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Waste to Energy from Municipal Wastewater Treatment Plants: A Science Mapping

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Abstract: Energy recovery, according to circular economy and sustainable principles, has established itself as an inevitable field of action in wastewater treatment plants (WWTPs). Energy costs are forcing the optimization of processes and increases in the development of applicable waste-to-energy (WtE) technologies. This study aims to analyze the existing knowledge on WtE research in municipal WWTPs using a systematic literature review and a bibliometric analysis from 1979 to 2021. For this purpose, Science Mapping Analysis Tool (SciMAT) and VosViewer, two softwares for analyzing performance indicators and visualizing scientific maps, were used to identify the most relevant figures in the research. The results show an exponential increase in the number of publications over time, which has yet to reach a stage of maturity. The analysis of the evolution of the topics exposes variability in the keywords over the years. The main field of WtE research has focused on sludge treatment, with technologies ranging from anaerobic digestion to more recently-emerging ones such as microalgae or membrane technologies. The analysis also identified the need for more publications on other wastes in WWTPs, which are necessary to achieve zero waste.

Keywords: municipal wastewater; domestic wastewater; waste to energy; energy valorization; energy production; energy recovery

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1. Introduction

In the last decade, the number of wastewater treatment plants (WWTPs) has increased around the world to comply with regulations and to mitigate the deterioration of the water environment. This increase will continue to grow to fulfill the targets included in Sustainable Development Goal (SDG) 6 of the United Nations' 2030 Agenda; additionally, more advanced and energy-intensive treatment processes will be adopted in the following decades [1]. As a result, WWTPs are expected to increase energy consumption, which may lead to a considerable boost in CO_2 emissions and to a substantial growth in operational costs [2]; therefore, the new challenges to the operation of these facilities should be overcome to improve their energy performance and environmental sustainability while ensuring the quality of the services provided.

Nowadays, the role of wastewater management in achieving the SDGs is very important; in fact, wastewater treatment could contribute to achieving 11 out of the 17 SDGs [3], including not only SDG2, zero hunger, and SDG6, clean water and sanitation, as a result of increasing water availability, but also enhancing human health (SDG3), providing a new source of income to reduce poverty and increase economic growth (SDG1 and SDG8), using waste to produce clean energy (SDG7 and SDG9), and reducing the environmental impact of wastewater (SDG11, SDG12, SDG13, and SDG14). Besides, the application of circular economy (CE) to municipal WWTPs causes these facilities to be viewed as energy and resource factories.

The treatment of municipal wastewater requires a high energy consumption, representing an important percentage of a municipality's energy costs, which has been reported to be between 24% [4] and 44% [2]. Energy costs in municipal WWTPs vary significantly depending on several internal factors, for example, onsite energy production from biogas or renewable sources [5], the technology applied, or the intensity of the treatment [6], as well as external factors, such as energy tariffs [5]. As a consequence, reducing energy consumption and increasing the efficiency of energy production are both required due to process optimization [7]. Besides, because of the high content of organic matter involved in these processes, WWTPs are also a rich source of chemical energy [5], their production of which is about 9.3 times higher than the energy necessary to treat wastewater in these facilities [7]. This energy can be converted for use during wastewater treatment [8], especially from waste produced during the treatment process.

Waste to Energy (WtE) technologies have been extensively applied to produce energy from sludge produced from municipal WWTPs, including the production of biogas from the digestion [9] and co-digestion [7] of the sludge, which is converted in a combined heat and power system into electricity and heat; biodiesel production [10]; combustion [11] and co-combustion [12]; gasification [13] and pyrolysis [14]. In relation to waste from the pretreatment process, only some studies have analyzed the application of anaerobic digestion [15–18].

As a consequence, and since no similar reviews have been found, the objective of this paper is to analyze the scientific literature to identify the evolution of technologies applied to produce energy from municipal WWTPs. To achieve this goal, a science-mapping approach has been applied because of its objective criteria for evaluating the work carried out by researchers [19] and its ability to provide a macroscopic overview of large amounts of academic literature [20]. This study will contribute to the existing body of knowledge by highlighting the trends and patterns in the research field, establishing its research themes and mapping researcher networks. From the results of bibliometrics, and in comparison with the more exhaustive analysis of the selected research, it is possible to pinpoint the current knowledge gaps from which future lines of research can be identified.

2. Materials and Methods

This paper analyzes the available research on WtE from municipal WWTPs to result in the generation of mapping of the most relevant actors in the field in terms of sources, authors, countries, and papers, as well as its evolution, and taking into account themes in terms of keywords. To do this, the methodology and tools applied were carried out in three main stages, as shown in Figure 1 and described below.

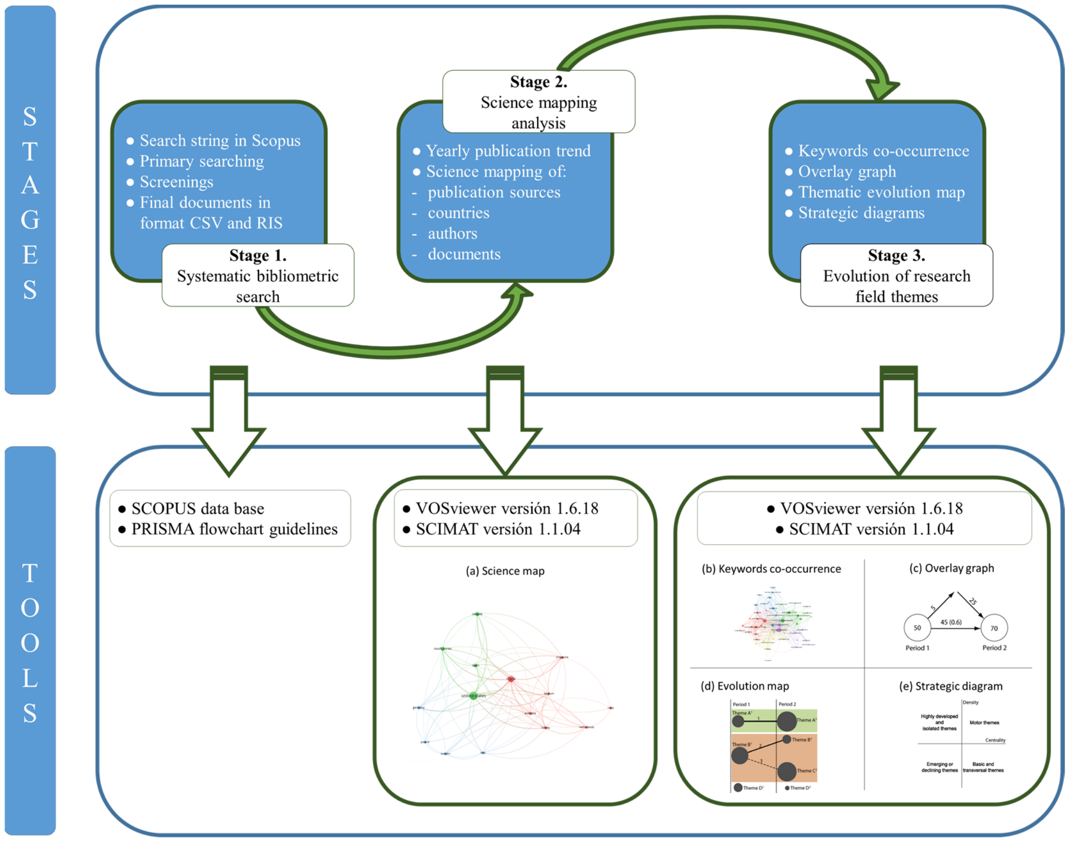

Figure 1. Summary of the methodology and tools applied [21].

2.1. Stage 1. Systematic Bibliometric Search

Scientific databases are necessary to finds documents in a given research field. Because the Scopus database has a broader bibliometric scope and the most current data compared to Web of Science, the documents for the present evaluation were retrieved from Scopus [22,23]. A data refinement of the total number of primary searches for documents was approached according to the PRISMA flowchart guidelines to remove documents published in 2022 and that did not fall within the scope of the review, as well as to limit the research to journals and conference documents in English. The resulting papers were stored in both formats developed by comma-separated values (CSV) files and Research Information Systems (RIS) for further analysis of the retrieved data using VOSviewer V1.6.18 and Science Mapping Analysis Software Tool (SciMAT V1.1.04), respectively. VOSviewer is a freely-available open-source software tool that is commonly employed in a range of sectors and is highly recommended for creating maps [24]. SciMAT is an open-source science mapping software tool that is based on a longitudinal science mapping approach. It incorporates methods, algorithms, and measures for all of the steps in the science mapping workflow, from preprocessing to the visualization of the results [21].

