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Review

Bibliometric Insights into Car Wash Wastewater Treatment Research: Trends and Perspectives

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Abstract: Car wash wastewater (CWW) poses a significant environmental danger due to its high chemical oxygen demand (COD), heavy metals, and anionic surfactant complex composition, all of which can have an adverse effect on the environment. Even with the extensive research on CWW treatment, further study is necessary to improve our comprehension in this field. With an emphasis on CWW treatment processes and research trends, this study offers a comprehensive bibliometric analysis of 208 articles from the Scopus database. The analysis reveals that more than 55.77% of the research publications were released within the last five years, suggesting that there is increasing interest in the treatment of CWW. According to the data, the most important journal in this field is Desalination and Water Treatment. China and India were major research contributors. The main research directions in this area are properly indicated by the frequently used keywords "carwash wastewater", "electrocoagulation", "wastewater treatment", and "water reuse", according to an analysis of the keywords. Electrocoagulation, coagulation, and adsorption are common methods that are gaining popularity. In recent years, the most often researched CWW contaminants included those measured by COD and heavy metals. The results of this research offer an overview of recent developments.

Keywords: bibliometric analysis; carwash wastewater; CWW; research trends; treatment methods; VOSviewer

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1. Introduction

One of the biggest challenges facing the global community in the present day is the growing scarcity of water resources driven by escalating demand for water [1]. Currently, less than 3% of the water supply on the Earth is readily accessible for human use, a situation exacerbated by escalating demand for water driven by population growth, industrialization, and economic development [2–4]. This widening imbalance between supply and demand has led experts to warn of a looming "water crisis" that threatens food and energy security, public health, and ecosystem stability worldwide [5,6]. As traditional water sources become depleted, there is a pressing need to pursue alternative strategies for water reclamation and reuse [5]. The substantial water used in different sectors, like textiles [7], dairy products [8], paper [9], food industries [10], and pharmaceuticals [11], generates large amounts of wastewater. Because of their hazardous, nonbiological components, these wastewaters have the potential to harm the environment and ecosystems [12].

Of all industrial activities, car wash facilities consume a significant amount of fresh water and, consequently, produce large amounts of car wash wastewater (CWW) containing numerous contaminants [13,14]. The rapid growth in population has led to an increase in the use of cars, which has led to an increasing need for car wash services [3,15]. Depending on the size and type, car wash facilities can utilize 150–600 L of fresh water per car washed [14,16,17], leading to the generation of thousands of liters of CWW [14]. Car wash practices use a variety of chemical products, soaps, and detergents to effectively remove accumulated particulate matter, such as mud, dirt, sand, grime, and dust, from the surface of cars [18].

This can increase the chemical oxygen demand (COD), biological oxygen demand (BOD), turbidity, total suspended solids (TSS), and total dissolved solids (TDS) in CWW [19,20]. Additionally, the CWW may contain surfactants, heavy metals, petroleum hydrocarbon residues, and oil and grease (O&G) originating from the connections, engine parts, and other automotive components [21]. CWW is distinct from conventional wastewater since it contains significant levels of O&G and pollutants with anionic surfactants. Although their values may vary across different automotive components and different chemical products used, the COD, BOD, turbidity, TSS, TDS, O&G, and anionic surfactant concentrations in CWW can range from 59 to 180 mg/L, 10.9 to 650 mg/L, 7.7 to 1400 NTU, 60 to 2458 mg/L, 120 to 7920 mg/L, 0.1 to 1750 mg/L, and 0.7 to 51 mg/L, respectively [14].

Wastewater from vehicle washes that is left untreated or is cleaned insufficiently has several negative impacts. Aquatic habitats may be negatively impacted by car wash wastewater discharged into conventional sewage systems or straight into natural water bodies, which can contaminate the land and water [16]. Because oils are hydrophobic and detergents contain surfactants, these two factors have the potential to upset the natural equilibrium, endangering aquatic life and, through the food chain, human health. Oher common elements in car wash effluent are heavy metals, which can build up in sediments and have long-term ecological effects [22]. The direct discharge of CWW into sewerage systems can be problematic, as the incompatible waste components may decrease the efficiency of sewage treatment operations [23]. As a result, in order to avoid contaminating the environment and lessen the impacts of vehicle wash services, the proper treatment of CWW is essential [24].

According to the literature, CWW has been treated using a variety of techniques, with varying degrees of effectiveness [15]. Conventional treatment methods, including biological, chemical, and physical treatments, have been utilized to treat CWW [15]. Chemical treatment methods, such as coagulation/flocculation (C/F) [25], electro-Fenton (EF) [19], electrocoagulation (EC) [26], and electro-oxidation (EO) [27] are commonly utilized to treat CWW. Physical treatment methods, including adsorption [28] and filtration [29], have also been effective. Biological treatment methods have also been used to treat CWW [30]. Additionally, combined treatment methods, such as EC followed by anodic oxidation [31] or EC followed by nanofiltration (NF) [32], are more effective and efficient treatments. However, each treatment has its merits and demerits.

In fact, implementing a suitable and reasonably priced treatment system not only offers carwash facilities a cost-effective alternative, but it also reduces water pollution and the risks it poses to the environment and to humans [1,33,34]. Meanwhile, understanding the methods and techniques for CWW treatment while taking compounds and contaminants into account is one of the most crucial aspects of recycling potential resources [1]. Previous studies concentrated on investigating reductions in particular contaminants [14,35], enhancing the effectiveness of diverse treatment techniques [36], elucidating the dynamics and mechanisms underlying the treatment approaches [1], and illustrating the relationship between the three pillars of sustainable development and applications of CWW treatments in use [36]. Nevertheless, a significant gap persists in terms of quantitative approaches that can thoroughly synthesize the body of research on CWW treatment. Therefore, gaining a comprehensive grasp of the field's research environment and determining potential future paths and trends in CWW treatment remain critical objectives.

One of the best methods for conducting both qualitative and quantitative studies of scientific activity is bibliometric analysis [37,38]. Bibliometrics analyzes the amount and external characteristics of literature, including patents, articles, books, and their references, using statistical and mathematical techniques [38,39]. As a result, new research directions can be found by allowing researchers to recognize and investigate quantitative trends within certain research fields [39]. A thorough grasp of the research landscape and the ability to identify new research directions are two benefits of using statistical indicators derived from bibliometric analyses to assess the productivity of research in a given field by individuals or institutions [40]. Researchers can discover new patterns and areas for possible research expansion, as well as attain a deeper grasp of the body of knowledge, by using bibliometric analysis to find influential studies. There are two primary categories of bibliometric analysis. The first is activity-level focused and identifies key nations, publications, and research topics. Social network analysis and relationship indicators are used in the second category to show relationships between institutions, nations, and keywords. These evaluations shed light on the main ideas and developing patterns in a field of research [37,41]. Scientometric analysis was selected because, among other study opportunities, it allows one to utilize the quantitative analysis of scientific production to explore the evolution, trends, structure, dynamics, and linkages of scientific practice.

Previous research has yielded a significant understanding of the features and outcomes of CWW treatment methods. Nevertheless, more investigation is required to guarantee the effective application of these methods. To bridge this study gap, the literature currently published stresses the importance of performing bibliometric research on CWW treatment methods. Therefore, the primary goal of this research is to use bibliometric analysis to thoroughly review the literature on CWW treatment processes. This study used bibliometric analysis to assess publications on CWW therapy from 2010 to 2024, both quantitatively and qualitatively, to fill the research gap found in other studies. The analysis concentrated on research articles and conferences obtained from the Scopus database. The study's goals are as follows: Firstly, the overall outputs of the studies on CWW treatment methods were analyzed, together with the productivity of studies in various countries across the world and the total number of publications. An overview of the research activity in this area was provided through this analysis. Secondly, to determine keywords and compile the research hotspots in the field of CWW treatment methods, a social network analysis was utilized. This method assisted in highlighting the connections and patterns among study topics. Both qualitative and quantitative insights were obtained from the analysis, which made it a valuable guide for further research projects. Furthermore, this data source has not been the subject of any prior bibliometric reviews on CWW treatment methods.

