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Continuous Electrocoagulation (CEC) for Sustainable Development Goals: Research Trends, Gaps, and Factor Assessment

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Abstract: Wastewater treatment requires effective technologies for pollutant removal and sustainable water management. This study aimed to map the development of Continuous Electrocoagulation (CEC) research, identify research gaps and emerging themes, and synthesize operational and implementation issues. A Systematic Literature Network Analysis (SLNA) integrating Bibliometric Analysis (BA) and Qualitative Content Analysis (QCA) was applied to 99 Scopus-indexed journal articles published between 2019 and 2024. BA examined publication trends, collaboration networks, and research hotspots, while QCA synthesized evidence on Sustainable Development Goals (SDGs), operational factors, and implementation challenges. Publication output increased from 7 articles in 2019 to a peak of 22 in 2022, followed by 20 in 2023 and 14 in 2024. Thematic analysis indicated increasing attention to continuous operation, reactor configuration, pollutant removal, and energy efficiency. QCA showed that CEC research repeatedly examines electrode material, current density, pH, electrode distance, flow rate, electrolysis time, conductivity, temperature, supporting electrolytes, and hydraulic retention time. Key implementation challenges include electrode passivation, energy and electrode consumption, sludge management, effluent-quality control, and limited reactor standardization and scale-up evidence. Overall, CEC shows potential to support SDGs, while future research should prioritize multivariable optimization, pilot-scale validation, and sustainability assessment.

Keywords: Continuous electrocoagulation; Sustainable development goals; Wastewater treatment

Introduction

Human activities driven by rapid urbanization and industrialization have substantially increased wastewater generation, posing serious risks to water resources, aquatic ecosystems, and environmental sustainability (Liu et al., 2024; Purba et al., 2023). Wastewater discharged without adequate treatment may contain organic pollutants, nutrients, heavy metals, and other hazardous substances that degrade water quality and threaten ecosystems and public health (Amri et al., 2020; Noviantika et al., 2024). Water quality degradation can be assessed through various physical and chemical parameters, including pH, dissolved oxygen, electrical conductivity, and temperature, which are important indicators of changes in aquatic environmental conditions (Pratiwi et al., 2023; Rumanta et al., 2024). Therefore, effective wastewater treatment technologies are essential to ensure compliance with environmental quality standards while supporting the Sustainable Development Goals (SDGs), particularly SDG 6 on Clean Water and Sanitation. Although numerous conventional and advanced wastewater treatment technologies have been developed, conventional treatment processes are often constrained by high operating costs, intensive chemical consumption, complex operation, and excessive sludge generation. These limitations have encouraged the

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development of more efficient, economically feasible, and environmentally sustainable wastewater treatment technologies. Recent studies on wastewater management have also emphasized the importance of evaluating treatment efficiency and the quality of treated effluent under actual operational conditions (Wardoyo et al., 2025).

Electrocoagulation (EC) has emerged as a promising technology for wastewater treatment because it combines electrochemical reactions, coagulation, and flotation within a single process. During electrocoagulation, direct current (DC) is applied to sacrificial electrodes, typically aluminum or iron, causing the anode to dissolve and generate coagulant species, while cathodic reactions contribute to hydrogen generation and flotation mechanisms (López-Guzmán et al., 2021). To overcome the operational limitations of conventional batch electrocoagulation, Continuous Electrocoagulation (CEC) systems have been developed to enable uninterrupted wastewater treatment and improve operational continuity (Hariri et al., 2024; AlJaberi et al., 2022; Mousazadeh et al., 2021). The importance of continuous treatment is particularly relevant for wastewater management because treatment performance must be maintained under changing water-quality conditions and continuous pollutant loading (Wardoyo et al., 2025). Compared with batch systems, CEC is more suitable for continuous industrial applications because it minimizes operational interruptions, facilitates process automation, and supports continuous treatment operation (Ardhan et al., 2015; Nguyen et al., 2017; Rajaniemi et al., 2019).

In addition, continuous operation enables continuous sludge withdrawal and more efficient solid–liquid separation, thereby improving sludge handling and separation management rather than implying that CEC inherently produces less sludge than batch electrocoagulation. This operational perspective is consistent with the broader need for effective wastewater and waste management practices in industrial activities, where treatment performance and environmental impacts must be considered together (Permatasari et al., 2023).

Recent technological developments have further expanded the application of CEC to different industrial wastewater streams, with studies increasingly examining operating conditions, reactor performance, and pollutant removal under continuous-flow conditions (Pandey & Thakur, 2021). Collectively, previous studies have demonstrated that CEC can treat various industrial wastewaters, including textile, coal stockpile, mining, and wastewater containing inorganic pollutants (Al-Qodah et al., 2025; Rodriguez-Prado, 2020; Rusdianasari, 2017; Sutanto et al., 2021). For example, CEC achieved removal efficiencies of 87.8% for total suspended solids (TSS), 91.8% for chemical oxygen demand (COD), and 83.9% for color in textile wastewater (Sutanto et al., 2021). Similarly, aluminum electrode CEC effectively reduced TSS, iron, and manganese concentrations in coal stockpile wastewater while improving wastewater pH (Rusdianasari, 2017). Rodriguez-Prado (2020) reported that integrating CEC with a settling unit improved sulfate removal and substantially reduced nitrate concentrations in mining wastewater. Furthermore, CEC has demonstrated the capacity to remove NH_4^+, Cu^{2+}, Ni^{2+}, and Zn^{2+} while producing smaller pH fluctuations than conventional batch systems. These findings indicate that CEC is an adaptable wastewater treatment technology capable of addressing diverse wastewater characteristics. Nevertheless, wider industrial implementation still requires reactor design standardization, process optimization, and stronger regulatory and economic support (Al-Qodah et al., 2025). The need for such optimization is also evident from studies of contaminated water, where pollutant levels and treatment requirements vary according to wastewater characteristics and environmental conditions (Afaz et al., 2025; Lensoni et al., 2023).

Despite the growing number of studies and review articles on CEC, existing reviews primarily emphasize treatment performance, reactor configuration, and pollutant removal efficiency. Comparatively less attention has been given to systematically mapping how the CEC research field has evolved in terms of publication development, scientific collaboration, emerging research themes, operational factors, implementation challenges, and their relationship with the SDGs. Moreover, although operational parameters such as electrode material, current density, pH, electrode distance, flow rate, electrolysis time, conductivity, temperature, supporting electrolytes, and hydraulic retention time have been extensively investigated experimentally, these factors have not been comprehensively synthesized through an integrated bibliometric and qualitative literature perspective to examine their development, interrelationships, implementation challenges, and implications for sustainable wastewater treatment. The relevance of systematically considering water-quality parameters and pollutant characteristics is further demonstrated by environmental studies published in JPPIPA, which examine parameters such as pH, dissolved oxygen, electrical conductivity, heavy metals, and other indicators of water pollution (Noviantika et al., 2024; Pratiwi et al., 2023; Rumanta et al., 2024).

Therefore, this study employs Systematic Literature Network Analysis (SLNA) to systematically examine the development of CEC research. The SLNA framework integrates Systematic Literature Review (SLR), Bibliometric Analysis (BA), and Qualitative Content Analysis (QCA) to identify publication trends, scientific collaboration patterns, emerging research themes, operational factors, implementation challenges, and the contribution of CEC to the SDGs (Colicchia et al., 2019). The novelty of this study lies not in identifying previously unknown operational factors, which have already been widely investigated experimentally, but in integrating bibliometric network mapping with qualitative literature synthesis to systematically connect research evolution, collaboration patterns, emerging themes, operational factors, implementation challenges, and sustainability contributions within a single analytical framework. In particular, the study examines how the development of CEC research can be interpreted in relation to SDG 6 and broader sustainable wastewater management objectives, a perspective that has received comparatively limited systematic bibliometric and network-based investigation.

By integrating these analytical perspectives, this study provides a comprehensive scientific synthesis of the current development of CEC research, identifies research gaps, and proposes future research directions for advancing CEC toward more efficient, practical, and sustainable wastewater treatment. The findings are expected to provide a useful scientific reference for researchers, engineers, and policymakers involved in the development and implementation of sustainable wastewater treatment technologies.

Method

Conceptual Framework

This study employed the Systematic Literature Network Analysis (SLNA) approach to investigate the scientific development of Continuous Electrocoagulation (CEC) research in wastewater treatment. The SLNA framework integrates Systematic Literature Review (SLR), Bibliometric Analysis (BA), and Qualitative Content Analysis (QCA) to provide a systematic basis for literature identification and screening, quantitative mapping of the scientific landscape, and qualitative synthesis of research findings (Colicchia et al., 2019; Wibowo et al., 2024). This integrated approach enables the identification of publication trends, collaboration patterns, research hotspots, and knowledge gaps through bibliometric analysis, while qualitative content analysis synthesizes conceptual discussions, Sustainable Development Goal (SDG) contributions, operational factors, and implementation challenges influencing the application of CEC.

Within the SLNA framework, Bibliometric Analysis was employed to quantitatively examine the evolution of CEC research, whereas Qualitative Content Analysis (QCA) based on Mayring's methodology (Mayring, 2015) was conducted to synthesize conceptual knowledge related to the Sustainable Development Goals (SDGs) and operational factors affecting CEC implementation. The methodological framework consisted of five sequential phases: formulation of research questions; literature retrieval and screening following the PRISMA 2020 guideline; bibliometric analysis; qualitative content analysis; and integration of quantitative and qualitative findings. The overall methodological framework is presented in Figure 1.

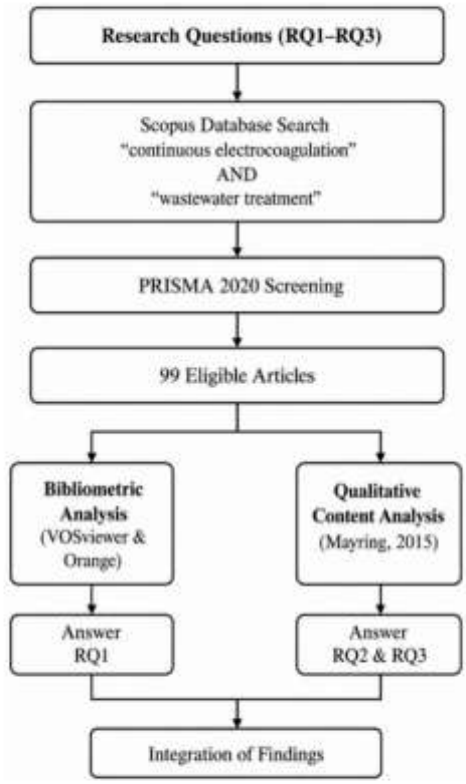

Figure 1. Workflow of the Systematic Literature Network Analysis (SLNA)

Research Questions

The review was guided by three research questions. The first research question (RQ1) examined the publication trends, research hotspots, collaboration patterns, research gaps, and future research directions in Continuous Electrocoagulation (CEC). The second research question (RQ2) explored how Continuous Electrocoagulation has been discussed in relation to the Sustainable Development Goals (SDGs). The third research question (RQ3) investigated the operational and implementation factors that influence the successful application of Continuous Electrocoagulation in wastewater treatment.

