

A Bibliometric Analysis on Water Footprint in Industry: Global Research Trends and Mapping of Scientific Networks

Elif Simsek-Yesil^{1*} , Emrah Ozturk² , Mehmet Kitis³ 

Abstract: This study aims to reveal the development and intellectual structure of global scientific production on the water footprint in industry through bibliometric methods. A total of 3,052 research and review articles published up to 22.12.2025 and indexed in the Web of Science Core Collection database were included in the analysis. Publication trends, citation performance, and scientific collaboration structures were evaluated using performance analysis and science mapping approaches. Co-authorship, co-citation, keyword co-occurrence, and bibliographic coupling analyses were visualized using VOSviewer software. The findings indicate that literature on industrial water footprint has seen an increase since 2020 with its highest number of publications anticipated for the year 2025 at about 485 articles based on current trends. This growth reflects the increasing recognition of water footprint assessment as a key instrument for cleaner production, resource efficiency, and sustainable industrial water management. Keyword analyses reveal that research is largely concentrated around the concepts of water footprint, life cycle assessment, and wastewater treatment. Citation and network analyses show that certain methodological references-particularly the works of Hoekstra and Mekonnen-form the intellectual backbone of the literature. In addition, publications are predominantly focused on environmental sciences and engineering while economic and managerial approaches remain limited. Overall this study provides a systematic framework for literature by identifying main trends gaps and future research priorities in industrial water footprint research.

Keywords: Bibliometric Analysis, Cleaner Production, Industry, VOSviewer, Water Footprint, Web of Science.

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1. Introduction

Global demand for water is escalating rapidly, driven by population growth, industrial activities, and the expanding production of food, which has resulted in acute scarcity of freshwater resources. The rate at which water is consumed for domestic and industrial purposes is increasing at a much higher rate than agricultural water demand (Ashok et al., 2017; Boretti and Rosa, 2019). About 9% of the total freshwater available across the globe is utilized by industries (Kumar et al., 2021). This scenario leads to major environmental concerns such as water scarcity and pollution due to wastewater discharge (Lellis et al., 2019). According to a report from the United Nations in 2018, in 2010 there were already 1.9 billion people living in areas with water scarcity which could rise to between 2.7-3.2 billion by the year 2050 (UN, 2018). The Water Footprint (WF) has gained recognition as an effective tool for assessing environmental impacts related to water use over time. It was first introduced in 2002 and comprises three components: green, blue, and grey WFs. The definition of grey WF according to (Hoekstra et al., 2011) is that it requires freshwater dilution of pollutants until acceptable levels are achieved in the receiving environment. This indicator may also be used for evaluating pressure exerted through polluted wastewater discharge into a receiving environment (Arastou et al., 2024). Blue WF refers to surface freshwater withdrawal from lakes, rivers, reservoirs as well as groundwater withdrawal from aquifers (McLellan et al., 2014). The blue WF does not return used water back into any system or cycle (Hoekstra et al., 2011). Green WF indicates consumption of rainwater temporarily stored either in soil or vegetation (Franke and Mathews, 2013). Publications indicate that the WF methodology has been utilized in several disciplines such as industry (Hoekstra, 2015), WF in agriculture (Jamshidi et al., 2022; Roudbari et al., 2023), domestic wastewater (Stejskalová et al., 2022), groundwater (Yapıcıoğlu and Yesilnacar, 2021) and in WF in aquaculture (Pérez Rincón et al., 2017; Jamshidi, 2019). Integrated assessment of blue, green, and grey water use in an industry sector is significant in the context of sustainable water management and resource efficiency. Thus, in the context of ascertaining the environmental effects and formulating appropriate strategies to manage water efficiently, examining the WF in industrial production is vital.

Industrial production warrants specific attention within WF research because water-related pressures in industrial systems arise not only from direct water withdrawals but also from wastewater generation, pollutant loads, energy–water interactions, and water embedded throughout product supply chains. These characteristics make the industrial sector particularly relevant for linking WF assessment with cleaner production, resource efficiency, process improvement, and managerial decision-making. Moreover, contemporary water-management frameworks increasingly emphasize the need to allocate and manage water effectively across productive economic sectors under growing water-security pressures (UNESCO WWAP, 2024). Therefore, examining industrial WF as a distinct research domain provides an opportunity to evaluate how water-related environmental knowledge has evolved at the intersection of

environmental assessment, production systems, and industrial sustainability (Hoekstra, 2015; Arastou et al., 2024).

The distribution and critical appraisal of prior research is an indispensable component of the growing body of scientific knowledge. However, the traditional literature reviews may be subjected to some bias due to the absence of a clearly articulated methodology (Shea et al., 2002). In contrast, García-Peñalvo (2022) and Brignardello-Petersen et al. (2024) argue that systematic literature reviews yield dependable and more objective outcomes from the selection, evaluation, and reporting of studies based on predefined criteria. Systematic literature reviews and bibliometric analyses, when paired together, help identify patterns of publications, the state of science, impact of science, and research voids (Zupic and Čater, 2015; Donthu et al., 2021). Also, semantic and thematic analyses help in capturing the literature more comprehensively by illuminating the conceptual structure of the domain (Braun and Clarke, 2006; Flick, 2018). Most of the current systematic literature reviews on WF cite studies that are restricted to particular sectors, regions, or time frames, and very few are based on bibliometric studies (Guzmán-Dimas et al., 2025). Despite the growing body of WF research, comprehensive bibliometric assessments focusing specifically on the industrial domain remain limited. In particular, there is a need for studies that jointly examine the methodological, thematic, structural, and interdisciplinary development of industrial WF research.

This study intends to analyze scientific output in the area of industrial WF through a broad and integrated perspective, revealing the intellectual structure, development dynamics, and research trends of the literature. In this framework, 3,052 scientific publications indexed in the Web of Science (WoS) Core Collection database were subjected to bibliometric methods analysis. By jointly applying performance analysis and science mapping approaches global publication trends as well as prominent countries, institutions, and researchers were identified while collaboration networks and thematic clusters were visualized with VOSviewer software. Since most existing studies in the literature are confined to particular sectors or periods or only quantitative bibliometric indicators, this research provides an original contribution by treating the industrial WF field concerning its methodological thematic as well as structural dimensions. Also, beyond technical WF calculations, it brings out interdisciplinary gaps in literature especially underrepresentation of economic managerial and policy-oriented approaches. In this respect, this study has sought to provide an evidence-based systematic reference framework for future academic studies policy development processes as well as industrial sustainability strategies.

2. Material and Method

In this study, a bibliometric approach was adopted to reveal the current state, developmental trends, and scientific collaboration structures of scholarly research conducted on the WF in industry. The applied methodology is based on a three-stage framework consisting of data collection, analysis, and evaluation.

2.1. Data Collection

The process of collecting data involves four major steps: choosing the database, figuring out the search words, applying filters, and getting the final dataset. Picking which database to use is very important for making sure the results of the analysis are correct. Even though some studies recommend using more than one database together, this method usually causes more duplicate records and makes the results less consistent. For this reason, in this article, scientific publication data were obtained from a single data source, the WoS Core Collection database. WoS is one of the most frequently preferred sources in international literature due to its comprehensive indexing structure and reliable citation data.

To identify publications related to industrial water footprint research, the Web of Science Core Collection database was searched on 22 December 2025 using the search term “Industrial Water Footprint.” No Boolean operators or additional keyword variants were used in the search strategy. The initial search yielded 3,259 records. The retrieved records were subsequently screened according to language and document type. Publications not written in English, conference proceedings, book chapters, and other document types outside the scope of the study were excluded, while research articles and review articles were retained. Following the filtering process, 3,052 publications constituted the final dataset for bibliometric analysis. The bibliographic records were exported in the “Full Record and Cited References” format for subsequent analysis. Figure 1 presents the selection criteria applied to construct the final bibliometric dataset.

2.2. Data Analysis

Two types of analyses were used during the data analysis process to show the developmental trends of the literature and the structures of scientific networks: performance analysis and science mapping. The aim of performance analysis is to evaluate quantitative indicators, such as annual distribution of publications, most productive authors, countries, institutions, and journals. Within this framework, highly cited studies, citation trends, and high-impact research outputs in the field are also examined. Through performance analysis, it was possible to determine the level of scientific production on WF in industry and its development trajectory over time. Science mapping consists of mapping techniques that visualize relationships within a research field. In this study, co-authorship analysis, keyword co-occurrence analysis, and co-citation analysis were performed in order to find out prominent thematic areas as well as research clusters and collaboration structures in industrial WF literature. Analyses were undertaken using different software tools: basic statistical evaluations were done using Microsoft Excel; conceptual networks were visualized with VOSviewer.