2.2. Stage 2. Science Mapping Analysis

The science mapping analysis of documents included:

- The yearly publication trend, including the total documents per year and the accumulative papers during the time horizon, was analyzed. The categorization of the horizon time into different subperiods was also included for better knowledge of the publication trend.
- Science mapping was conducted for publication sources, countries, authors, and documents. VOSviewer was applied to produce science maps (Figure 1a) and construct tables with statistical values. A comprehensive quantitative analysis according to the

number of documents and citations for each item was applied, and also in terms of the value of the normal citation, average publication year, average citation, and average normalized citations [25]. The normal citation is defined as the citation of all the articles within the same journal, author, or country; the average publication year is the average publication year of the articles; the average citation is the total citations per article; finally, the average normal citation is defined as the total number of citations divided by the average number of citations published in the same year and it is used to correct the misinterpretation that older articles have more time to garner citations than the new ones [25]. In networks generated, the size of nodes is related to their repercussions in terms of the number of documents, citations, or average normal citations; The thickness and the colors of the linking lines indicate the inter-relatedness among them [24].

2.3. Stage 3. Evolution of Research Field Themes

Finally, the evolution of research field themes was analyzed in terms of mapping of the co-occurrence of keywords (Figure 1b) generated with VOSviewer and the overlay graph (Figure 1c), thematic evolution map (Figure 1d), and strategic diagrams (Figure 1e) generated with SCIMAT. The overlay graph represents the number of items shared by different time periods in the time horizon. The keywords co-occurrence diagrams were used to identify the relationship and the connectedness of the articles. The evolution map represents the number of documents associated with each theme and the relationships between them. Finally, the strategic diagrams represent themes. In terms of the number of documents or h-index, the criteria used were showing motors, highly developed and isolated, emerging or declining and basic research topics [21].

3. Results

The most relevant results obtained in the three stages defined in the previous section are summarized, analyzed, and discussed below.

3.1. Stage 1. Systematic Bibliometric Search

The Scopus database was searched for bibliometric data in July 2022 using the following search string, according to the combination of keywords in the title, abstract, or keywords: (*municipal wastewater* OR *municipal waste water* OR *domestic wastewater* OR *domestic waste water*) AND (*waste to energy* OR *WtE* OR *waste-to-energy* OR *energy valorisation* OR *energy valorization* OR *energy production* OR *energy recuperation* OR *energy recovery*).

The total number of primary searches for documents in Scopus was 468. The data refinement, which was conducted according to the PRISMA flowchart guidelines to exclude documents published in 2022 and those that did not fall within the scope of the review, as well as to limit the research to journals and conference documents in English, resulted in a total of 337 documents that were finally selected for the analysis (Figure 2). They were stored in both CSV and RIS file formats for further analysis in the next section.

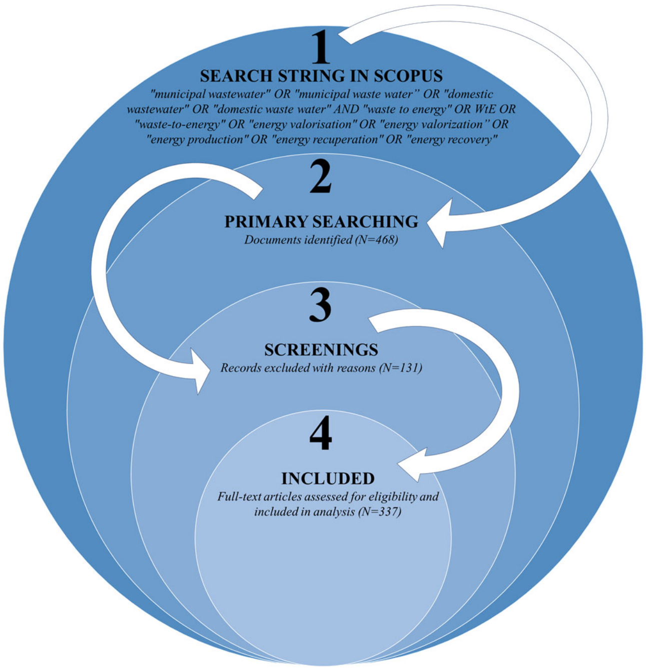

Figure 2. PRISMA flowchart.

3.2. Stage 2. Science Mapping Analysis

The yearly publication trend, science mapping, and evolution of research field themes were analyzed using SciMAT and VOSviewer. The most relevant results and a discussion of those results are summarized below.

3.2.1. Yearly Publication Trend

The publications and citations of the documents included in the analysis of a considered field depict the developments and patterns in the research [25]. As a consequence, the yearly publication trend, including the cumulative papers during the time horizon for the searching strings defined, is included in Figure 3. The first article was found in the year 1979; therefore, the horizon time of this research was defined from this year to 2021. A preliminary analysis of Figure 3 shows a gradual increase in the number of publications, especially from 2008 onwards. According to the growth pattern, the horizon time was classified in the following three subperiods:

- Initial phase, or first subperiod: from 1979 to 2008, a total of 20 documents were published. This period is characterized by a very low number of documents per year; in fact, none or only one or two documents per year were published in most of the period, although, in the latter years, a slight increase to five papers was observed.
- Active phase with relative growth, or second subperiod: from 2009 to 2015, a total of 100 documents were published in seven years. A significant increase in the number of documents was observed in comparison with the previous phase and coincided with the approval of the Directive 2008/98/EC on waste, which establishes a legal framework for treating waste in the European Union (EU) and is designed to protect the environment and human health by emphasizing the importance of proper waste management, recovery, and recycling techniques to reduce pressure on resources and improve their use [26]; it also reinforces the waste hierarchy, which includes, in this order: prevention, preparing for reuse, recycling, other recovery (including energy recovery), and, finally, disposal [26]. As a consequence, the development of technologies to produce energy from waste began to grow faster.
- Active phase with high growth or third subperiod: from 2016 to 2021, a total of 217 documents were published in six years. In September 2015, the 2030 Agenda for Sustainable Development was adopted by the United Nations General Assembly with

the aim of stimulating action in five critical areas: people, planet, prosperity, peace, and partnership. This document contains 17 Sustainable Development Goals (SDGs) and 169 targets associated with achieving these goals by the year 2030, and it has since driven the approval of policy frameworks around the world, for example the first EU action plan for the circular economy [27]. Different waste treatment operations classified as waste to energy (WtE) processes are essential to fulfill the objectives included in all of these policy strategies; therefore, as result, a very significant growth of this research field has been identified, which is reflected in the increase in publications.

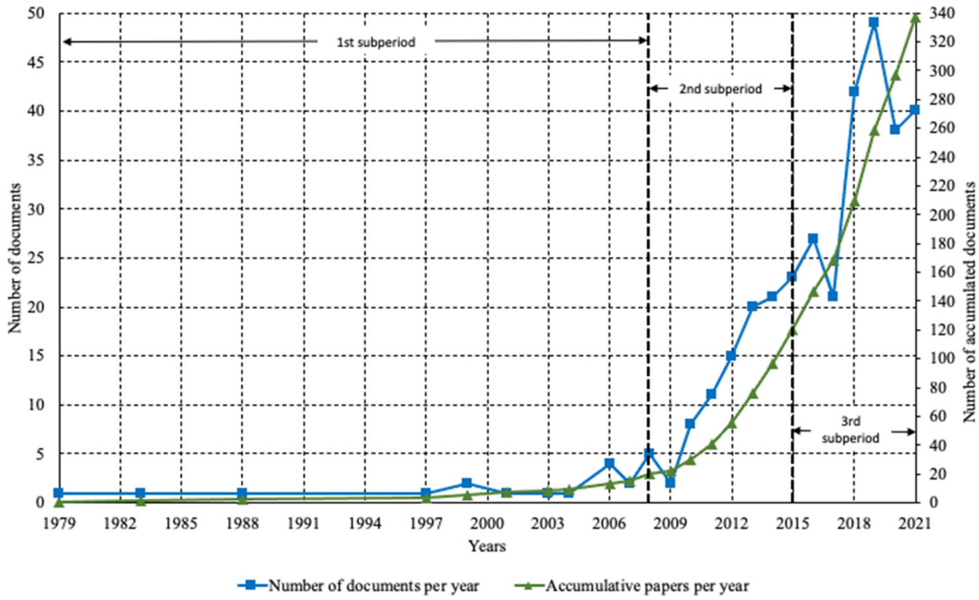

Figure 3. Number of documents in the horizon-time (1979–2021). Documents per year and accumulated documents.

3.2.2. Science Mapping

In a preliminary analysis, a total of 123, 1200, and 55 sources, authors, and countries, respectively, were included in Figure 4, which shows their relationship with the number of documents published. Figure 4 shows a high concentration of the number of documents in the lower values of number of sources, authors, and countries; specifically, 69 sources, representing 59% of the total sources, 81.7% of the authors (980 authors), and 25.5% of the countries (14 countries) have published only one document in the field. These results highlight the diversity and breadth of the research field. As a result, in the case of the authors, Lotka's Law, which establishes that the number of those who have published a number of works is a fixed relationship with a constant number of authors who have published one or very few articles, is not fulfilled [28]. To identify sources, authors, countries, and documents with a higher relevance in the field, VOSviewer science maps were used, and the results are summarized and discussed below.

