyword co-occurrence analysis

Figure 1 presents a keyword density map with a co-occurrence threshold of 5, identifying five main thematic clusters in the field of electrocoagulation for wastewater treatment. Among these, three nodes stand out due to their high interconnection and frequency: Electrocoagulation (EC) (35 occurrences, TLS=189), Wastewater treatment (28 occurrences, TLS=156), and COD (18 occurrences, TLS=132). These terms have maintained a dominant presence in the scientific literature between 2020 and 2024, demonstrating their centrality in the research of this field. Their grouping in Cluster 1 (Electrocoagulation Process) and Cluster 3 (Target Pollutants), along with their high TLS values, reveals that they constitute the conceptual core of the analyzed studies. The distribution observed in Figure 1 highlights a primary focus on: (1) technical optimization of the process (electrodes, operational parameters), and (2) removal of key pollutants (organics, metals), while emerging topics such as circular economy (Cluster 5, TLS=89) show relatively less development (see Table 1). This configuration suggests that future research could delve deeper into specific sectoral applications (e.g., pharmaceuticals, microplastics) or into integration with complementary technologies (e.g., electro-Fenton, membranes), which remain underexplored despite their innovative potential.

Table 1. Identified Thematic Clusters

CLUSTER	NODE	MAIN TOPIC	KEY TERMS	APPLICATIONS
1	12	Electrocoagulation Process	Electrocoagulation (EC), Electrodes (Al/Fe), Current density, Passivation, Batch reactor, Operating cost	Parameter optimization, reactor design
2	8	Types of Effluents	Dairy, textile, oily, olive mill, hospital wastewater, bilge water	Food industry, petroleum, marine sectors
3	7	Target Pollutants	COD, BOD_5, heavy metals, synthetic dyes, polyphenols, micropollutants, pharmaceuticals	Organic matter and toxic compounds removal
4	5	Complementary Technologies	Electro-Fenton, electrochemical oxidation, membrane filtration, nano-adsorbents, ozonation	Hybrid or advanced treatment systems
5	4	Sustainability and By-products	Circular economy, sludge, resource	Waste valorization (e.g.,

	recovery, water reuse, ecological sanitation	sludge as fertilizer)

Note. Data obtained through keyword co-occurrence analysis conducted using VOSviewer software, based on bibliographic records extracted from Scopus. Own elaboration.

Cluster 1: Electrocoagulation Process.
This was the group with the highest number of nodes (12), where the keyword "Electrocoagulation (EC)" recorded the highest Total Link Strength (TLS) value (189), highlighting its strong connection with the terms "iron/aluminum electrodes" (TLS: 145) and "current density" (TLS: 112). These links reflect the prevailing focus on the technical optimization of the process, particularly regarding material selection and operational conditions. A secondary connection with "operating cost" (TLS: 67) was also observed, suggesting that research additionally evaluates the economic feasibility of this technology.

Cluster 2: Types of Effluents.
This group comprised 8 terms, with "industrial wastewater" being the node with the highest link strength (TLS: 132) and 34 occurrences. This term showed a direct relationship with "dairy effluents" (TLS: 98) and "textile wastewater" (TLS: 85), indicating that the most extensively studied applications belong to these sectors. A relevant connection with "organic pollutants" (TLS: 76) was also identified, highlighting the diversity of pollutant loads addressed in the literature.

Cluster 3: Target Pollutants.
This set included 7 items, with "COD (Chemical Oxygen Demand)" having the highest TLS (156) and 28 occurrences, followed by "heavy metals" (TLS: 121) and "synthetic dyes" (TLS: 89). The strong association among these terms indicates that electrocoagulation is primarily used to remove complex pollutants, with a focus on reducing organic load and toxicity. The connection with "operating parameters" (TLS: 64) emphasizes the importance of adjusting conditions such as pH or treatment time to enhance efficiency.

Cluster 4: Complementary Technologies.
This cluster included 5 nodes, with "Electro-Fenton" as the central term (TLS: 118), closely linked to "electrochemical oxidation" (TLS: 92) and "membrane filtration" (TLS: 75). These links reflect a growing trend toward hybrid systems that combine electrocoagulation with other advanced methods to treat emerging contaminants (e.g., pharmaceuticals or microplastics). The presence of "nano adsorbents" (TLS: 53) also suggests early exploration into innovative materials.

