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REVIEW ARTICLE

An overview of agro-food industry wastewater treatment: a bibliometric analysis and literature review

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Abstract

Agro-food (AF) industry provides great investment opportunities in its treated water and solid wastes, by conversion into value-added products. Our study accumulated extensive bibliometric data on this field from the Scopus database, between 1974 and 2021, and conducted a scientometric analysis using Science Mapping Analysis Software Tool (SciMAT) and VOSviewer for analyzing the retrieved data. The leading journals, highly used keywords in the published articles, authors and papers with the highest citations, and relevant regions were all identified in the scientometric analysis. Goal 6 of the Sustainable Development Goals (SDGs) pledge to "ensure the availability and sustainable access to water and sanitation for all." To fulfill this demand, decentralized technologies are being developed. The scientometric analysis found significant flaws in previous studies on the adoption and use of decentralized treated AF wastewater, as well as its potential benefits for a sustainable future, particularly in the developing countries. Coagulation/electrocoagulation/ultrasonic processes, hybrid constructed wetlands and microbial inoculation are emerging efforts to achieve SDG6, particularly, in the emerging economy nations. Our scientometric findings can help academics collaborate on research, form joint ventures, and implement sophisticated technologies for treating AF wastewater and producing beneficial byproducts.

Keywords Agro-food wastewater · Bibliometric analysis · Decentralized treatment · Microbial inoculation · Value-added products · Construction material

Introduction

Over the last few decades, there is a gradual shift of wastewater treatment systems toward resource—recovery systems (Sutton et al. 2011). The 2030 agenda for Sustainable Development has made it a priority to increase water productivity by 50%, in all sectors, by implementing a water demand management strategy and increasing safe wastewater reuse. In this context, agro-food, AF, industries is one of the largest water users and wastewater producers among

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all sectors (Valta et al. 2015), (Mavrov and Bélières 2000). This large amount of wastewater results from the processing of raw food sources, washing, heating and cooling stages of its use. According to the published data, the industrial sectors consume 4 trillion m^3 of water each year, whereas clean water for daily human consumption is estimated to be approximately 0.01 trillion m^3/day (Walsh et al. 2016).

Despite its wide range of quantity and quality of the pollutants, related to the kind of AF industry (e.g., fruit juices, dairy products, table oils, vegetables, meat processing, etc.) and the size of production (e.g., small and large scale; local or global production), wastewater differs greatly from other forms of industrial wastewater in that it is easily degradable and usually free of toxicity; it contains significant levels of biological oxygen demand (BOD) and suspended solids (Sehar and Nasser 2019), in addition to nitrogen in various chemical forms, fats and oils, phosphorus, chlorides (Sehar and Nasser 2019; Rajagopal et al. 2013); . The organic content, specific characteristics and usable nutrients from agro-food wastewaters range from low strength wastewater such as wash water from sugar mills and dairy effluents (Slavov 2017) to high-strength wastewater such as meat processing and oil mills (Sun et al. 2012), providing great investment opportunities in its wastes which may be converted into value-added products for industrial purposes.

Industrial wastewater treatment in centralized systems is a challenge to offer consistently and affordably in many parts of the world, especially in developing countries. Due to the huge differences in complexity and concentrations of pollutants originating from various industries, centralized wastewater collection and treatment systems are very expensive to create and maintain (Walsh et al. 2016). In consequence, the decentralized agro-food wastewater treatment, which includes onsite and/or cluster systems, has shown potential benefits to the sustainable future. The special issue by Akratos et al. (2021) illustrated a number of tested decentralized AF wastewater treatment technologies, including physicochemical and biological systems, or hybrid systems including two or more of both approaches, which allowed for management flexibility.

A useful technique for quantifying growth and progress in a certain area of research is provided by bibliometrics. Recent bibliometric techniques have been used in various related research fields, such as treatment of the entire industrial wastewater (Mao et al. 2021), reuse of treated wastewater for agriculture (López-Serrano et al. 2020), costs of the wastewater treatment (Gallego-Valero et al. 2021). However, very few bibliometric analysis have been involved in specified wastewater fields; for example trends of biotreatment linked to patents analysis (Jin et al. 2023), patents related to industrial wastewater treatment (Mao et al. 2022), wastewater treatment costs (Gallego-Valero et al. 2021), treatment using floating wetlands (Colares et al. 2020), treatment of sulfate-rich wastewater (Ding and Zeng 2022) and treatment of rubber wastewater. Yet, there is no bibliometric review about AF wastewater management.

The objective of this study is to collect, synthesize and analyze the available research on agro-food industry wastewater treatment, conduct a scientometric evaluation of the bibliometric data and highlight evolution, current trends, patterns and future lines. It has been also included a review of emerging technologies for decentralized agro-food wastewater resource recovery in order to reduce the pressures of water demand and energy scarcity in emerging economy nations, particularly the developing countries. Scientometric evaluation provides objective criteria for evaluating the work done by researchers (Nunen et al. 2018), as well as macroscopic view of a large amount of research documents (Pritchard 1969). This tool solves the difficulties of manual review studies to obtain valuable and unbiased information for future research as well as to have a comprehensive review integrating a high knowledge of these contributions and provide a critical perspective. As result, this study is an important contribution to the existing body of knowledge by highlighting the trends and patterns in the research field, establishing its research themes, mapping researcher networks and recommending areas for future studies.

Methodology

This paper collects and synthesizes the available research on agro-food industry wastewater treatment to result in the generation of mapping and visualization of various parts of the bibliometric records which identify, among others, sources with the highest publications, keyword co-occurrence, author and countries alliance, the highly cited authors and papers, and locations strongly connected in the research. To do that, it has been necessary to use a scientific database to choose documents in the research field. In this sense, Scopus and Web of Science are two very successful, objective and comprehensive sources for doing publications search; however, the Scopus database has a broader bibliometric scope, and more up-to-date data than Web of Science, and thus the data from the present evaluation were retrieved from Scopus (Aghaei chadegani et al. 2013; Meho 2019).