Data Collection

The literature search was conducted in the Scopus database on 7 October 2025 following the PRISMA 2020 guideline (Page et al., 2021). Scopus was selected because it provides comprehensive coverage of peer-reviewed scientific publications and reliable bibliographic metadata suitable for bibliometric studies. The search strategy employed the query "continuous electrocoagulation" AND "wastewater treatment", which initially retrieved 277 documents. The retrieved records were subsequently screened using predefined inclusion criteria, including publication year, document type, publication stage, Scopus indexed keywords, language, and source type. The screening process retained publications from 2019 to 2024, document type Article, publication stage Final, Scopus indexed keywords relevant to Continuous Electrocoagulation and wastewater treatment, English-language publications, and Journal as the source type. After applying all eligibility criteria, a total of 99 journal articles were included in the final dataset for bibliometric and qualitative analyses. The complete screening process is presented in Figure 2.

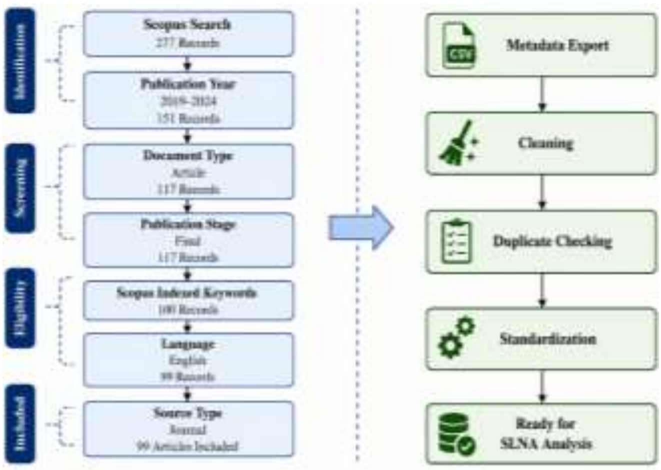

Figure 2. PRISMA 2020 screening process and metadata preparation for Systematic Literature Network Analysis (SLNA)

Data Analysis

The collected dataset was analyzed using a combination of quantitative and qualitative approaches within the Systematic Literature Network Analysis (SLNA) framework. Bibliometric Analysis was performed to quantitatively examine publication trends, collaboration networks, citation structures, and thematic evolution of Continuous Electrocoagulation research. Subsequently, Qualitative Content Analysis was conducted to synthesize conceptual discussions related to the Sustainable Development Goals (SDGs), operational factors, implementation challenges, and future research directions. Finally, findings from both analytical approaches were integrated to provide a comprehensive understanding of the current state and future development of Continuous Electrocoagulation research.

Bibliometric Analysis

Bibliometric Analysis (BA) was conducted to answer RQ1 by quantitatively mapping the scientific development of Continuous Electrocoagulation (CEC) research. This analysis aimed to identify publication trends, collaboration patterns, influential publications, research hotspots, and knowledge gaps within the selected literature (Ramadan et al., 2022). Prior to bibliometric analysis, the bibliographic metadata exported from Scopus were prepared through metadata cleaning, duplicate checking, and standardization of bibliographic information, including author names, affiliations, and keywords, to ensure data consistency before network construction and text mining. The metadata preparation process is presented in Figure 2.

The prepared dataset was subsequently analyzed using VOSviewer and Orange Data Mining 3.34. VOSviewer was employed to construct bibliometric networks, including citation analysis, co-authorship analysis, country collaboration analysis, and keyword co-occurrence analysis. Orange Data Mining 3.34 was employed to perform text mining and semantic analysis of article titles, abstracts, and author keywords through Word Cloud visualization, Latent Dirichlet Allocation (LDA), Multidimensional Scaling (MDS), and Marginal Topic Probability (MTP) analysis. The combination of these tools provided a comprehensive quantitative exploration of the CEC research landscape, thereby complementing the subsequent qualitative synthesis.

VOSviewer Analysis

VOSviewer was employed exclusively to construct and visualize bibliometric networks. Four analyses were performed, namely citation analysis, keyword co-occurrence analysis, co-authorship analysis, and country collaboration analysis. Citation analysis identified the most influential publications in the CEC research field based on citation frequency. Co-authorship analysis examined collaboration patterns among researchers, whereas country collaboration analysis illustrated international scientific cooperation. Keyword co-occurrence analysis identified frequently occurring author keywords and thematic relationships within the literature, enabling the identification of research hotspots and emerging topics.

In VOSviewer, nodes represent bibliometric items such as publications, authors, countries, or keywords, whereas links indicate relationships among these items. Larger nodes indicate higher publication frequency or citation impact, while stronger links indicate stronger relationships among bibliometric items. Clusters represent groups of closely related items describing major research themes within the CEC literature (Kholidah et al., 2022; Sawassi & Khadra, 2021).

The results obtained from VOSviewer were interpreted to explain publication trends, collaboration networks, influential studies, and research hotspots, thereby addressing RQ1.

Orange Data Mining Analysis

Orange Data Mining 3.34 was employed for text mining analysis of the selected CEC literature. The analysis included Word Cloud visualization, Latent Dirichlet Allocation (LDA) topic modeling, and Marginal Topic Probability (MTP) analysis. Word Cloud analysis was used to identify frequently occurring terms in the title, abstract, and author keywords. LDA topic modeling was applied to identify groups of terms representing major research topics, while MTP analysis was used to examine the relative prominence of the identified topics within the dataset.

Word Cloud visualization was used to identify frequently occurring terms within the literature, where word size represents term frequency (BiĭLen & Kurtuluş, 2021). Subsequently, LDA was applied to identify latent thematic structures by grouping frequently co-occurring words into research topics (Li et al., 2021). To validate the identified topics, MDS was employed to visualize similarities among research topics, while MTP was used to quantify the contribution of each topic within the literature corpus, thereby identifying dominant and emerging research themes (Abayomi-Alli et al., 2022; Yao et al., 2016).

The combination of VOSviewer and Orange Data Mining provided complementary perspectives by integrating bibliometric relationships with semantic analysis of the literature. VOSviewer was used to visualize bibliometric networks, including keyword co-occurrence, co-authorship, country collaboration, and citation relationships, whereas Orange Data Mining was used for text-based thematic analysis. The complete text-mining workflow is presented in Figure 3.

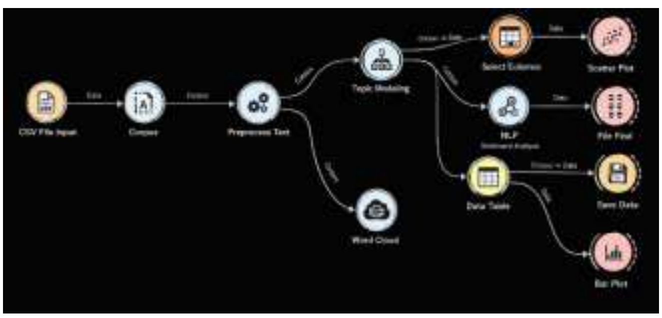

Figure 3. Text mining workflow using Orange Data Mining 3.34

Qualitative Content Analysis

To answer RQ2 and RQ3, a Qualitative Content Analysis (QCA) based on Mayring's methodology (Mayring, 2015) was conducted. The selected articles were systematically examined using a combined deductive–inductive coding approach (Paul & Criado, 2020). During the deductive phase, coding categories were established based on the predefined research questions, including CEC concepts, Sustainable Development Goals (SDGs), operational parameters, and implementation challenges. Subsequently, inductive coding was applied to identify additional themes emerging from the reviewed literature.

The qualitative synthesis focused on two principal aspects. First, it examined how Continuous Electrocoagulation has been conceptualized and discussed in relation to the Sustainable Development Goals (RQ2). Second, it synthesized the operational and implementation factors influencing CEC performance and application, including electrode material, current density, pH, electrode spacing, hydraulic retention time, flow rate, electrolysis time, conductivity, temperature, supporting electrolytes, and reactor configuration (RQ3). The coded evidence was subsequently interpreted to identify recurring implementation challenges and areas requiring further investigation. These findings were then integrated with the bibliometric results to identify research gaps and future research directions.

Integration of Findings

The final stage involved integrating the findings obtained from Bibliometric Analysis (BA) and Qualitative Content Analysis (QCA). Bibliometric Analysis provided quantitative evidence regarding publication trends, collaboration patterns, influential publications, research hotspots, and knowledge gaps, thereby addressing RQ1. Qualitative Content Analysis synthesized conceptual discussions regarding CEC, its contribution to the Sustainable Development Goals (SDGs), and the operational and implementation factors influencing successful CEC application, thereby addressing RQ2 and RQ3.

The integration of both analytical approaches enabled a comprehensive interpretation of the current state of CEC research by combining bibliometric mapping with qualitative evidence from the reviewed literature. This integrated perspective facilitated the identification of research gaps, implementation challenges, and future research directions, thereby strengthening the overall conclusions of the review.

Result and Discussion

Bibliometric Analysis (BA) – RQ1

This section presents the findings of the Systematic Literature Network Analysis (SLNA), integrating Bibliometric Analysis (BA) and Qualitative Content

Analysis (QCA) to examine the development of Continuous Electrocoagulation (CEC) research in wastewater treatment. Following the methodological framework, the results and discussion are organized according to the three research questions. Bibliometric Analysis addresses RQ1 by examining publication trends, publication sources, collaboration networks, influential authors, and research hotspots within the CEC research field. Qualitative Content Analysis addresses RQ2 and RQ3 by synthesizing the contribution of CEC to the Sustainable Development Goals (SDGs) and identifying the operational and implementation factors influencing CEC performance and application. Finally, findings from both analytical approaches are integrated to identify research gaps and formulate future research directions.

Unlike conventional literature reviews that primarily summarize experimental findings, the SLNA framework combines quantitative mapping of the scientific landscape with qualitative synthesis of the reviewed literature. Bibliometric Analysis provides evidence of how the CEC research field has developed in terms of publication productivity, scientific collaboration, influential research, and thematic patterns. In contrast, Qualitative Content Analysis provides contextual interpretation of these patterns by synthesizing evidence concerning CEC applications, SDG contributions, operational parameters, and implementation challenges. The integration of these complementary perspectives provides a broader understanding of the current development of CEC research and helps identify areas requiring further scientific and technological investigation.

Publication Trends

Publication trends are widely recognized as an important indicator of the development of a scientific field because changes in publication output can reflect variations in research attention and scientific activity over time (Donthu et al., 2021). In bibliometric research, publication growth is commonly examined together with collaboration patterns and thematic development to understand the evolution of a research domain (Donthu et al., 2021; Zupic & Čater, 2015).

Figure 4 illustrates the annual scientific production related to Continuous Electrocoagulation (CEC) during the 2019–2024 period. A total of 99 journal articles met the predefined screening criteria and were included in the bibliometric analysis. Publication output increased from 7 articles in 2019 to 18 articles in 2020, remained at 18 articles in 2021, and reached the highest number of publications in 2022 with 22 articles. The number subsequently decreased to 20 articles in 2023 and 14 articles in 2024. Overall, the publication trajectory demonstrates that CEC research received increasing scientific attention during the first four years of the observation period, followed by a moderate decline in annual output during 2023–2024.