Cluster 5: Sustainability and By-products.
This group, consisting of 4 terms, was led by "circular economy" (TLS: 89), which showed strong correlations with "by-product recovery" (TLS: 67) and "sludge" (TLS: 58). The similarity in TLS values (ranging from 50 to 70) indicates that these concepts are addressed in an integrated manner, emphasizing strategies to valorize the waste generated during treatment—such as reusing sludge in agriculture or construction.

The overall interpretation of the clusters reveals a thematic structure organized around three fundamental axes: technical, applied, and innovative. Electrocoagulation emerges as the core axis of research, encompassing everything from the optimization of operational parameters and material selection (Cluster 1) to its application in various types of industrial effluents and specific contaminants (Clusters 2 and 3), including organic compounds and heavy metals. Additionally, a trend is evident toward the incorporation of complementary technologies and sustainability strategies (Clusters 4 and 5), suggesting an evolution from the traditional approach toward more efficient hybrid systems with lower environmental impact. Thus, electrocoagulation stands out not only as a well-established technique but also as a versatile platform for the development of advanced solutions in wastewater treatment.

Discussion

Publications by Country

Out of the 50 articles selected for this review, a broad geographical distribution was identified, with publications originating from a total of 23 countries, each contributing between 1 and 4 articles during the period from 2004 to 2024. This information is presented in Figure 3.

Note. Geographical distribution of academic publications related to wastewater treatment using electrocoagulation, based on data extracted from the Scopus database. Developed by the author.

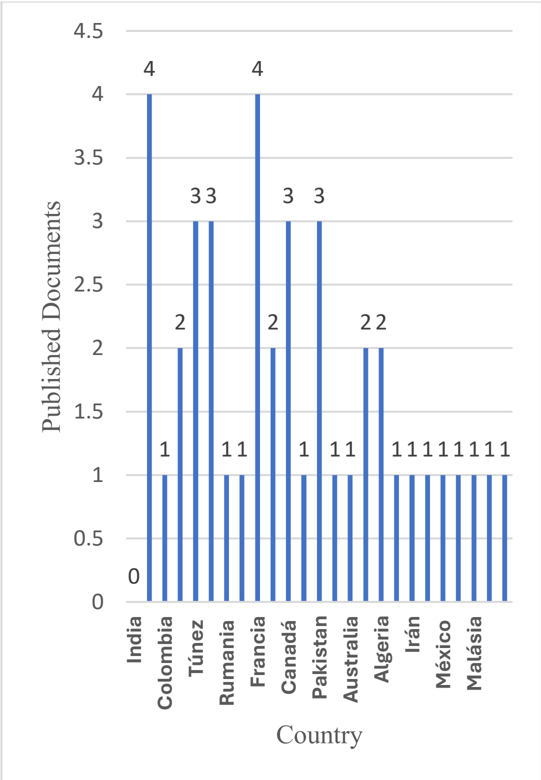

Figure 3. Articles published by country (2004–2024)

The analysis of academic production on electrocoagulation as a wastewater treatment method reveals a notable contribution from countries such as India and Turkey, each with four publications, followed by Brazil, China, and the United States, each with three articles. This distribution suggests a strong research presence in Asia and the Americas, positioning these continents as the main generators of knowledge on this topic. Europe also shows significant participation, although more dispersed across several countries. A growing trend toward international collaboration is observed, as evidenced by eight multinational studies involving researchers from countries such as India, Brazil, Spain, Iran, and Australia, among others. These alliances reflect a collective effort to address the challenges of wastewater treatment through multidisciplinary and transnational approaches. Overall, the data show that electrocoagulation not only generates interest in highly industrialized contexts, but also in developing countries seeking efficient and sustainable solutions for wastewater management.

Publication Trends

The temporal behavior of publications on electrocoagulation for industrial wastewater treatment shows a growing trend, with a gradual increase in scientific output over time. As shown in Figure 4, 74% of the reviewed publications were produced between 2015 and 2023. This pattern highlights the increasing research interest in electrocoagulation in recent years.