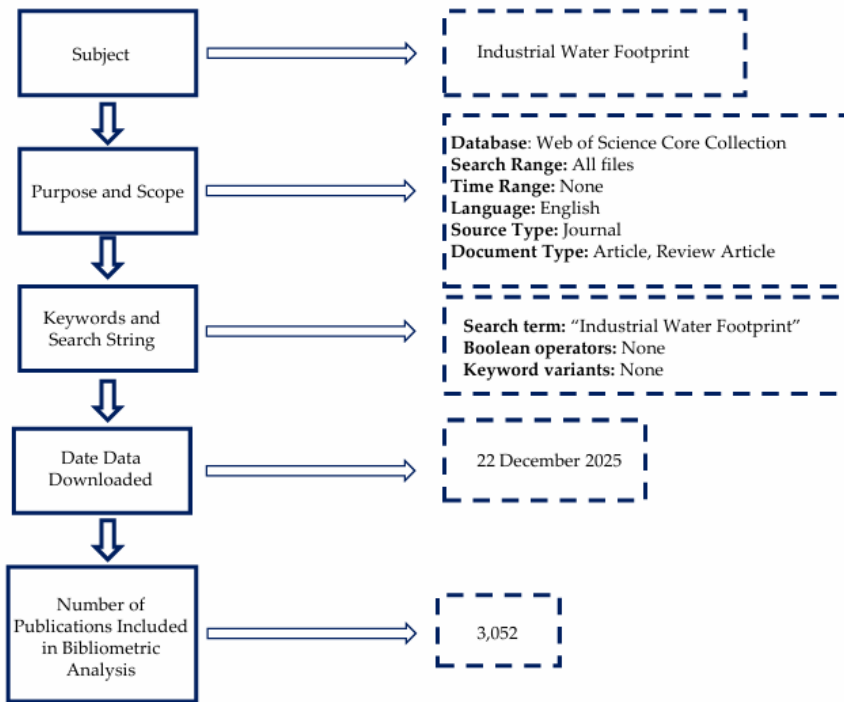


Figure 1. Selection criteria for studies included in the bibliometric analysis

2.3. Scientific Review

At the third step, the results obtained from bibliometric analyses were reviewed together, and a scientific review was conducted to assess the current state of industrial WF literature. It has three main parts: reviewing major findings, discussing problems that exist, and highlighting future research needs. This integrated assessment not only shows what is happening now in studies about industrial industrial WF research but also helps in determining general conclusions for the article.

3. Results

3.1. Data Sources of the Research

This study applies the bibliometric analysis method to examine scientific publications concerning the WF within the industry. The records related to the WF in industry from the WoS Core Collection database are classified by document types, which is illustrated in Figure 2. A search in the WoS Core Collection database for the analysis resulted in a total of 3,259 records. The publications reviewed span all years and consist of works from various fields.

Most of the examined papers consist of research articles (2,701), while the following articles are less common, including review articles (351) and proceedings papers (247). Editorial materials (14), letters (5), and retracted articles (2) concerns (1), data papers (1), and other papers are present at little except for book chapters (40) and early access articles (39) which are scarce. The distribution of articles in terms of the WoS indexes shows that the majority of studies are referenced in the indices of SCI/SCIE, SSCI, and

ESCI. This demonstrates that the WF in the industry has a considerable amount of scientific attention and an interdisciplinary research scope. The findings show that there has been a significant increase in scholarly attention in the last few years, and the WF has increasingly become a focal point in the studies of sustainability in industry.

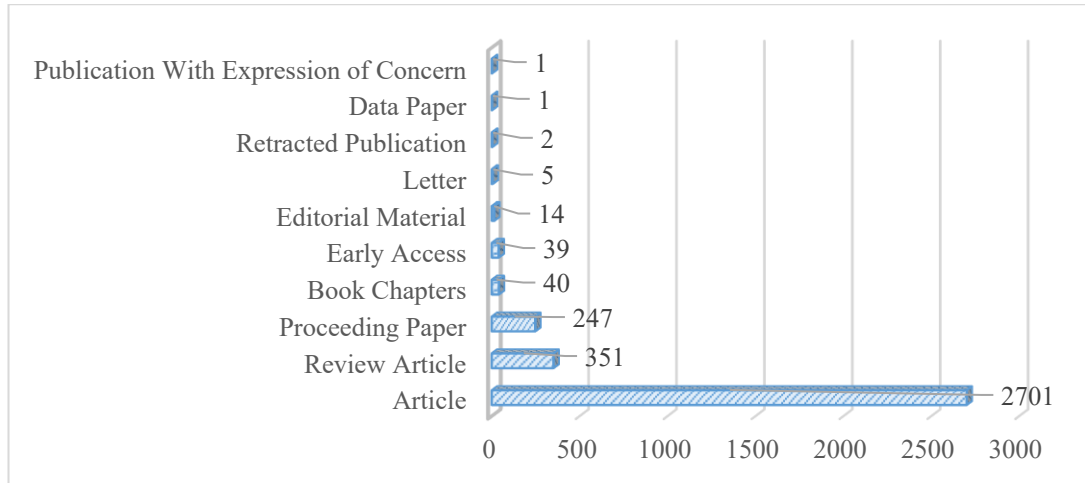


Figure 2. Distribution of publications by document type

Figure 3 shows the distribution of studies published in the area of the industrial WF using a treemap visualization according to WoS research categories. The treemap very well shows which disciplines are quantitatively more significant in the literature and how much weight different research areas have relatively.

It can be seen from the figure that most of the studies fall under categories that relate to environmental sciences, environmental engineering, and water resources. This suggests that WF is mainly discussed within the frame of context for environmental sustainability, pollution management, and resource efficiency. However, other fields such as chemical engineering, energy, manufacturing technologies as well as sustainable industrial systems do take up a considerable share too. Such a distribution proves that industrial WF studies do not confine themselves only to assessing environmental impacts but rather integrate with process optimization, energy–water nexus, and cleaner production approaches. More specifically, joint consideration of impacts from industrial processes on both water consumption and pollution loads has helped create an interdisciplinary research structure.

The categories that take up smaller areas in the treemap, like economics, management, policy, and decision support systems, show that socio-economic dimensions and managerial approaches have been very little considered in WF studies up to now. This finding presents a literature that mainly focuses on technical and environmental assessments with no integration of results into industrial decision-making processes or into mechanisms for policy development and economic analyses.