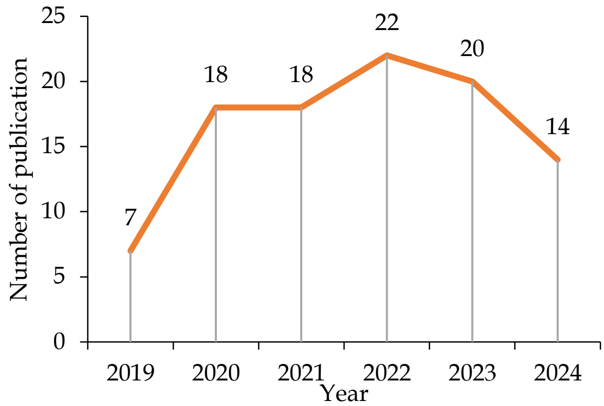

Figure 4. Annual scientific production of continuous electrocoagulation publications (2019–2024).

The increase in publication output from 2019 to 2022 indicates a growing scientific interest in CEC as a continuous wastewater treatment approach. The development of CEC is relevant to wastewater treatment because continuous reactor operation provides an alternative to batch treatment by enabling wastewater to be treated through a continuously operated reactor system. Previous studies have investigated CEC for different wastewater matrices and have examined treatment performance under varying electrode configurations and operating conditions (Mousazadeh et al., 2021; Pandey & Thakur, 2021). Thus, the increase in publication activity during 2019–2022 suggests that research attention was not limited to the basic electrocoagulation mechanism but increasingly addressed the application of electrocoagulation under continuous operating conditions.

The peak of 22 publications in 2022 can therefore be interpreted as an indication of the period of highest research productivity within the analyzed dataset. This finding is consistent with the broader development of electrocoagulation research, where recent studies have increasingly examined process optimization, reactor configuration, electrode characteristics, and treatment performance (Al-Qodah et al., 2025; Mao et al., 2023). However, the publication trend alone cannot establish that CEC had already reached technological maturity. Such an interpretation requires consideration of the thematic and qualitative findings presented in the subsequent bibliometric and content analyses.

The decline in publication output after 2022, from 22 articles in 2022 to 20 articles in 2023 and 14 articles in 2024, should also be interpreted cautiously. Because the dataset covers publications indexed in Scopus and the analysis represents a defined search and screening period, differences in annual output may be influenced by publication and indexing timing. Therefore, the lower number of publications in 2024 should not be directly interpreted as evidence of declining scientific interest without additional longitudinal data. Instead, the results indicate that 2022 represented the highest publication productivity within the present dataset.

More importantly, publication quantity alone does not describe the substantive development of CEC research. The subsequent analyses of publication sources, country collaboration, author productivity, keyword co-occurrence, word clouds, and topic modeling provide additional evidence regarding how research interests have developed within the field. These analyses are particularly important for determining whether the increase in publication activity has been accompanied by diversification of research themes, greater international collaboration, and increased attention to operational and sustainability-related issues.

The publication trend therefore provides the quantitative starting point for answering RQ1, demonstrating the temporal development of CEC research between 2019 and 2024. The results indicate that scientific productivity increased substantially from 2019 to 2022 before decreasing moderately in the final two years of the dataset. However, the meaning of this trend must be interpreted together with the subsequent bibliometric and qualitative findings rather than being used alone to conclude that the field has reached maturity.

Publication Sources

Publication sources provide additional information on where Continuous Electrocoagulation (CEC) research is disseminated and how publication activity has developed across different journals. Figure 5 presents the annual distribution of CEC-related publications across the main publication sources identified in the dataset.

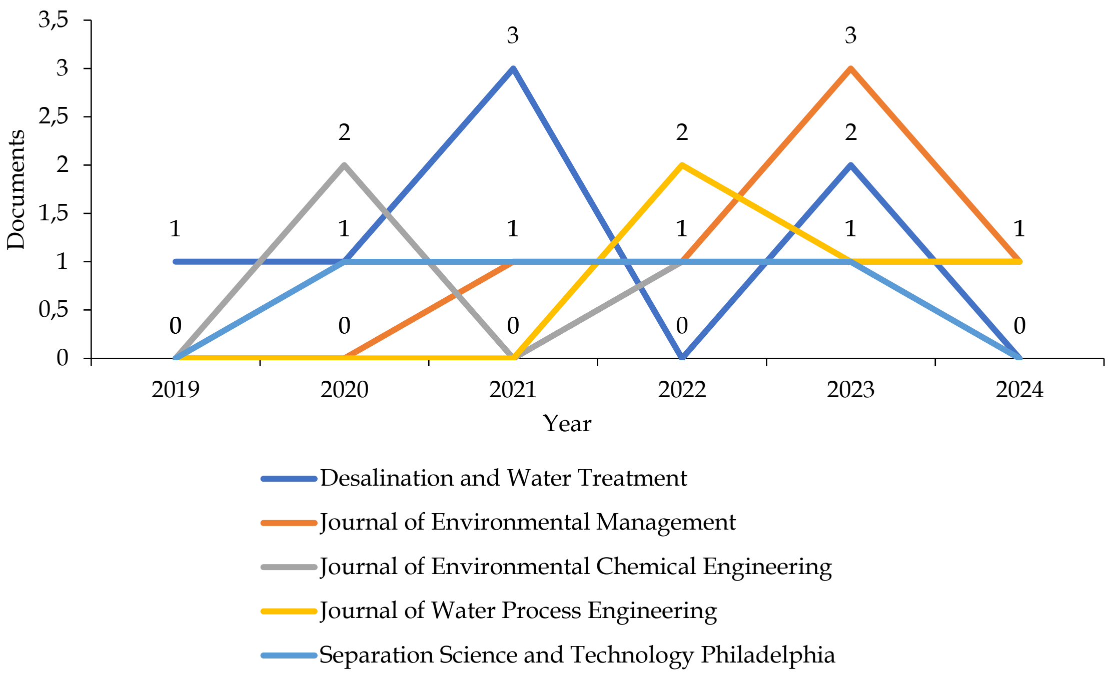

Figure 5. Annual publication output by source in continuous electrocoagulation research

Desalination and Water Treatment recorded the highest number of CEC-related publications, with seven articles, followed by the Journal of Environmental Management, with six articles. Other publications were distributed across several journals covering wastewater treatment, environmental engineering, water resources, and related environmental technologies. The concentration of publications in these sources indicates that CEC research is predominantly positioned within the broader fields of water and wastewater treatment and environmental management.

The publication pattern also demonstrates that CEC research is not concentrated in a single publication outlet. Instead, studies have been disseminated across journals with different but related environmental and engineering scopes. This distribution is consistent with the multidisciplinary nature of electrocoagulation, which involves electrochemical reactions, coagulation, pollutant removal, reactor operation, and wastewater management (Mousazadeh et al., 2021; Pandey & Thakur, 2021).

The prominence of Desalination and Water Treatment is particularly relevant because of its focus on water and wastewater treatment technologies. Meanwhile, the presence of the Journal of Environmental Management indicates that CEC research is also connected with broader environmental management considerations. However, the distribution of publications across journals should not be interpreted as evidence of differences in scientific quality; rather, it identifies the principal publication outlets through which CEC research has been disseminated.

The predominance of journals specializing in water treatment and environmental engineering is consistent with recent reviews describing electrocoagulation as a wastewater treatment technology that has received increasing attention because of its potential for removing diverse contaminants and supporting more sustainable treatment practices (López-Guzmán et al., 2021; Mao et al., 2023). The concentration of publications within these journals also indicates that the development of CEC has been closely associated with practical environmental engineering applications, including reactor operation, process optimization, electrode development, and industrial wastewater treatment.

Overall, the publication-source analysis demonstrates that CEC research is primarily disseminated through water treatment, wastewater management, and environmental engineering journals, with Desalination and Water Treatment and Journal of Environmental Management representing the most productive sources in the analyzed dataset. These findings contribute to RQ1 by identifying the principal publication outlets and demonstrating the disciplinary positioning of CEC research within wastewater treatment and environmental engineering.

Country Collaboration

The analysis of country collaboration provides insight into the geographical distribution of scientific productivity and the extent of international cooperation in Continuous Electrocoagulation (CEC) research. In bibliometric studies, co-authorship networks are commonly used to identify collaboration patterns and the development of scientific research communities (Donthu et al., 2021; Zupic & Čater, 2015). Such networks can also indicate how researchers from different countries contribute to knowledge exchange and the development of a research field.

Figure 6a illustrates the co-authorship network based on country affiliations. India occupies the most prominent position in the network, followed by China, while Brazil, Iran, the United States, the United Kingdom, France, Vietnam, and Iraq also contribute to the CEC research landscape. The relatively larger nodes for India and China indicate their higher publication productivity within the analyzed dataset, while the connecting links represent collaborative relationships among countries.

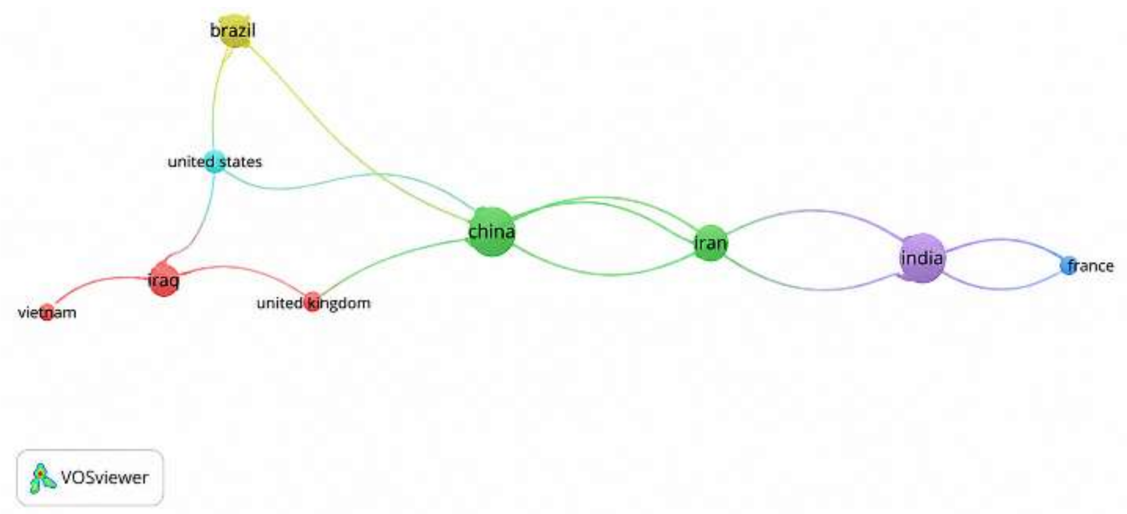

Figure 6(a). Co-authorship network visualization based on country

The network shows that CEC research involves collaboration among researchers from several geographical regions rather than being concentrated entirely within a single country. India and China occupy relatively central positions and are connected with other countries in the network. This pattern indicates that these countries have contributed substantially to the development and dissemination of CEC research within the analyzed literature. International collaboration is particularly relevant to wastewater treatment research because wastewater characteristics, treatment requirements, and operational conditions can differ among geographical and industrial contexts. Collaboration across countries can therefore facilitate the exchange of methodological approaches and research experience across different wastewater treatment conditions (Donthu et al., 2021).

The geographical distribution also demonstrates that CEC research has attracted contributions from different geographical and research contexts. The participation of countries from Asia, Europe, and the Americas indicates that CEC is being investigated across diverse regional settings. This international distribution is consistent with the broad application of electrocoagulation to different wastewater types and under varying operational conditions (Mousazadeh et al., 2021; Pandey et al., 2025).