2. Materials and Methods

2.1. Data Source and Search Strategy

In this study, the latest literature was reviewed using the PRISMA principles [42]. We adhered to PRISMA guidelines without considering meta-analysis techniques. In systematic literature reviews, bibliometric analysis is a useful technique for creating an extensive, reproducible database [42]. When performing bibliometric analysis, it is crucial to clearly define the study's scope and provide a thorough description of the methods utilized to find pertinent sources. The wide acceptance and efficacy of bibliometric analysis may be attributed to its capacity to provide an all-encompassing synopsis of research domains, publications, institutions, and patterns [43]. This approach is commonly employed to scrutinize and evaluate vast amounts of scholarly information to comprehend the connections between journal citations and provide an overview of the present or developing field of study [44]. Researchers can expand on earlier work and enhance subsequent studies by utilizing bibliometric analysis and its indications [45]. Because of these characteristics, bibliometric approaches are widely used in many different fields [46,47].

In order to monitor trends and advancements in CWW treatment methods research, this study utilized bibliometric analysis. The Scopus database served as the source of the data for this research. The selection of the Scopus database was made due to its comprehensive compilation of scholarly works from many disciplines and its extensive coverage of technology-related literature [46–48]. Significantly, Scopus provides around 20% greater coverage than Web of Science (WOS), and there are differences in the levels of precision with Google Scholar findings [38,49,50]. The addition of a diverse range of publications to enhance the study was made possible by the use of Scopus.

The following query string and given keywords were used to conduct a literature search: "(TITLE-ABS-KEY (("Carwash Wastewater" OR "car Wash Wastewater" OR "Carwash Waste Water" OR "CWW" OR "Car Wash Effluents" OR "Vehicle Wastewater" OR "Vehicle Washing" OR "Automobile Wastewater") AND ("Treatment" OR "Treatment Process" OR "Wastewater Treatment Process") AND PUBYEAR > 2009 AND PUBYEAR < 2025) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English")))". Additionally, key research works for this study were published within a timeframe spanning from 2010 to June 2024. In addition, as the majority of scholarly research is conducted in English, this study's shortlist only included English-language papers. The method of searching is displayed in Figure 1.

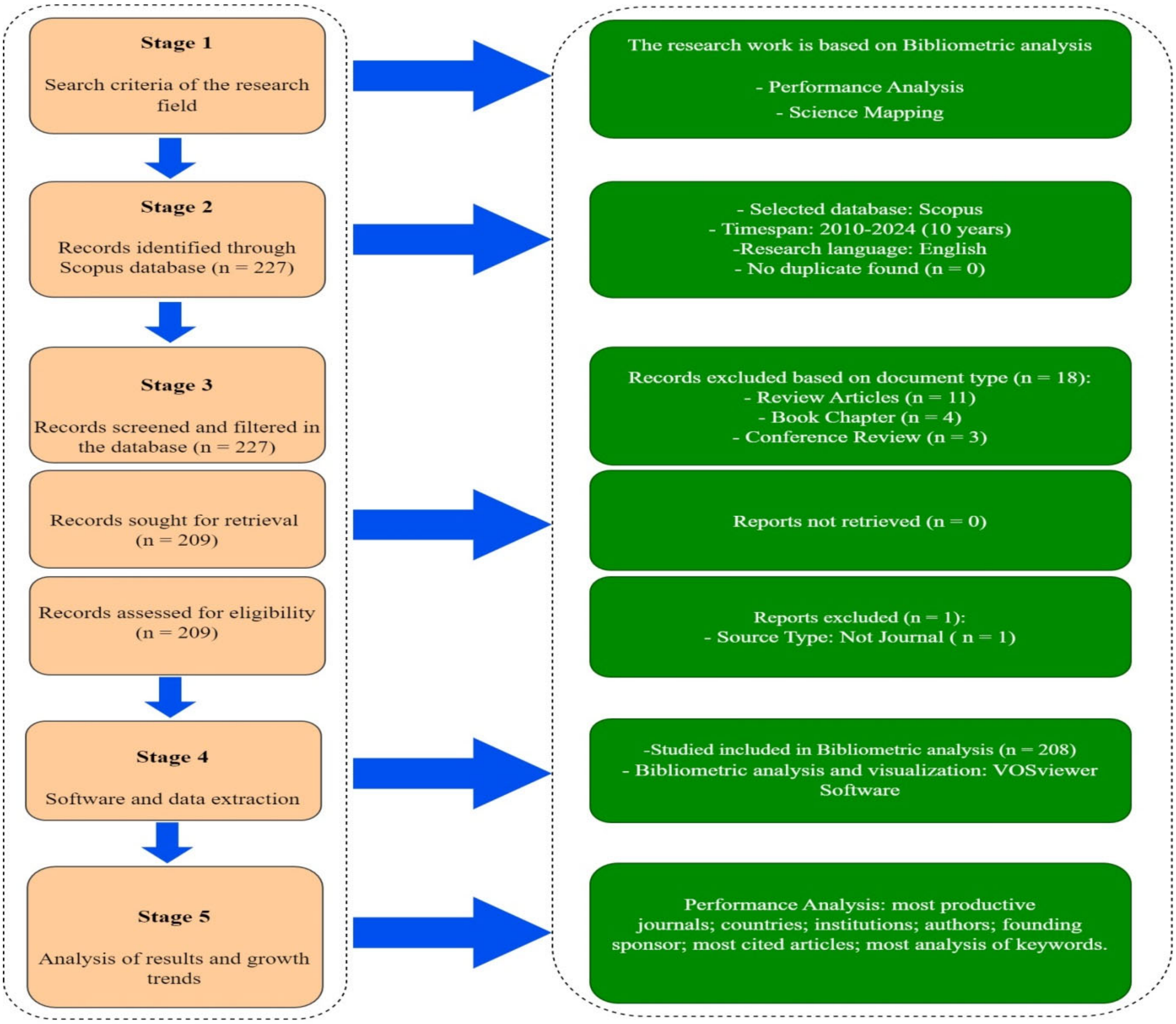


Figure 1. Research methodology.

As shown in Figure 1, our first search revealed a total of 227 publications, including articles, conference papers, review articles, book chapters, and conference reviews. After, we rigorously filtered this corpus such that only English-language journal and conference papers remained. Following this filtering process, 208 documents were ultimately chosen.

2.2. Data Extraction and Filtering

Comma separated values (CSV) files were created once the data were taken from the Scopus database. During the research selection process, a number of filtering processes were used to guarantee the data's dependability and correctness. Several processes were used during these phases, including the detection and elimination of duplicate entries, as well as the application of inclusion and exclusion criteria predicated on elements such as source, document type, and language. After the records were filtered, they were retrieved, and every column—including the year, title of the source, and names of the authors and their affiliations—was carefully examined. Furthermore, the documents' quality was assessed by an examination of their titles, abstracts, and keywords. Any inaccurate or missing entries were appropriately removed throughout the data filtering process, further honing the dataset in preparation for subsequent analysis.

2.3. Data Analysis

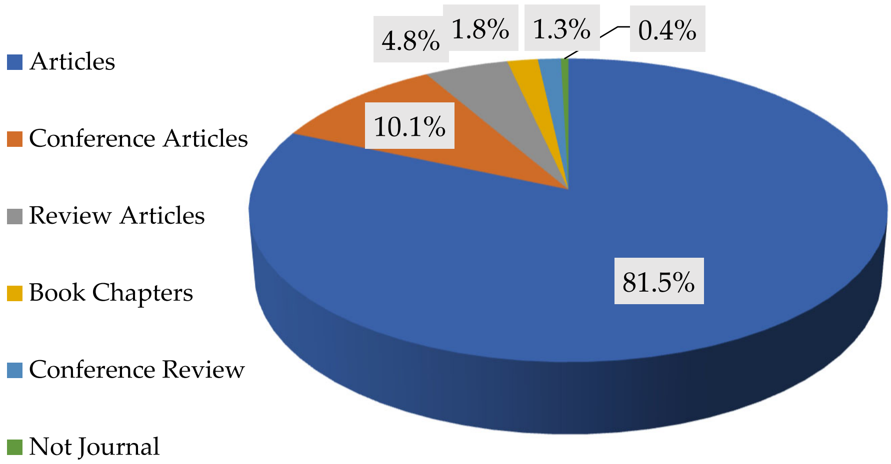
In bibliometric research, the practice of creating and displaying bibliometric maps for readability is becoming more popular. This approach simplifies the processes of gathering literature and identifying the connections among selected publications. We downloaded the data for VOSviewer processing so that we could examine the results and gain an understanding of the bibliometric patterns. This open-source, user-friendly program is used for creating networks and viewing bibliometric data. Compared to other software applications, like SciMAT, Gephi, CiteSpace, and Bib Excel, it has unique features [41,51]. VOSviewer software was used for the data processing and analysis because it can handle huge networks and has text-mining features [46]. To help with the discovery of patterns, trends, and links within the literature, bibliometric maps were created using VOSviewer to graphically depict the interconnections among the chosen articles [52]. One of VOSviewer's key advantages is that it can dynamically change the display labels according to the algorithm, which makes it an excellent tool for seeing co-occurrences [52]. The analysis concentrated on the following three main areas in the investigation: authors' keywords utilized in the documents, journals in which the articles were published, and countries of origin. These elements are essential to bibliometric studies since they offer a thorough grasp of the state of research [53,54]. The important metrics considered in the analysis included average normalized citations, papers, and the total number of links. These metrics are critical for assessing the articles' level of exposure and effects [55].