- Publication sources mapping

In the case of sources mapping, journals with a minimum number of eight documents from a source were identified, resulting in the eight sources summarized in Table 1 in terms of publication count, total citations, and average normalized citations. The journal *Bioresource Technology*, which promotes research to support bioresource development, processing, and utilization in a sustainable manner, clearly leads the ranking with 38 documents, 3227 total citations, and an average normalized citations index of 1.5648; on the other hand, *Water Research*, which publishes studies on all aspects of the science and technology of the anthropogenic water cycle, water quality, and its management worldwide, leads the ranking in terms of average normalized citations (1.9456), with only 17 documents published (third position in this ranking) but 1153 citations (second position in this ranking). Both journals are included in the top three ranking in terms of the number of documents, total citations, and average normal citations. *Water Science and Technology*, focused on all fields relevant to water research, is included in both top three rankings in terms of average normal citations ranking; however, it is only in the eighth position in the case of the number of documents and total citations. Finally, *Journal of Cleaner Production*, a transdisciplinary journal with nine documents published and 374 citations that is focused on cleaner production, and environmental and sustainability research, is in the third position in average normal citations ranking, although it is in the sixth position in the other rankings.

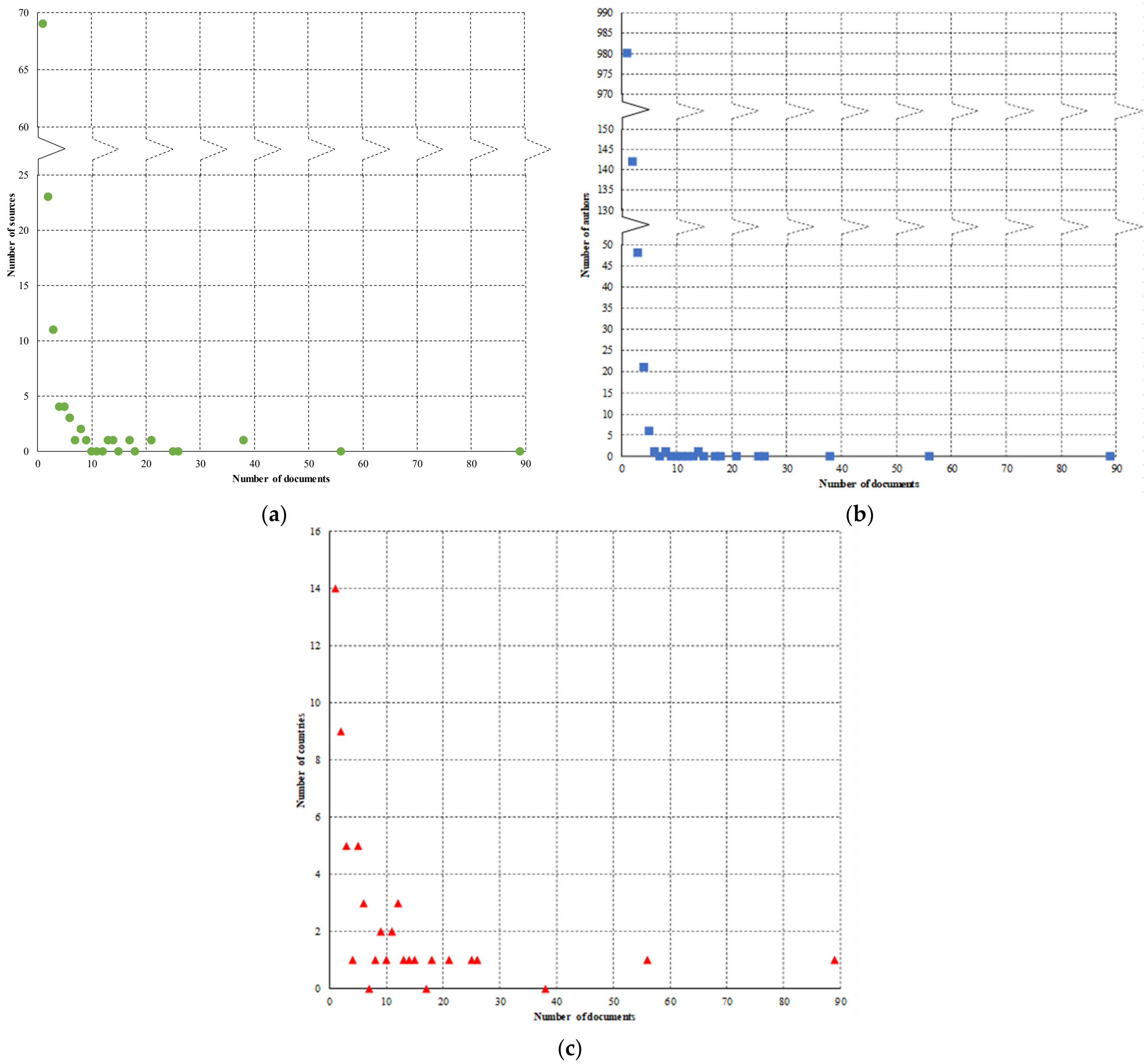

Figure 4. Relationship between the number of documents and (**a**) the number of sources, (**b**) authors, and (**c**) countries.

Table 1. List of leading sources of publications in terms of publication count, total citations, and average normalized citations.

Position	Source	Number of Documents	Total Citations	Normal Citations	Average Citations	Average Normalized Citations
Publication count						
1	Bioresource Technology	38	3227	59.4616	84.9211	1.5648
2	Water Science and Technology	21	498	6.9348	23.7143	0.3302
3	Water Research	17	1153	33.0759	67.8235	1.9456
4	Science of the Total Environment	14	344	13.9512	24.5714	0.9965
5	Journal of Environmental Management	13	393	17.8791	30.2308	1.3753
6	Journal of Cleaner Production	9	374	12.6744	41.5556	1.4083
7	Chemosphere	8	394	9.6039	49.25	1.2005
8	Chemical Engineering Journal	8	317	9.5925	39.625	1.1991
Total citations						
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Average normalized citations						
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Table 2 summarizes the categories of the sources which lead the ranking. A total of nine categories were identified, showing the transdisciplinary nature of the field, which has been analysed from many different points of view. Nevertheless, ENVIRONMENTAL, SCIENCES (F) and ENGINEERING, ENVIRONMENTAL (E) are the most representative, with six and four journals included in them, respectively, which emphasizes the environmental dimension of the field, as well as the use of engineering to develop solutions to recover the energy from waste from municipal wastewater treatment plants. On the other hand, it is important to highlight that, although the category ENERGY & FUEL (C), which is directly related to the production of energy from the waste of municipal wastewater treatment plants, is only identified in one of the journals, *Bioresource Technology*, which has the largest number of documents published and total citations.

Finally, Figure 5 depicts a network visualization of the eight sources included in the ranking in terms of citations. All of them are connected and the dimensions of the cycle imply the source's contribution; a bigger dimension signifies more influence in terms of the number of citations. For example, *Bioresources Technologies* has larger circle sizes than the other journals, which means that this journal has the higher impact on the research field in terms of total citations. Additionally, circles with the same color indicate groups of associated sources, discovered using VOSviewer analysis. Three groups or clusters were detected and denoted by the distinct colors red, green, and blue, with four, two, and two journals in each one, respectively. Clusters are constructed using the scope of research outlets or the number of times they are co-cited, and the connections between sources that are close together are stronger than those amongst frames that are farther apart (Yang et al., 2022). Thus, *Bioresources Technologies* (Cluster 2 green) shows the strongest connection with *Water Research* (Cluster 1 red).

Table 2. Categories of the sources leading the ranking.

Category	A	B	C	D	E	F	G	H	I
Bioresource Technology	✓	✓	✓						
Chemical Engineering Journal				✓	✓				
Chemosphere						✓			
Journal of Cleaner Production					✓	✓		✓	
Journal of Environmental Management						✓	✓		
Science of the Total Environment						✓			
Water Research					✓	✓			✓
Water Science and Technology					✓	✓			✓
TOTAL	1	1	1	1	4	6	1	1	2

A. AGRICULTURAL ENGINEERING
B. BIOTECHNOLOGY & APPLIED MICROBIOLOGY
C. ENERGY & FUELS
D. ENGINEERING, CHEMICAL
E. ENGINEERING, ENVIRONMENTAL
F. ENVIRONMENTAL, SCIENCES
G. ENVIRONMENTAL STUDIES
H. GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY
I. WATER RESOURCES

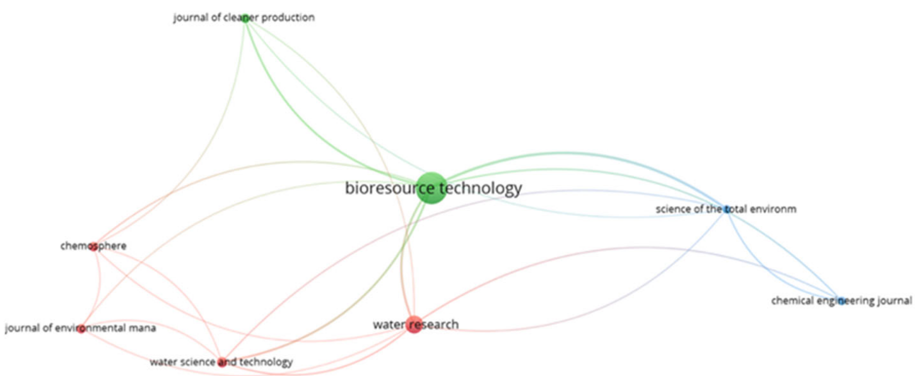

Figure 5. Network visualization of leading sources connected in terms of the number of documents.