The Scopus database was searched for bibliometric data in March 2022 using the following search string, according to the combination of keywords: *(food industr* OR agro-food industry OR agro-food industr* OR agro food industr*) AND (wastewater treatment OR waste water treatment OR waste-water treatment)*. To exclude needless records, data refinement approaches were employed. According to the PRISMA flowchart guidelines (Fig. 1), the total number of primary searches for documents in Scopus was 1223; after filtering documents for title and abstract to remove papers

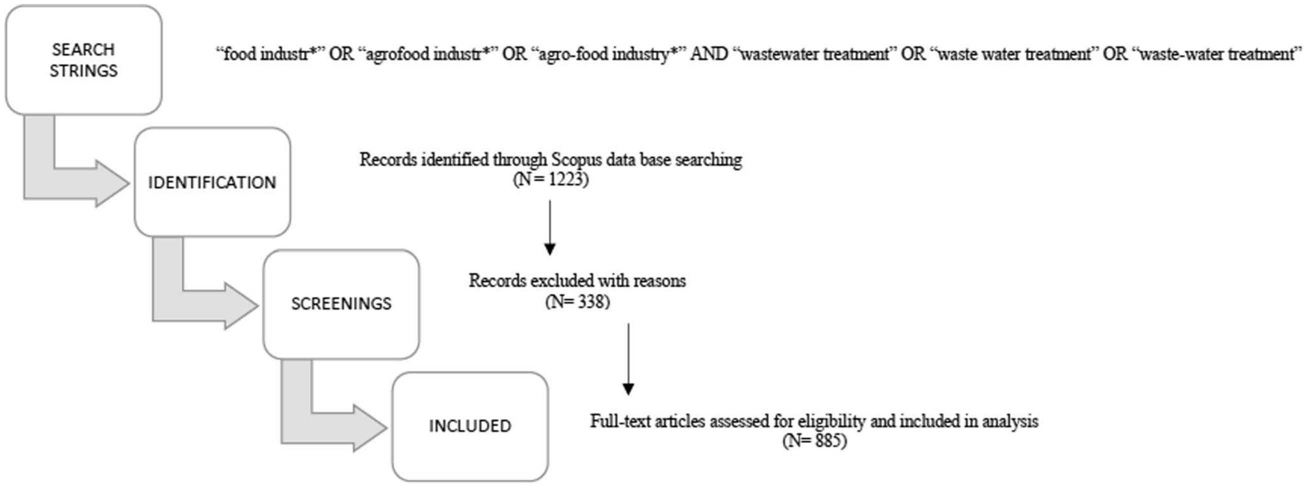


Fig. 1 PRISMA flowchart

published in 2022 or documents which did not fall withing the scope of the review, and to limit the research to journals and conference documents in English, the final number of relevant documents reached was 885.

The resulting papers were stored in two formats, Research Information Systems (RIS) and comma-separated values (CSV) files, for further assessment to be analyzed using Science Mapping Analysis Software Tool (SciMAT) and VOSviewer, respectively, for further analysis of the retrieved data. 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 the steps in science mapping workflow, from preprocessing to the visualization of the results (Cobo et al. 2011). VOSviewer is an open-source software tool freely available and is commonly employed in a range of sectors and is highly recommended by scholars to create maps (Yang et al. 2022).

The scientometric analysis has included: (1) yearly publication trend; (2) science mapping of publication sources, countries, authors and articles; (3) keywords analysis by keywords co-occurrence and strategy diagrams. SciMAT has been applied for yearly publication trend and strategy diagrams generation and VOSviewer for the rest of analysis.

Scientometric analysis results and discussion

The scientometric analysis results and discussion has been developed according to the defined sequence. More relevant results have been analyzed and discussed below.

Yearly publication trend

The publications and citations of the articles relevant to a considered field depicts the developments and patterns in the researches. Consequently, the yearly publication trend, including the accumulated number of papers during the time horizon for the searching strings defined, has been included in Fig. 2a,b, respectively. The first article was found in the year 1974, so the horizon time of this research has been defined from that year to the last available year, that is, 2021. A preliminary analysis of Fig. 2 shows a gradual increase in the number of publications with irregular scientific production with a lower number of accumulated documents until 2000 and a noticeable increase from this date that results on a categorization of the horizon time into the following three subperiods (Fig. 3):

- Initial period. From 1974 to 2000. In this 27 years period 125 documents have been published. Here researches have been conducted on the area of interest, but not yet developed or manifest. In this stage there is fairly a small number of articles. Nonetheless, there is a slight tendency to increase the number of publications up to 1992 after the adoption on of the Council Directive 91/271/EEC concerning urban waste water treatment to protect the water environment from the adverse effects of discharges of urban waste water and from certain industrial discharges. It could be considered that during this period the research on technologies to reduce environmental impacts of wastewater produced during food industry is still in a preliminary stage.
- Development period. From 2001 to 2015. This period includes 15 years, a substantially lower number of years than the first one, however the number of documents increases up to 400. In 2000 the eight international development goals for the year 2015, known as the Millennium Development Goals (MDGs), were adopted by the United Nations. These goals were based on the Cooperation and Economic Development Aid Committee (OECD DAC).