3. Results and Discussion

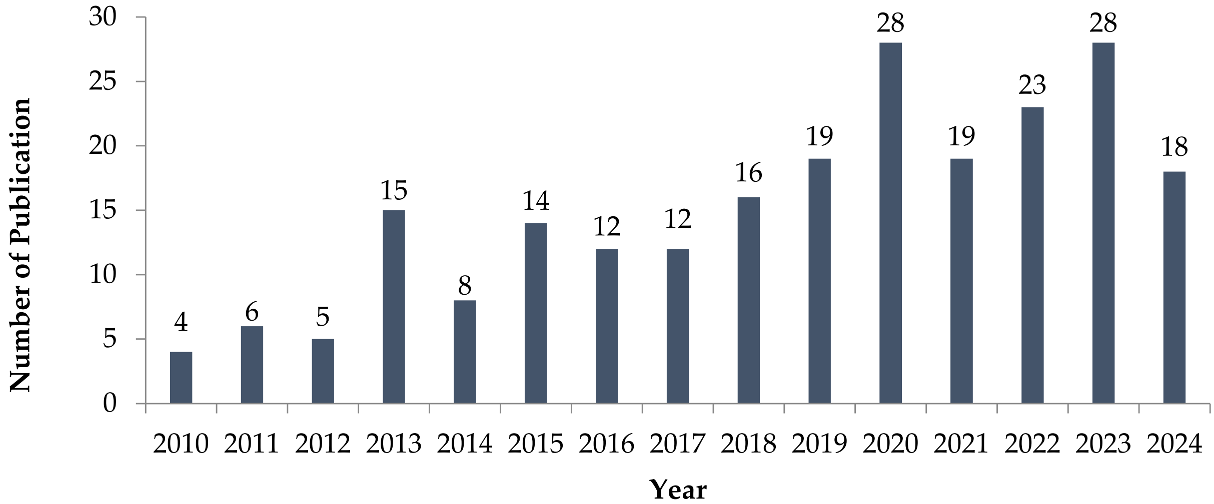
3.1. Publications Output

Figure 2a shows the trends in the publication outputs on CWW treatment processes, including the seven main Scopus subject categories. The Scopus database search resulted in 208 research documents on CWW treatment processes published between 2010 and June 2024. The most common type among them is "articles", of which there were 185, or 81.5% of all the publications. "Conference articles" (10.1%), "review articles" (4.8%), and others (such as "book chapters", "conference reviews", and "not journal") make up the remaining publication categories. As "articles" and "conference articles" constituted the majority of publications, other categories were excluded from further examination.

Figure 2b charts the trends in CWW treatment methods related to research papers through June 2024. Over the last 10 years, the topic of treating CWW has witnessed remarkable development at the level of scientific research, as seen by the steady rise in research publications on this topic, which reached 208 papers as of June 2024. This can be linked to the population's rapid growth, which has increased automobile use and which has led to an increasing need for car wash services [3,15]. As a result, in order to handle the CWW generated, appropriate treatment techniques must be developed. Starting in 2010, which witnessed only four publications, this number increased to six publications in 2011, and then five publications in 2012. In 2013, this field witnessed increasing interest from researchers, as the number of publications increased to 15 in that year. This upward trend continued over subsequent years, with the number of publications reaching a peak in 2020 and 2023 with 28 publications each year, reflecting the marked increase in research interest in CWW treatment processes. This trend can be linked to several factors, most notably the growing awareness of the environmental and health impacts of CWW. Additionally, there is a pressing need to create effective and sustainable technologies for treating CWW by reusing treated wastewater in many applications.



(**a**)



(**b**)

Figure 2. (**a**) Proportion of document-type reports on CWW research; (**b**) publication patterns in CWW research for various treatment processes, as determined using the Scopus database until June 2024 (n = 208).

This paper presents research trends in various treatment methods by analyzing the distribution of publications on CWW treatment. Figure 3 presents an analysis of the primary fields that were studied over the past ten years. We note that the environmental sciences constitute the most dominant research field at 31.4%. This focus reflects the growing interest in the negative environmental impacts of these waters and the importance of developing effective methods to treat CWW and reduce its impacts. In contrast, the fields of engineering

(10.69%) and chemical engineering (10.24%) are next in terms of categories, and they focus directly on the design and improvement of the technologies and technological processes needed to treat CWW. These efforts are integrated with research in the fields of chemistry (8.46%) and energy sciences (7.13%), focusing on understanding the chemical properties of wastewater and the energy requirements associated with treatment processes. In addition, the data show an interest in agricultural and biological sciences (4.68%) and molecular biology (3.56%), indicating recognition of the biological and environmental impacts of CWW and the potential for using biological technologies in treatment processes. The fields of computer science (4.45%) and materials (3.79%) contribute to the development of monitoring and control systems and materials used in processing. Finally, the social sciences (3.12%) show the interest in the economic and social aspects associated with CWW management. This emphasizes the importance of a comprehensive perspective for addressing this complex environmental problem. Our analysis demonstrates that the research on CWW treatment methods is not limited to a specific field of study. The lack of a specific topic category within Scopus for CWW treatment indicates the multidisciplinary nature of this field of inquiry.

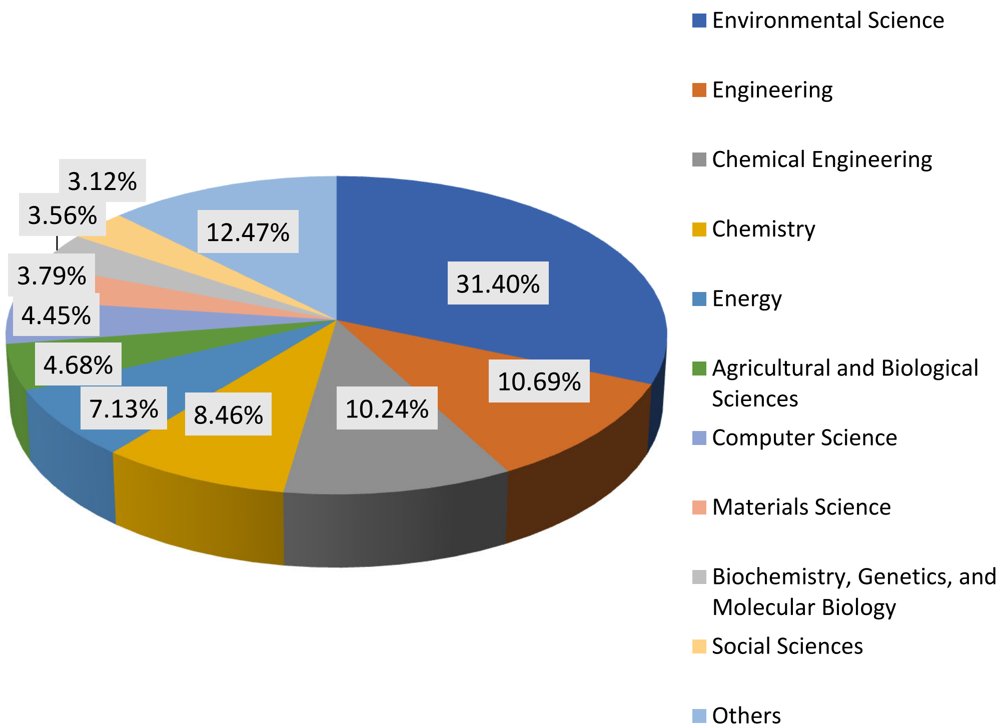


Figure 3. Scopus publications categorized by subject.

According to Figure 3, the field of research on CWW treatment has gradually changed from emphasizing "Environmental Science" and "Engineering" to adopting a framework that is interdisciplinary. A variety of disciplines, including chemical engineering, chemistry, energy, and other pertinent fields, are integrated into this multidisciplinary approach. As a result of this change, there has been a notable increase in research endeavors concerning the treatment of CWW, along with the introduction of new ideas and improvements in treatment methodologies.