- Countries mapping

Countries with a minimum number of 10 documents were identified, resulting in a total of 15 countries represented in the network visualization of Figure 6 in terms of total documents. Three groups or clusters were detected, denoted by the distinct colors red (Cluster 1), green (Cluster 2), and blue (Cluster 3), with seven, four, and four countries in each one, respectively. An overlay visualization of the previous network shows that Belgium and Sweden, in the purple color, are the countries that have been working on the field for the longest time; however, the countries in the yellow color (i.e., Singapore, India, or China) are the ones that have joined the field most recently. Based on the graphical description of the occupied countries, the larger size of the circles of the United States and China makes clear the leadership of these countries in terms of total documents, as mentioned above.

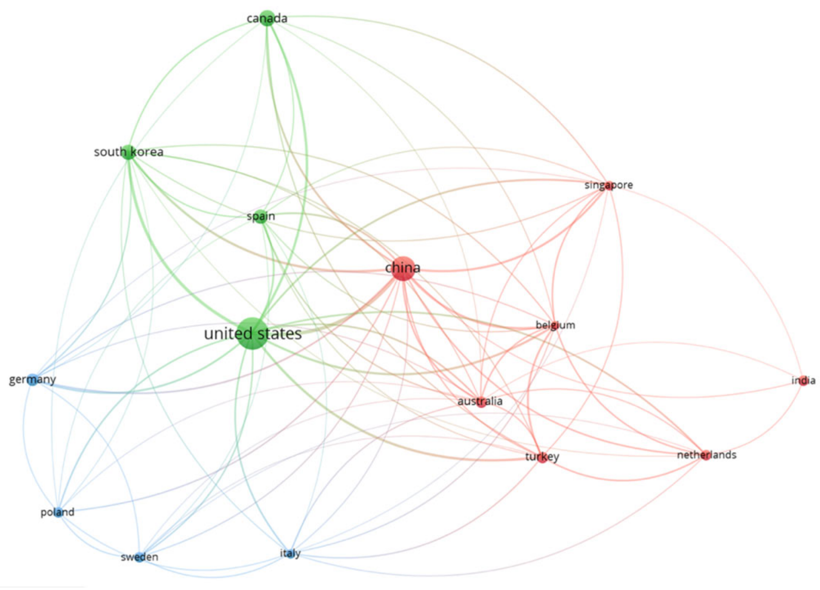

Figure 6. Network visualization of the countries included in the top 10 ranking lists in terms of total documents.

Table 3 shows the top five rankings of these countries in terms of the number of documents, total citations, and average normalized citations. A total of nine countries are included in the three top lists. As shown in Figure 7, the United States and China lead the ranking in terms of the number of documents and citations; in the case of the average normalized citations ranking, Australia and Netherlands are the leaders. Furthermore, China is the only country that is included in the three rankings; therefore, it is considered the country with the strongest influence in the research on the field, followed by the United States, South Korea, Australia, and the Netherlands, which are each included in two of the rankings; finally, the other three countries are each included in only one of the lists (Spain, Singapore, and Belgium).

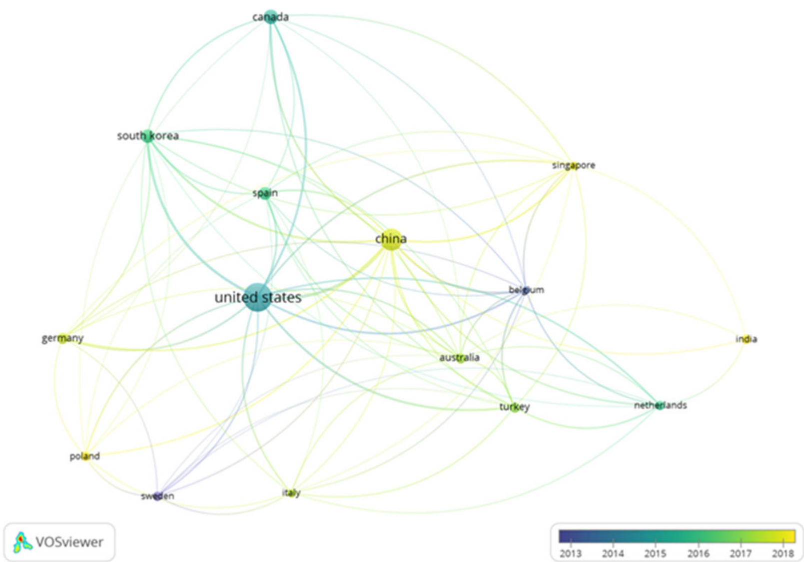

Figure 7. Overlay visualization of the countries included in the top 10 ranking lists.

Table 3. List of the leading five countries in terms of the publication count, total citations, and average normalized citations.

Position	Country	Number of Documents	Total Citations	Normal Citations	Average Citations	Average Normailzed Citations
Publication count						
1	United States	89	5790	108.2587	65.0562	1.2164
2	China	56	2234	73.9738	39.8929	1.321
3	Canada	26	767	21.4767	29.5	0.826
4	South Korea	25	996	22.433	39.84	0.8973
5	Spain	21	578	17.6773	27.5238	0.8418
Total citations						
1	United States	89	5790	108.2587	65.0562	1.2164
2	China	56	2234	73.9738	39.8929	1.321
3	Australia	15	1092	25.9684	72.8	1.7312
4	Netherlands	12	1073	18.2619	89.4167	1.5218
5	South Korea	25	996	22.433	39.84	0.8973
Average normalized citations						
1	Australia	15	1092	25.9684	2017.1333	72.8
2	Netherlands	12	1073	18.2619	2015.8333	89.4167
3	Singapore	11	429	14.7389	2017.7273	39
4	China	56	2234	73.9738	2017.6429	39.8929
5	Belgium	10	785	13.1196	2013.4	78.5

- Authors mapping

Authors with a minimum number of five documents were identified, resulting in a total of nine authors, with eight of them being connected and represented in the network visualization in Figure 8 in terms of total citations. Two clusters can be identified, denoted by the red (Cluster 1) and green (Cluster 2) colors, with five and three in each one, respectively. Based on the graphical description of the active authors, the larger size of the circles of Liu Y. denotes a stronger influence in terms of the number of documents. Table 4 summarizes the top five authors in terms of their publication count, total citations, and average normalized citations, and it includes six authors in total. Ersahin M.E. is included only in the ranking of total documents; Logan B.E. is included both in the total citations and average normalized citations; finally, Liu Y., Gu J., Zhang X., and De Clippeleir H. are in the three rankings and are thus considered the most influential authors. The themes analyzed by these authors are centered on opportunities, through technology, for achieving energy-efficient sewage treatment by minimizing energy consumption, for example, using nitrogen removal by anaerobic treatment or an integrated anaerobic moving bed biofilm reactor (AMBBR) and integrated fixed-biofilm and activated sludge sequencing batch reactor (IFAS-SBR) process. Another example is the recovery of energy from sludge by applying anaerobic digestion or nutrient removal using microbial fuel cell techniques.

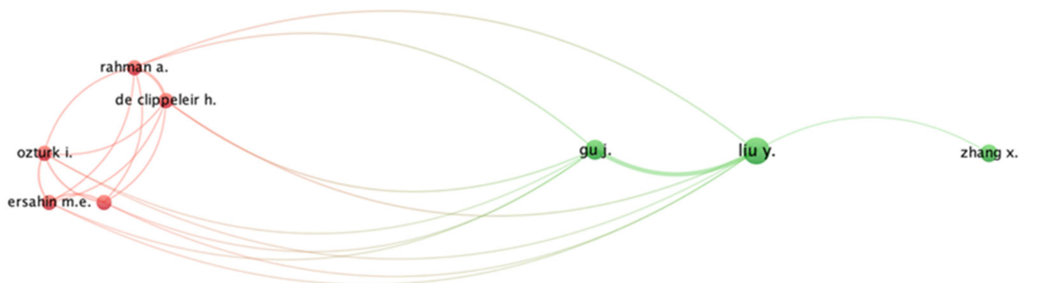

Figure 8. Network visualization of authors with a minimum number of five documents and connections between them denoting total citations.

Table 4. List of ranking countries in terms of publication count, total citations, and average normalized citations.