Figure 6(b) presents the overlay visualization of country collaboration and provides a temporal perspective on the development of international contributions. Earlier publications are primarily associated with Vietnam and Iraq, whereas more recent contributions are represented by countries including Iran, China, India, Brazil, the United States, the United Kingdom, and France. The temporal distribution indicates that geographical participation in CEC research has expanded during the study period, with a broader range of countries represented in the later stages of the analyzed literature.

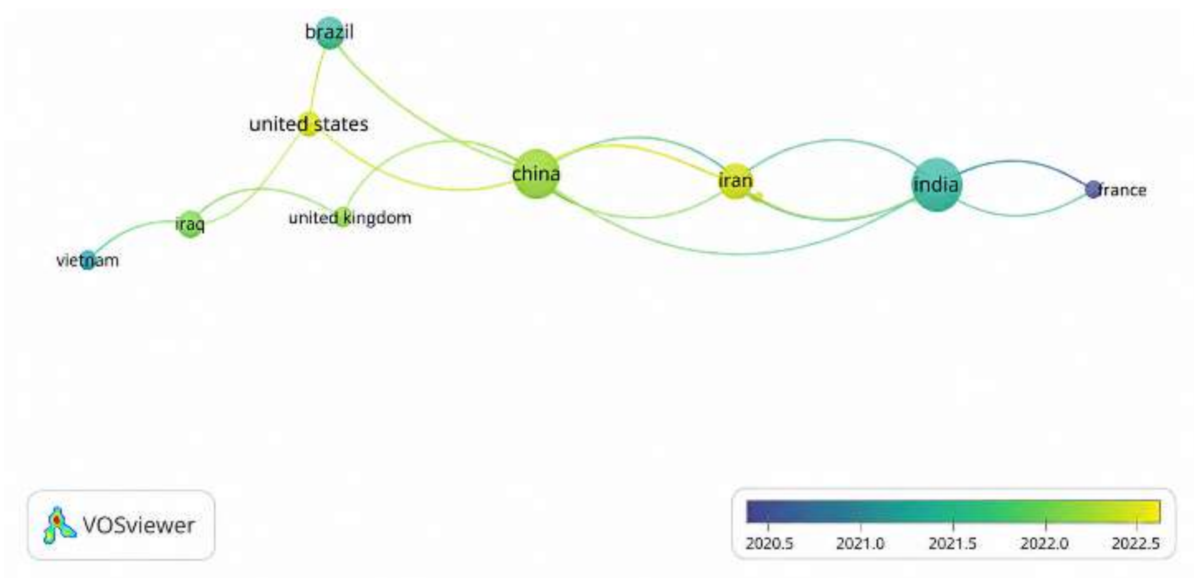

Figure 6(b). Co-authorship overlay visualization based on country affiliations

The expansion of geographical participation suggests that CEC research has progressively developed from contributions associated with a relatively limited number of countries toward a broader international research community. This development may facilitate knowledge exchange concerning reactor configurations, electrode materials, operating parameters, and wastewater characteristics. However, the collaboration network should be interpreted primarily as evidence of international research connectivity, rather than as direct evidence of research quality or technological maturity. Overall, CEC research has developed through contributions from researchers across Asia, Europe, and the Americas, with India and China occupying prominent positions in the analyzed network. The increasing geographical diversity observed in the overlay visualization further indicates broader international participation over time. These findings address RQ1 by demonstrating the geographical distribution and collaboration patterns underlying the international development of Continuous Electrocoagulation research.

Author Productivity and Scientific Influence

The analysis of author productivity and citation impact provides further insight into the intellectual development of Continuous Electrocoagulation (CEC) research. Publication productivity indicates the extent of individual contributions to the literature, while citation counts provide an indication of how frequently published studies have been referenced in subsequent research. Examining both indicators therefore helps identify authors whose publications have received relatively greater attention within the CEC research field (Donthu et al., 2021).

As presented in Figure 7, Forat Yasir Aljaberi recorded the highest citation impact among the most productive authors, with approximately 120 citations, despite contributing a relatively limited number of publications. Kiran Kumar Kurilla ranked second with approximately 58 citations, while Mateusz Luba, Bogusław Pierożyński, and Madhuri Damaraju each received approximately 40–50 citations. The differences between publication productivity and citation counts indicate that publication quantity and citation impact do not necessarily increase proportionally. Authors with fewer publications may nevertheless receive substantial scholarly attention when their publications are frequently cited by subsequent studies.

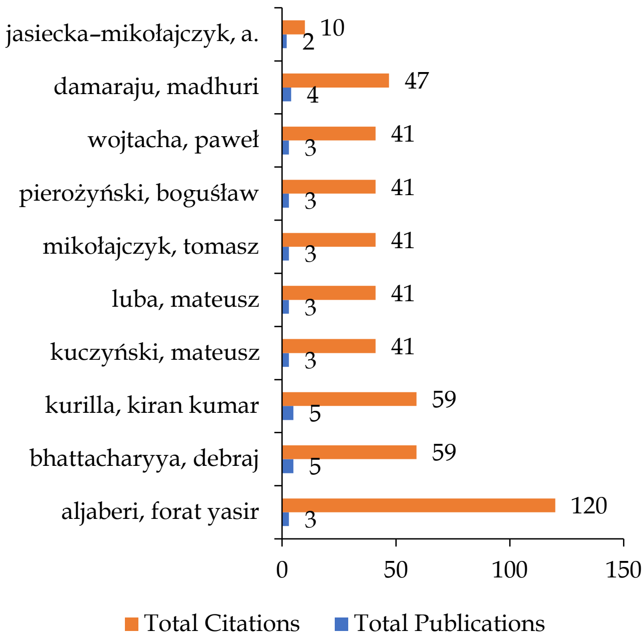

Figure 7. Publication and citation performance of the most productive authors in Continuous Electrocoagulation research

The observed variation in citation impact suggests that some publications have become more frequently referenced within the CEC research literature than others. Citation counts can provide an indication of the visibility and subsequent use of published research, although they should not be interpreted as a direct measure of research quality. Citation patterns can also be influenced by publication age, research topic, journal visibility, and the extent to which a particular study addresses topics of broad interest (Zupic & Čater, 2015). Therefore, the relatively high citation counts of several authors indicate their scholarly visibility and influence within the analyzed literature, rather than providing a definitive assessment of research quality.

The presence of several highly cited authors also indicates that CEC research has been influenced by a group of researchers whose publications have received considerable attention within the field. This concentration of citation impact provides an indication of the intellectual contributions that have been most visible in the development of CEC research. However, identifying the specific scientific contributions of these authors requires examination of their individual publications and research themes rather than citation data alone. The author-level findings can therefore be interpreted together with the subsequent thematic and keyword analyses to determine how influential research has contributed to the broader development of CEC topics.

Overall, the author productivity and citation analysis demonstrates that scientific influence within the CEC literature is unevenly distributed, with several authors receiving substantially more citations than others despite differences in publication productivity. Forat Yasir Aljaberi shows the highest citation impact among the authors represented in Figure 7, followed by Kiran Kumar Kurilla and other highly cited contributors. These findings address RQ1 by identifying the authors whose publications have received relatively greater scholarly attention and by providing an additional perspective on the intellectual development of CEC research.

Research Hotspots

Research hotspots represent the dominant themes and emerging directions within a scientific field. In bibliometric analysis, keyword co-occurrence is widely used to identify the conceptual structure of a research domain because frequently co-occurring keywords indicate topics that are commonly investigated together (Donthu et al., 2021). By examining keyword relationships, it is possible to identify the dominant research themes and areas receiving substantial scientific attention.

The thematic structure of Continuous Electrocoagulation (CEC) research was analyzed using keyword co-occurrence analysis in VOSviewer, followed by text-mining analysis using Orange Data Mining 3.34. VOSviewer was used to examine relationships among keywords and their temporal distribution, whereas Orange Data Mining was used to identify frequently occurring terms and thematic structures through Word Cloud visualization, Latent Dirichlet Allocation (LDA) topic modeling, and Marginal Topic Probability (MTP) analysis. These complementary analyses provide a broader perspective on CEC research hotspots by combining bibliometric network relationships with semantic analysis of the selected literature.

Keyword Co-Occurrence Analysis

Keyword co-occurrence analysis was conducted to identify the conceptual structure and dominant research themes within Continuous Electrocoagulation (CEC) research. Two complementary datasets were examined: terms extracted from titles and abstracts and author keywords. Title and abstract terms provide a broader representation of concepts discussed throughout the literature, whereas author keywords represent terms explicitly selected by researchers to characterize the main focus of their studies. Examining both datasets therefore allows the research hotspots to be interpreted from complementary perspectives.

Title and Abstract Terms

The network visualization presented in Figure 8(a) reveals two major thematic clusters. The first cluster is centered on electrocoagulation and wastewater treatment, with terms such as wastewater treatment, electrodes, iron, aluminum, electrocoagulation, electrolysis, and effluents. The close association among these terms indicates that a substantial component of CEC research focuses on the application of electrocoagulation to wastewater treatment and the role of electrode-related processes in treatment performance.

The second cluster is associated with operational and environmental aspects of CEC performance. This cluster includes terms such as pH, current density, electrode, chemical oxygen demand (COD), wastewater management, pollutant removal, water pollutants, and waste disposal. The co-occurrence of these terms indicates that CEC research also places considerable attention on the relationship between operating conditions, pollutant characteristics, and treatment outcomes. Parameters such as electrode characteristics, current density, and pH are therefore positioned within the broader context of pollutant removal and wastewater management.

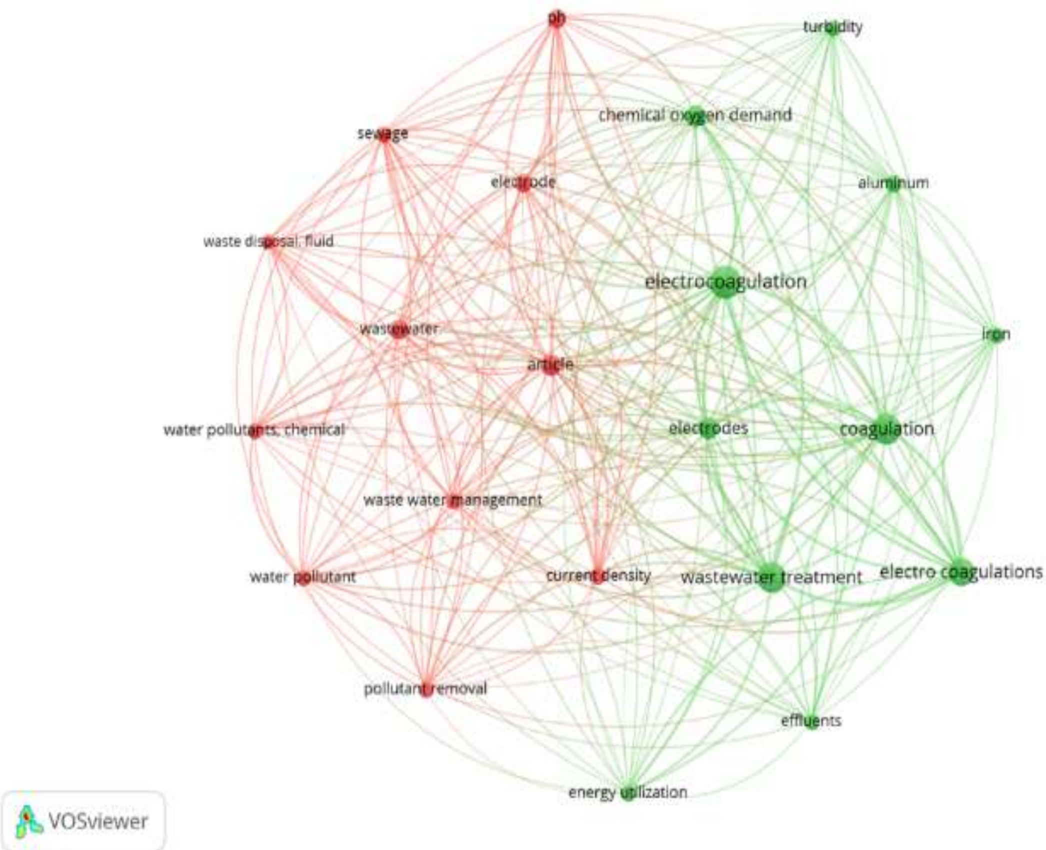

Figure 8(a). Co-occurrence keyword network visualization based on title and abstract terms

The overlay visualization in Figure 8(b) provides a temporal perspective on the development of these research themes. Earlier publications are primarily associated with terms such as pH, iron, and coagulation, indicating an earlier emphasis on the fundamental chemical and electrochemical aspects of electrocoagulation. These terms are closely related to the generation of coagulant species and the mechanisms involved in pollutant destabilization.