3.2. Top Journals for Research on the CWW Treatment

The Scopus database was used to determine which journals were most cited related to CWW treatment processes. Table 1 lists the 17 eminent journals involved in publishing on CWW treatment processes, along with the total number of published documents, total citations, total link strength (TLS), H-index, and SCImago Journal Rank (SJR).

Table 1. The top 17 journals by citation count for CWW treatment research.

Source Journal	TLS	Total Number of Published Documents	Total Citations	H-Index	SJR
Desalination and Water Treatment	61	9	123	75	0.267
Water Science and Technology	44	9	125	153	0.548
Chemosphere	96	8	277	311	1.806
Environmental Science and Pollution Research	40	8	142	154	0.944
Sustainability (Switzerland)	51	7	20	169	0.672
Bioresource Technology	22	5	281	364	2.576
Journal of Environmental Management	59	5	129	218	1.678
Journal of Water Process Engineering	67	5	81	89	1.278
Case Studies in Chemical and Environmental Engineering	5	4	21	35	1.283
Environmental Technology (United Kingdom)	8	4	23	84	0.546
Journal of Hazardous Materials	46	4	96	329	2.57
Chemical Engineering Journal	39	3	126	280	2.803
Physics and Chemistry of the Earth	4	3	117	110	0.729
Science of the Total Environment	11	3	42	353	1.998
Separation and Purification Technology	44	3	117	191	1.339
Water Research	36	3	85	354	3.338
Water, Air, and Soil Pollution	3	3	26	42	0.237

The 208 publications that this study collected were published in 132 different journals. Table 1 displays the top 17 journals (or around 41.35% of the 132 journals) based on the number of articles. The *Journal of Bioresource Technology* (281), *Chemosphere* (277), *Environmental Science and Pollution Research* (142), *Journal of Environmental Management* (129), and *Chemical Engineering Journal* (126) are the top five journals in the mentioned domain in terms of citation production. With nine publications, the most productive journal for CWW treatment processes is the *Journal of Desalination and Water Treatment*. Water Research requires more citations in order to achieve the same level of impact on CWW treatment processes, despite having a higher SJR and H-index score. Researchers can use these results to select journals that would be a good fit for publishing their research articles.

Journals with three or more papers published on CWW treatment processes between 2010 and 2024 were chosen as the primary sources. Out of the sources that were found, 17 of them satisfied these requirements, as Figure 4 illustrates. The majority of research on the use of treatment methods to treat CWW may be found in these 17 journals, which are also vital to the subject of study. Research findings can be shared thanks to scientific publications [56].

Over the past ten years, the journals depicted in Figure 4 have played a significant role in supporting research on the use of various techniques to treat CWW. These findings can help researchers identify possible journals to submit their work to for publication. The twelve journals in the top 17 have an H-index > 110. Furthermore, the abundance and variety of sources show the interest of the editors in this area of study.

3.3. Country Collaboration Network for CWW Treatment

Despite the fact that CWW treatment remains a global issue, several treatment methods have been developed that have high treatment efficiency and satisfy the necessary discharge standards. Research in this field is being conducted in numerous countries. As such, it was imperative to perform an analysis of the publications that have been published worldwide in this field. The results can be used as a gauge to measure which treatment modalities are most effective in treating CWW and which countries are at the forefront of this field of study [15].

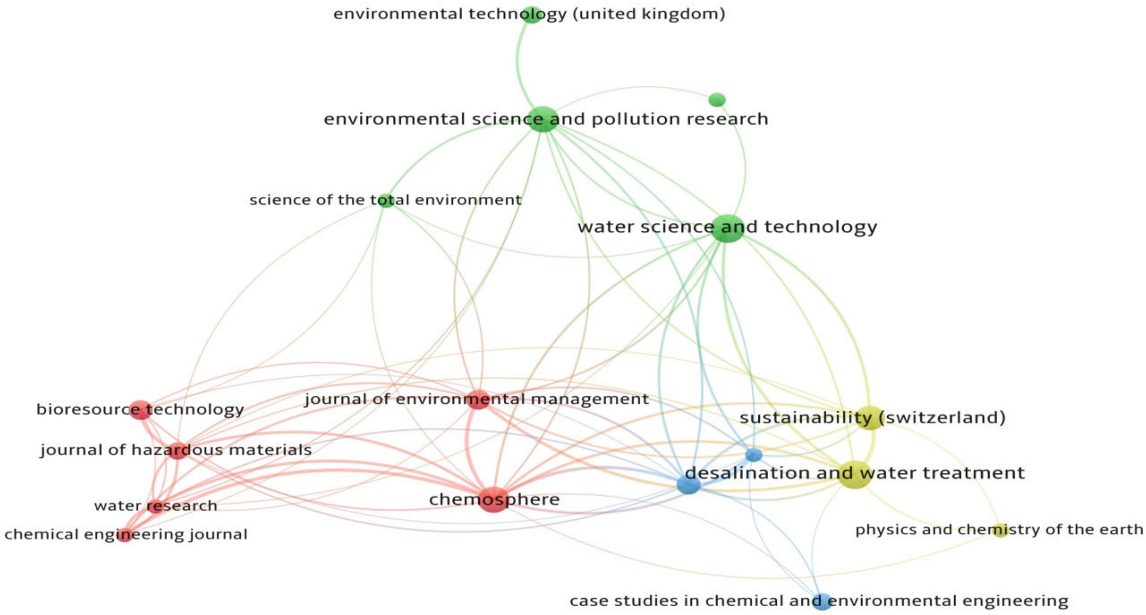


Figure 4. Co-occurrence map of journals that have more than three articles published in 2010–2024 pertaining to the use of treatment processes for CWW.

Collaborating to produce new scientific knowledge is known as research collaboration [57]. There are several types of scientific collaboration, the most prevalent of which is cooperation between authors, institutions, and countries [57]. A network diagram was made for this study in order to determine which countries are more influential and collaborative. Countries are shown in the diagram as labeled nodes, created with VOSviewer, and the links and cooperative efforts among the countries are depicted by the lines connecting the nodes. The degree of collaboration is shown by the thickness of the lines. Furthermore, the number of citations from a country represents the size of each node. Larger labels and nodes are found in countries where authors have authored more articles. Moreover, links between nodes representing the various countries are displayed to denote co-authorship among those countries [58]. The network of worldwide co-authorship countries is depicted in Figure 5, and it was discovered that 17 nations indicated interest in researching CWW treatment methods.

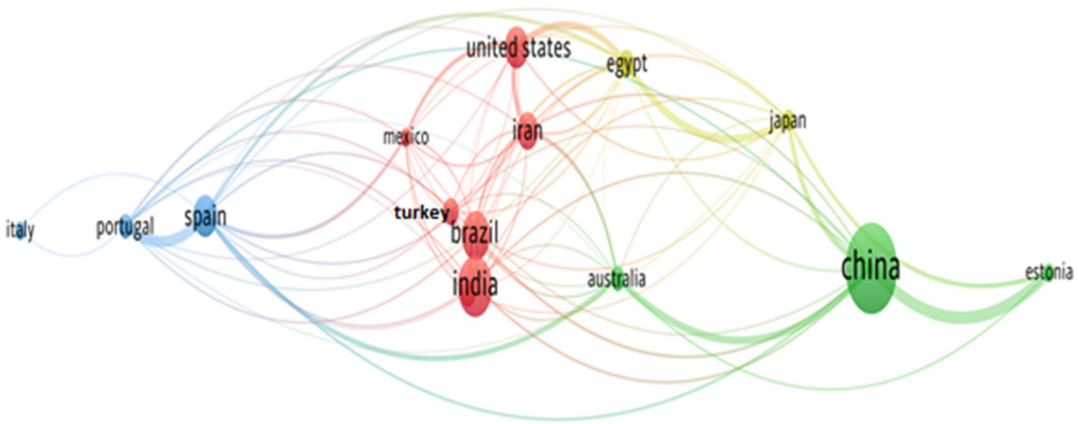


Figure 5. A network visualization showing the major countries involved in the study examining the use of different methods to treat CWW.

Figure 5 displays statistics pertaining to the number of publications within the top seventeen countries. Figure 5 shows that China, India, and Brazil are the top three nations in terms of publications. With 710 citations and a total link strength of 667 (TLS), China was found to be the largest contributor. India came in second with 313 citations and a TLS of 148, and Brazil came in third with 348 citations and a TLS of 166. Together, the three nations contributed around 36.54% of the total documents.