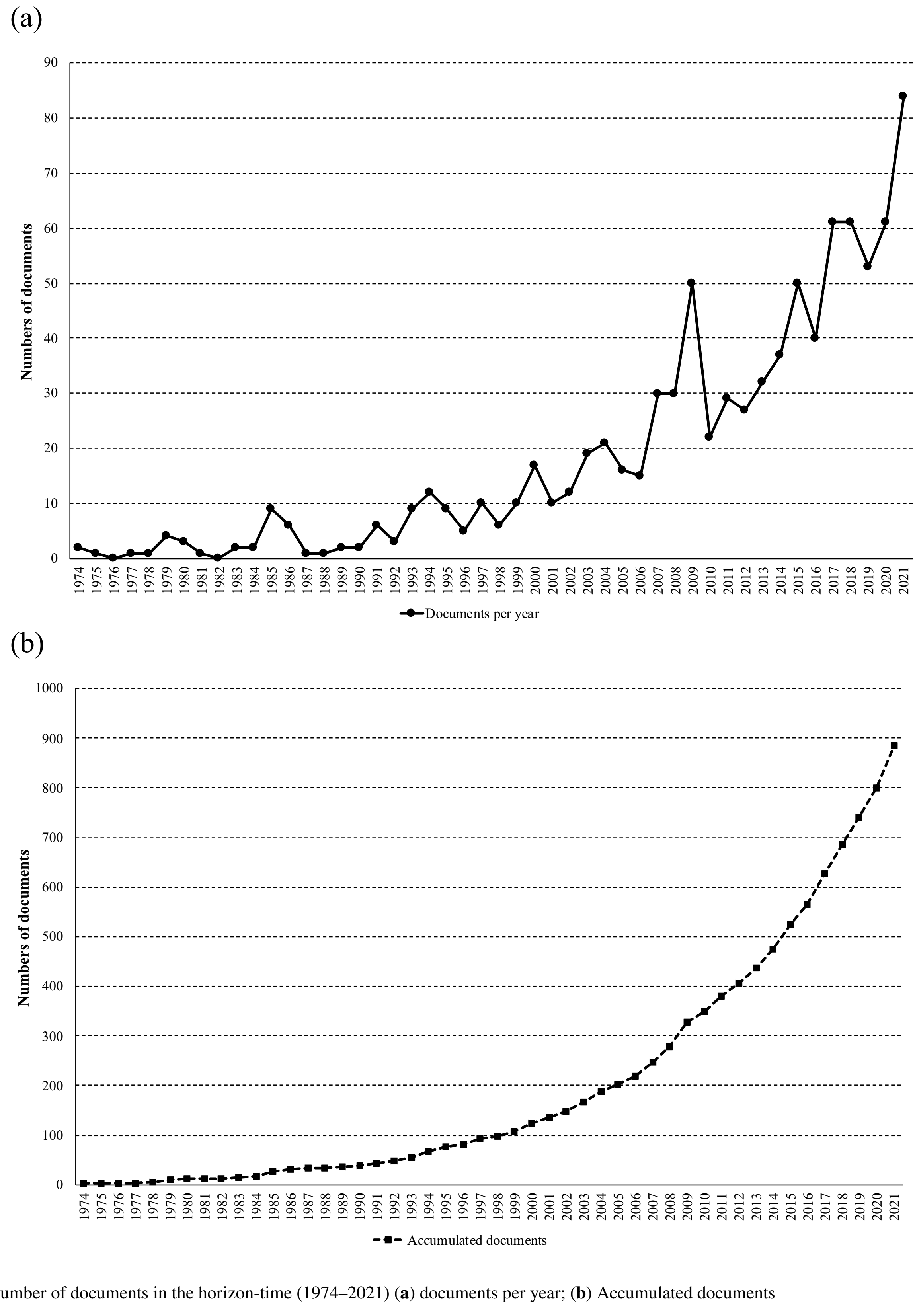


Fig. 2 Number of documents in the horizon-time (1974–2021) (**a**) documents per year; (**b**) Accumulated documents

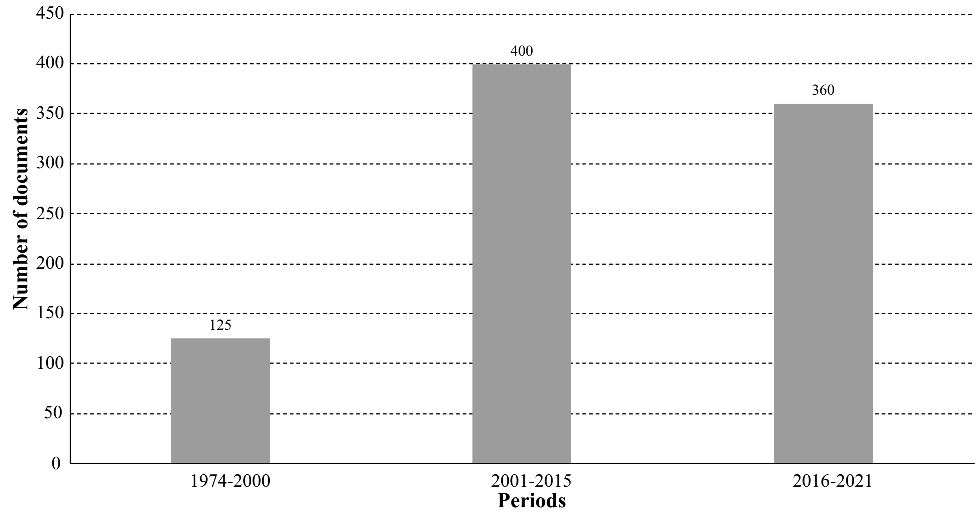


Fig. 3 Number of documents per period

Objective 7 was established to ensure environmental sustainability and it included some targets related with cycle water management, for example integrate the principles of sustainable development into country policies and programs; reverse loss of environmental resources (Target 7A), reduce biodiversity loss, achieving, by 2010, a significant reduction in the rate of loss (Target 7B) and halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation (Target 7C). The significant increase in the number of articles can be seen when compared with the previous phase, according to the increased concern for the environment with an important peak which surpasses the number 50 as the number of articles per year is marked in 2009. From here onwards a decrease is seen in the number of articles per year which is recovered at the end of the period, in 2015.

- Consolidation period 3, from 2016 to 2021, corresponds with the research consolidation in the field, meaning the existence of a knowledge in technologies to treat food industrial wastewater, reached in the development phase, that allows promoting technological development and its wide application. As result, the number of documents has increased up to 360 in only 6 years. This period corresponds with the adoption of the Agenda 2030 and the Sustainable Development Goals (SDGs) by the United Nations, as a universal call to action to end poverty, protect the planet (United Nations 2015). Despite the establishment of the Millennium Development Goals (MDGs) made it possible to achieve important achievements, the Sustainable Development Goals (SDGs) of the 2030 Agenda represent an opportunity to incorporate the lessons learned in the previous process. In consequence, significant measures have been stablished by Governments; for example, in the case of Europe it is possible to highlight the approval of strategies to stimulate Europe's transition toward a circular economy, boost global competitiveness, foster sustainable economic growth and generate new jobs (European Commission 2015, 2020) and the European Green Deal (European Commission 2019). In fact, circular economy practices associated with closed-loop systems for wastewater recycling and reuse, and recycling of sewage sludge will be indispensable to achieve SDG 6 (Clean Water and Sanitation), in particular targets related to Life Below Water (Schröder et al. 2018).