Position	Author	Number of Documents	Total Citations	Normal Citations	Average Citations	Average Normailzed Citations
			Publication count			
1	Liu Y.	14	667	22.1932	47.6429	1.5852
2	Gu J.	8	412	14.0843	51.5	1.7605
3	Zhang X.	6	366	10.4878	61	1.748
4	De Clippeleir H.	5	239	5.2834	47.8	1.0567
5	Ersahin M.E.	5	127	3.9343	25.4	0.7869
			Total citations			
1	Logan B.E.	5	758	7.3728	151.6	1.4746
2	Liu Y.	14	667	22.1932	47.6429	1.5852
3	Gu J.	8	412	14.0843	51.5	1.7605
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To analyze the collaboration between authors, the mapping of co-authorship by authors with a minimum of 3 documents and 10 citations per author was carried out. Figure 9 shows the large number of small collaboration groups in which the 78 identified authors are working; it is possible to highlight the greater collaboration network that includes clusters in the red, green, purple, and yellow colors and 32 authors. With the objective of identifying this collaboration in terms of countries, the mapping of co-authorship by countries with a minimum of 10 documents (Figure 10) was developed, resulting in 15 countries that work together in the studied research field. Important collaborations between countries, which include four scientific communities, were identified, highlighting the one in the red color, with six countries, including Poland, Germany, Spain, Belgium, the Netherlands, and Sweden.

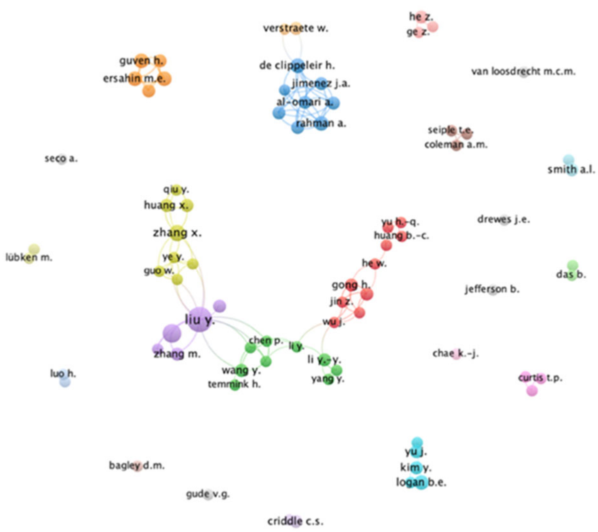

Figure 9. Network visualization co-authorship by authors with a minimum of 3 documents and 10 citations.

Figure 10. Network visualization co-authorship by countries with a minimum of 10 documents.

- Articles mapping

Tables 5 and 6 summarize the list of top 10 documents in terms of total citations and normal citations, respectively, including a total of 16 documents, reflecting the documents with the highest impact in the research field. Only four of them are included in both rankings; therefore, they could be considered the four papers with the highest contribution to the research field. These documents have been published in 11 journals, highlighting *Bioresource Technology* and *Water Research*, with four and three papers published, respectively, and both journals were identified as the most relevant in sources mapping. On the other hand, 8 of the 16 papers included in both of the top 10 document rankings belong to the second subperiod or active phase with relative growth, 6 of them to the third one, and only 2 of them to the initial phase. Finally, the titles of the papers show different themes related to the research field and include WtE technologies as anaerobic treatments, biofuel production, microbial fuel cells, or biomass from algae mass cultivation integrated in wastewater treatment.

Table 5. List of top 10 documents in terms of total citations.

Position	Documents	Authors	Total Citations	Normal Citations	Publication Year	Journal
1	Characterization of a microalga *Chlorella* sp. well adapted to highly concentrated municipal wastewater for nutrient removal and biodiesel production	Yecong Li, Yi-Feng Chen, Paul Chen, Min Min, Wenguang Zhou, Blanca Martinez, Jun Zhub, Roger Ruan	540	6.0923	2011	Bioresource Technology 102(8), 5138–5144
2	Sewage sludge as a biomass resource for the production of energy: Overview and assessment of the various options	Wim Rulkes	400	2.9718	2008	Energy Fuels, 22(1), 9–15
3	Perspectives on anaerobic membrane bioreactor treatment of domestic wastewater: A critical review	Adam L. Smith, Lauren B. Stadler, Nancy G. Love, Steven J. Skerlos, Lutgarde Raskin	316	3.4548	2012	Bioresource Technology 122, 149–159
4	Maximum use of resources present in domestic "used water"	Willy Verstraete, Pieter Van de Caveye, Vasileios Diamantis	309	1.7557	2009	Bioresource Technology 100(23), 5537–5545
5	Effectiveness of domestic wastewater treatment using microbial fuel cells at ambient and mesophilic temperatures	Youngho Ahn, Bruce E. Logan	303	2.3858	2010	Bioresource Technology, 101(2), 469–475
6	Long-term performance of liter-scale microbial fuel cells treating primary effluent installed in a municipal wastewater treatment facility	Fei Zhang, Zheng Ge, Julien Grimaud, Jim Hurst, Zhen He	240	4.3478	2013	Environmental Science Technology, 47(9), 4941–4948

Table 5. *Cont.*

Position	Documents	Authors	Total Citations	Normal Citations	Publication Year	Journal
7	Platforms for energy and nutrient recovery from domestic wastewater: A review	D.J. Batstone, T. Hülsen, C.M. Mehta, J. Keller	237	4.933	2015	Chemosphere, 140, 2–11
8	Experimental determination of energy content of unknown organics in municipal wastewater streams	Ioannis Shizas, David M. Bagley	224	1.0000	2004	Journal of Energy Engineering, 130(2)
9	Energy capture from thermolytic solutions in microbial reverse-electrodialysis cells	Roland D. Cusick, Younggy Kim, Bruce E. Logan	212	2.3178	2012	Science, 335 (6075), 1474–1477
10	Autotrophic nitrogen removal from low strength waste water at low temperature	Tim L.G. Hendrick, Yang Wang, Christel Kampman, Grietje Zeeman, Hardy Temmink, Cees J.N. Buisman	189	2.0663	2012	Water Research, 46(7), 2187–2193

Table 6. List of top 10 documents in terms of normal citations.

Position	Documents	Authors	Total Citations	Normal Citations	Publication Year	Journal
1	Characterization of a microalga *Chlorella* sp. well adapted to highly concentrated municipal wastewater for nutrient removal and biodiesel production	Yecong Li, Yi-Feng Chen, Paul Chen, Min Min, Wenguang Zhou, Blanca Martinez, Jun Zhub, Roger Ruan	540	6.0923	2011	Bioresource Technology 102(8), 5138–5144
2	Recent progress on biodiesel production from municipal sewage sludge	Xiaoyan Liu, Fenfen Zhu, Rongyan Zhang, Luyao Zhao, Juanjuan Qi	26	5.6522	2021	Renewable and Sustainable Energy Reviews, 135, 110260
3	One-year operation of 1000-L modularized microbial fuel cell for municipal wastewater treatment	Peng Liang, Rui Duan, Yong Jiang, Xiao Yuan, Zhang Yong Qiu, Xia Huang	160	5.4194	2018	Water Research, 141, 1–8
4	Platforms for energy and nutrient recovery from domestic wastewater: A review	D.J. Batstone, T. Hülsen, C.M. Mehta, J. Keller	237	4.933	2015	Chemosphere, 140, 2–11
5	Hydrochar derived from municipal sludge through hydrothermal processing: A critical review on its formation, characterization, and valorization	Huan Liu, Ibrahim Alper Basar, Ange Nzihou, Cigdem Eskicioglu	21	4.5652	2021	Water Research, 199, 117186
6	Long-term performance of liter-scale microbial fuel cells treating primary effluent installed in a municipal wastewater treatment facility	Fei Zhang, Zheng Ge, Julien Grimaud, Jim Hurst, Zhen He	240	4.3478	2013	Environmental Science Technology, 47(9), 4941–4948

Table 6. *Cont.*

Position	Documents	Authors	Total Citations	Normal Citations	Publication Year	Journal
7	Revealing the role of adsorption in ciprofloxacin and sulfadiazine elimination routes in microalgae	Peng Xie, Chuan Chen, Chaofan Zhang, Guanyong Su, Nanqi Rena, Shih-Hsin Ho	69	4.2427	2020	Water Research, 172, 115475
8	COD capture: a feasible option towards energy self-sufficient domestic wastewater treatment	Junfeng Wan, Jun Gu, Qian Zhao, Yu Liu	154	3.8933	2016	Scientific Reports, 6, 25054
9	Towards a sustainable paradigm of waste-to-energy process: Enhanced anaerobic digestion of sludge with woody biochar	Yanwen Shen, Jessica L. Linville, Patricia Anne A., Ignacio-de Leon, Robin P. Schoene, Meltem Urgun-Demirtas	130	3.2865	2016	Journal of Cleaner Production, 135, 1054–1064
10	Municipal wastewater sludge as a sustainable bioresource in the United States	Timothy E. Seiple, André M. Coleman, Richard L. Skaggs	110	3.2673	2017	Journal of Environmental Management Volume, 197, 673–680

3.3. Stage 3. Evolution of the Research Field

Keywords of a document represent the core content of the considered article within the relevant domain of knowledge [29]; therefore, their analysis is a way to recognize and indicate the essential areas of the research field [24]. In this case, the keywords analysis was developed with VOSviewer in terms of keywords co-occurrence and SCIMAT to analyze the evolution of themes using overlay graphs and strategic and thematic diagrams. The results are analyzed and discussed below.