As can be seen in Figure 5, China produced the most publications on CWW treatment methods from 2010 to 2024, according to the Scopus database. Of the 208 papers in this field, 37 were submitted by researchers from China, or 17.79%. Indian scholars, on the other hand, produced 22 publications, or 10.58% of the total. Seventeen publications, or 8.17%, were contributed by researchers from Brazil.

Table 2 lists the top 17 countries according to their TLS. China, Spain, and Brazil are renowned for their significance in collaboration networks at the country level compared to other countries. The Scopus database indicates that these three countries significantly advanced the body of knowledge on CWW treatments. More than 76 articles, 1389 citations, and 981 links were created by these countries.

Table 2. Leading 17 nations in publishing and collaboration on CWW treatment methods from 2010 to 2024 (ranked by TLS).

Country	TLS	Number of Publications	Total Citations	Avg. Pub. Year
China	667	37	710	2020
India	148	22	331	2019
Brazil	166	17	348	2018
Spain	475	14	417	2016
United States	314	14	135	2020
Iran	277	12	183	2019
Egypt	348	8	131	2020
Malaysia	127	8	178	2017
Turkey	64	8	233	2018
Australia	278	7	248	2020
Portugal	332	7	124	2017
Japan	352	6	92	2020
Estonia	393	5	53	2022
Italy	4	5	352	2012
Mexico	145	5	63	2022

3.4. Authors' Co-Citation Networks in CWW Treatment Research

Co-citation network analysis is a useful method for methodically mapping scientific literature since it identifies publications that are often cited and have similar themes [43].

Finding the underlying conceptual framework and themes of a given study topic requires the use of this analytical method. We performed a thorough examination of the authors' co-citation patterns in our study using the VOSviewer software's co-citation network feature. This method allowed us to see how the mentioned works were related to one another and to the themes they covered, giving us a thorough grasp of the state of research in our area of study, as shown in Table 3.

Table 3 displays the involvement of authors depending on the number of documents published, after taking into account a criterion of four or more publications per author. It is important to note that because this method concentrates on authors with a larger number of publications, it can unintentionally enhance the Matthew effect.

Grandjean et al. [59] have called attention to the Matthew effect, which is a phenomenon in which a small number of specialized authors provide a disproportionately large amount of information and attention, whereas a greater number of transient authors produce comparatively fewer articles. This effect suggests that scientific production is distributed unevenly, with some authors becoming more well known and influential in the scientific community, while a broader group of authors may find it difficult to achieve a similar degree of impact. When evaluating bibliometric data, it is critical to be aware of and take these biases into account.

Table 3. Co-occurrence map of researcher collaboration from 2010 to 2024.

Author	Number of Publications
Wei, C.	9
Carvalho, F.	7
Prazeres, A.R.	6
Qiu, G.	6
Rivas, J.	6
Zhu, S.	6
Dadebo, D.	5
Preis, S.	5
Wu, H.	5
Chaudhari, P.K.	4
Fujii, M.	4
Ibrahim, M.G.	4
Mkilima, T.	4
Nasr, M.	4
Patanita, M.	4
Verma, V.	4

In this instance, the analysis found 16 primary authors who authored at least four publications in this area of study. Wei, C., is clearly the most significant author, as seen by the findings displayed in the included Table 3, where she has the greatest number of publications (nine papers). This suggests that Wei, C., is taking more interest in CWW research. Similarly, the second-position author, Carvalho, F., has released seven documents. The first two authors with the highest productivity in this field compose 7.7% of the total. This indicates that the study of CWW treatment methods is a collaborative area involving several authors. These results imply that these two authors have influenced CWW treatment method research in a major way.

3.5. Most Important Conferences and Publications in CWW Research

In scientific mapping, citation analysis is a basic method used to determine the intellectual relationships among publications, especially when one paper is cited in another [43]. This approach facilitates the analysis of citation trends and patterns, in addition to aiding in the identification of the most significant research publications within a certain academic field [60]. In this regard, we performed a citation analysis on the publications. Table 4 lists the top 27 papers, as determined from the Scopus database, that have garnered the most citations. The only criterion utilized to rank these articles is compliance with the Scopus database.

Table 4. The top 27 most-cited articles and conference articles.

First Author	Year	Document Title	Journal	Citations	Ref.
Panizza, M.,	2010	Applicability of Electrochemical Methods to Carwash Wastewaters for Reuse. Part 2: ElectroCoagulation and Anodic Oxidation Integrated Process.	*Journal of Electroanalytical Chemistry*	102	[31]
Lau, W. J.,	2013	Car Wash Industry in Malaysia: Treatment of Car Wash Effluent Using Ultrafiltration and Nanofiltration Membranes.	*Separation and Purification Technology*	81	[61]
Panizza, M.,	2010	Applicability of Electrochemical Methods to Carwash Wastewaters for Reuse. Part 1: Anodic Oxidation with Diamond and Lead Dioxide Anodes.	*Journal of Electroanalytical Chemistry*	78	[62]

Table 4. *Cont.*

First Author	Year	Document Title	Journal	Citations	Ref.
Ganiyu, S. O.,	2018	Electrochemical Advanced Oxidation Processes (EAOPs) as Alternative Treatment Techniques for Carwash Wastewater Reclamation.	*Chemosphere*	76	[27]
Gönder, Z. B.,	2017	Electrochemical Treatment of Carwash Wastewater Using Fe and Al Electrodes: Techno-Economic Analysis and Sludge Characterization.	*Journal of Environmental Management*	75	[16]
Zaneti, R.,	2011	Car Wash Wastewater Reclamation. Full-Scale Application and Upcoming Features.	*Resources, Conservation, and Recycling*	70	[63]
Priya, M.,	2019	Removal of COD, Oil and Grease from Automobile Wash Water Effluent Using Electrocoagulation Technique.	*Microchemical Journal*	69	[64]
Boluarte, I. A. R.,	2016	Reuse of Car Wash Wastewater by Chemical Coagulation and Membrane Bioreactor Treatment Processes.	*International Biodeterioration & Biodegradation*	68	[6]
Bhatti, Z. A.,	2011	Chemical Oxidation of Carwash Industry Wastewater as an Effort to Decrease Water Pollution.	*Physics and Chemistry of the Earth*	62	[65]
Moazzem, S.,	2018	Performance of Ceramic Ultrafiltration and Reverse Osmosis Membranes in Treating Car Wash Wastewater for Reuse.	*Environmental Science and Pollution Research*	40	[66]
Pinto, A. C. S.,	2017	Carwash Wastewater Treatment by Micro- and Ultrafiltration Membranes: Effects of Geometry, Pore Size, Pressure Difference and Feed Flow Rate in Transport Properties.	*Journal of Water Process Engineering*	40	[17]
Mohammadi, M. J.,	2017	Removal of Turbidity and Organic Matter from Car Wash Wastewater by Electrocoagulation Process.	*Desalination and Water Treatment*	38	[67]
Bazrafshan, E.,	2012	Application of Combined Chemical Coagulation and Electrocoagulation Process to Carwash Wastewater Treatment.	*Fresenius Environmental Bulletin*	38	[68]
Gönder, Z. B.,	2020	An Integrated Electrocoagulation–Nanofiltration Process for Carwash Wastewater Reuse.	*Chemosphere*	33	[32]
Kiran, S. A.,	2015	Influence of Bentonite in Polymer Membranes for Effective Treatment of Car Wash Effluent to Protect the Ecosystem.	*Ecotoxicology and Environmental Safety*	32	[69]
Al-Gheethi, A. A.,	2016	Treatment of Wastewater from Car Washes Using Natural Coagulation and Filtration System.	In IOP Conference Series: Materials Science and Engineering	31	[23]
Tony, M. A.,	2021	Performance of Acid Mine Drainage Sludge as an Innovative Catalytic Oxidation Source for Treating Vehicle-Washing Wastewater.	*Journal of Dispersion Science and Technology*	29	[18]
Gönder, Z. B.,	2019	Treatment of Carwash Wastewater by Electrocoagulation Using Ti Electrode: Optimization of the Operating parameters.	*International Journal of Environmental Science and Technology*	29	[26]
Uçar, D.	2018	Membrane Processes for the Reuse of Car Washing Wastewater.	*Journal of Water Reuse and Desalination*	26	[70]
Etchepare, R.,	2015	Application of Flocculation–Flotation Followed by Ozonation in Vehicle Wash Wastewater Treatment/Disinfection and Water Reclamation.	*Desalination and water Treatment*	26	[71]