In contrast, more recent publications increasingly contain terms such as waste disposal, fluid, water pollutants, chemical, and pollutant removal. The emergence of these terms suggests an increasing emphasis on the practical treatment of wastewater and the environmental implications of pollutant removal. Importantly, the newer themes do not indicate that fundamental electrochemical research has been abandoned. Rather, they suggest a broadening of CEC research from fundamental process understanding toward practical wastewater treatment and environmental applications.

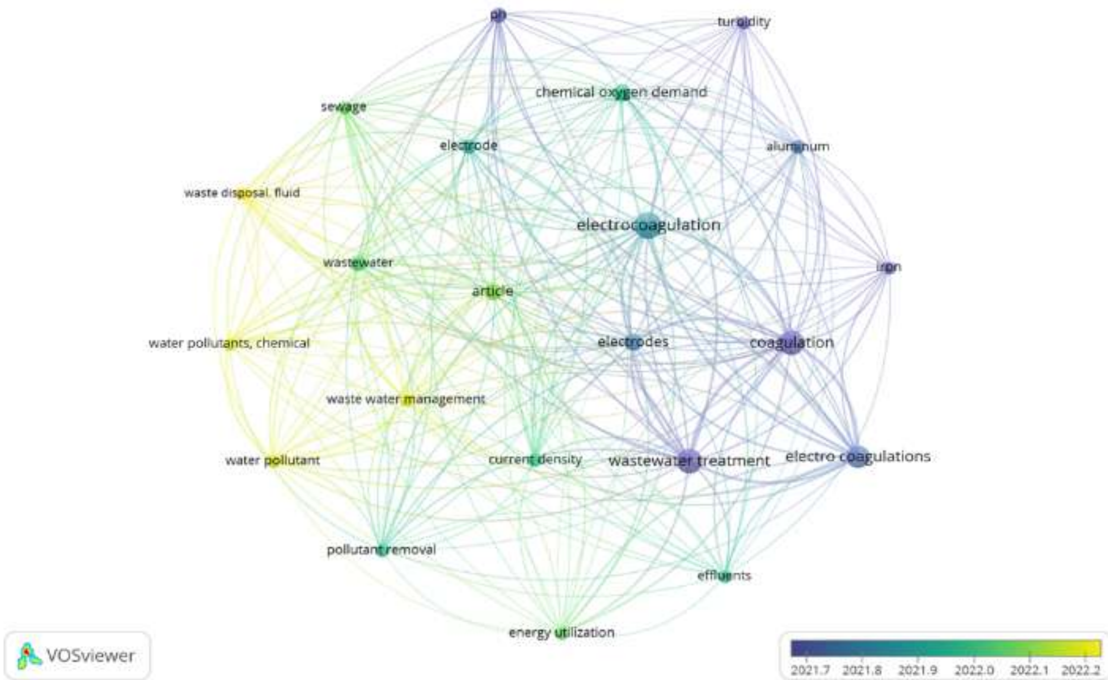

Figure 8(b). Co-occurrence keyword overlay visualization based on title and abstract terms

Overall, the title and abstract analysis identifies two closely related dimensions of CEC research: the electrochemical and operational mechanisms underlying treatment performance and the application of these processes to wastewater and pollutant removal. The connection between these dimensions reflects the interdisciplinary character of CEC research, in which electrochemical processes, operating conditions, and wastewater-treatment objectives are investigated together.

Author Keyword Co-Occurrence

The author keyword analysis presented in Figure 9(a) provides a more focused representation of the concepts explicitly emphasized by researchers. Three major clusters can be identified. The red cluster is associated with the electrocoagulation process and electrochemical mechanisms, the blue cluster focuses on water-quality indicators, and the green cluster represents system optimization and treatment performance.

The red cluster reflects continued attention to the electrocoagulation process and electrode-related mechanisms. The blue cluster represents parameters used to characterize wastewater quality and evaluate treatment outcomes. Meanwhile, the green cluster contains operational terms associated with continuous operation, flow conditions, and process optimization. The presence of these three interconnected clusters indicates that CEC research combines process mechanisms, treatment-performance assessment, and operational optimization.

The overlay visualization in Figure 9(b) further illustrates the temporal distribution of author-selected research themes. Earlier keywords include turbidity, batch, and continuous mode, whereas more recent keywords include flow rate, electrode, cathode, aluminum, and pollutant. The appearance of these more recent terms indicates increasing attention to hydraulic operation, electrode configuration, and pollutant removal in continuous electrocoagulation systems. The results from Figures 8 and 9 are complementary. The title and abstract analysis captures the broader conceptual structure of CEC research, whereas author keywords provide a more focused representation of topics intentionally emphasized by researchers. Despite this difference, both analyses consistently identify electrocoagulation mechanisms, wastewater treatment, pollutant removal, electrode characteristics, and operational optimization as important research themes. The convergence between the two analyses strengthens the interpretation that CEC research is developing around the interaction between electrochemical mechanisms and practical process optimization for wastewater treatment.

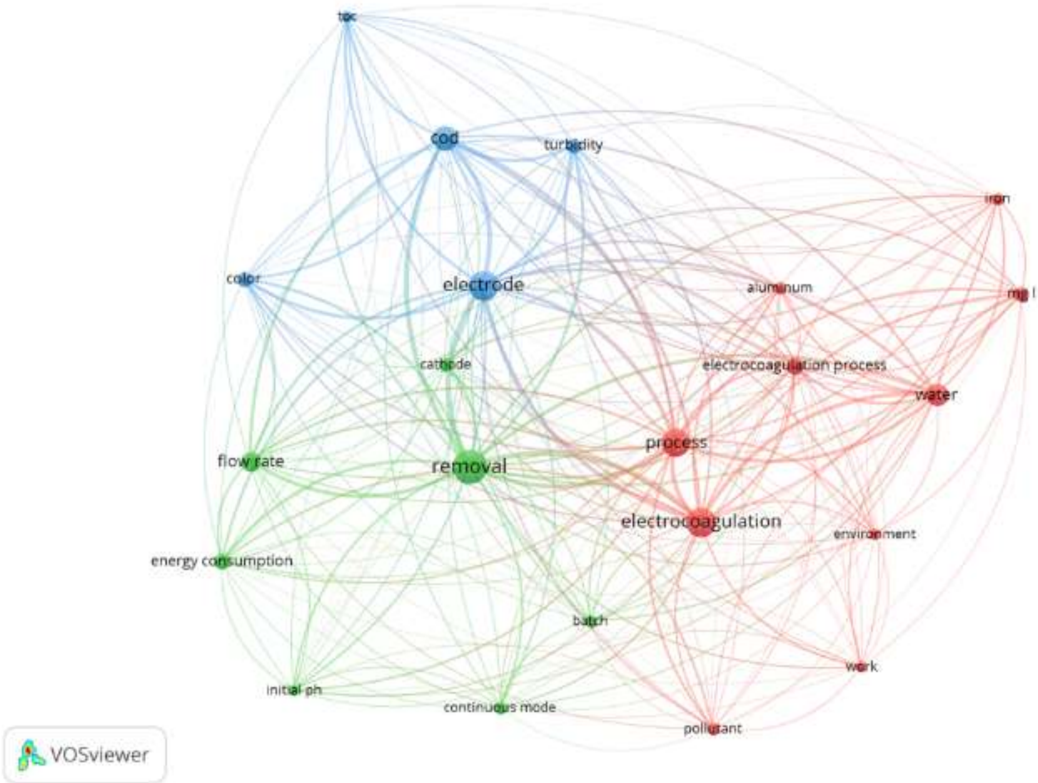

Figure 9(a). Co-occurrence network visualization based on author keywords

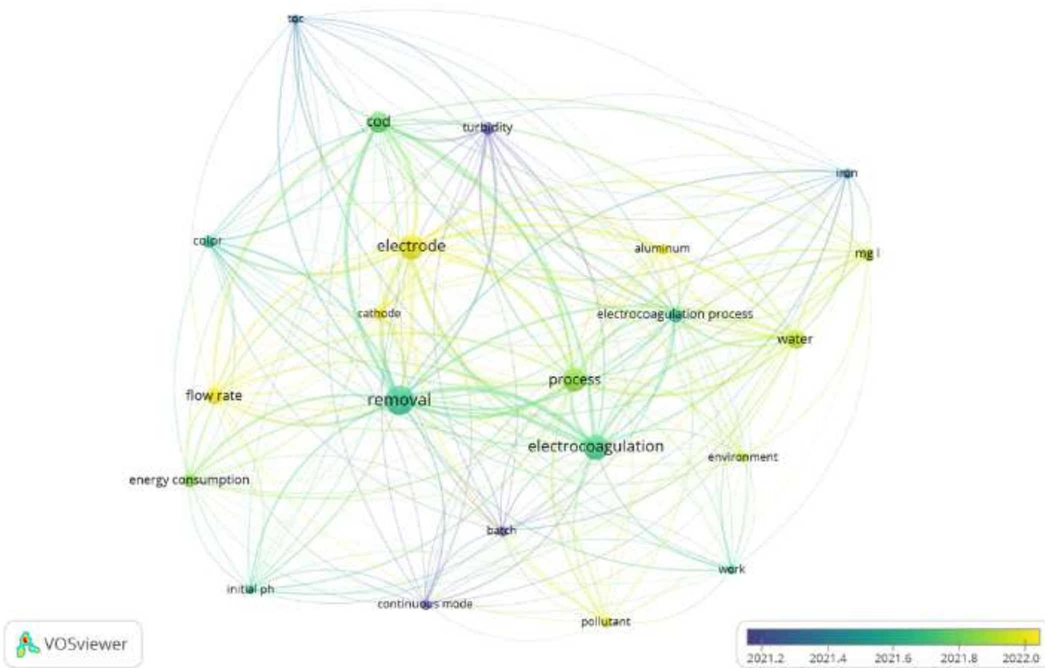

Figure 9(b). Co-occurrence overlay visualization based on author keywords

Word Clouds Analysis

Word cloud analysis was subsequently performed to identify the most frequently occurring terms in the CEC literature. This analysis complements the VOSviewer network analysis by emphasizing term frequency rather than relationships among terms.