Science mapping

The representation of progress and innovation evaluation is made viable by science mapping. To do that, VOSviewer has been used to develop a mapping of publication sources, authors, documents and countries applying a comprehensive quantitative analysis according to the number of documents and citations for each item, but also in terms of the number of normal citations, average publication year, average citations and average normalized citations (Lwg et al. 2020). Normal citation index is defined as the citations of all the articles within the same journal, author or country; the average publication year is the average publication year of articles in a given journal, country or by a given author; the average citation is the total citations per article in a given journal, country or by a given author; finally, the average normal citation index is the normalized number of citations of a journal, document, author or country and it equals the total number of citations divided by the average number of citations in the same year, and it is used to correct the misinterpretation that the old articles have more time for more citations than the new ones (Kawshalya et al. 2020). Besides, a simple visualization of this quantitative analysis has been developed using VOSviewer resulting in a set of figures in which the size of the node and the size of the font corresponds to the journal, authors, documents and countries number of articles; besides, the thickness and the colors of the linking lines indicate the inter-relatedness among them (Kawshalya et al. 2020; Yang et al. 2022) using a variety of visualization algorithms built in the Sci2 Tool; it is embedded with a variety of database functions and it can load data sets in the different formats to conduct fundamental analysis on Scientometrics, such as co-occurrence analysis and citation analysis, among others (Yang et al. 2022). Results obtained have been discussed below.

Publication sources mapping

A total number of 283 sources have been included in this study. The top 10 publication journals in terms of publication count, total citations and average normalized citations are included in Table 1.

The journal Bioresource Technology leads clearly the Publication count and Total citations rankings with 89 documents and 5283 citations. In the case of the number of documents, Bioresource Technology is followed by Water Science and Technology, with 78 documents published in the field; the second position in total citations ranking is occupied by Desalination, with 3191 citations. Seven of the journals includes in the top 10 ranking in terms of the number of documents are also included in the raking of the sources with higher number of citations, Supplementary S1 (Bioresource technology, Water science and technology, Journal of hazardous materials, Water research, Science of the total environment, Journal of environmental management and Desalination); Environmental technology, Environmental science and pollution research and Waster environment research are sources included only in the top 10 ranking in terms of the number of documents and Journal of Membrane Science, Journal of Chemical Technology and Biotechnology and Chemosphere are included only in the top 10 of more cited journals in the field. Finally, none of the top 10 ranking in terms of average normalized citations collected sources are included in the other top 10 rankings; in fact, these sources have only 1 or 2 papers published in the field; however, the number of citations is really high in a short time. For example, both journals in 1st and 2nd position have 2021 as average publication year, but 123 and 70 citations, respectively, showing the important impact of the documents published.

Figure 4 depicts a network visualization of sources that contain 13 of the 23 of the sources included in the three top 10 rankings defined previously, those one which are connected. The dimensions of the clusters are related to the source's publication count; a bigger dimension signifies more influence. Such as Bioresource technology and Waster science and technology have larger circles sizes than the other journals, indicating that they have a more impact on the research, in terms of number of papers. Additionally, circles with the same color indicate groups of associated sources discovered using VOSviewer analysis. Four groups or clusters were detected, denoted by distinct colors, red, green, blue and yellow, with 4, 3, 3 and 3 items, respectively. Clusters are constructed using the keywords of research outlets or/and the number of times they are co-cited and the connections between sources that are close together are stronger than those amongst clusters that are farther apart (Yang et al. 2022). For example, Bioresources technologies have a stronger connection with Water research and Water science and technology, both of them in cluster 4 that includes journals in water resources field.

Table 1 List of leading 10 sources of publications in terms of publication count

Position	Source	Number of documents	Total citations	Normal citations	Average publication year	Average citations	Average normailzed citations
Publication count							
1	Bioresource technology	89	5283	124.0621	2008	59.3596	1.3940
2	Water science and technology	78	1330	37.9941	2008	17.0513	0.4871
3	Journal of hazardous materials	30	1999	38.9120	2010	66.6333	1.2971
4	Water research	30	1988	53.7540	2004	66.2667	1.7918
5	Science of the total environment	28	794	38.8159	2018	28.3571	1.3863
6	Environmental technology	27	418	16.8600	2010	15.4815	0.6244
7	Journal of environmental management	25	1240	40.1073	2016	49.6000	1.6043
8	Environmental science and pollution research	23	255	12.7897	2018	11.0870	0.5561
9	Desalination	22	3191	47.4319	2004	145.0455	2.1560
10	Water environment research	22	211	5.4560	2007	9.5909	0.2480