Note. Annual trend of publications related to effluent treatment between 2004 and 2024. Prepared by the author based on data obtained and visualized using Scopus.

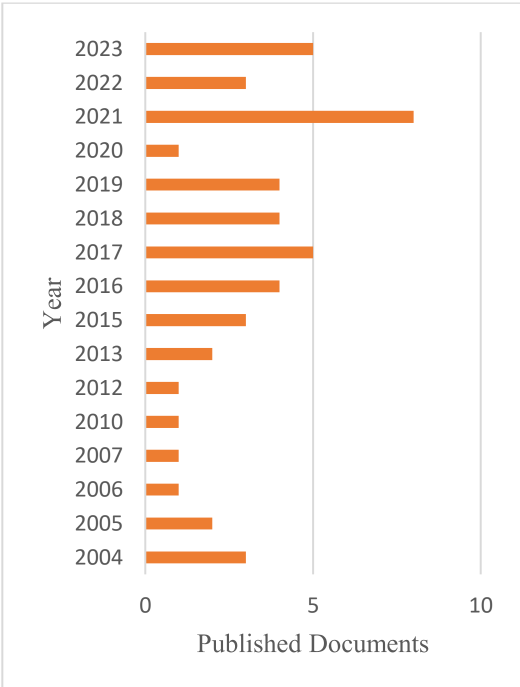

Figure 1. *Publication Trends by Year*

As a result, when analyzing the database of articles found in Scopus, it can be observed that the oldest studies focused on the application of electrochemical processes such as electrocoagulation for the treatment of wastewater with high organic load and metal content, highlighting their efficiency in removing contaminants that are difficult to treat by conventional methods (Adhoum & Monser, 2004; Bayramoglu et al., 2004; Chen & Guohua, 2004).

In contrast, more recent studies have delved into the optimization of the electrocoagulation process, incorporating operational cost analysis, energy efficiency, and integration with complementary technologies. For example, Khan et al. (2023) and Zelada Romero & Vázquez (2023) focused on the detailed evaluation of operational variables such as electrode type, current density, treatment time, and electrolyte concentration, achieving high removal percentages of COD, TSS, and turbidity, while also considering sustainability and process efficiency. Both studies contribute to the design of more effective electrochemical cells for urban and textile wastewater, respectively, emphasizing the achievement of optimal operating conditions for different types of effluents.

Likewise, Chandra et al. (2023) explore the synergy between electrocoagulation and biological processes (such as anaerobic treatment), representing a current trend towards hybrid systems that maximize treatment efficiency and reduce sludge generation. On the other hand, Delgado-Vargas et al. (2023) integrate the electrocoagulation process with electro-oxidation techniques and the use of advanced electrode materials, enabling the treatment of water containing emerging and persistently toxic contaminants, thus expanding the applicability of these technologies.

This evolution reflects a progressive shift from basic experimental studies to a more comprehensive, efficient, and sustainable vision of water treatment, in line with current demands for environmental impact mitigation, resource recovery, and industrial scalability. Furthermore, this trend also responds to the growing concern over the availability of clean water in water-stressed contexts, as well as to global commitments regarding environmental sustainability.

Electrocoagulation: Current Landscape, Interdisciplinary Approaches, and Sustainability Perspective

Electrocoagulation (EC) has emerged as a versatile technique for wastewater treatment, ranging from complex industrial effluents to emerging contaminants. Recent bibliographic analysis allows this field to be structured into five fundamental clusters, which interact with contemporary trends in technological innovation, sustainability, and environmental governance.

Fundamentals of the Electrocoagulation Process

This cluster encompasses the technical-operational principles of the process, highlighting the use of Al/Fe electrodes, the influence of current density, pH control, conductivity, and reactor configuration. In this regard, Moreno-Casillas et al. (2007), Moussa et al. (2017), Khan et al. (2023), Lu et al. (2021), and Yavuz & Ögütveren (2018) indicate that electrode passivation can limit system efficiency. Recent developments, such as automated controllers proposed by Martínez-Huitle & Panizza (2018), aim to improve energy efficiency. This technical knowledge is essential for scaling the technology efficiently, as emphasized by Brillas & Martínez-Huitle (2015), who highlight the urgent need for industrial-scale studies.