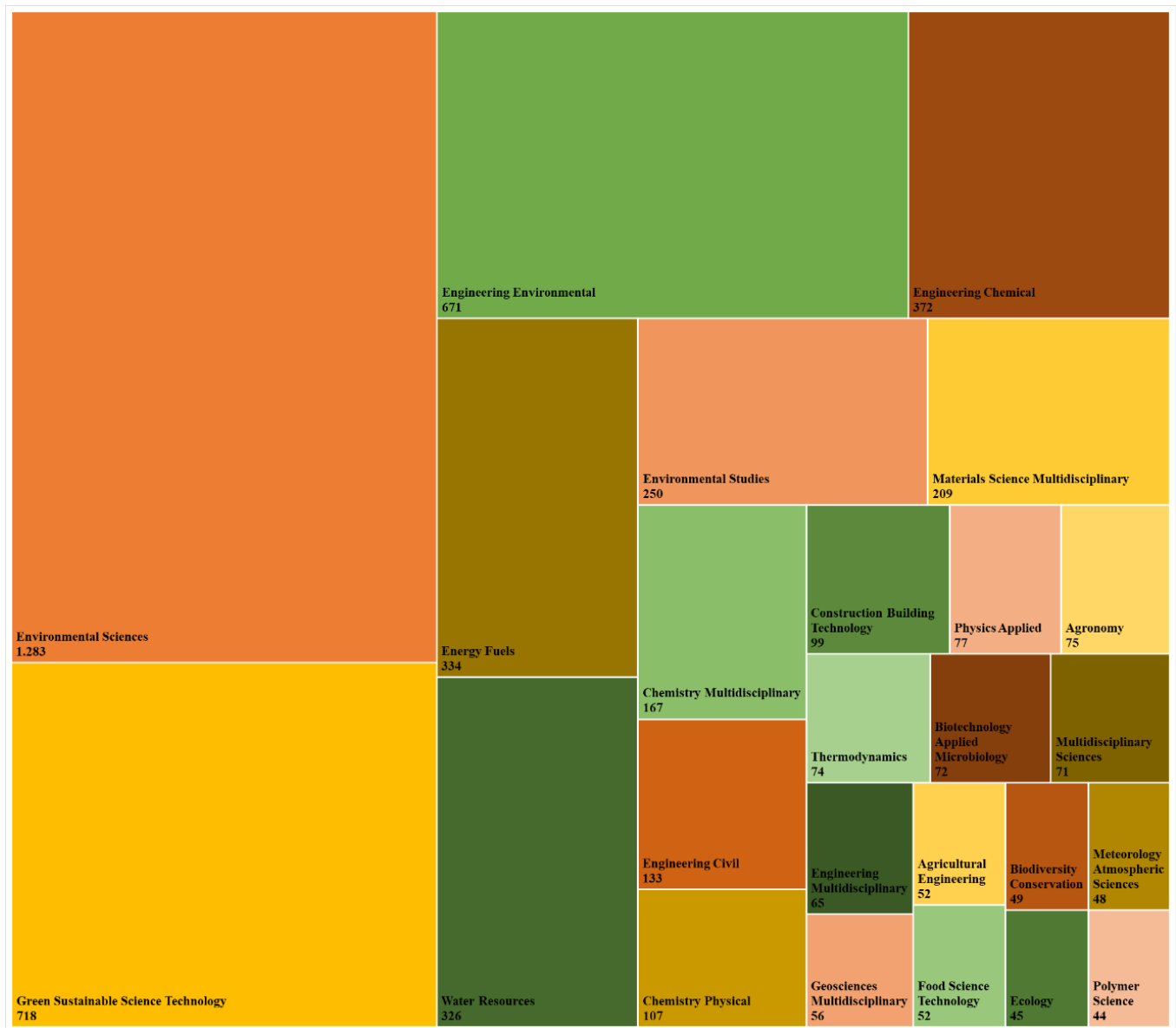


Figure 3. Analysis of publications in terms of WoS categories

Overall, these findings indicate that industrial WF research has been concentrated primarily within the environmental and engineering sciences, while the increasing maturity of the field highlights the need for stronger multidisciplinary approaches.. Future studies that integrate economic, managerial, and policy-oriented analyses with technical industrial WF assessments could enhance both the scientific depth and the practical applicability of the field.

As can be seen in Figure 4, there is an annual distribution of studies that have been published in the area of industrial WF. The number of publications has shown a marked increase especially post-2020. The maximum level for this indicator is reached in 2025 with 485 publications followed by years 2024 (378) and 2023 (326). A relatively small number of publications prior to 2010 coupled with sharp increases over recent years indicates rapidly growing academic interest in the topic.

This publication growth is consistent with the broader trajectory reported by Feng et al. (2024), who identified a substantial expansion of WF research through a bibliometric assessment of international and Chinese literature. However, whereas their analysis addressed the broader WF research domain, the present study demonstrates that a comparable expansion has also occurred specifically within the industrial context. This suggests that the recent growth of WF scholarship is not confined to general water-resource assessment but increasingly extends to production-oriented and sector-specific applications.

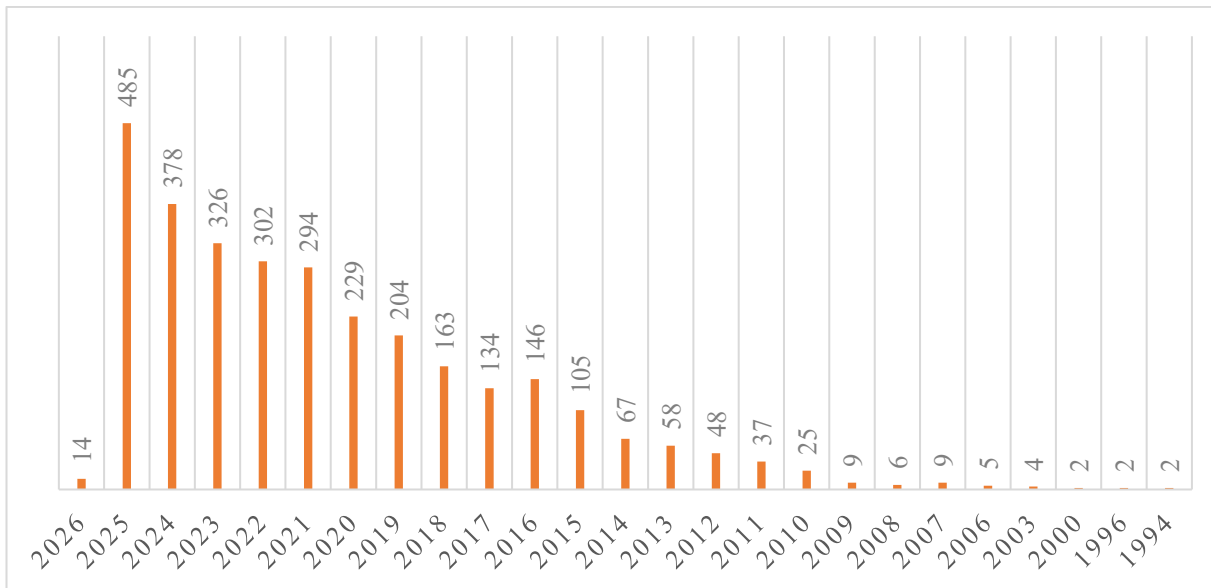


Figure 4. Analysis of publications by year of publication

3.2. Keyword Analysis

Through an analysis of the industrial WF literature's keyword co-occurrence structure using VOSviewer software, it was found that there were a total of 8,691 keywords in the data set. The keyword search included all keywords that had a minimum occurrence threshold of one; thus, at least one of that keyword must have been present/used in the search. As a result, 7,635 of these keywords met the inclusion criteria based on the minimum occurrence threshold established, and were used for the co-occurrence keyword analysis. Additionally, to obtain a more accurate representation of the keyword co-occurrence network, VOSviewer was used to filter the network by retaining only keywords with at least one linkage to another keyword. As a result, isolated keywords without any co-occurrence relationships were excluded from the analysis. The relationship among these keywords and their linkages are presented in the keyword co-occurrence network map in Figure 5.

WF is the most central concept in Figure 5 with the highest frequency of occurrence (290). It also has the highest total link strength (TLS) (TLS=1,279) indicating strong links to other themes of research. Life Cycle Assessment (LCA) is a close second in terms of number of occurrences (257), and has also had the

second-highest TLS (1,232). Therefore, LCA represents a prominent methodological approach in industrial WF research.

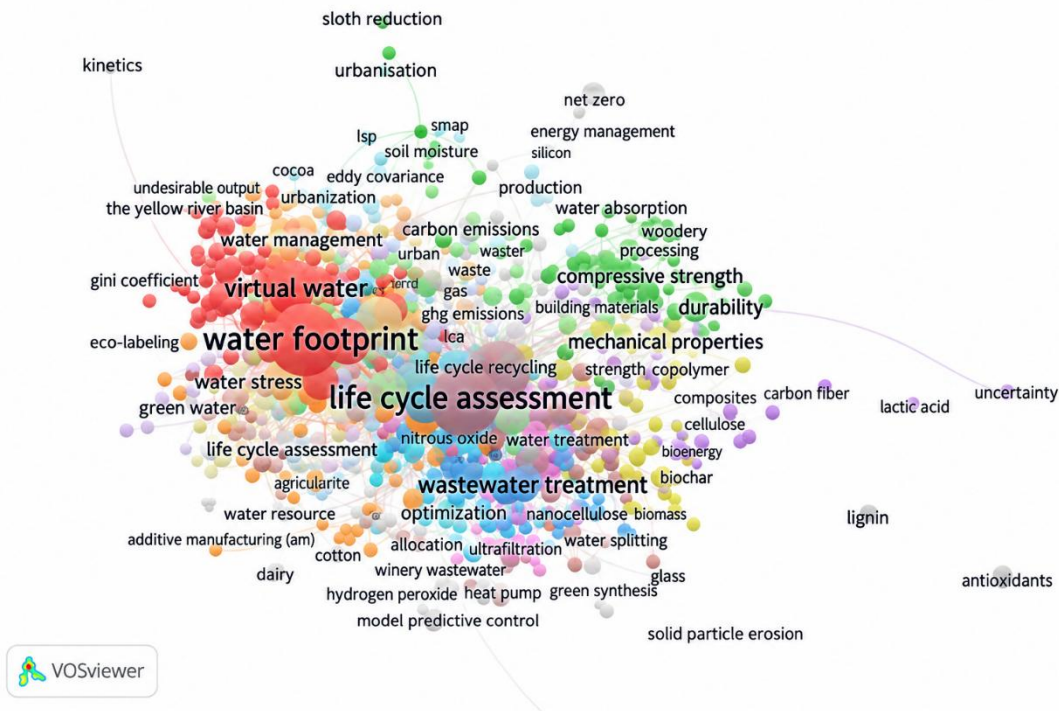


Figure 5. Keyword co-occurrence network map

The abundance of the terms "carbon footprint" (210 occurrences; TLS = 1,038) indicates the continual integration of WF research with more comprehensive evaluations of the environmental performance of organizations, primarily through the use of life cycle-based assessments. Other key terms associated with WF research include sustainability (166 occurrences; TLS = 798), circular economy (81 occurrences; TLS = 385), and industrial ecology (77 occurrences; TLS = 385). These keywords highlight the strong linkage between industrial WF research and the principles of resource efficiency, cleaner production, and a broader systemic approach to sustainability.

Furthermore, climate change (70 mentions; TLS = 387) and Virtual Water (62 mentions; TLS = 261) serve as evidence of a rise in interest towards connecting Industrial WF evaluations with global environmental pressures along with indirect water embedded in trade & supply Chain systems. The keyword China (60 occurrences; TLS = 253) appears as the most prominent geographical focus in industrial WF research. This pattern indicates that a substantial share of the literature concentrates on industrial systems in China, likely due to the scale of Chinese industry, prevailing water stress conditions, and the strong policy relevance of water management issues in the country.