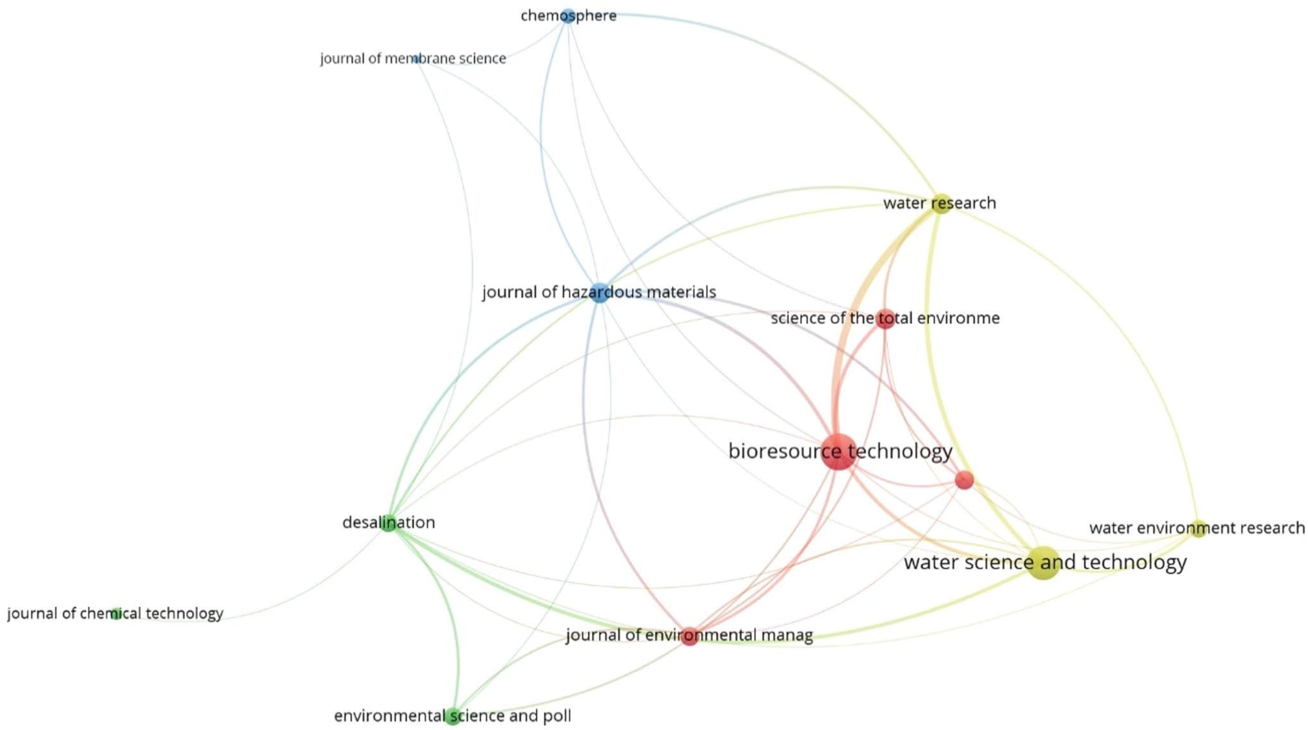


Fig. 4 Network visualization of sources of top 10 connected

Countries mapping

Research on agro-food industry wastewater treatment has included 99 countries, but it is centralized around Spain, both in the number of published documents and in citations with 91 documents and 4237 citations. Other countries that have also focused on this field are India, China and USA with 71, 72 and 81 documents published and 2519, 3121 and 2505 citations, respectively, as well as UK with 2128 citations. When considering the Average Normalized Citations of countries, Singapore, United Arab Emirates, Sweden, Egypt and Australia have an Average Normalized Citations higher than 2 indicating that the articles from these countries have been cited the most irrespective of the time of publication.

Figure 5 illustrates the overlay visualization of the 11 countries included in top 5 rankings of Table 2 based on number of documents. All of them are linked based on citations and the degree to which a country has contributed to the research of field is shown by the size of the box. Based on the graphical description of active countries, this analysis will aid academics in forming scientific collaborations, producing joint venture articles and sharing new approaches and ideas. The higher size of the circles of Spain, USA and China makes it clear the aforementioned leadership of these countries. Besides, the USA and UK (in purple color) have a more long time of publication in the field, in fact their average years publication are 2006 and 2007, respectively; in the other side, China, Singapore and United Arab Emirates, in yellow color, have been incorporated more recently to the research in the field, as the most recent average publication year included in Table 2.

Authors mapping

The number of citations received by a researcher in a certain discipline is used to quantify their influence. This shows the leading writers in the research who have the most publications and citations. In terms of count, a total of 3357 authors have been included in this analysis and the number of papers published in this field per one is low, in fact Table 3 shows that the maximum number of papers per author is 5. In this sense, 8 authors are in top ranking with this number of papers. In terms of citations, 7 authors show more than 1000 citations and the citations ranking is led by Hilal N. with 3 documents and 1612 citations, followed by Alkhudhiri A. and Darwish N. with 1512 citations and only 1 document but with the higher value of average the normalized citations (12.3054). It is also important to highlight that the average publication year included in the raking in terms of total citations and average normalized citations, except in the case of Hilal N., is between 2011 and 2013; besides, in the case of total documents, Zhang Y. and Li Y. show as average publication year 2017 and Wang J. 2019. These results show

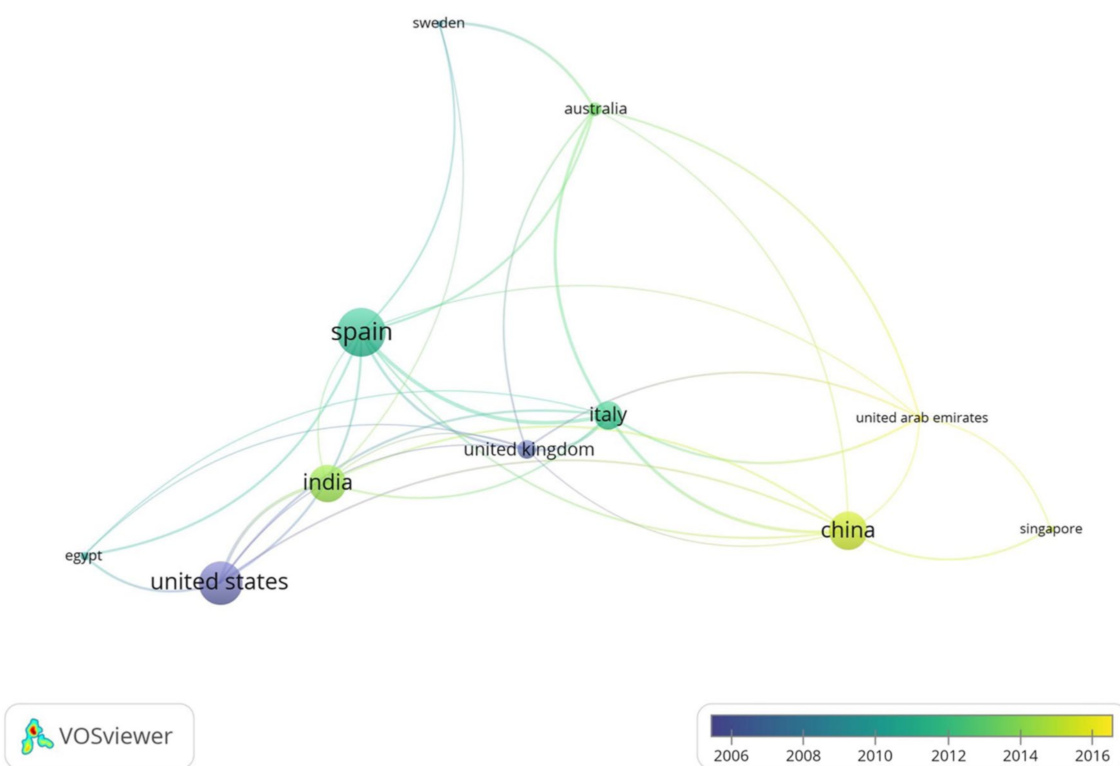


Fig. 5 Overlay visualization of countries included in top 5 ranking based on number of documents

Table 2 List of leading 5 countries in terms of publication count, total citations and average normalized citations