Table 4. *Cont.*

First Author	Year	Document Title	Journal	Citations	Ref.
Emamjomeh, M. M.,	2019	Carwash Wastewater Treatment by the Application of an Environmentally Friendly Hybrid System: An Experimental Design Approach.	*Desalination and Water Treatment*	26	[72]
Dadebo, D.,	2022	Bio-Coagulation Using Cicer arietinum Combined with Pyrolyzed Residual Sludge-Based Adsorption for Carwash Wastewater Treatment: A Techno-Economic and Sustainable Approach.	*Journal of Water Process Engineering*	19	[73]
Hashim, N. H.,	2016	Pollutants Characterization of Car Wash Wastewater.	In MATEC Web of Conferences	15	[74]
Veréb, G.,	2019	Purification of Real Car Wash Wastewater with Complex Coagulation/Flocculation Methods Using Polyaluminum Chloride, Polyelectrolyte, Clay Mineral and Cationic Surfactant.	*Water Science and Technology*	14	[75]
Istirokhatun, T.,	2015	Treatment of Car Wash Wastewater by UF Membranes.	*In AIP Conference Proceedings*	14	[76]
Moazzem, S.,	2020	Application of Enhanced Membrane Bioreactor (eMBR) for the Reuse of Carwash Wastewater.	*Journal of Environmental Management*	14	[77]
Tajuddin, M. F.,	2020	Optimizing of Heavy Metals Removal from Car Wash Wastewater by Chitosan-Ceramic Beads Using Response Surface Methodology.	*Materials Today: Proceedings*	11	[78]

The top four papers, as determined by a search of the Scopus database, are summarized by the following data: "Applicability of Electrochemical Methods to Carwash Wastewaters for Reuse. Part 2: Electrocoagulation and Anodic Oxidation Integrated Process". With 102 citations in the literature, this is the most referenced paper. This work was published in 2010 in the *Journal of Electroanalytical Chemistry*. In this study, a combination treatment process comprising an EC method using Fe anodes followed by an EO method using boron-doped diamond (BBD) anodes was devised to treat real CWW. It offers insights into the best operating parameters, effectiveness of the energy consumption, and COD removal related to this integrated treatment process. The outcomes show that this combined process, when applying a current of 10 mA cm^{-2}, was responsible for achieving the complete removal of the COD in the CWW, whereby the residual organics originating from the EC were degraded by EO. The EC process reduced pollutants significantly in only 6 min of electrolysis, including the COD, by around 75%. At optimal operating conditions, such as a 2 mA cm^{-2} applied current and a pH of 6.4, the process consumed only 0.14 kWh m^{-3} of energy. For the whole mineralization of the CWW, the electrolysis time and energy consumption were 100 min and 12 kWh m^{-3}, respectively. This top-cited study examines the energy consumption sustainability of EO and EC [31].

With 81 citations, the second most referenced work on in the list is the article titled "Car Wash Industry in Malaysia: Treatment of Car Wash Effluent Using Ultrafiltration and Nanofiltration Membranes", authored by Lau et al. [61] and appearing in *Separation and Purification Technology* in 2013. The aim of this research was to study the feasibility of using membranes to treat CWW. Three types of membrane—nanofiltration (NF) 270, ultrafiltration (UF) PES30 (MWCO 30 kDa), and UF PVDF100 (MWCO 100 kDa)—were used to treat CWW. The process was evaluated by the turbidity, COD, TDS, rejection of conductivity, and permeate flux. Economical methods have also been used to clean the backflushing, using physical cleaning to retrieve the flux. The NF270 membrane outperformed the PVDF100 and PES30 membranes in treating car wash wastewater. NF270 showed higher flux recovery, greater flux stability, and a minimum 92% turbidity removal, indicating higher resistance to fouling. It also achieved the highest COD retention rate (70.9–91.5%) and at least 60% separation of the TDS and conductivity, significantly better than the UF membranes. The NF270 membrane's pollutant separation capabilities and stable water production make it a suitable and environmentally sustainable option for CWW treatment, providing the possibility of reusing treated CWW in the same industry [61].

The third most referenced paper was published by the same author as the first, Panizza, M., in "*Journal of Electroanalytical Chemistry*", with the title "Applicability of Electrochemical Methods to Carwash Wastewaters for Reuse. Part 1: Anodic Oxidation with Diamond and Lead Dioxide Anodes", which has been cited 78 times. This study differs from the previous study [31] in that a single treatment process (EO) was used to treat real CWW. Also, the lead dioxide (PbO_2) and BDD anodes were used to evaluate the effectiveness of this process in reducing COD. When it comes to anode performance, the BDD always outperformed PbO_2, needing less time for electrolysis to attain total mineralization. This resulted in a notably lower specific energy consumption and greater current efficiency, which were 375 kWh m^{-3} for BDD and 770 kWh m^{-3} for PbO_2 [62].

The fourth top-cited study has received 76 citations. The paper titled "Electrochemical Advanced Oxidation Processes (EAOPs) as Alternative Treatment Techniques for Carwash Wastewater Reclamation" was authored by Ganiyu et al. [27] and appeared in *Chemosphere* in 2018. The study investigated the complete removal of COD and anionic surfactants from real CWW using the following three electrochemical advanced oxidation processes (EAOPs): electro-Fenton process (EF), EO with hydrogen peroxide generation (EO-H_2O_2), and EO. The EAOPs were performed using a carbon-felt cathode and a boron-doped anode. The results show that the COD removal efficiency increased with a higher applied current, achieving complete organic matter degradation at $\geq$500 mA after 6 h for all processes. The EF treatment process demonstrated faster and higher COD decay compared to EO or EO-H_2O_2 across all electrolysis times and currents. Complete degradation of the major organic content (i.e., anionic surfactants) was achieved with all processes. EF had a higher current efficiency and lower energy consumption than EO-H_2O_2. Overall, the electrochemical treatments were effective for the complete remediation of organic matter in CWW, enabling potential reuse [27].

Table 4 shows that the employment of inexpensive, easily operated, and ecologically friendly treatment methods has been the main emphasis of the top 27 top referenced papers in the field of CWW treatment [26]. These works have explored a range of treatment methods, including catalytic oxidation [18], AOPs [62], EC [64], membranes [70], and combined treatment processes [66,73]. Most of the highly referenced studies placed significant attention on the reduction of certain contaminants in CWW. These contaminants include anionic surfactants [27], COD [62], turbidity [67], and oil and grease [64]. The aim of the studies was to develop efficient treatment plans that would lower the pollutants' concentrations [64]. While a lot of attention has been paid to experimental research, there has been limited study of modeling strategies for the treatment of CWW. In addition to aiding in the optimization and design of treatment methods, modeling can provide insightful information on the behavior of contaminants and help in the optimization and design of treatment methods. Nevertheless, modeling approaches have only been used in a small number of studies to comprehend and forecast CWW treatment system performance.

In conclusion, even if the highly cited research in the field of CWW treatment has made important contributions, some areas—like the application of biological treatment methods and modeling approaches—still need more focus. These domains provide opportunities for forthcoming research and inventiveness in the realm of CWW treatment.

3.6. Primary Research Areas of the CWW Treatment Research

The keywords used in scientific research provide an overview of the research that was conducted. Important knowledge of an article's main topic may be gained by analyzing these keywords, and it also helps to identify areas that need more research. The expected relationship between the chosen keywords gives birth to this anticipation. This association may be established by looking at the co-occurrence frequency of the terms [79]. It is feasible to identify a coherent body of research that focuses on certain topics and shares similar themes by employing keyword cluster analysis. As such, this technique makes it easier to analyze research patterns [42,80,81].

Using VOSviewer, we performed a keyword co-occurrence analysis of the methods utilized to treat CWW in the scientific papers. The analysis used a complete counting method, by looking at the keyword frequency in 208 conference and article publications in the Scopus database. In the analysis, 42 of these keywords were discovered to co-occur. The network visualization shown in Figure 6 depicts the patterns of keyword co-occurrence in studies that highlight the CWW treatment processes.