The effectiveness of the electrocoagulation (EC) process applied to wastewater is highly dependent on the type and configuration of electrodes. Findings reported in several publications show that metallic electrodes, especially iron and aluminum, are the most commonly used due to their high performance in generating coagulants through the dissolution of species such as Fe(II), Fe(III), and Al(III). These species combine with hydroxide ions to remove contaminants via precipitation or flotation (Adhoum & Monser, 2004; Brillas & Martínez-Huitle, 2015; Chen & Guohua, 2004; García-Segura et al., 2017). Iron is effective across a wide pH range (3.5 to 7.0), whereas aluminum tends to form lighter flocs that play an important role in flotation processes (Mousazadeh et al., 2021). The choice of electrode also depends on the type of contaminant targeted for removal. In the case of industrial wastewater, aluminum and iron electrodes are a suitable choice for removing organic, inorganic, or pathogenic contaminants without producing toxic byproducts (Qasim & Mane, 2013).

In the meat and dairy industries, the use of electrodes has already proven effective, considering the influence of parameters such as the number of electrodes and treatment time (Rodríguez-Díaz et al., 2021). Additionally, combined-type electrodes, such as iron–aluminum, have shown potential for improving the removal efficiency of heavy metals (Gatsios et al., 2015). The electrode arrangement—either monopolar or bipolar—also significantly affects the effectiveness of the treatment process. Studies such as those by Holt et al. (2005) and Jasim & AlJaberi (2023), as well as other systems and modifications in electrode design, have favored experimental configurations that enhance chemical oxygen demand (COD) removal. Other configurations, such as the use of stainless-steel mesh as cathodes, can increase oil removal efficiency and reduce operating costs (Wang et al., 2022).

Regarding alternative materials, boron-doped diamond electrodes are noted for their high efficiency, although their very high energy consumption limits widespread use (Ghazouani et al., 2019). Dimensionally stable anodes (DSA), such as IrO_2-Ta_2O_3/Ti, are preferred for their longevity and their ability to promote oxidation without generating sludge (Markou et al., 2017).

Studies by Magaña-Irons et al. (2020) and Valente et al. (2015) demonstrate that the removal of contaminants such as COD, turbidity, and suspended solids depends heavily on operational conditions such as pH and current density. For example, with a pH close to 5 and a current density of 61.6 A/m², significant removals have been achieved using aluminum electrodes. Finally, Trompette and Lahitte (2021) also highlight that the interaction between electrodes and electrolytes—such as sodium or ammonium salts—can be decisive in the evolution of the coagulation process, depending on the type of particles present in the water.

In light of these findings, it can be concluded that the selection of electrode type and arrangement, along with operational parameters, are critical factors for optimizing the electrocoagulation process across different industries. Future research should also consider the diversity of effluents to be treated, the specific contaminants or target variables, and complementary technologies aimed at achieving sustainability and/or circular economy goals.

Diversity of Treated Effluents

The literature reports successful applications of electrocoagulation in treating effluents from textile, dairy, oily, hospital, and marine origins. Studies such as those by An et al. (2017) and Chandra & Verma (2023) report removal rates exceeding 90% in complex wastewater matrices. In the case of bilge water, several studies (Aswathy et al., 2016; Bayramoglu et al., 2004; Cabrera et al., 2022; Feier et al., 2018; Ghazouani et al., 2019; Zelada & Vásquez, 2023) demonstrate effective results without the need for external reagents. This versatility is key to addressing industrial contexts with high pollutant loads—one of the strengths also highlighted by Madhavan et al. (2022), who advocate for the use of accessible and flexible technologies in response to health and societal risks posed by potentially carcinogenic contaminants.