Position	Country	Number of documents	Total citations	Normal citations	Average publication year	Average citations	Average normailzed citations
Publication count							
1	Spain	91	4237	107.4739	2011	46.5604	1.181
2	USA	81	2505	91.89	2006	30.9259	1.1344
3	China	72	2519	84.9559	2015	34.9861	1.1799
4	India	70	3121	76.8257	2014	44.5857	1.0975
5	Italy	53	2003	67.5965	2012	37.7925	1.2754
Total citations							
1	Spain	91	4237	107.4739	2011	46.5604	1.181
2	India	70	3121	76.8257	2014	44.5857	1.0975
3	UK	36	2821	50.4289	2007	78.3611	1.4008
4	China	72	2519	84.9559	2015	34.9861	1.1799
5	USA	81	2505	91.89	2006	30.9259	1.1344
Average normalized citations							
1	Singapore	6	1493	29.3218	2015	248.8333	4.887
2	United Arab Emirates	5	1642	16.0673	2016	328.4	3.2135
3	Sweden	13	1406	39.2957	2009	108.1538	3.0227
4	Egypt	17	636	34.9726	2010	37.4118	2.0572
5	Australia	26	2474	53.1463	2013	95.1538	2.0441

Table 3 List of leading authors in terms of publication count, total citations and average normalized citations

Position	Source	Number of documents	Total citations	Normal citations	Average publication year	Average citations	Average normailzed citations
Publication count							
1	Zhang Y	5	494	13.7265	2017	98.8	2.7453
2	Méndez R	5	280	9.2465	2006	56	1.8493
3	Wang J	5	158	6.0623	2019	31.6	1.2125
4	Nakhla G	5	198	4.3791	2006	39.6	0.8758
5	Li Y	5	105	2.3827	2017	21	0.4765
6	Peres J.A	5	111	2.2506	2010	22.2	0.4501
7	Lucas M.S	5	141	1.9115	2011	28.2	0.3823
8	Sirianuntapiboon S	5	174	1.7188	2008	34.8	0.3438
Total citations							
1	Hilal N	3	1612	15.3264	2017	537.3333	5.1088
2	Alkhudhiri A	1	1576	12.3054	2012	1576	12.3054
3	Darwish N	1	1576	12.3054	2012	1576	12.3054
4	Mulcahy D	1	1020	7.9641	2012	1020	7.9641
5	Tang C.Y	1	1020	7.9641	2012	1020	7.9641
6	Zhao S	1	1020	7.9641	2012	1020	7.9641
7	Zou L	1	1020	7.9641	2012	1020	7.9641
Average normalized citations							
1	Alkhudhiri A	1	1576	12.3054	2012	1576	12.3054
2	Darwish N	1	1576	12.3054	2012	1576	12.3054
3	Chen J	1	412	10.1493	2013	412	10.1493
4	Hong H	1	412	10.1493	2013	412	10.1493
5	Lin H	1	412	10.1493	2013	412	10.1493
6	Peng W	1	412	10.1493	2013	412	10.1493
7	Zhang M	1	412	10.1493	2013	412	10.1493
8	Schröder J.J	1	553	10.0609	2011	553	10.0609
9	Smit A.L	1	553	10.0609	2011	553	10.0609

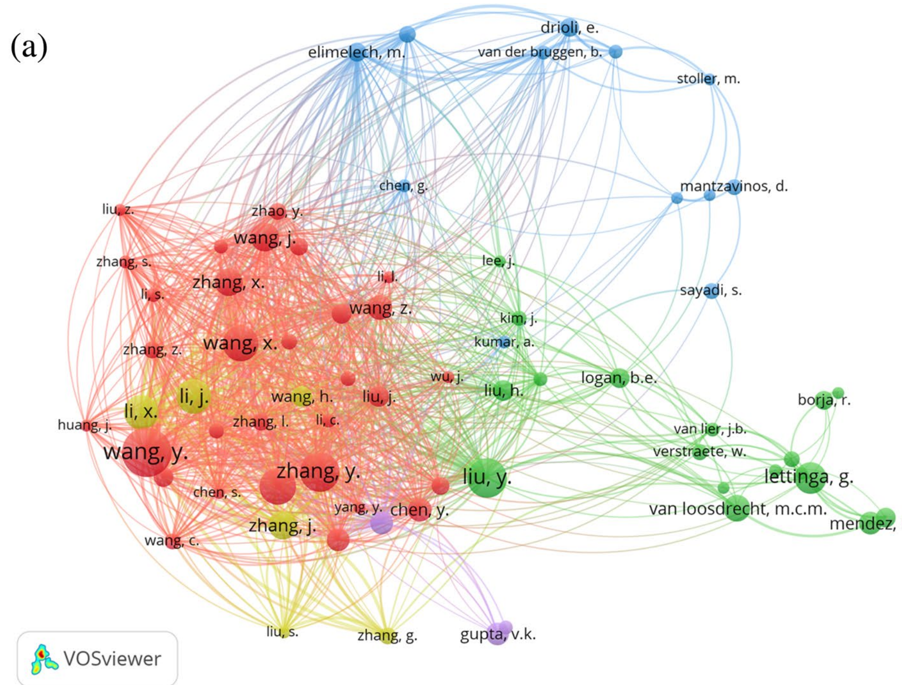
the higher impact of these authors during the last years, in this research field.

The mapping of co-citation researchers with minimum 50 citations and co-authorship by countries with minimum 10 documents are shown in Fig. 6a,b, respectively. The analysis reveals that co-citations linked 70 researchers, specially located in red cluster, with 31 items; cluster in green, yellow and purple include 12, 6 and 3 authors (Fig. 6a). In the other hand, Fig. 6b shows 31 countries that works together in the research field, highlighting the strong relationship in the case of countries as Spain and Italy, with a higher connection size line while Egypt is the only African country with co-authorship by countries with minimum 10 documents.

Articles mapping

The number of citations that an article obtains reflects its impact in a certain study field. Citation-dense article are recognized as pioneers in their study fields (Yang et al. 2022). Table 4 summarizes the list of top 10 documents in terms of total citations and average normalized citations. Six of the documents are included in both lists, so they could be considered as the papers with the higher contribution to the research field. There is a high recognition for the research themes related to membrane techniques and advanced oxidation processes, with 4 and 3 top cited documents, respectively, while the adsorption has appeared only in the average normalized citations, indicating an emerging research trend. It can be highlighted Salem et al. paper entitled "Green Synthesis of Metallic Nanoparticles and Their Prospective Biotechnological Applications: An Overview," which in only one year it has achieved a total of 123 citations. The leading linked articles in the present area are depicted in Supplementry (Fig. S1).