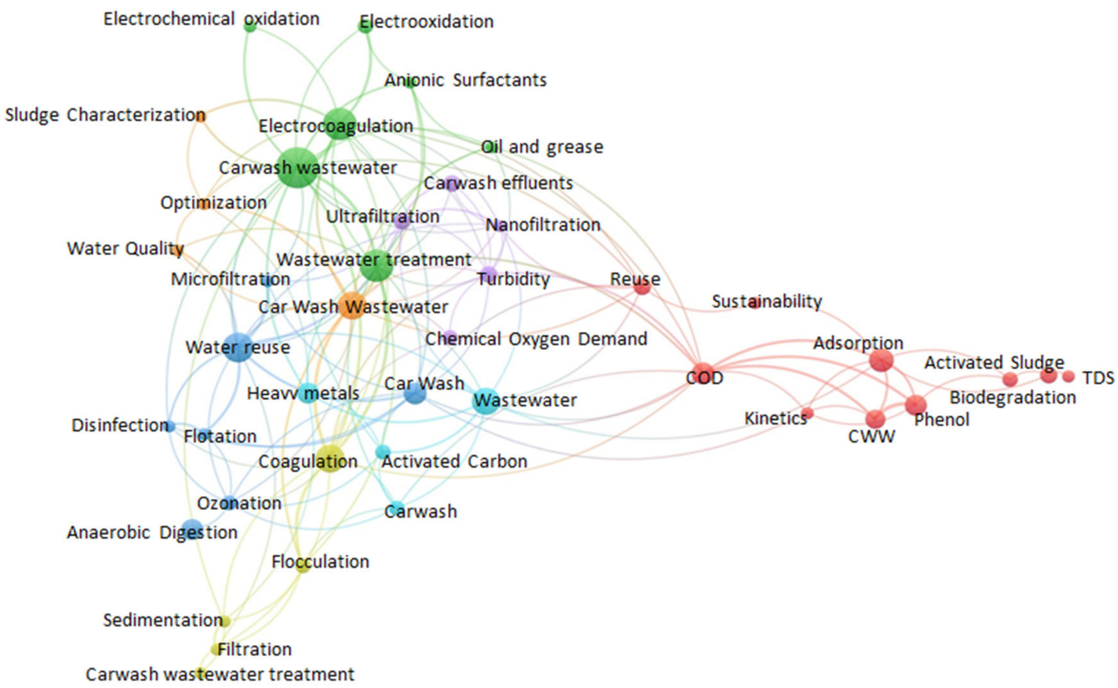


Figure 6. Co-occurrence clustering of author keywords in a network visualization.

The co-occurrence patterns of the keywords, as nodes, are shown in Figure 6. Seven clusters were found in the keyword co-occurrence network map. The varying hues of the clusters show their commonalities within the subject of research. Each cluster, which is made up of nodes with distinct colors, stands for a distinct field of CWW treatment research. Greater relationships between keywords are shown by thicker connecting lines, whereas larger nodes show higher occurrence frequencies. The top 42 keywords are included in Table 5, with the terms listed in descending order of occurrence. A thorough scientific study is used to establish the ranking of these keywords, taking into account variables like the frequency of their occurrence, the quantity of links pointing to each keyword, and the cumulative link strength. "Carwash wastewater" is the most frequently utilized author keyword.

The most well-known characteristics of CWW treatment methods include "organic matter reduction", "chemical treatment methods", "physical treatment methods", "biological treatment methods", and "CWW reuse", all of which were included in the top 15 keywords. The keyword "carwash wastewater" exhibits the highest TLS, bearing 33, while the keyword "water reuse" follows with 25, "coagulation" with 25, and "electrocoagulation" demonstrates 24. The keywords "carwash wastewater" and "electrocoagulation" reveal the intellectual origins of CWW treatment methods.

Table 5. Top 42 keywords from the studied papers on CWW treatment (sorted by frequency of occurrence).

Keyword	Cluster	TLS	Occurrence	% Occurrence	Avg. Citations
Carwash Wastewater	2	33	23	9.1	24.39
Electrocoagulation	2	24	15	5.91	33.60
Wastewater Treatment	2	23	15	5.91	6.53
Water Reuse	3	25	13	5.12	24.38
Car Wash Wastewater	7	24	12	4.72	23.67
Coagulation	4	25	12	4.72	24.00
Wastewater	6	14	11	4.33	14.55
Adsorption	1	12	9	3.54	6.67
Car Wash	3	17	8	3.15	19.50
COD	1	20	8	3.15	11.50
Anaerobic Digestion	3	1	7	2.76	11.00
Heavy Metals	6	9	7	2.76	13.43
Phenol	1	12	7	2.76	22.00
TDS	1	11	6	2.36	24.50
Activated Sludge	1	3	5	1.97	38.40
Carwash effluents	5	6	5	1.97	41.00
Reuse	1	7	5	1.97	15.60
Turbidity	5	13	5	1.97	36.80
Ultrafiltration	5	13	5	1.97	35.80
Activated Carbon	6	7	4	1.57	14.75
Biodegradation	1	3	4	1.57	13.50
Carwash	6	7	4	1.57	1.75
Chemical Oxygen Demand	5	3	4	1.57	26.75
Electrooxidation	2	5	4	1.57	31.00
Flocculation	4	10	4	1.57	21.25
Ozonation	3	9	4	1.57	25.00
Anionic Surfactants	2	7	3	1.18	35.00
Carwash Wastewater Treatment	4	2	3	1.18	15.00
Disinfection	3	8	3	1.18	36.00
Electrochemical Oxidation	2	3	3	1.18	65.00
Filtration	4	6	3	1.18	24.00
Flotation	3	8	3	1.18	42.67
Kinetics	1	5	3	1.18	10.67
CWW	1	1	3	1.18	35.67
Microfiltration	3	6	3	1.18	18.00
Nanofiltration	5	10	3	1.18	46.67
Oil and Grease	2	6	3	1.18	7.00
Optimization	7	7	3	1.18	14.33
Sedimentation	4	7	3	1.18	20.67
Sludge Characterization	7	5	3	1.18	44.00
Sustainability	1	2	3	1.18	2.67
Water Quality	7	5	3	1.18	2.67

Figure 6 and Table 5 illustrate the top 15 keywords in the Scopus database, which are as follows: "car wash wastewater" (9.1%), "electrocoagulation" (5.91%), "wastewater treatment" (5.91%), "water reuse" (5.12%), "car wash wastewater" (4.72%), "coagulation" (4.72%), "wastewater" (4.33%), "adsorption" (3.54%), "car wash" (3.15%), "COD" (3.15%), "anaerobic digestion" (2.76%), "heavy metals" (2.76%), "phenol" (2.76%), "TDS" (2.36%), and "activated sludge" (1.97%). These top 15 most-utilized keywords reflect the abundance of literature on the development of EC, coagulation, adsorption, anaerobic digestion, and activated sludge into an economic and effective method for COD, heavy metals, phenol, and TDS removal from CWW.

Seven large groups, or clusters, are visible on the network map used in this research, as shown in Figure 6. In other words, cluster 1 in this study's network diagram, which is highlighted in red, stands for "the utilization of physical and biological treatment processes to reduce pollutants for sustainable wastewater reclamation in CWW". Cluster 2, which is symbolized by green, focused on "electrochemical processes for CWW treatment: removing anionic surfactants and oil and grease". Cluster 3, which is colored blue, represents "a comprehensive approach to sustainable CWW reuse: electrochemical, biological, and membrane filtration processes". Cluster 4, denoted by yellow, concentrates on the "physiochemical process for efficient CWW treatment". Cluster 5, represented by purple, concentrates on "the application of the filtration treatment processes for CWW". Cluster 6, which is symbolized by the color light blue, is dedicated to the "removal of heavy metals from CWW using activated carbon adsorption". Cluster 7, represented by orange, is dedicated to "enhancing CWW management through optimization, sludge characterization, and water quality assessment".

Among these clusters, cluster 1 focuses on the comprehensive treatment and sustainable reclamation of CWW through physical and biological processes. At the core of this domain is the employment of adsorption processes to effectively remove a range of pollutants from CWW, such as COD, phenol, and TDS. Alongside adsorption, biological treatment processes, including activated sludge, have been extensively investigated for their ability to biodegrade and mineralize the organic contaminants present in CWW, enhancing the overall treatability and sustainability of wastewater management strategies. Furthermore, the kinetics of these treatment processes, which describe the rate and efficiency of pollutant removal, have been studied to optimize the performance of the CWW treatment processes. Understanding the kinetic behavior of the adsorption and activated sludge processes can lead to the development of more efficient and cost-effective treatment strategies. The aim of this research cluster is to enable the reuse of CWW, fostering the development of more sustainable water management practices that can be implemented in various applications.