Keywords like water scarcity (51 total occurrences; TLS=228) have lower levels (compared to industry) of associated networks showing that this type of analysis is not fully integrated into the core WF industry based areas of research. Further, the peripheral placement as well as lower strength of associations with

decision support tools; policy frameworks; and economic valuations indicate that the literature is primarily focused on technical and environmental based assessments of WF. This demonstrates an imbalance and, therefore, a significant research gap regarding using WF indicators as a basis to support decision making in the area of both management and water governance jurisdictions.

Beyond the individual occurrence and link-strength values, the network structure in Figure 5 reveals several interconnected thematic concentrations within industrial WF research. One prominent research stream links water footprint with virtual water, water management, water stress, and green water, representing the resource-accounting and water-allocation dimension of the field. A second thematic concentration is organized around life cycle assessment, carbon emissions, greenhouse-gas emissions, recycling, and related sustainability concepts, indicating the increasing integration of water use with broader life-cycle environmental performance assessment. A third stream is associated with wastewater treatment, optimization, ultrafiltration, and water resources, reflecting process-level efforts to reduce water consumption and pollutant loads. The network also contains a production- and materials-oriented dimension represented by terms such as mechanical properties, compressive strength, durability, composites, and geopolymer, illustrating the extension of water-related sustainability assessments into material-intensive industrial applications. Overall, the proximity among these thematic areas suggests that industrial WF research is increasingly connected with life-cycle assessment, cleaner production, circularity, and process optimization rather than functioning as an isolated water-accounting field. Conversely, the comparatively peripheral position of economic valuation, policy, and decision-support concepts indicates that the managerial and institutional integration of WF information remains less developed.

3.3. Co-authorship Analysis

A co-authorship analysis was carried out in this study to explore the scientific collaboration structure of research on the industrial WF. A total of 3,039 authors were considered from publications retrieved from the WoS database for evaluation in the analysis; relationships among those authors who have collaborated at least once in any publication are visualized. The co-authorship network is primarily clustered around specific research groups, as illustrated in Figure 6. An examination of node sizes and connection densities indicates that a limited number of authors occupy central positions within the network, suggesting that industrial WF research is largely driven by a small core group of researchers.

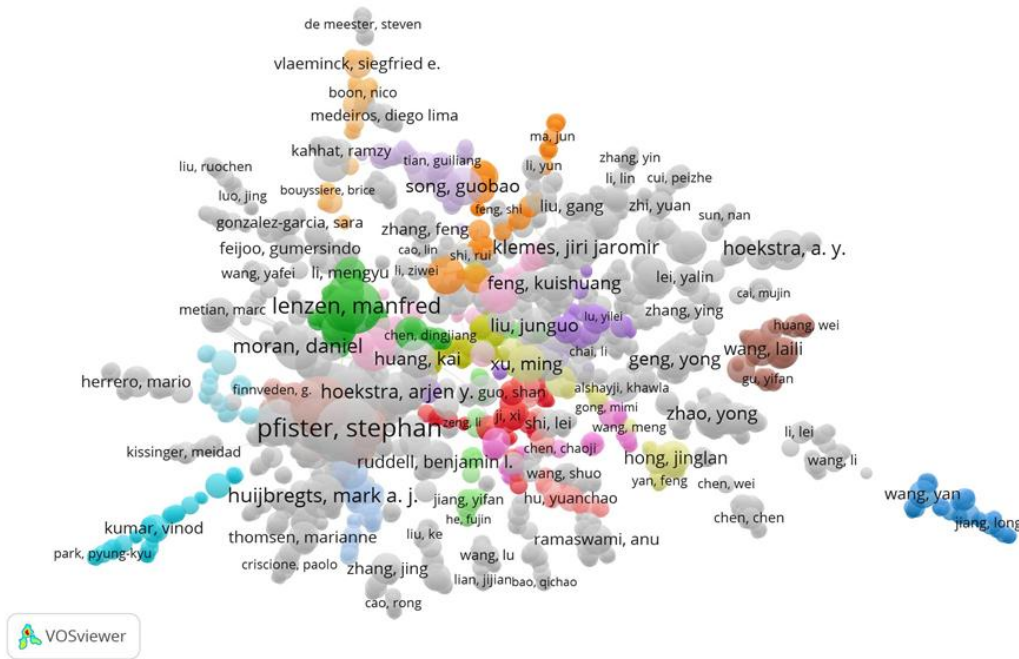


Figure 6. Co-authorship network map

The density of connections in the network shows that collaborations are mostly limited to institution- or country-based research groups. The small number of links between different clusters, however, means that interdisciplinary and international collaborations have not yet developed sufficiently. In particular, some clusters at the periphery of the network indicate that these groups contribute to the literature but are only weakly integrated into the main flow of knowledge. The figure also highlights certain nodes that act as bridges by establishing connections between multiple clusters-these researchers facilitate knowledge transfer between different academic communities and contribute to integrating the literature. However, since there are relatively few such bridging authors, this reveals a fragmented collaboration structure in this field.

In general, results from the co-authorship analysis reveal that core research groups shape industrial WF literature with limited interaction among these groups. This indicates future studies designed with stronger international and interdisciplinary collaborations could significantly enhance scientific development in this field and improve knowledge sharing.

3.4. Authors' Citation Analysis

To show the authors' citation networks, an analysis was carried out using VOSviewer software, where threshold values of at least 1 document and 0 citations were set for each author. Under these conditions, a total of 12,907 authors in the dataset were identified initially. However, to avoid the impact on network structure from those without any citation relationships between them and others, the filtering option provided by this very software was used so that only 4,041 authors with such links could be included in

this analysis. A network map based on those relationships among these people was then created as shown in Figure 7.

The citation network was visualized based on TLS among authors (Figure 8). This approach allows us to assess not just individual citation counts but the intensity of intellectual interactions between authors within the literature. According to the analysis results, the author with the highest TLS is Pfister, Stephan (TLS: 2046), followed by Hoekstra, Arjen Y. (TLS: 1519), Wood, Richard (TLS: 1229), Mekonnen, Mesfin M. (TLS: 1201), and Motoshita, Masaharu (TLS: 1173).

The results show that TLS does not always equate to total citation counts. For example, high citation numbers are attributed to Hoekstra, Arjen Y. and Mekonnen, Mesfin M. (Figure 9), while Pfister, Stephan has a higher TLS—indicating a denser and more central interaction network within the literature. This finding proves that scientific influence in industrial WF literature is determined by both the number of citations and the strength of reciprocal referencing relationships among authors.