Fig. 6 Network visualization (**a**) co-citation researchers with minimum 50 citations (**b**) co-authorship countries with minimum 10 documents



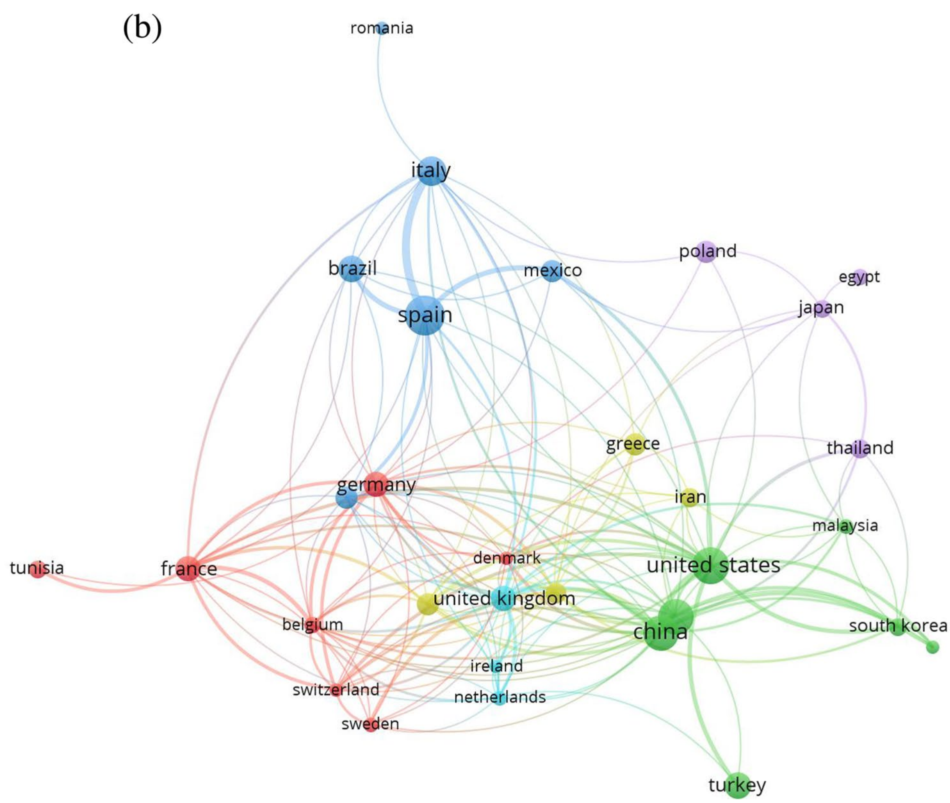


Table 4 List of top 10 documents in terms of total citations and average normalized citations

Posi-tion	Document	Authors	Research Theme	Total citations	Normal citations	Publication year	Average normailzed citations	References
Total citations								
1	Membrane distillation: a comprehensive review	Abdullah Alkhudhiri, Naif Darwish, Nidal Hilal	Membrane techniques	1576	12.3054	2012	12.3054	Alkhudhiri et al. (2012)
2	Recent developments in forward osmosis: Opportunities and challenges	Shuaifei Zhao, Linda Zou, Chuyang Y.Tang, Dennis Mulcahy	Membrane techniques	1020	7.9641	2012	7.9641	Zhao et al. (2012)
3	Microbial pectinolytic enzymes: a review	Ranveer Singh Jayani, Shivalika Saxena Reena Gupta	Biological/ Microbial processes	700	8.3582	2005	8.3582	Jayani et al. (2005)
4	Drawbacks of applying nanofiltration and how to avoid them: a review	B.Van der Bruggen, M.Mänttäri, M.Nyström	Membrane techniques	613	5.3788	2008	5.3788	Bruggen et al. (2008)
5	Toward global phosphorus security: a systems framework for phosphorus recovery and reuse options	D.Cordell, A.Rosemarin, J.J.Schröder, A.L.Smit	Value added products	553	10.0609	2011	10.0609	Cordell et al. (2011)
6	An overview of the application of Fenton oxidation to industrial wastewaters treatment	P Bautista, A F Mohedano,J A Casas,J A Zazo,J J Rodriguez	Advanced oxidation processes	506	4.4399	2008	4.4399	Bautista et al. (2008)
7	Transformation of vegetable waste into value added products: (A) the upgrading concept; (B) practical implementations	Günther Laufenberg, Benno Kunz, Marianne Nystroem	Value added products	477	6.4231	2003	6.4231	Laufenberg et al. (2003)
8	Use of ozone in the food industry	Zeynep B.Guzel-Seydim, Annel K.Greene, A.C.Seydim	Advanced oxidation processes	428	6.4292	2004	6.4292	Guzel-Seydim et al. (2004)
9	A review on anaerobic membrane bioreactors: Applications, membrane fouling and future perspectives	Hongjun Lin, Wei Peng, Meijia Zhang, Jianrong Chen, Huachang Hong, Ye Zhang	Membrane techniques	412	10.1493	2013	10.1493	Lin et al. (2013)
10	Contributions of electro-chemical oxidation to waste-water treatment: fundamentals and review of applications	Ángela Anglada, Ane Urtiaga, Inmaculada Ortiz	Advanced oxidation processes	387	7.4942	2009	7.4942	Anglada et al. (2009)

Table 4 (continued)