In cluster 2, keywords such as "carwash wastewater", "electrocoagulation", "wastewater treatment", "electrooxidation", "anionic surfactants", "electrochemical oxidation", and "oil and grease" are interconnected. This cluster focuses on the application of advanced electrochemical methods for the treatment of CWW. At the core of this cluster is the utilization of EC, a process that employs electrochemically generated coagulants to effectively destabilize and aggregate the suspended contaminants present in CWW, with a particular focus on the removal of anionic surfactants. Complementing the EC approach, the cluster also explores the use of EO and electrochemical oxidation methods, which leverage the application of electrical current to drive redox reactions, causing organic contaminants to deteriorate and turn into minerals, such as oil and grease compounds.

Cluster 3 presents a comprehensive approach to sustainable CWW reuse that utilizes electrochemical, biological, and membrane filtration processes. At the core of this cluster is the emphasis on water reuse, whereby researchers explore ways to recover CWW for diverse applications, including car washing. The cluster leverages a strategic mix of treatment technologies, such as electrocoagulation and electrooxidation, to remove contaminants, complemented by biological methods like anaerobic digestion. Underpinning this holistic approach are membrane filtration techniques, including microfiltration, which enable efficient separation and purification of the CWW. Additional processes, such as ozonation and flotation, further enhance disinfection and pollutant removal, ensuring the treated water meets the required quality standards for safe reuse.

Cluster 4 focuses on the application of physicochemical processes for the efficient treatment of CWW. Within this cluster, the keywords include terms such as "coagulation", "flocculation", "carwash wastewater treatment", "filtration", and "sedimentation". Key aspects include coagulation and flocculation to destabilize and aggregate suspended contaminants, as well as the filtration process to separate and concentrate the removed pollutants. Additionally, the cluster addresses the optimization of sedimentation processes to effectively remove the coagulated and flocculated particles.

Cluster 5 is associated with words like "carwash effluents", "turbidity", "ultrafiltration", "chemical oxygen demand", and "nanofiltration". The concentrate of this cluster is on the filtration method. At the heart of this approach are techniques like ultrafiltration (UF) and nanofiltration (NF). UF is investigated for its ability to remove suspended solids, colloids, and high-molecular-weight organic compounds from the CWW, while NF is explored for its selective removal of dissolved salts and smaller organic molecules. By strategically integrating these advanced filtration methods, the cluster aims to address key parameters such as turbidity and COD in the CWW, ensuring the treated water meets the necessary quality standards for safe reuse or discharge.

Cluster 6 is associated with words like “wastewater”, “heavy metals”, “activated carbon”, and “carwash”. The concentration of this cluster is on the use of activated carbon adsorption methods to remove heavy metals from CWW. The focus on activated carbon adsorption suggests that this technique is seen as a promising and potentially efficient method for extracting these metallic contaminants from CWW.

Finally, cluster 7 focuses on enhancing CWW management through optimization, sludge characterization, and water quality assessment. This cluster includes words such as “car wash wastewater”, “optimization”, “sludge characterization”, and “water quality”. By concentrating on these key aspects, researchers in this cluster are working to develop more efficient and sustainable strategies for handling CWW. The optimization efforts aim to enhance the overall effectiveness of treatment methods, while the sludge characterization helps inform better disposal or reuse practices. Importantly, the water quality assessments provide crucial feedback to ensure the treated effluent meets the necessary standards for environmental protection and potential reuse applications. This holistic perspective on CWW management reflects a commitment to advancing the industry’s capabilities in managing this complex wastewater stream.

Based on Table 5, the most commonly used treatment methods for CWW during the period from 2010 to 2024 were EC, adsorption, anaerobic digestion, activated sludge, UF, activated carbon, oxidation, flocculation, ozonation, filtration, flotation, microfiltration (MF), nanofiltration (NF), and sedimentation. A variety of treatment methods have been developed to handle CWW, each with its own benefits and drawbacks, and the choice of technology will depend on factors like treatment efficiency, operational complexity, energy consumption, and cost.

The EC method utilizes the electrochemical dissolution of sacrificial anodes upon application of a direct current. This generates metal hydroxide species that effectively destabilize pollutants by neutralizing their electrostatic charges. The destabilized particles then aggregate to form flocs, which simultaneously float through the electroflotation mechanism facilitated by hydrogen gas generation at the cathode [26,64]. EC is one of the most promising techniques, which can result in an excellent removal efficiency of contaminants [26]. The main advantages of EC are that it demonstrates effective removal of COD and O&G from CWW, enhances the filterability of the treated CWW solution, operates without the need for additional chemical reagents, generates a more stable and decreased amount of sludge, can be reused as a soil additive, and has relatively low operating and capital costs, ranging from (0.3–0.812) USD/m^3 of treated CWW [16,67]. However, a general drawback of EC is electrode passivation, because it may result in the formation of toxic byproducts and requires frequent electrode replacement [10,11].

The C/F method shares the same underlying principle as EC treatment, where the destabilization of pollutants and the aggregation of flocs are central to the removal mechanism. However, the C/F method relies on the addition of chemical coagulants and flocculants, while the EC treatment generates the destabilizing metal hydroxide species electrochemically through the dissolution of sacrificial anodes under an applied current. Both methods ultimately lead to the aggregation of destabilized particles into settleable or floatable flocs. The main advantage of C/F is the effective removal of suspended solids [11,68]. However, a general drawback of C/F is that it requires the addition of chemicals, which may have an impact on the costs and generate a significant amount of sludge [11,68].

Advanced oxidation processes (AOPs), such as EF and EO, have been extensively studied for the treatment of CWW. These methods are highly versatile and efficient, often requiring minimal or no chemical addition to produce oxidants, making them environmentally friendly methods, but may lead to the formation of harmful byproducts and require precise control of operational parameters. In EF and EO, the oxidation of organic compounds is primarily driven by the mediation of hydroxyl radicals (-OH), which can react in a nonselective manner with organic molecules, leading to their oxidation until a high degree of mineralization is achieved [27]. The main limitations of EF and EO methods for wastewater treatment include their high energy consumption, which can be a significant operating cost. Additionally, electrode fouling and deactivation over time can reduce the efficiency of these systems, requiring periodic maintenance [27].

Adsorption is effective in removing a wide range of organic and inorganic pollutants but is characterized by high capital and operating costs. Disposing of the spent adsorbent material can also be a challenge [8,10,73]. Activated carbon adsorption is the oldest adsorbents utilized. However, its usage is occasionally limited due to its expensive cost [82]. One of the most reliable forms of energy recovery, biogas recovery, as a byproduct of anaerobic digestion, has the potential to be achieved, but it has to be left for extended periods of time and is unstable in the atmosphere [24]. In contrast, activated sludge produces a substantial amount of extra sludge and has a large footprint for the treatment system in order to remove a wide range of organic contaminants [24]. Finally, the filtration method is effective in removing O&G and suspended solids using porous media but has limited ability to remove dissolved contaminants, can cause filter clogging, and is prone to membrane fouling [22,23]. Membrane methods, such as MF and NF, can remove a wide range of contaminants but are energy-intensive and prone to fouling [61,66].

4. Conclusions

The main aim of this study was to perform a bibliometric analysis of research on the treatment processes for CWW. VOSviewer bibliometric software was used to assess 208 articles and conference articles that were filtered from the Scopus database to meet the objectives of this study. Important new directions in the study of CWW treatment methods have been revealed by this publication. According to the analysis, around 55.77% of research publications on CWW treatment processes have been published in the last five years. The results from the analysis indicate that over the last ten years, there has been a rise in the interest in CWW treatment processes, reaching the maximal value in 2020 and 2023 with 28 publications each year.

It has been demonstrated that the scientific community is very well acquainted with the rise of CWW, which will lead to the development of novel treatment methods. According to the study's findings, the most significant journal for CWW treatment processes research is *Water Science and Technology*. Most of the research in this field is conducted in the following subject areas: environmental science, engineering, among others (31.4% and 32.07%), in that order. China, India, and Brazil made significant contributions to the study of CWW treatment processes (17.79%, 10.58%, and 8.17%, respectively).

The CWW treatment process article keywords were examined utilizing clustering and co-occurrence analysis. The author's keywords were helpful in identifying fresh, pressing issues and insightful study patterns. The most used keywords in this field are "carwash wastewater", "electrocoagulation", "wastewater treatment", "water reuse", and "coagulation". These keywords properly represent the principal direction of study in this field. The most popular study topics include pollutants, such as COD, heavy metals, phenol, TDS, and turbidity.

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