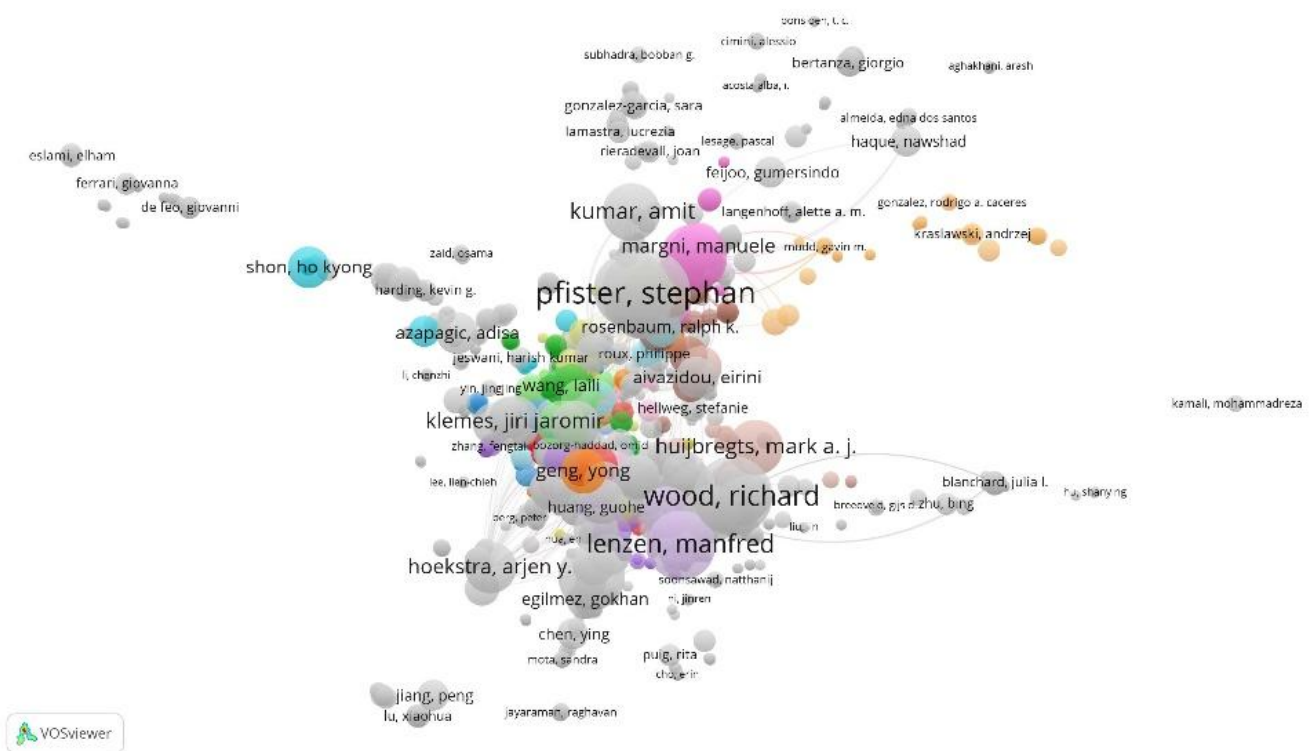


Figure 7. Authors' citation network map

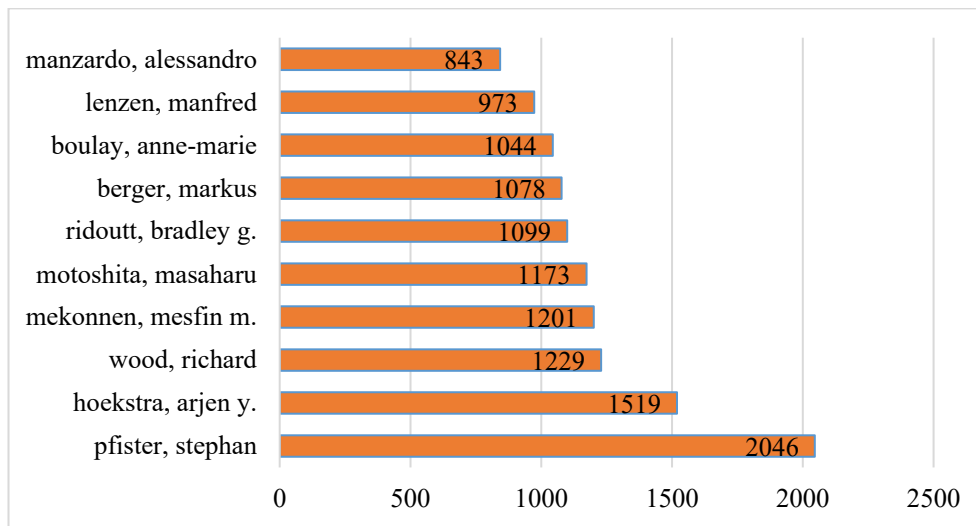


Figure 8. Total link strength among authors

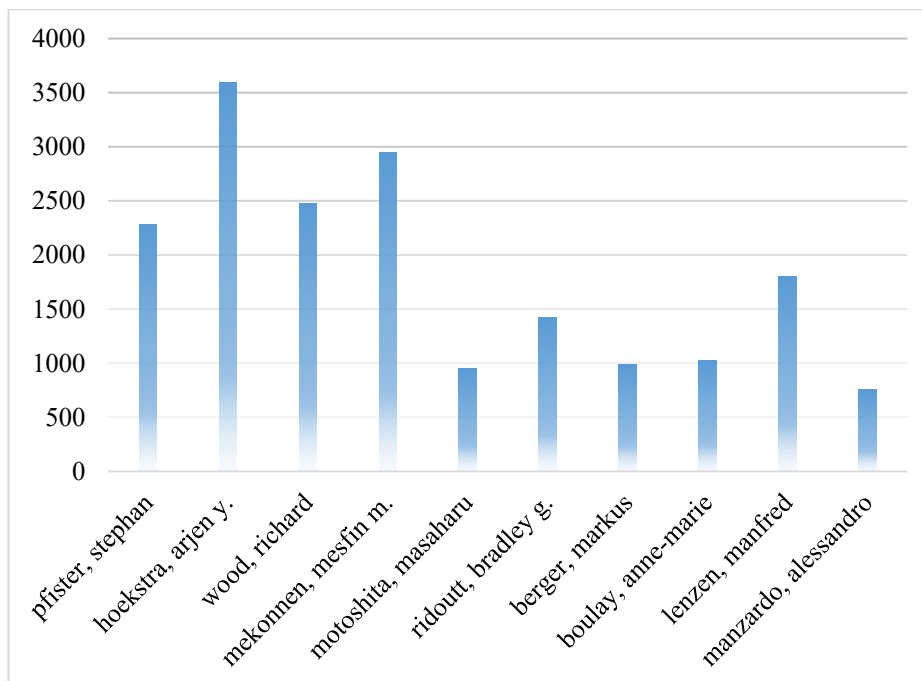


Figure 9. Top ten authors by citation counts

3.5. Citation Analysis of Documents

A VOSviewer analysis was done to examine the citation networks of documents with an initial threshold of one document per document. Using this threshold, a total of 2,724 documents were included in the analysis based on the total of 3,052 articles in the dataset. Documents that did not have any citation connections were removed from the network, using VOSviewer's filter options. Thus, the constructed citation network used only 989 documents which had citation connections (Figure 10).

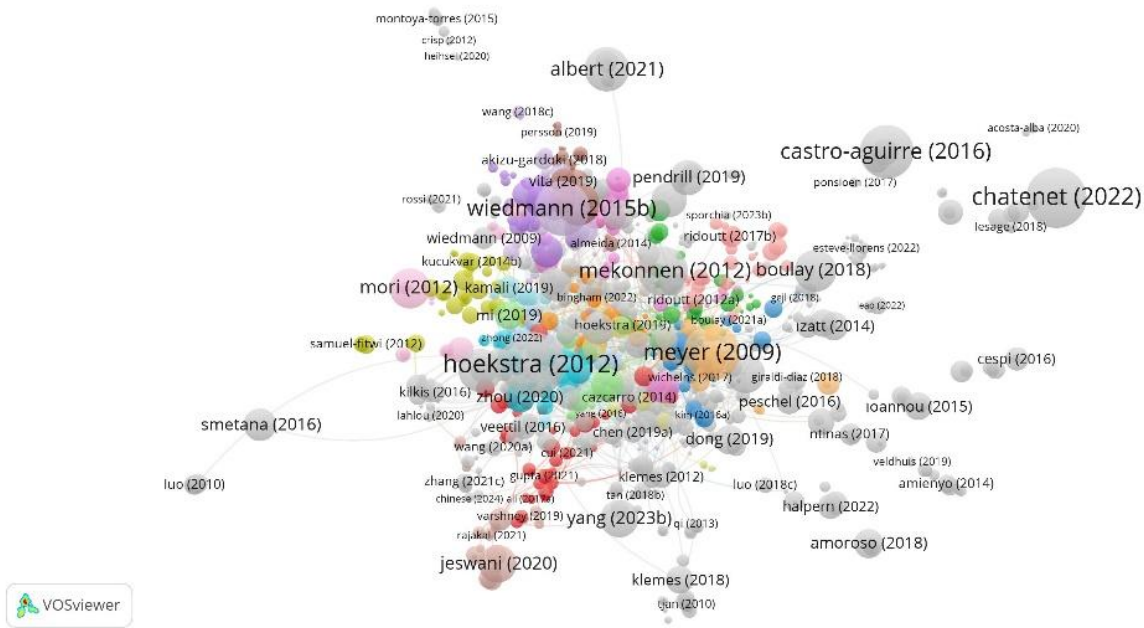


Figure 10. Document citation network map

Based on citation counts, the studies that had the most influence in this field were (2,459 citations), (2,103 citations) and (1,597 citations). The high number of citations of these three studies means they represent key references in the industrial WF literature. When viewed as a citation network, however, Hoekstra and Mekonnen (2012) is centrally located with 141 links. Hoekstra and Mekonnen (2012) also has more connections than both Boulay (2018) and Ridoutt (2010b), who have 75 links each.

The fact that citations and linkages are differentiated suggests that the way a study/author created an influence on the published literature with respect to both citations and linkages is related not only to the degree that other studies are referring to or using a study/author's work but also how intensely a study/author's work interacts with the research of other studies/authors. There are some studies/authors that have a very high citation score but a low number of linkages to other studies/authors, while there are other studies/authors that have a large number of linkages to other studies/authors on top of having a high citation score. This shows that there are many core studies/authors in the industrial WF literature that have been used as a guide for developing the conceptual foundation of this area of study.

3.6. Countries' Citation Analysis

To showcase the interactions between countries clearly in scientific research, a citation analysis was also performed using VOSviewer software by depicting that no less than 1 document and at least one citation are required for each country. Based on these criteria, 118 countries from the dataset were first selected. However, in order to avoid contamination of the network structure by countries being related neither by citation nor production or just hardly, a filtering option offered by the software was used and only 95 countries with citation links were considered. A citation map among these countries was also produced and is shown in Figure 11.