Contaminants, Target Factors or Variables

The variety of contaminants and target variables in wastewater that can be treated by electrocoagulation (EC) includes chemical oxygen demand (COD), biological oxygen demand (BOD_5), heavy metals, synthetic dyes, polyphenols, and pharmaceutical compounds. The removal of organic matter is based on the formation of metal hydroxides (Lu et al., 2021; Martínez & Panizza, 2018). Furthermore, EC stands out for its efficiency in reducing trace contaminants at low concentrations (Rodríguez et al., 2021). In parallel, Brillas and Martínez-Huitle (2015) emphasize the usefulness of advanced electrochemical processes for degrading persistent dyes, while Kryuchkova et al. (2021) explore the adsorption of pharmaceuticals using modified clays, highlighting the growing necessity of hybrid approaches.

Complementary Technologies

This cluster includes hybrid systems such as EC-Fenton, EC-O_3, electrooxidation, and the use of nanomaterials and membranes, emphasizing the combined action of these methods in removing hard-to-degrade pollutants. In this regard, Mojiri et al. (2021) suggest using algae as natural biofilters. This technological complementarity addresses the need to enhance environmental performance and adapt to specific conditions, such as eutrophic water bodies or those contaminated with Pharmaceuticals and Personal Care Products (PPCPs) (Chandra et al., 2023; Delgado et al., 2023; Feier et al., 2018). The analyses by Brillas & Martínez (2015) and Madhavan et al. (2022) underscore the importance of linking technical knowledge with social and regulatory considerations.

Thus, an interdisciplinary approach is proposed, combining physicochemical processes (such as EC and adsorption) with biological methods (algae, phytoremediation) to more comprehensively address emerging contaminants. Kryuchkova et al. (2021) and Mojiri et al. (2021) expand on this approach through adaptive and biomimetic-based solutions, although they also acknowledge the technical and financial limitations of such technologies.

As an integrative alternative, a sequential combination of electrocoagulation and algal biological treatment is proposed, which would allow for:

(1) Initial removal of priority contaminants (COD, pharmaceuticals, heavy metals);

(2) A second "polishing" stage that integrates carbon capture and PPCP treatment via vegetative biofilters; and

(3) Enhanced overall system sustainability through by-product reuse.

Sustainability and Circular Economy

In this thematic area, Mojiri et al. (2021) and Chandra et al. (2023) emphasize resource recovery, water reuse, and the beneficial use of by-products generated during the process. They analyze the potential use of sludge produced by electrocoagulation (EC) as agricultural fertilizer and advocate for its integration into eco-sanitation systems and life cycle assessments. From this perspective, EC is considered a carbon-neutral technology, although they highlight the importance of proper sludge management. Additionally, they propose algae-based systems as sustainable complements due to their capacity for carbon capture and degradation of Pharmaceuticals and Personal Care Products (PPCPs), although their performance depends on environmental conditions.

Conclusions

This document presents the findings of a bibliometric analysis encompassing 50 scientific articles on electrocoagulation (EC) for the treatment of industrial effluents, published between 2004 and 2023. Tools such as Scopus, Mendeley, and VOSviewer were employed to manage, analyze, and visualize bibliographic data, and to evaluate the scientific literature's impact. Regarding the application of EC for the treatment of various types of wastewater—originating from industries such as petroleum, food, textile, hospital, pharmaceutical, and agricultural—significant advances were identified in the removal of contaminants such as COD, BOD_5, heavy metals, synthetic dyes, and pharmaceutical compounds. EC stands out for its ability to treat micro-contaminants at low concentrations and for its efficiency in removing persistent dyes and pharmaceuticals through the use of modified clays.

The integration of EC with complementary technologies—such as EC-Fenton, EC-O_3, electrooxidation, and the use of nanomaterials and membranes—enhances the removal of hard-to-degrade contaminants. Furthermore, the use of algae as natural biofilters is highlighted, contributing to a more sustainable treatment approach.

From the perspective of sustainability and circular economy, emphasis is placed on resource recovery and the reuse of by-products such as EC-generated sludge for agricultural fertilizer. EC, regarded as a carbon-neutral technology, offers viable solutions for improving overall sustainability. A sequential combination of electrocoagulation with biological treatments—such as algae-based systems—is suggested, enabling effective removal of priority contaminants, followed by a "polishing" stage involving carbon capture and PPCP treatment. Finally, it is recommended to expand the bibliometric analysis by incorporating additional databases such as Google Scholar to strengthen the findings.

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