As shown in Figure 10(a), the most frequently occurring terms in the title and abstract, excluding the phrase continuous electrocoagulation, were removal (f = 272), process (f = 157), EC (f = 150), current (f = 138), and COD (f = 123). In Figure 10(b), the most frequent terms among the author keywords were removal (f = 111), chemical (f = 110), coagulation (f = 85), oxygen (f = 81), and aluminum (f = 73).

Figure 10. Word clouds of terms extracted from (a) title and abstract and (b) author keywords

The high frequency of terms related to removal, treatment, water, and wastewater indicates that pollutant removal and wastewater treatment are central topics within the analyzed CEC literature. The frequent occurrence of terms such as coagulation, EC, electrode, current, COD, and aluminum further reflects the importance of electrochemical treatment processes and electrode-related factors in the research corpus. The prominence of current and COD also indicates that treatment performance and operating conditions are frequently discussed in relation to CEC applications.

The word-frequency results reinforce the findings from the keyword co-occurrence analysis. While VOSviewer mapping illustrates relationships among research terms, the word cloud highlights the relative frequency of individual terms across the literature. The convergence of these findings indicates that wastewater treatment, pollutant removal, electrocoagulation processes, electrode-related aspects, and operational conditions constitute prominent themes in the analyzed CEC literature.

Taken together, the word cloud and co-occurrence analyses provide complementary evidence for RQ1. The co-occurrence networks reveal how research concepts are interconnected, whereas the word-frequency analysis identifies the terms that appear most prominently across the literature. This consistency strengthens the identification of the principal research hotspots before the thematic structure is further examined through topic modeling.

Topic Modeling Analysis

Latent topic modeling was conducted to identify broader thematic structures within the analyzed corpus. Latent Dirichlet Allocation (LDA) groups terms according to their probabilistic associations within documents and therefore provides a complementary perspective to keyword co-occurrence analysis. While co-occurrence analysis emphasizes relationships among terms, topic modeling provides a thematic grouping of terms that frequently appear within the same documents.

As presented in Table 1, three topics were identified from title and abstract terms, while two broader topics were identified from author keywords. The different number of topics reflects the different nature of the two datasets: title and abstract terms provide a broader textual corpus, whereas author keywords represent more explicitly selected research concepts.

For title and abstract terms, Topic 1 represents the electrocoagulation process and pollutant removal. The presence of terms such as aluminum, electrocoagulation, electrocoagulation process, iron, water, and pollutant indicates that the application of electrocoagulation to pollutant removal and wastewater treatment constitutes an important thematic component of the literature.

Topic 2 represents operational parameters and energy efficiency. Terms including batch, cathode, continuous mode, energy consumption, flow rate, initial pH, and removal indicate that operational conditions and treatment performance are frequently discussed together within the analyzed literature. The presence of continuous mode and flow rate is particularly relevant to CEC because continuous operation requires consideration of hydraulic conditions alongside electrochemical operating parameters.

Topic 3 focuses on water quality and monitoring parameters, represented by terms such as COD, color, electrode, TOC, and turbidity. These terms represent physicochemical indicators commonly used to characterize wastewater and evaluate pollutant removal performance. The topic therefore complements Topic 1 by emphasizing the parameters used to assess treatment outcomes.

Table 1. Topics generated from title and abstract terms and author keywords

Topic label (title and abstract)	Terms in title and abstract	Topic label (author keywords)	Author keywords
Topic 1: Electrocoagulation process and pollutant removal	Aluminum, electrocoagulation, electrocoagulation process, environment, iron, mg L, pollutant, process, water, work	Topic 1: Pollutant removal and wastewater management	Article, current density, electrode, pH, pollutant removal, sewage, waste disposal (fluid), wastewater, wastewater management, water pollutant, water pollutants (chemical)
Topic 2: Operational parameters and energy efficiency	Batch, cathode, continuous mode, energy consumption, flow rate, initial pH, removal	Topic 2: Electrocoagulation process and chemical performance	Aluminum, chemical oxygen demand, coagulation, effluents, electrocoagulations, electrocoagulation, electrodes, energy utilization, iron, turbidity, wastewater treatment
Topic 3: Water quality and monitoring parameters	COD, color, electrode, TOC, turbidity		

The author keyword analysis produced two broader thematic groups. Topic 1 represents pollutant removal and wastewater management, with terms including article, current density, electrode, pH, pollutant removal, sewage, waste disposal, wastewater, wastewater management, and water pollutants. This topic combines treatment objectives with operational parameters and wastewater-management concepts. Topic 2 represents the electrocoagulation process and chemical treatment performance, characterized by terms such as aluminum, chemical oxygen demand, coagulation, effluents, electrocoagulation, electrodes, energy utilization, iron, turbidity, and wastewater treatment.

The topic structures identified by LDA are broadly consistent with the keyword co-occurrence results presented in Figures 8 and 9. Across the two analytical approaches, several recurring themes can be identified, particularly electrocoagulation processes, pollutant removal, wastewater treatment, electrode-related parameters, operational conditions, and treatment-performance indicators. This consistency provides additional support for the identification of these themes as important research hotspots within the CEC literature.

However, the topic structures should be interpreted as probabilistic thematic groupings rather than mutually exclusive research categories. The overlap of terms such as electrode, removal, aluminum, wastewater, and electrocoagulation across different topics indicates that these research aspects are interconnected rather than independently investigated. This finding is particularly relevant to CEC because treatment performance depends on the interaction between electrochemical conditions, reactor operation, electrode characteristics, and wastewater properties.

Overall, the LDA results strengthen the interpretation of the research hotspots identified through VOSviewer. The analysis demonstrates that CEC research is organized around interconnected themes involving electrocoagulation mechanisms, pollutant removal, wastewater management, operational parameters, and treatment-performance evaluation. These findings contribute to RQ1 by further defining the thematic structure underlying the development of CEC research.

Marginal Topic Probability Analysis

Marginal Topic Probability (MTP) analysis was used to examine the relative prominence of the topics identified through Latent Dirichlet Allocation (LDA) within the analyzed corpus. The results are presented in Figure 11(a) for title and abstract terms and Figure 11(b) for author keywords. MTP provides an additional quantitative perspective on the topic structure by indicating the relative contribution of the identified topics within the literature corpus.

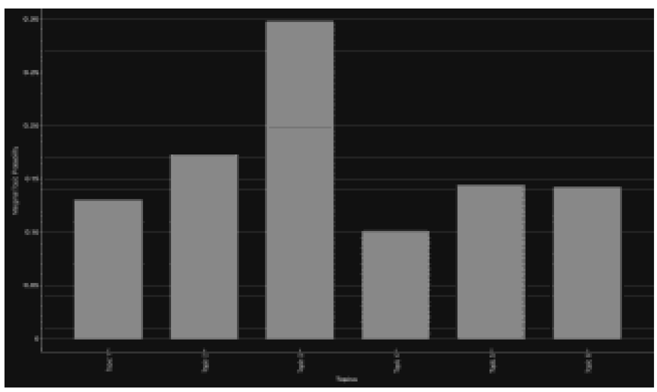

Figure 11(a). Marginal Topic Probability (MTP) of topics derived from title and abstract terms

The MTP results provide additional evidence for interpreting the thematic structures identified through LDA. For the title and abstract corpus, the topics related to operational parameters and energy efficiency and electrocoagulation process and pollutant removal represent important components of the analyzed literature. The topic related to water quality and monitoring parameters provides an additional dimension by emphasizing the indicators used to evaluate treatment performance.

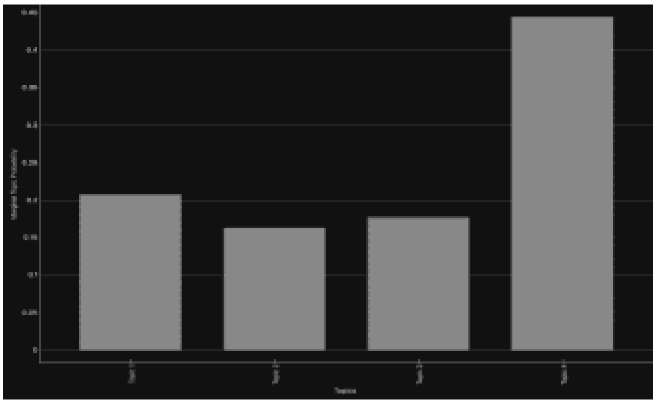

Figure 11(b). Marginal Topic Probability (MTP) of topics derived from author keywords

For the author keyword corpus, the MTP results further indicate the prominence of themes related to pollutant removal and wastewater management and electrocoagulation process and chemical performance. These themes are consistent with the author-keyword topic structure presented in Table 1 and reinforce the importance of wastewater treatment, pollutant removal, electrocoagulation processes, and treatment-performance evaluation within the CEC literature.

The MTP findings complement rather than replace the VOSviewer analysis. VOSviewer emphasizes the relationships and co-occurrence patterns among terms, whereas MTP describes the relative prominence of the latent topics identified through LDA. Differences between these analytical approaches are therefore expected because they characterize different dimensions of the research corpus.

The consistency among the keyword co-occurrence analysis, word-frequency analysis, LDA topic modeling, and MTP analysis provides converging evidence for the identification of major research hotspots. Across these analytical approaches, recurring themes include wastewater treatment, pollutant removal, electrocoagulation processes, electrode-related aspects, and operational conditions. The convergence of these findings strengthens the interpretation that these themes constitute important components of CEC research and provides a basis for identifying emerging research directions in the subsequent analysis.

Emerging Topics

The integration of keyword co-occurrence, word-cloud analysis, topic modeling, and MTP reveals several interconnected directions in Continuous Electrocoagulation (CEC) research. The dominant themes identified across these analyses include CEC mechanisms, process optimization, electrode materials and configurations, operational factors, pollutant removal, and sustainable wastewater treatment.

The results indicate that CEC research encompasses both fundamental electrochemical mechanisms and practical process optimization. The increasing prominence of terms related to flow rate, electrodes, continuous operation, energy consumption, and pollutant removal in the temporal analysis suggests growing attention to the operational requirements associated with continuous wastewater treatment. These themes indicate that research interest extends beyond pollutant removal itself toward understanding how CEC systems can be operated and optimized under continuous conditions.

The bibliometric results also indicate that operational factors constitute an important research theme. However, keyword mapping and topic modeling alone cannot explain the mechanisms through which these factors influence treatment performance or the trade-offs that may occur during practical operation. Parameters such as electrode distance, hydraulic retention time, pH, current density, temperature, conductivity, and flow rate may interact with wastewater characteristics and reactor configuration. These relationships therefore require further examination through qualitative synthesis of the experimental literature.

Importantly, the identification of these operational factors does not imply that they are newly discovered in CEC research. Rather, the bibliometric analysis demonstrates their recurring and interconnected position within the CEC research landscape. This distinction is important because the factors themselves have been investigated extensively in previous electrocoagulation studies, whereas their broader relationship with CEC development, sustainability, and implementation can be further synthesized through the qualitative analysis.

Accordingly, the bibliometric analysis provides the thematic structure required to address RQ1, while the subsequent Qualitative Content Analysis (QCA) examines these themes in greater scientific and practical depth. The QCA specifically evaluates the contribution of CEC to the Sustainable Development Goals (RQ2) and synthesizes the operational factors, implementation considerations, and challenges associated with CEC performance (RQ3).