3.3.1. Keywords Co-Occurrence

The co-occurrence of the authors' keywords, which take into account synonyms, various spellings, and plurals, was done using the full counting method, which means that each co-occurrence link has the same weight. Of the 798 keywords that resulted from merging the different variants of keywords, 52 met the threshold. For each of the 52 keywords, the total strength of the co-occurrence links with other keywords was calculated and a minimum of five occurrences were used for the keyword analysis, resulting in the five clusters in Figure 11 in the colors red (Cluster 1), green (Cluster 2), blue (Cluster 3), yellow (Cluster 4), and purple (Cluster 5). The most relevant characteristics in terms of influential keywords, theme assigned, and average normal citation of each cluster are summarized in Table 7. To summarize the relevant characteristics, firstly, the terms with the highest average normal citation in each cluster were selected and the clusters were separated into the principal theme according to their keywords; then, an average number was obtained for the average publication year as well as for the average normalized citation of each cluster.

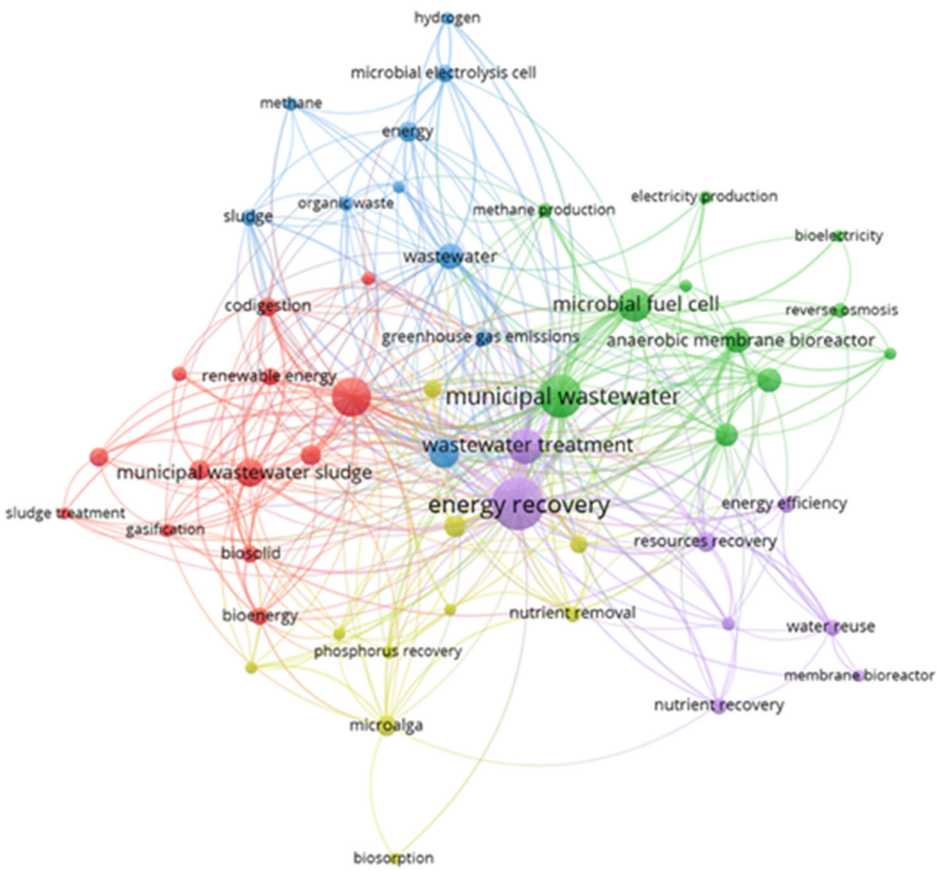

Figure 11. Network visualization of the authors' index keywords with a minimum of five occurrences in terms of average citations.

Table 7. Description of keyword clusters in terms of number and influential keyword, theme assigned, and average normal citation of the cluster.

Cluster Number	Color	Number of Keywords	Influential Keywords		Theme Assigned	Average Publication Year	Average Normal Citations
			Keyword	Average Normal Citations			
1	Red	13	Bioenergy	1.3821	Application of anaerobic process	2016.4141	0.9355
2	Green	11	Electricity production	1.4127	Bioelectricity from wastewater treatment plants	2016.6438	1.0792
3	Blue	10	Energy	1.5025	Energy from wastewater treatment plants	2014.5849	0.9567
4	Yellow	10	Biorefinery	1.8614	Wastewater plants as urban biorefinery	2016.3955	1.3160
5	Purple	8	Nutrient recovery	1.2602	Circular economy in wastewater treatment plants	2017.0926	0.8317

The analysis of the cluster characteristics shows that the most relevant are clusters 4 (yellow) and 2 (green), with 1.3160 and 1.0792 average normal citations values, 10 and 11 keywords assigned, an average publication year of 2016, and the assigned themes being wastewater plants as urban biorefinery and bioelectricity from wastewater treatment plants, respectively. Both biorefinery and bioelectricity are emerging concepts that have been under research and development over the last decades, coinciding with increased restrictions in environmental regulations regarding the elimination of micropollutants and gas emissions, and sludge management [30]. These terms continue to evolve to be applied for wastewater treatment plants as a solution to generate the highest benefit from these facilities and represent a step forward to pave the way for a bio-based circular economy and the obtaining of bio-based chemicals, biofuels, bioenergy, and food [31]. Thus, moving towards a circular economy, WWTPs are now conceived as biorefineries because both wastewater and residues from them can be valorised for recovering nutrients, and producing value-added products, energy vectors, and biofuels [15]. Although the sizes of the circles of keywords in cluster 4 are similar, they are slightly larger in the case of *microalga*, in reference to a bio-treatment that is particularly attractive because of their photosynthetic capabilities, converting solar energy into useful biomasses and incorporating nutrients such as nitrogen and phosphorus, causing eutrophication [32]. This technology, in the context of biorefineries, presents several challenges, as the growth of microalgae requires large amounts of carbon, nitrogen, and phosphorus [33], thus having high harvesting, pre-treatment, and microalgal purification costs [34]. However, the use of microalgae has been shown to have significant advantages, as it reduces emissions and leads to energy savings compared to conventional processes [35]. On the other hand, bioelectricity is a renewable and sustainable electricity produced from biomasses [36]. The most recent promising technology for the recovery of energy from wastewater includes *microbial fuel cells* (MFCs), a bioelectrochemical system (BES) that shows simultaneous power production while treating wastewater, and microbial electrolysis cells (MECs) that recover energy as biogas by treating wastewater [37]; in fact, microbial fuel cell is one of the keywords with the highest co-occurrence value, according to its circle size in Figure 11. Although this technology is still in its infancy and must be tested on an industrial pilot scale and in natural wastewater [38], it promises to cut the costs of wastewater management in the future through the production of hydrogen and other fuels [39]. Finally, Cluster 5 (purple), identified with circular economy in wastewater treatment plants, had the most recent average publication year and includes *energy recovery* as the keyword with a higher co-occurrence value, revealing that municipal wastewater treatment plants play an important role due to the integration of energy production [29,32].

Finally, the only waste from wastewater treatment for which its treatment has been studied in depth has been sludge, which shows the largest volume amongst all the components removed during the process [40]. Technologies based on sludge anaerobic digestion are considered to be economical and environmentally-friendly methods for treating municipal wastewater sludge [41], and they have been identified in different clusters with keywords such as *methane*, *gasification*, and *methane production*, revealing the largest number of researchers related to this theme, as well as the greatest consolidation of the technology, with more than 1000 anaerobic digestion systems based on sewage sludge in operation or under construction throughout the world [40]. Nevertheless, some studies have reported poor efficiency and long processing times for anaerobic digestion [42–44]. As an alternative, the application of thermochemical techniques to WWTP sludge has been studied in recent years [45]. Processes such as incineration, gasification, or pyrolysis can improve the efficiency and profitability of sludge through the production of syngas, bio-oil, or char, and their various applications.

The absence of keywords that address the treatment of screening waste, from the point of view of obtaining energy, as a viable alternative to its current landfill disposal [15,18,35] shows the low interest in this type of waste because it has historically been an unrepresented part of the waste generated compared to sludge [46]. In fact, only some works have dealt with the possible application of anaerobic digestion [15–18], and they have reported difficulties in the process because of the presence of plastics and textiles [31] and a low methane production yield because it requires higher biomass concentrations [15]. However, the higher fraction of sanitary textiles and other fractions, such as paper and cardboard, vegetables, and plastics, translate into a lower calorific value and low values on the chlorine and mercury contents; therefore, it could be considered suitable to produce solid fuel recovered for energy recovery in thermochemical processes [46]. At this point, as for sludge, the application of processes such as gasification or pyrolysis is considered a necessary field of study for screening waste.