In terms of citation counts, it is clear that the USA has the greatest number of citations for scientific research with a total of 34,533 citations compared to People's Republic of China and Australia with 22,563 and 18,166 respectively. The total number of linkages was also considered to give an even more comprehensive evaluation of the degree of citation collaboration and importance between countries by creating a network map based upon TLS. In this analysis, the USA (with a TLS of 2,485) was still ranked first in terms of centrality and a strong connection to the USA, however, Australia's TLS at 2,231 is ranked second in Centrality and has strong links to a number of countries including the Netherlands (TLS: 2,212) and the People's Republic of China (TLS: 2,109).

China ranks as the largest producer of papers in industrial WF research having 793 documents, while the USA follows in second place with 482, and Australia holds the third position with 285. In contrast, the countries of India and Malaysia are producing relatively large numbers of papers compared to their TLS, meaning they are not receiving the expected amount of citations internationally. Therefore, while a country can produce many papers regarding a subject, if they do not have strong links to other countries, then those countries will not receive as many citations. Overall, the overall study shows that there are only a few countries that dominate the field of industrial WF literature on the global stage with their central roles in shaping the concepts and methods.

The prominence of China and the United States is also consistent with recent assessments of the broader WF literature, in which these two countries have been identified among the principal contributors to scientific production (Yi et al., 2026). The present analysis therefore indicates that the geographical concentration observed in general WF research is also reproduced within the industrial WF domain.

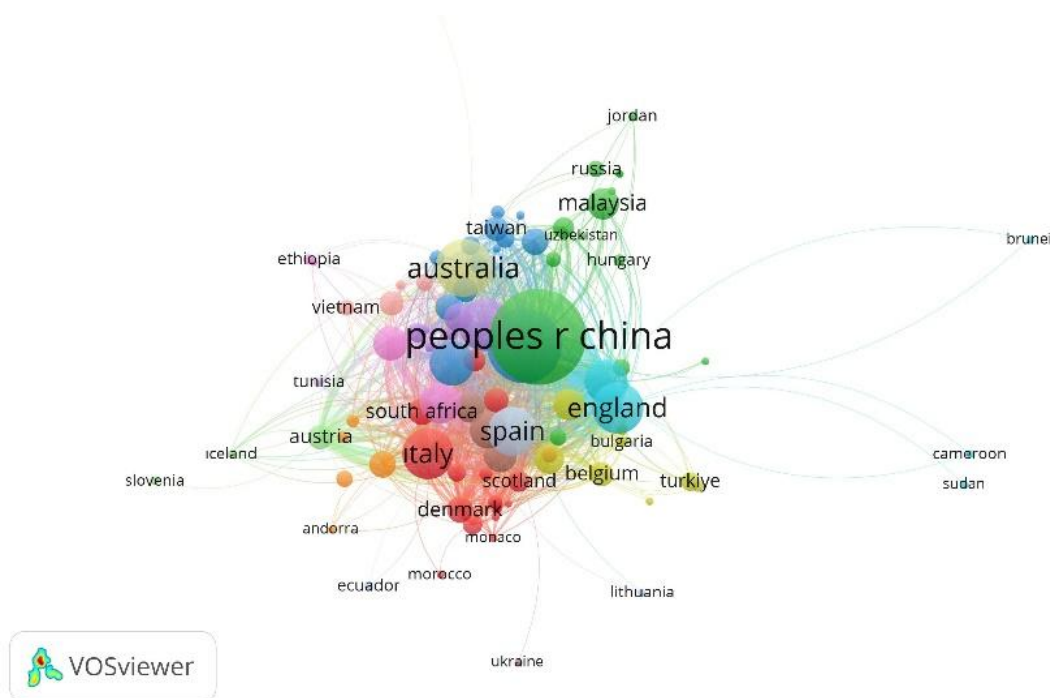


Figure 11. Countries' citation network map

3.7. Institutions' Citation Analysis

A citation analysis was performed using VOSviewer software to identify the scientific collaborations of the various institutions. Citation analysis parameters were that each institution had to have at least one published document and zero citations, this resulted in identifying 4,089 institutions in the dataset. The VOSviewer software was used to remove institutions with no citation relationships from the analysis and hence, the patterns observed in the data were based on the 1,763 institutions which had citations and citation networks created by establishing citation patterns between these institutions as illustrated in Figure 12.

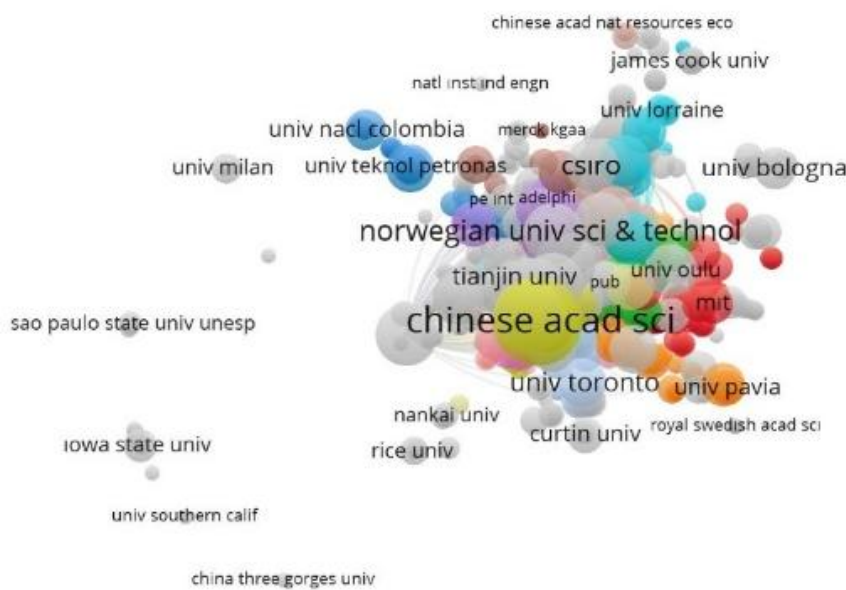


Figure 12. Institutions' citation network map

The inter-institutional citation network reveals that the Chinese Academy of Sciences is at the center of the citation network as it has the largest node, which indicates its significant role as an authoritative source in this field; this is supported by both its high publication output and numerous citations in the literature. Other influential organizations in this network that have high citation counts and central nodes include the Norwegian University of Science and Technology, Tianjin University, the University of Toronto and CSIRO.

The map of the network indicates that some institutions, including MIT, the University of Bologna and the University of Pavia, act as facilitators or 'bridges' connecting different research groups together and through this process make a significant contribution to the interdisciplinary sharing of knowledge. This concentration of citation intensity at a small number of institutions indicates that the scientific basis of the policies and practices related to the management of industrial water resources is created in these leading institutions; thus, a vital step towards increasing the scientific diversity in this area would be to encourage

more institutions from different geographical regions to participate in the process and further promote global collaboration between these institutions.

Although the University of Twente (5,834 citations), the University of Sydney (5,075 citations), and the University of Queensland (4,672 citations) are the top 3 ranked institutions by citation counts, the top 2 ranked institutions by document counts are the Chinese Academy of Sciences (96 documents) and Beijing Normal University (60 documents). The network map was then evaluated for TLS (TLS) to provide a better indication of the level of collaboration and the intensity of referencing between the institutions. The University of Twente has the highest TLS (1,753), followed by the Norwegian University of Science and Technology (1,091), the Technical University of Berlin (1,048), and the University of Sydney (999); each of which, represent a strong international connection to citations.

The study found that institutions have both direct and indirect impacts on the water resources sector via publication numbers and total citations, as well as through their intensity of collaboration with other institutions (thus their link strength). Thus, some institutions may have both a relatively smaller actual publication count compared to others, but this does not imply that they are not as strongly connected (i.e., they do not have high link strength). This also indicates that these institutions hold very important roles in the development of the field of industrial WF.

3.8. Bibliographic Coupling Analysis of Documents

An analysis was conducted to determine the thematic and conceptual links between the various documents in the database. This was done using a bibliographic coupling technique; that is, the use of a threshold correlation of at least 1 document for each document included in the analysis as defined by VOSviewer. Following this method of analysis, 2,724 documents were identified through the data; however, to eliminate the effects on the analysis of documents that did not have comparable treatments, the filtering feature within the VOSviewer software was utilized, and a final count of 2,613 documents was included in this phase of the study. The result of this filtering process was the generation of a visual model illustrating the relationships of bibliometric coupling within these documents as indicated in Figure 13.