Qualitative Content Analysis

Qualitative Content Analysis (QCA) was conducted to synthesize findings from previous experimental studies and provide a deeper interpretation of the technological characteristics, operational factors, implementation challenges, and sustainability contributions of Continuous Electrocoagulation (CEC). The qualitative synthesis complements the bibliometric findings by examining how the factors identified as research hotspots influence CEC performance in practical wastewater-treatment applications.

The analysis indicates that CEC performance is determined by the interaction between electrochemical reactions, reactor configuration, hydraulic conditions, electrode characteristics, and wastewater properties. Therefore, treatment efficiency cannot be interpreted solely from individual operating parameters. Instead, the practical performance of CEC depends on the balance between pollutant removal, energy consumption, electrode consumption, hydraulic throughput, sludge handling, and the requirements of the treated effluent.

Definition, Key Features, Mechanism, Optimization, and Challenges of CEC

Continuous Electrocoagulation (CEC) is an electrochemical wastewater-treatment process in which wastewater continuously passes through an electrochemical reactor containing electrodes, commonly aluminum or iron. When direct current is applied, the sacrificial anode undergoes oxidation and releases metal ions into the wastewater. These ions undergo hydrolysis and form hydroxide species that destabilize and aggregate pollutants. At the cathode, water reduction generates hydrogen gas, which can contribute to flotation and the separation of formed flocs (Benazzi et al., 2016).

The combination of electrochemical reactions, coagulation, and flotation allows CEC to address different pollutant groups within a single treatment process. Previous studies have demonstrated its application for the removal of suspended solids, organic matter, color, and other pollutants from different wastewater matrices. The continuous configuration further enables uninterrupted wastewater treatment, continuous sludge withdrawal, and integration with downstream or complementary treatment units. These characteristics make CEC potentially suitable for industrial applications in which wastewater is generated continuously and treatment interruptions are undesirable.

However, continuous operation does not automatically guarantee higher treatment efficiency than batch operation. CEC performance remains strongly dependent on reactor configuration and operating conditions. The qualitative synthesis identified several important factors, including electrode material, current density, pH, electrode distance, flow rate, electrolysis time, conductivity, temperature, supporting electrolytes, and hydraulic retention time (HRT). These parameters do not operate independently; their effects depend on wastewater composition, reactor geometry, electrode arrangement, and the intended treatment objective.

One important operational challenge is electrode passivation or the formation of deposits on the electrode surface. Deposits can reduce the effective electrode area and interfere with electrochemical reactions, potentially reducing treatment stability over prolonged operation. Consequently, periodic electrode cleaning and appropriate electrode-operation strategies may be required to maintain stable performance. These considerations become increasingly important when CEC is operated continuously because long-term operation requires not only effective pollutant removal but also stable electrode performance and manageable maintenance requirements.

Overall, CEC demonstrates potential as a flexible wastewater-treatment technology, but successful implementation requires optimization according to wastewater characteristics and continuous-reactor configuration rather than relying on a single universal operating condition.

Development of Electrode Materials and Configurations

Electrode materials and configurations are important components of Continuous Electrocoagulation (CEC) because the electrodes directly participate in the electrochemical processes responsible for coagulant generation. The selection and arrangement of electrodes can influence current distribution, coagulant generation, treatment performance, energy requirements, and electrode consumption. Previous studies have investigated different electrode materials and configurations to improve the performance of electrocoagulation under various wastewater-treatment conditions.

Aluminum and iron remain commonly investigated sacrificial electrode materials because their anodic dissolution generates metal species that participate in the coagulation process. The selection between aluminum and iron depends on the characteristics of the wastewater, target pollutants, operating conditions, and the intended treatment performance. Studies included in the literature synthesis have examined different electrode types and their effects on electrocoagulation performance (Benazzi et al., 2016; Companhia & Scalize, 2025; Gasmi et al., 2022; Li et al., 2021; Pandey & Thakur, 2021; Zailani & Zin, 2018).

The literature also indicates that electrode selection should not be evaluated solely based on pollutant-removal efficiency. Electrode consumption is an important operational consideration because sacrificial electrodes undergo anodic dissolution during treatment. Ehsani et al. (2022) for example, considered electrode consumption as one of the factors affecting continuous electrocoagulation operation. Therefore, electrode selection involves a balance between coagulant generation, treatment performance, electrode consumption, and operational requirements.

The comparison of electrode materials also needs to consider the specific wastewater matrix. Differences in pollutant composition, pH, conductivity, and other wastewater characteristics can affect the electrochemical behavior of the electrodes. Consequently, an electrode material that performs effectively for one wastewater type cannot necessarily be considered universally optimal for other wastewater applications.

Electrode configuration is another important consideration in CEC because it determines how electrodes are arranged within the reactor and influences electrical and hydraulic conditions. Relevant configurations include monopolar and bipolar arrangements, series or parallel connections, electrode surface area, plate arrangement, and electrode spacing. These configurations can affect current distribution, electrical resistance, coagulant generation, and the interaction between wastewater and the electrochemically generated species.

For continuous systems, electrode configuration is particularly important because the reactor must simultaneously accommodate continuous wastewater flow and sufficient electrochemical contact. Therefore, electrode arrangement should be considered together with hydraulic conditions rather than evaluated independently. The relationship between electrode configuration, electrode spacing, and flow conditions can affect both treatment performance and reactor operability.

The literature synthesized in this study also indicates that electrode configuration involves practical trade-offs. For example, electrode spacing affects electrical resistance and energy requirements, but excessively narrow spacing may create operational limitations associated with electrode contact, passivation, or accumulation of sludge and flocs. Therefore, the optimum configuration is dependent on the reactor design and wastewater characteristics rather than being universally applicable to all CEC systems.

Overall, the development of electrode materials and configurations demonstrates that CEC optimization requires consideration of both electrochemical and reactor-design characteristics. Conventional aluminum and iron electrodes remain important because of their role as sacrificial coagulant sources, while electrode arrangement determines how effectively the electrochemical reactions can be integrated with continuous wastewater flow. These considerations provide the basis for the subsequent analysis of operational factors affecting CEC performance.

Factors Affecting Successful CEC

The qualitative synthesis identified several operational factors that influence the performance and successful implementation of Continuous Electrocoagulation (CEC). These factors include electrode material, current density, pH, electrode distance, flow rate, electrolysis time, conductivity, temperature, supporting electrolytes, and hydraulic retention time (HRT). The relevant factors and supporting studies identified from the reviewed literature are summarized in Table 2.

Table 2. Operational factors influencing continuous electrocoagulation performance identified from previous studies

Dimension/factor	Terms or keywords	References
Electrode material	Type of electrode; electrode consumption	Benazzi et al. (2016), Companhia & Scalize (2025), Ehsani et al. (2022), Gasmi et al. (2022), Li et al. (2021), Pandey & Thakur (2021), Zailani & Zin (2018)
Current density	Optimal range; impact on pollutant removal	Amusa et al. (2023), Ehsani et al. (2022), Fotovat & Hosseini (2023), Li et al. (2021), Mousazadeh et al. (2021)
pH level	Optimal pH; effect on pollutant removal	Boinpally et al. (2023), Ehsani et al. (2022), Liu et al. (2024), Suhartana et al. (2019), Yanes et al. (2021)
Electrode distance	Impact on efficiency	Ehsani et al. (2022), Sutanto et al. (2021)
Flow rate	Optimal flow rate	Amusa et al. (2023), Pandey & Thakur (2021), Sutanto et al. (2021)
Electrolysis time	Duration	Abbasi et al. (2020), Fotovat & Hosseini (2023), Yanes et al. (2021)
Conductivity	Importance	Abbasi et al. (2020), Boinpally et al. (2023)
Temperature	Effect on efficiency	(Elazzouzi et al. (2018), Liu et al. (2024)
Supporting electrolytes	Addition of electrolytes	Abbasi et al. (2020), Shaker et al. (2021)

Hydraulic retention time	Impact on pollutant removal	Ehsani et al. (2022), Hachimi et al. (2025), Pandey et al. (2025)

Electrode Material

Iron and aluminum are among the most frequently used sacrificial electrode materials. Their selection influences the type of coagulant species generated and therefore affects pollutant destabilization and removal. Electrode consumption is also an important consideration because excessive dissolution can increase operating costs and influence sludge generation.

Current Density

Current density affects the rate of anodic dissolution and therefore the amount of coagulant generated. Increasing current density can improve pollutant removal when the applied current is insufficient; however, excessively high current density can increase electrode consumption and energy demand. Therefore, an optimum rather than simply a maximum current density is required.

pH

pH affects electrochemical reactions, hydroxide formation, pollutant speciation, and coagulation behavior. Consequently, the optimum pH depends on wastewater characteristics and the target pollutant. A neutral or slightly acidic condition may be favorable for some wastewater types, but there is no universal pH value that can be considered optimal for all CEC applications.

This finding is important because the literature should not be interpreted as establishing a single optimum pH for every wastewater. Instead, pH optimization should be conducted according to pollutant characteristics and electrode chemistry.

Electrode Distance

Electrode spacing influences the electrical resistance of the wastewater and the distribution of the electric field within the reactor. A shorter electrode distance can reduce ohmic resistance and electrical energy requirements; however, excessively narrow spacing may create practical limitations such as short-circuiting, electrode passivation, or sludge/floc accumulation. Therefore, the optimum spacing is system- and wastewater-dependent.

For concentrated organic wastewater, such as soy-sauce wastewater, electrode spacing also needs to be considered from a hydraulic and mechanical perspective. Nurlaili & Amalia (2024) reported that the highest pollutant removal efficiency was obtained at an electrode distance of 4 cm, with removal efficiencies of 72% for BOD, 83.30% for COD, and 90.60% for TSS.

This result does not contradict the general electrical principle that a shorter electrode distance can reduce ohmic resistance. Instead, it indicates that the optimum electrode distance represents a balance between electrical efficiency and the physical operating conditions of the reactor. In continuous treatment of concentrated wastewater, excessively narrow electrode gaps may increase the potential for sludge or floc accumulation between electrode plates, which can interfere with wastewater flow and reactor operation.

Therefore, the 4 cm distance reported by Nurlaili & Amalia (2024) should be interpreted as an optimum condition for the specific wastewater and reactor configuration investigated, rather than as evidence that a wider electrode distance is universally more efficient.

Flow Rate

Flow rate directly affects the time available for wastewater to interact with electrochemically generated coagulants. Lower flow rates generally increase hydraulic contact time and can improve pollutant removal when insufficient residence time limits treatment. However, excessively low flow rates may reduce reactor throughput and negatively affect treatment capacity.

Consequently, flow rate should be optimized together with reactor volume and treatment objectives rather than interpreted solely as a parameter for maximizing removal efficiency.

Electrolysis Time

Electrolysis time influences the duration of electrochemical reactions and coagulant generation. Longer treatment times can increase pollutant removal when treatment is limited by insufficient electrochemical contact. However, excessive treatment time can increase electricity consumption and operating costs. For continuous systems, electrolysis time is closely related to hydraulic retention time and flow rate and should therefore be considered as part of the overall reactor design rather than as an isolated parameter.

Conductivity and Supporting Electrolytes

Wastewater conductivity affects electrical resistance and energy consumption. Low conductivity can increase electrical resistance and therefore require greater energy input. Supporting electrolytes such as NaCl may be added to increase conductivity and improve current transport. However, electrolyte addition should also consider secondary environmental effects, including changes in salinity and the potential formation of unwanted by-products. Therefore, increasing conductivity should not automatically be interpreted as environmentally beneficial; the type and concentration of the supporting electrolyte must be considered.