3.3.2. Evolution of Research Themes Field

The evolution of topics over time in the research field has been studied using overlay graphs, thematic evolution maps, and strategic diagrams. All of these were generated with SciMAT.

The overlay graph was used for a preliminary approximation to know the dynamics of changes in the themes across the horizon time [21]. As seen in Figure 12, the number of keywords of different periods, which is included in circles, increases from one period to the next one; in fact, the greatest increase is observed from the initial to the active phase in terms of relative growth (first to second subperiod), with an increase of 358% in comparison to the growth from the increment to the active phase, with growth (second and third subperiod) of 47.34%. In relation to the stability across the different periods, the analysis of the horizontal arrows, which represent the number of keywords shared by both subperiods, and the upper-incoming and upper-outcoming arrows of each one, which represent the number of new keywords in each period, shows the important renewal of terms related to the novelty of the field, which was much larger in the second period, with 89.25% of new keywords; in fact, the Stability Index is lower (0.1) than in the case of the third subperiod, which shows 68.8% of new keywords. Accordingly, with the yearly publication trend, and although the third subperiod showed a very significant growth of the research field because of the possibility of applying WtE technologies according to policies to develop circular economy practices, in the second subperiod, the development of technologies to produce energy from waste began to grow faster. Therefore, the foundations for the technological development of solutions to obtain energy from waste were laid, and coincided with the approval of the Directive 2008/98/EC, which reinforced the waste hierarchy and boosted WtE technologies development.

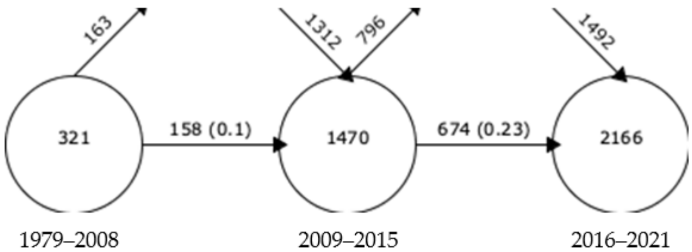

Figure 12. Overlay graph of the research field.

Figure 13 shows the thematic evolution maps of the research field in terms of the number of documents. Their analysis leads to the following:

- None of the themes remained unchanged during all subperiods and only two were changed during two of them; this is the case for WASTEWASTER TREATMENT PLANTS and MEMBRANE. Both of them were included in the second and third subperiods. These results are in accordance with the great renovation in the themes of interest discussed in the overlay graph. In fact, it is clear that the evolution of WtE technologies in wastewater treatment plants, beginning with the anaerobic process (ANAEROBIOSIS), have been extensively applied throughout the world [40], for example, in recent years, the application of technologies to produce bioenergy such as MICROBIAL FUEL CELLS.
- Some areas of the research field present great cohesion given that some of the identified themes are connected, with high thickness of the edges in many cases. For example, RECYCLING, in the first period, shows a large number of connections with themes in the second period, including WASTEWATER, ANAEROBICS, BIOELECTRIC ENERGY SOURCE, WASTEWATER TREATMENT PLANT, and RECOVERY. WASTEWATER, in

the second period, showed connections with the following themes in the third period, BIOREACTOR, MICROBIAL FUEL CELLS, WASTEWATER TREATMENT PLANTS, MEMBRANE, and CARBON. These results reveal the potential of waste [32,47].

- However, other areas of the research field present a lower cohesion, not connecting with other ones, for example, SUSTAINABILITY, or with a low number of them; this is the case for BOD (biological oxygen demand) and WASTEWASTER MANAGEMENT, which are only connected with CARBON and WASTEWATER, respectively. These results mean that they could be considered as the beginning of a new thematic area [21], for example, as with SUSTAINABILITY, which appears in the last subperiod. The themes are now well described by keywords and it is not possible to detect their connections with others, for example, as with the theme BOD or CARBON. Some of the themes were connected with many thematic areas and it was difficult to categorize them [21], for example, as with the themes WASTEWATER MANAGEMENT and WASTEWATER.
- The solid line reveals that the connected themes are labelled with the same keywords or the label of one them is part of the other one [21], i.e., WASTE MANAGEMENT and WASTEWATER TREATMENT PLANTS or RECYCLING and RECOVERY. All of these keywords are related with the waste management concept and principles. A larger number of dotted lines is observed, meaning that the themes connected with them shared elements that are not the name as the themes they are connected to, i.e., RECYCLING and ANAEROBICS, GREEN HOUSE GASES, WASTEWATER TREATMENT PLANTS, and ENERGY RECOVERY and ANAEROBICS, sharing different themes related not only with the treatment of waste produced in wastewater treatment facilities but also with energy production or the positive effects in terms of greenhouse gas reduction.

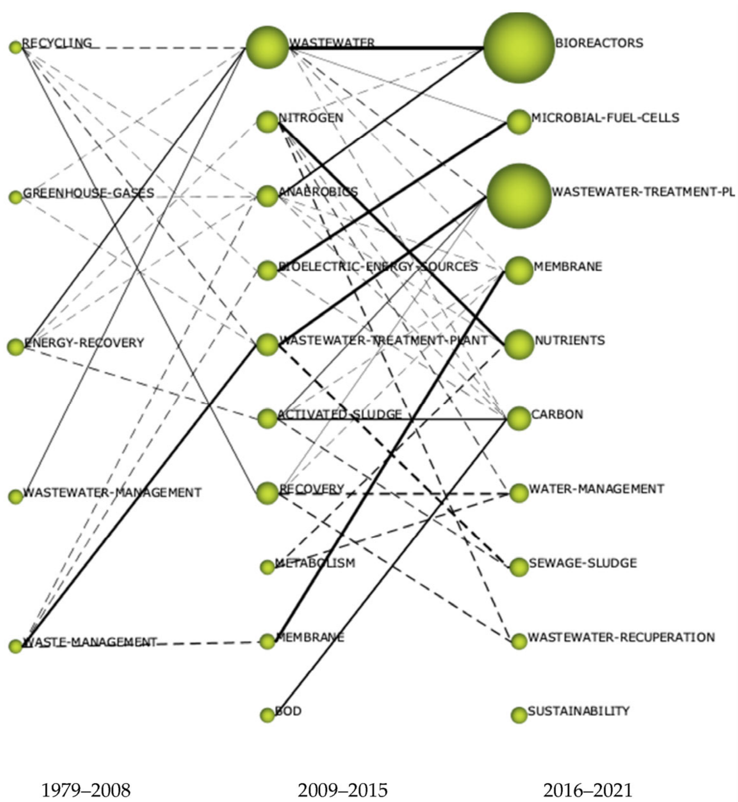

Figure 13. Thematic evolution map of the research field in terms of number of documents.

Strategy diagrams for each subperiod were generated with SciMAT to show the performance of the evolution of research topics in terms of the number of documents published.

These diagrams are included in Figure 14, and the quantitative and impact measures used to analyze each one is shown in Table 8. The numbers of transversal themes to the scientific field and highly-developed and isolated themes, located in the lower right and upper left quadrants, respectively, are very low; thus, in the case of transversal themes, only WASTE MANAGEMENT appears in the first subperiod, ACTIVATED SLUDGE and RECOVERY appear in the second one, and CARBON appears in the last one. On the other hand, only four isolated themes were identified along the horizon time, specifically, GREEN HOUSE GASES in 1979 to 2008 and BIOELECTRIC ENERGY SOURCES and METABOLISM in 2009 to 2015. None of the themes are included in the last subperiod. Motors themes, in the upper right quadrant, are shown to be well-developed and essential themes in the field and include RECYCLING and ENERGY RECOVERY in the first subperiod; WASTEWATER, NITROGEN, and ANAEROBICS, in the 2nd subperiod, and finally BIOREACTORS, NITROGEN, MEMBRANE, and WASTEWATER TREATMENT PLANT in the third subperiod. In the case of WASTEWATER TREATMENT PLANT, which is just on the border of the four quadrants in the second period, it has evolved to be included in motor themes in the last one. The lower-left quadrant includes emerging or declining research topics, which lack development and relevance, although they may evolve and be relevant or disappear; in this group, the theme WASTEWATER MANAGEMENT is the only one that appears in the first subperiod; MEMBRANE and BOD are in the second one, and SUSTAINABILITY, WASTEWATER RECUPERATION, and SEWAGE SLUDGE are in the third subperiod. In this case, the theme MEMBRANE has evolved from being an emerging theme to motors themes from the second to the third subperiod. Finally, in the last subperiod, both MICROBIAL FUEL CELLS and WATER MANAGEMENT are on the border of the two quadrants, specifically, between isolated and motor themes, and emerging and isolated, respectively.