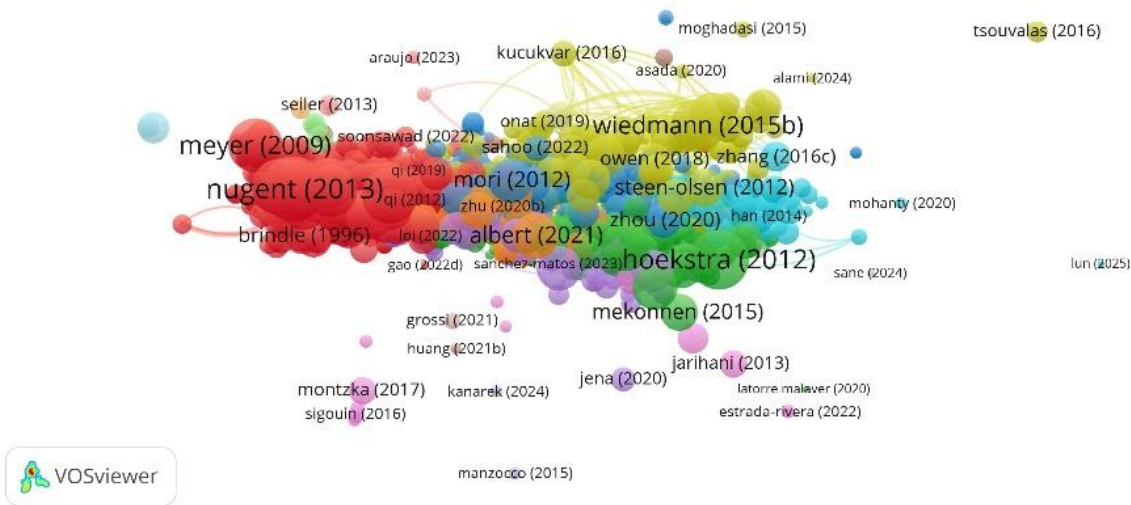


Figure 13. Bibliographic coupling network map of documents

Unlike citation analysis, bibliographic coupling analysis was performed to illustrate how closely-related and similarly oriented researchers have studied similar areas of research; the results of this analysis are shown in Figure 14. Bibliographic coupling provides a means of determining how closely-related two publications are by identifying the references they have in common. Figure 14 also provides a visual representation of a number of research clusters based on the common references found within the studies being examined. Examination of the map network represented in Figure 14 indicates that topics within the Industrial WF area of study are represented by clusters based upon similar methodological approaches such as LCA, Water Management, and Environmental Impact Analysis. In particular, the location of the studies, Hoekstra and Mekonnen (2012), Nugent et al. (2013), indicates that they occupy a high central location within the overall network structure and that these works possess a significant degree of content and reference similarity with one another and with many other works in the literature.

Combining the findings from the citation analysis (Figure 10) and the bibliographic coupling analysis (Figure 13), it is apparent that Hoekstra and Mekonnen (2012) has the largest node size and is positioned at the center of both network maps. The conclusion can be drawn that Hoekstra and Mekonnen (2012) is a highly cited article in the literature, but more importantly, it is a key methodological reference point for any future research projects regarding WF calculations at a global scale. It has been established through both citation and bibliographic coupling analyses that Hoekstra and Mekonnen (2012)'s role as a dominant intellectual bridge in the field of industrial WF calculations at a global scale was supported by the overall methodology developed by Hoekstra and Mekonnen (2012). Thus, the intellectual coherence of the field of industrial WF calculations is based on Hoekstra and Mekonnen (2012).

3.9. Bibliographic Coupling Analysis of Authors

A bibliographic coupling analysis was performed to demonstrate intellectual proximity and similar research orientations among authors. Within the scope of the analysis, threshold values of at least 1 document and 0 citations were defined for each author in VOSviewer. According to these criteria, 12,907 authors in the dataset were initially identified. To ensure that authors who do not share common references do not affect the network structure, filtering by software option was applied; thus only 12,369 authors with bibliographic coupling relationships were included in this analysis. The network map based on bibliographic coupling relationships between these included authors was created as an output result and is presented here as Figure 14.

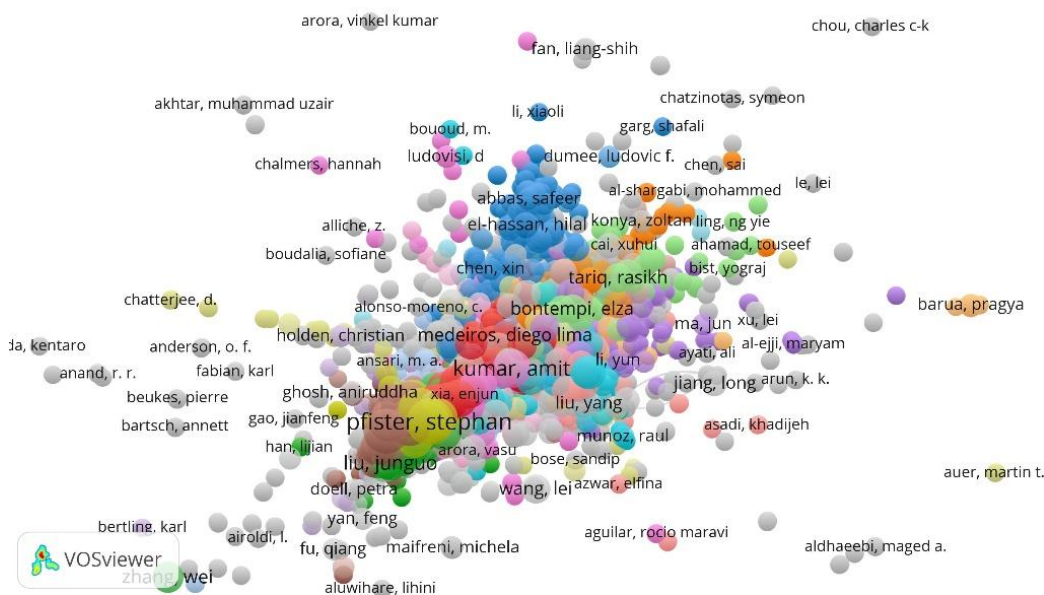


Figure 14. Bibliographic coupling network map of authors

By analyzing the constructed network structure, it is apparent that distinct clusters of authors exist in terms of shared reference citations. Authors sharing a high strength of bibliographic coupling are more likely to be using the same theoretical foundations and methodological approaches in the literature. Therefore, Authors are developing similar lines of research not only by being co-cited, but also through their usage of similar literature or sources of knowledge.

Bibliographic coupling analysis determines researchers' relationships to each other. In essence, bibliographic coupling does not directly indicate authors' scientific relationship but rather an indirect indicator of researchers' potential intellectual connection. The relationship between authors is based on citations made by the authors to other authors' works; therefore, citation analysis is a reflection of the authors' scientific impact and visibility. Bibliographic coupling analysis reveals the thematic and methodological similarities among researchers and indicates the collaborative efforts of researchers across several fields of expertise. Based on this evidence, the results show that the industrial WF literature is

being produced by a limited number of authors, but on the other hand, there are many authors producing the literature who share a common research agenda.

3.10. Source Citation Analysis

In order to reveal scientific interaction among sources and the flow of knowledge within the literature, a source citation analysis was conducted. In the VOSviewer software, threshold values of a minimum of 1 document and 0 citations were defined for each source. Based on these criteria, a total of 872 sources were identified in the dataset; however, to prevent sources without citation relationships from affecting the network structure, the filtering option provided by the software was applied, and only 816 sources with citation relationships were included in the analysis. A network map based on the citation relationships among these sources was generated, and the results are presented in Figure 15.

In the ranking based on citation counts, Journal of Cleaner Production stands out as the most influential source in the literature with 9,954 citations. This journal is followed by high-impact factor journals such as Environmental Science & Technology, Applied Energy, and Nature. However, when the network map is evaluated based on TLS in order to better reflect the intensity of interactions among sources, Journal of Cleaner Production is clearly the most central source (TLS: 56,574). In addition, journals such as Science of the Total Environment, Journal of Industrial Ecology, and Sustainability form important bridges in the flow of knowledge within the literature due to their high link strengths. The Journal of Cleaner Production, Sustainability, and Science of the Total Environment are the three leading publications in terms of their number of published articles. However, some journals publish fewer articles than the three leading sources while still exhibiting high total link strength, indicating their central or methodologically influential role within industrial WF research.

In summary, this analysis indicates that the literature in this area is populated primarily around certain key core journals, and these key journals primarily provide guidance to researchers in regard to developing new scientific content in industrial WF research.