Temperature

CEC generally operates under the temperature conditions of the wastewater entering the reactor. For municipal and many ambient industrial wastewaters, this typically corresponds to approximately ambient temperature rather than 45–55°C.

Higher temperatures may improve reaction kinetics in certain systems, but the optimal temperature depends on wastewater characteristics and reactor conditions. In some industrial applications, wastewater may naturally enter the treatment system at elevated temperatures because of upstream production processes. In such cases, the existing thermal condition may influence CEC performance without requiring additional heating.

Therefore, the previous statement that urban wastewater treatment generally operates at 45–55°C is not appropriate. Such temperatures should instead be discussed as conditions that may occur in specific hot industrial wastewaters, not as a general operating range for urban wastewater treatment.

Hydraulic Retention Time

Hydraulic retention time (HRT) is an important factor in continuous treatment because it represents the average time wastewater remains in the reactor. The relationship between reactor volume and flow rate can be expressed as:

$$\mathrm{HRT} = \frac{V}{Q} \tag{1}$$

where V represents reactor volume and Q represents flow rate. Therefore, for a fixed reactor volume, increasing HRT corresponds to reducing the flow rate and providing wastewater with more time to interact with electrochemically generated coagulants.

The study cited by Ehsani et al. (2022)) reported improved removal with longer retention conditions, while Pandey et al. (2025) reported substantial removal at an HRT of 120 minutes. Similarly, the comparison reported by Hachimi et al. (2025) in which HRT was reduced from 24 hours to 16 hours and ammonia-nitrogen removal decreased from approximately 90% to 58%, should be interpreted as evidence that shortening HRT reduced removal efficiency, rather than evidence that longer HRT decreases efficiency.

In general, insufficiently short HRT can reduce pollutant removal because wastewater has less time to interact with the electrochemically generated coagulants. However, the optimum HRT depends on wastewater characteristics, reactor configuration, and the balance between treatment efficiency and hydraulic throughput. Insufficiently short HRT can reduce treatment efficiency, while excessively long HRT may improve removal but reduce hydraulic throughput and increase reactor volume requirements. The optimum HRT therefore represents a balance between pollutant removal and treatment capacity.

Implementation of CEC Systems Supporting the SDGs

CEC has potential relevance to sustainable wastewater management, particularly SDG 6, which focuses on clean water and sanitation. The ability of CEC to reduce suspended solids, organic pollutants, color, and other contaminants provides a potential technological pathway for improving wastewater quality.

The contribution of CEC to SDG 6 is also connected with broader sustainability objectives. Improved wastewater treatment can support responsible water management and contribute indirectly to SDG 12 through more efficient resource use and SDG 13 through opportunities to improve energy efficiency and reduce environmental burdens. However, these contributions depend on actual operating conditions, energy requirements, sludge generation, and overall life-cycle performance.

The Surabaya domestic laundry wastewater study reported optimum conditions of 5 A current, 5 cm electrode spacing, 0.5–1 L/min flow rate, and 90 minutes treatment time. Under these conditions, phosphate removal reached 47.37%, surfactant removal 96.85%, TSS removal 78.38%, and COD reduction 86.98%. These results demonstrate the potential of electrocoagulation for domestic wastewater containing surfactants and organic contaminants. However, the conditions should not be generalized to all wastewater types because optimum parameters depend on wastewater characteristics and reactor configuration.

The Izzudin et al. (2024) batik wastewater case further demonstrates both the potential and limitation of CEC. Using aluminum anodes and copper cathodes at 20 A for 30 minutes, with voltage variations of 10, 20, and 30 V, TSS decreased from 311 to 60.70 ppm, TDS from 8294 to 1977 ppm, and COD from 1345.20 to 623.30 ppm. However, the final pH of 10.90 represents an important limitation because the treated wastewater became strongly alkaline. Therefore, the pH increase should not be presented as evidence of successful treatment by itself; additional pH adjustment or a final neutralization stage may be necessary before discharge.

The electrode interpretation should also be clarified. Aluminum functions as the anode, where oxidation releases aluminum species that contribute to aluminum hydroxide coagulant formation. The copper cathode does not function as a sacrificial coagulant source. Instead, cathodic water reduction generates hydrogen gas, which can contribute to flotation and floc separation. Thus, the previous claim regarding $Cu(OH)_2$ formation as a coagulant has been removed.

The soy-sauce wastewater case reported by Nurlaili & Amalia (2024) further demonstrates that treatment performance must be interpreted together with reactor operation. At a 4 cm electrode distance, BOD, COD, and TSS removal reached 72, 83.30, and 90.60%, respectively. As discussed above, this result represents an optimum for the specific wastewater and reactor configuration rather than evidence that wider electrode spacing is universally superior.

These cases demonstrate that CEC can contribute to sustainable wastewater treatment, but treatment efficiency alone is insufficient to determine sustainability. Final effluent quality, pH, energy consumption, electrode consumption, sludge production, hydraulic throughput, and additional treatment requirements must also be considered.

Integration of Findings

The integration of bibliometric and qualitative findings provides a broader interpretation of the development of Continuous Electrocoagulation (CEC) research. The bibliometric analysis identified wastewater treatment, pollutant removal, electrochemical mechanisms, electrode characteristics, and operational optimization as major research hotspots. The qualitative synthesis subsequently demonstrated that these themes are closely connected to practical factors such as electrode material, current density, pH, electrode spacing, flow rate, conductivity, temperature, supporting electrolytes, and hydraulic retention time (HRT).

The integration also demonstrates that CEC research has progressed from fundamental investigations toward increasingly practical and application-oriented research. Earlier research themes were more strongly associated with electrochemical mechanisms and coagulation, whereas newer themes increasingly involve flow rate, electrode configuration, pollutant removal, energy consumption, wastewater management, and continuous operation. This development indicates that research attention has expanded from understanding the electrocoagulation process toward addressing the operational requirements associated with continuous wastewater treatment.

However, the integrated findings reveal that the field remains relatively fragmented. Many studies investigate individual operational parameters under specific wastewater conditions, while fewer studies systematically evaluate the interactions among multiple parameters in continuous reactors. This limitation makes it difficult to directly transfer optimum operating conditions from one wastewater type or reactor configuration to another.

Several research gaps emerge from the integrated findings. First, standardization of continuous reactor design remains limited. Differences in reactor volume, electrode configuration, electrode spacing, hydraulic conditions, and operating modes make direct comparison between studies difficult. Standardized reporting of reactor characteristics and operating conditions would therefore improve the comparability and reproducibility of CEC research.

Second, operational parameters are often evaluated independently. Although current density, pH, flow rate, electrode distance, temperature, conductivity, and HRT are repeatedly identified as important variables, their interactions are less consistently examined. Future studies should therefore consider multivariable optimization rather than optimizing one parameter at a time.

Third, energy efficiency and treatment performance need to be evaluated simultaneously. High pollutant removal does not necessarily indicate a sustainable process if it requires excessive electrical energy or electrode consumption. Therefore, future research should report removal efficiency together with energy consumption, electrode consumption, sludge production, and treatment throughput.

Fourth, scale-up remains an important challenge. Laboratory-scale results cannot automatically be transferred to industrial systems because hydraulic behavior, electrode passivation, sludge accumulation, and energy requirements may change as reactor size increases. Long-term and pilot-scale investigations are therefore required to evaluate the stability and practical feasibility of CEC under realistic operating conditions.

Fifth, sustainability assessment remains less developed than treatment-performance evaluation. Although CEC is frequently described as a sustainable wastewater-treatment technology, a comprehensive assessment should consider life-cycle, techno-economic, energy, and environmental indicators rather than pollutant removal alone. This is particularly important when evaluating the contribution of CEC to the Sustainable Development Goals.

Future Research Directions

Based on the integrated findings, future CEC research should focus on several directions. First, research should develop standardized continuous reactor configurations and reporting protocols to improve comparison among studies and facilitate scale-up. Second, future studies should investigate interactions among operational parameters, particularly current density, pH, flow rate, electrode spacing, and HRT. Such approaches would provide a more realistic representation of continuous reactor operation than independent single-factor experiments.

Third, research should place greater emphasis on energy and resource efficiency, including electricity consumption, electrode consumption, sludge production, and chemical requirements. Treatment performance should therefore be evaluated together with resource demand to provide a more comprehensive assessment of process efficiency.

Fourth, future studies should investigate industrial-scale and long-term operation, including electrode passivation, sludge accumulation, maintenance requirements, and fluctuations in wastewater composition. These studies are important for determining whether laboratory-scale performance can be maintained under realistic continuous operating conditions.

Finally, future research should integrate CEC performance with sustainability assessment and SDG indicators. Such integration would help determine whether improvements in pollutant removal are accompanied by acceptable energy consumption, resource use, environmental impacts, and operational requirements.

Overall, the findings demonstrate that CEC has developed into an increasingly interdisciplinary wastewater-treatment research field. Its future development will depend not only on achieving high pollutant-removal efficiency but also on improving reactor design, operational stability, energy efficiency, economic feasibility, and sustainability performance. The integration of bibliometric mapping and qualitative literature synthesis therefore provides a comprehensive framework for understanding the current state of CEC research and identifying directions for its transition toward practical and sustainable wastewater-treatment applications.

Conclusion

This study employed Systematic Literature Network Analysis (SLNA) integrating Bibliometric Analysis (BA) and Qualitative Content Analysis (QCA) to examine the development of Continuous Electrocoagulation (CEC) research in wastewater treatment. The analysis of 99 journal articles published between 2019 and 2024 shows that CEC research increased from 2019 to 2022, with 2022 representing the highest publication productivity in the analyzed dataset. The bibliometric analysis identified wastewater treatment, pollutant removal, electrocoagulation mechanisms, electrode characteristics, and operational optimization as major research themes, indicating increasing attention toward the practical development of continuous wastewater-treatment systems. The findings also demonstrate that global research, involving countries from Asia, Europe, the Americas, and other regions, has contributed to the development of CEC research. India and China occupied prominent positions in the country collaboration network, while researchers from Brazil, Iran, the United States, the United Kingdom, France, Vietnam, and Iraq also contributed to the research landscape. This indicates that CEC has developed as an internationally connected research field rather than being concentrated within a single geographical region. The qualitative synthesis identified several factors affecting CEC performance, including electrode material, current density, pH, electrode distance, flow rate, electrolysis time, conductivity, supporting electrolytes, temperature, and Hydraulic Retention Time (HRT). Their effects are dependent on wastewater characteristics and reactor configuration. The findings also indicate that CEC has potential to support SDG 6 (Clean Water and Sanitation) through wastewater-quality improvement, while its broader sustainability requires consideration of energy consumption, electrode consumption, sludge management, effluent quality, and resource use. The integrated findings reveal several research priorities, including multivariable optimization of operating parameters, standardized continuous-reactor design and reporting, long-term and pilot-scale validation, energy and resource-efficiency assessment, and techno-economic and life-cycle evaluation. Future studies should also examine the contribution of CEC to SDG 6 and SDG 12 using measurable environmental and economic indicators, particularly for practical applications in industrial wastewater treatment. While this study is limited to metadata retrieved from the Scopus database, the identified trends provide a useful baseline; thus, future bibliometric research should integrate alternative databases such as Web of Science or Google Scholar to broaden literature coverage and minimize potential publication bias.

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Author Contributions

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