Finally, Table 8 summarizes the performance measures of the themes by subperiod, and it complements the information displayed in Figure 14. A higher centrality value shows a higher importance of a theme in the development of the entire research field analyzed [48]. WASTEWATER, in the second subperiod, shows the higher centrality value (949.03), followed by BIOREACTORS and WASTEWATER TREATMENT, both in the third subperiod, with centrality values of 708.8 and 457.24, respectively. High centrality values are related to the importance of these themes with the global development of the analyzed scientific field, as well as the higher degree of their external cohesion. On the other hand, and according to the concept of density, RECYCLING is the theme with the strongest strength of internal ties among all keywords describing the research theme, indicating that it has a higher level of development [48]. These results are related to the fact that anaerobic digestion of municipal wastewater sludge, which results in the production of a biogas and of a digestate, and is regarded by Directive 98/2008 for waste as a recycling operation, is a widely-applied technology to produce energy from waste produced in wastewater plants.

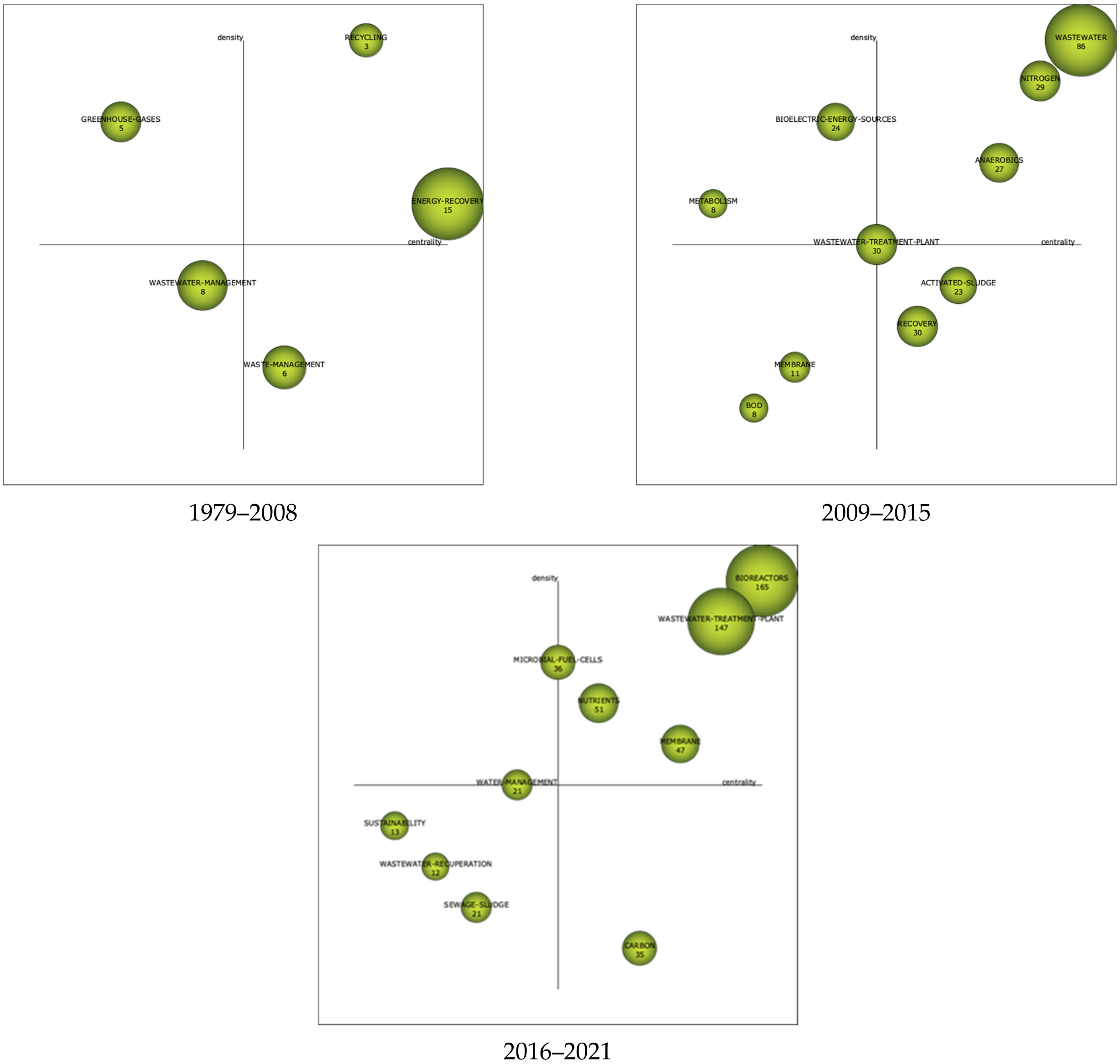

Figure 14. Strategy diagrams in terms of the number of documents published.

Table 8. Performance measures for the themes for subperiods of the time horizon.

Theme Name	Number of Documents	h-Index	Average Citations	Number of Citations	Centrality	Density
			1979–2008			
RECYCLING	3	3	71	213	192.43	169.31
GREENHOUSE-GASES	5	5	81.4	407	98.53	84.67
ENERGY-RECOVERY	15	14	97.13	1457	296.44	79.32
WASTEWATER-MANAGEMENT	8	8	88	704	103.73	73.53
WASTE-MANAGEMENT	6	5	62.17	373	117.7	35.37

Table 8. *Cont.*

Theme Name	Number of Documents	h-Index	Average Citations	Number of Citations	Centrality	Density
2009–2015						
WASTEWATER	86	43	80.5	6923	949.03	124.56
NITROGEN	29	26	105.38	3056	309.45	68.04
ANAEROBICS	27	21	84.93	2293	276.42	51.33
BIOELECTRIC-ENERGY-SOURCES	24	21	107.08	2570	151.5	54.11
WASTEWATER-TREATMENT-PLANT	30	21	60.77	1823	223.87	40.49
ACTIVATED-SLUDGE	23	20	123.22	2834	252.22	20.92
RECOVERY	30	23	88.07	2642	230.09	19.89
METABOLISM	8	8	58.38	467	39.59	42.44
MEMBRANE	11	9	83.45	918	56.25	16.96
BOD	8	8	62.5	500	47.18	16.53
2016–2021						
BIOREACTORS	165	39	25.61	4226	708.8	134.33
MICROBIAL-FUEL-CELLS	36	20	31.5	134	86.24	41.01
WASTEWATER-TREATMENT-PLANT	147	36	25.24	3711	457.24	60.28
MEMBRANE	47	20	24.85	1168	188.78	29.95
NUTRIENTS	51	22	26.82	1368	128.45	35.54
CARBON	35	17	24.89	871	150.82	9.63
WATER-MANAGEMENT	21	12	26.95	566	56.93	25.4
SEWAGE-SLUDGE	21	13	27.43	576	53.02	12.4
WASTEWATER-RECUPERATION	12	9	32.42	389	40.12	15.48
SUSTAINABILITY	13	10	22.31	290	10.76	23.11

4. Conclusions

Research trends in waste to energy from municipal wastewater treatment plants were analyzed from the publication of the first paper in the research field in 1979 to 2021. The results show an exponential increase in the number of papers that, although it has been aborded from years, has not yet reached a stage of maturity because of the important roles that the circular economy paradigm and energy sustainability are playing nowadays in the transformation of wastewater treatment plants toward biorefineries.

A low concentration of documents per source, country, and author was observed, which indicates the great interest in the field. On the other hand, the leading journals are in the environmental science and environmental engineering categories, meaning that the analysis of the research field both from a scientific and technological perspective is necessary to address challenges in sustainability and circular economy. In fact, the research field presents a great cohesion in topics related to technologies to produce energy from the waste of wastewater treatment plants. Finally, although China leads the rankings in the research field, co-authorship analysis showed important collaborations between countries, as well as small collaborative groups of authors.

The analysis of the evolution of themes shows the novelty of the topics with an important incoming and outcoming of keywords since 1979, which is also reflected in the different themes of the thematic evolution maps. In this sense, studies on energy from wastewater treatment have focused on energy from sludge, mainly in anaerobic digestion processes. However, no significant presence of thermochemical processes applicable to sludge, such as combustion, gasification, or pyrolysis, was detected. Emerging technologies such as microalgae, microbial fuel cells, and the use of membrane technologies, all of them directed to the consolidation of the concept of biorefinery according to circular economy principles, are at an early stage. Thus far, they can only be considered as potential alternatives, as their implementation at the industrial level has yet to be studied. Research should focus on the reduction of the cost of these processes, along with improving efficiency in producing biofuel and bioelectricity.

Scientific mapping shows how other waste fractions, such as primary screening waste, have yet to be considered in the literature. In the detailed analysis of the publications on this waste, only anaerobic digestion processes were found, which, unlike their sludge application, could not be successfully developed due to the exact composition of the screening. To achieve zero waste in municipal wastewater facilities, it is considered necessary to open new lines of research to valorize the screening waste.

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