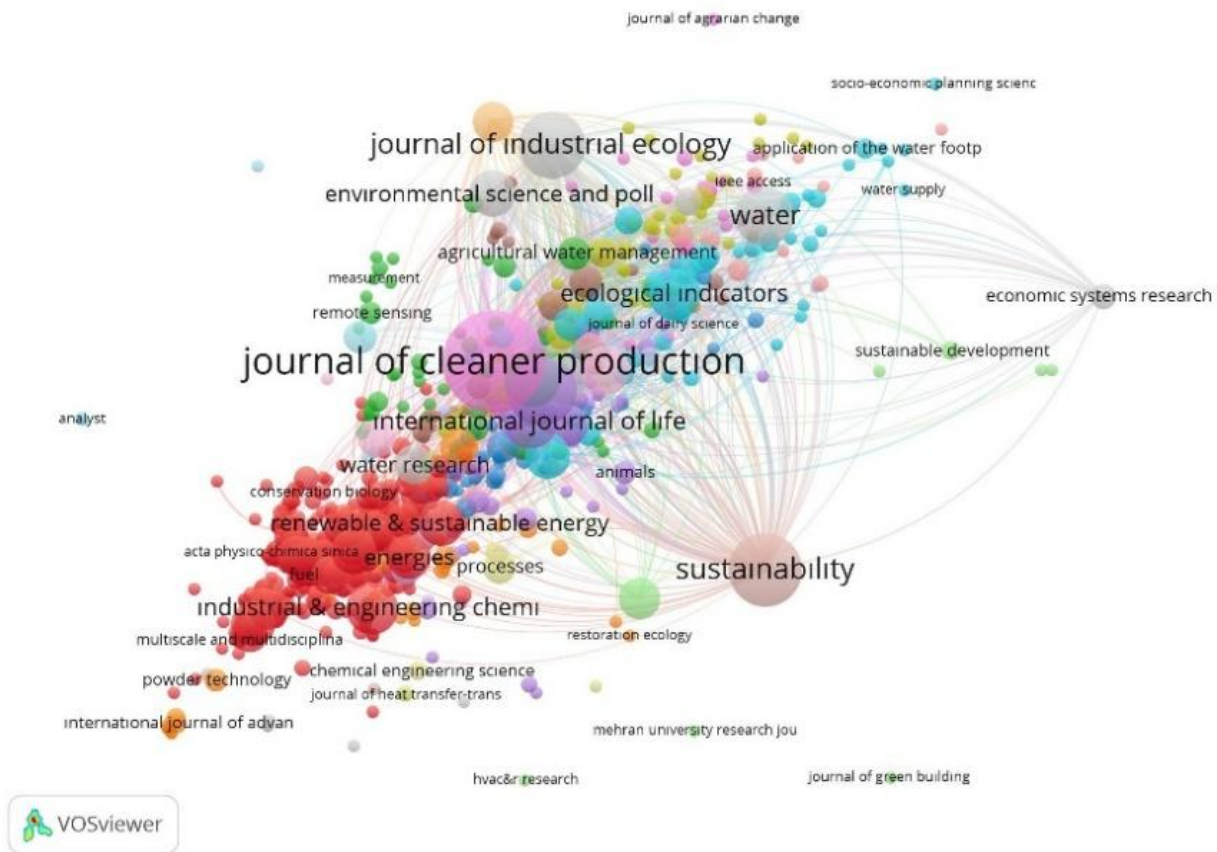


Figure 15. Source citation network map

4. Evaluation of Bibliometric Analyses

This study demonstrates significant growth in the field of industrial WF research over the last fifteen years based on bibliometric indicators. Since 2020, publications on industrial WF research have increased markedly, coinciding with growing concerns over water scarcity, climate change, and sustainable industrial production. The surge in research output implies that the industrial WF is now viewed as a strategic management tool rather than just an environmental tool.

The acceleration observed after 2020 should not be attributed to a single policy or institutional development. Rather, it coincides with an intensification of international initiatives addressing resource efficiency, corporate environmental performance, and water security. The European Union's Circular Economy Action Plan, adopted in 2020, reinforced life-cycle thinking, resource efficiency, and circularity in production systems (European Commission, 2020), while Regulation (EU) 2020/852 explicitly recognized the sustainable use and protection of water and marine resources as an environmental objective (European Parliament and Council of the European Union, 2020). More recently, the 2023 United Nations Water Conference and the resulting Water Action Agenda renewed international commitments to accelerating progress towards Sustainable Development Goal 6 (SDG 6: Clean Water and Sanitation) (United Nations, 2023). In parallel, the European Sustainability Reporting Standards

introduced specific disclosure requirements under European Sustainability Reporting Standard E3 (ESRS E3: Water and Marine Resources) concerning corporate water consumption, withdrawals, discharges, water-related impacts, risks, policies, and targets (European Commission, 2023). These developments, together with increasing concerns over water scarcity and climate-related risks, provide a broader policy and institutional context for the growing scholarly attention to industrial WF after 2020. Nevertheless, the temporal correspondence observed in this bibliometric analysis should not be interpreted as evidence of a direct causal relationship.

Through keyword co-occurrence and thematic clustering analyses, the majority of the literature reviewed relates to the methodology employed within a small number of areas. Specifically, the close positioning of industrial WF, life cycle assessment, and wastewater treatment indicates an evolution in the industrial water management literature. Earlier studies primarily focused on user-based and quantity-oriented measurements of water consumption. More recent research incorporates water quality considerations related to pollution from industrial processes and adopts integrated assessment frameworks that evaluate environmental and social impacts across the entire product life cycle from a sustainability perspective.

Analyses of citation and bibliographic coupling suggest that the Hoekstra/Mekonnen framework of methodology is the most applied methodology dominating the literature on industrial WF estimates. This suggests that industrial WF assessment has developed around a relatively consistent methodological framework at the global level, indicating an increasing degree of methodological consolidation within the field. The concentration of many citations within a relatively small number of studies (and thus researchers) also indicates the continued reliance on a few key players in producing knowledge in the field.

A country- and institution-based analysis shows that the most published and most cited works in the field come from China and the United States. These countries have significant volumes of industrial production and thus provide significant input into the WF literature. There remains a significant research void regarding the equitable and just distribution of knowledge about the WF methodology to many developing countries due to limited levels of representation in this area of research.

Combining WoS category distribution information and thematic analyses shows that most of the WF literature is concentrated in the Environmental Sciences and Engineering fields, while comparatively fewer studies are found in the Economics, Business, and Policy areas. This imbalance indicates a disconnect between WF results derived from technical calculations and their application in industrial decision-making processes. Therefore, future studies should integrate WF assessments with economic evaluations, decision-support systems, and policy-oriented frameworks to enhance their practical applicability.

This disciplinary pattern can be interpreted more clearly when compared with recent reviews of the broader WF literature. Guzmán-Dimas et al. (2025), who examined WF research from the perspective of the Sustainable Development Goals and economic-administrative sciences, emphasized the multidimensional character of WF research and the need to integrate environmental assessment with broader socio-economic perspectives. The present findings complement this conclusion from an industrial perspective: although environmental sciences and engineering constitute the dominant knowledge base, economics, management, policy, and decision-support approaches remain comparatively peripheral. This suggests that methodological development in industrial WF assessment has progressed more rapidly than its integration into managerial and policy-oriented decision processes. A recent review by Yi et al. (2026) similarly identified limited policy uptake as one of the persistent barriers in WF research. Taken together, these findings indicate that a major future challenge is not merely to refine WF calculation methods, but to translate WF information into operational, economic, and policy decisions within industrial systems.

In general, the results of this research show that the industrial WF literature has evolved considerably in terms of methodology. Nevertheless, substantial opportunities remain for future research that integrates diverse disciplinary perspectives and applies WF concepts across broader industrial, managerial, and policy contexts. By identifying underexplored themes and overlaps within the literature, the bibliometric analysis presented in this study provides a roadmap for directing future research efforts.

5. Discussion and Conclusions

This research utilized bibliometric methodologies to analyze the intellectual structure, development dynamics and trends of the literature relating to the industrial WF based on 3052 publications retrieved from the WoS database, and produced visualization and network analyses using VOSviewer software showing that the literature has been rapidly transformed in its last fifteen years.

The results of this analysis showed that the number of publications on industrial WF research has generally increased since 2011, with a particularly marked rise after 2020. The largest number of published works in 2025 also indicates that the impact of global freshwater constraints, climate change policies and sustainable production objectives have helped shape the academic agenda in this field. Therefore, it is evident that the WF as an approach has developed beyond being simply an environmental indicator to being a principal means for achieving the objectives of industrial sustainability and strategic resource management.

The results from this study suggest future recommendations on conducting further WF research in the following areas:

- Using bibliometric approaches to analyze literature from additional databases beyond just the WoS - such as Scopus and PubMed, among others - will provide a more thorough analysis of literature related to WF research.
- Combining studies of WF with studies related to economics and decision-support systems (managerial) and policy tools (non-technical) would help narrow the gap between the production of academic research and the implementation of results from the studies in practice.
- When comparing different sectors (for example: textile, food, or chemical industries), a bibliometric analysis of WF research across these sectors will enable researchers to determine how they are similar/different and how important it is for all industries to utilize a common methodology.
- As the literature is dominated by studies performed in developed countries, increased numbers of region/country based studies would allow for a better balance in global distribution of the WF methodology.

A summary of the present research provides an overview of the structure and evolution of the industrial WF body of research and identifies gaps in this area using bibliometric techniques. The results serve as a useful guide for researchers and practitioners to shape the future of industrial water management, and contribute to the sustainability and interdisciplinary growth of this research area.

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N/A

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Author Contributions

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Conflict of Interest

The authors have no conflicts of interest to declare.

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