Posi-tion	Document	Authors	Research Theme	Total citations	Normal citations	Publication year	Average normailzed citations	References
Average normalized citations								
1	Green synthesis of metallic nanoparticles and their prospective biotechnological applications: an overview	Salem S. Salem, Amr Fouda	Adsorption techniques	123	19.5312	2021	19.5312	Salem and Fouda (2021)
2	Membrane distillation: acomprehensive review	Abdullah Alkhudhiri, Naif Darwish, Nidal Hilal	Membrane techniques	1576	12.3054	2012	12.3054	Alkhudhiri et al. (2012)
3	A critical review on advances in the practices and perspectives for the treatment of dye industry wastewater	Toral Shindhal, Parita Rakholiya, Sunita Varjani, Ashok Pandey, Huu Hao Ngo, Wenshan Guo, How Yong, Mohamad J. Taherzadeh	General treatment technologies	70	11.1153	2021	11.1153	Shindhal et al. (2021)
4	A review on anaerobic membrane bioreactors: applications, membrane fouling and future perspectives	Hongjun Lin, Wei Peng, Meijia Zhang, Jianrong Chen, Huachang Hong, Ye Zhang	Membrane techniques	412	10.1493	2013	10.1493	Lin et al. (2013)
5	Toward global phosphorus security: a systems framework for phosphorus recovery and reuse options	D.Cordell, A.Rosemarin, J.J.Schröder, A.L.Smit	Value added products	553	10.0609	2011	10.0609	Cordell et al. (2011)
6	Microbial pectinolytic enzymes: a review	Ranveer Singh Jayani, Shivalika Saxena Reena Gupta	Biological/ Microbial processes	700	8.3582	2005	8.3582	Jayani et al. (2005)
7	Adsorption of ibuprofen, ketoprofen and paracetamol onto activated carbon prepared from effluent treatment plant sludge of the beverage industry	Angélica F.M. Streit, Gabriela C. Collazzo, Susanne P. Druzian, Rodrigo S.Verdi, Edson L. Foletto, Luis F.S. Oliveira, Guilherme L.Dotto	Value added products	52	8.2571	2021	8.2571	Streit et al. (2021)
8	Recent developments in forward osmosis: opportunities and challenges	Shuaifei Zhao, Linda Zou, Chuyang Y.Tang, Dennis Mulcahy	Membrane techniques	1020	7.9641	2012	7.9641	Zhao et al. (2012)

Table 4 (continued)

Posi-tion	Document	Authors	Research Theme	Total citations	Normal citations	Publication year	Average normailzed citations	References
9	Antimicrobial and antioxidant properties of chitosan and its derivatives and their applications: a review	Mohamed E.Abd El-Hack, Mohamed T.El Saadony, Manal E.Shafi, Nidal M.Zabermawi, Muhammad Arife Gaber Elsaber Batiha, Asmaa F. Khafaga, Yasmina M. Abd El-Hakim, Adham A.Al-Sagheer	Adsorption techniques	94	7.9418	2020	7.9418	Abd El-Hack et al. (2020)
10	Contributions of electro-chemical oxidation to waste-water treatment: fundamentals and review of applications	Ángela Anglada, Ane Urtiaga, Inmaculada Ortiz	Advanced oxidation processes	387	7.4942	2009	7.4942	Anglada et al. (2009)

Keywords analysis

Keywords of a document represents the core content of the considered article within the relevant domain of knowledge (Su and Lee 2010) so their analysis is vital to recognize and indicate the essential areas of the research field (Yang et al. 2022). In this document, the keywords analysis has been developed in terms of keywords co-occurrence using VOSviewer, and overlay graph and strategic diagrams applying SciMAT. Results obtained are analyzed and discussed below.

Keywords co-occurrence

The co-occurrence of the words has been used to identify the relationship and the connectedness of the articles. The co-occurrence of the "Index Keywords" (keywords chosen by content suppliers and are standardized based on publically available vocabularies; unlike author keywords, the indexed keywords take into account synonyms, various spellings and plurals), "Full Counting" (it means that each co-occurrence link has the same weight) and a minimum of 20 occurrences were used for the keyword analysis, resulting in 204 keywords included in 5 clusters in colors red (cluster 1), green (cluster 2), blue (cluster 3), yellow (cluster 4) and purple (cluster 5) (Supplementary Fig. S2). The keywords with the higher number of occurrences were wastewater treatment (cluster 1) and biological/ microbial process (cluster 2) with 634 and 610 occurrences, respectively.

Besides, Table 5 describes clusters in terms of influential keyword, theme assigned, average publication year and average normal citation of the cluster. To do that, first the terms with the highest average normal citation in each cluster was selected and the clusters were described by the principal theme according to their keywords; then we computed the average publication year as well as the average normalized citations of each cluster. In general terms, the keywords with higher average results show that the clusters with the higher number of keywords is the red color (cluster 1) followed by green one (cluster 2), with 59 and 50 keywords, respectively. Three of the clusters have shown an average normal citations index higher than 1 (clusters 1, 3 and 5), and they represent the clusters with higher impact in the research field; they are related with general wastewater treatment, physical and chemical process and biotechnology. These represent a current research trend in agro-food wastewater treatment. Emerging technologies based on coagulation/electrocoagulation/ultrasonic processes (Moradi et al. 2021), hybrid constructed wetlands (Shukla et al. 2021) and microbial inoculation in treatment systems (Nzila et al. 2016) are being developed to meet the needs of decentralized treatment. It will be vital for effective implementation to develop and

Table 5 Description of keywords 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 of cluster
			Keyword	Average normal citations			
1	Red	59	Particle size	2.5985	General wastewater treatment	2012.85	1.2622
			Fertilizer	2.5848			
2	Green	50	Biodegradability	1.5987	Biological/Microbial process	2008.11	0.9899
3	Blue	43	Unclassified	2.304	Physical and chemical process	2013.83	1.1347
			Physical chemistry	1.8693			
4	Yellow	30	Industrial wastewaters	1.3174	Wastewater process design	2011.05	0.8925
5	Purple	22	Biotechnology	1.6924	Biotechnology	2012.96	1.1066
			Bioremediation	1.5059			

demonstrate how these technologies work together to satisfy the climate, society and sustainability requirements.

Overlay graph and thematic evolution map

The evolution of topics over time in the research field has been studied using overlay graph and thematic evolution map, both of them using SciMAT.

Figure 7 shows the overlay graph, and it represents the stability of keywords between two consecutive subperiods; this general overlapping measures the number of shared keywords between successive subperiods (Cobo et al. 2011). The circles represent the subperiods and their number of associated keywords; the horizontal arrow represents the number of keywords shared by both periods, and, in parentheses, the Similarity Index between them; finally, the upper-incoming arrow represents the number of new keywords in each period and the upper-outcoming arrow the keywords that are present in one period but not in the following one. The analysis of overlay graph shows that the number of keywords increases between the first and the second subperiod but it remains stable in the next one. Besides, the number of keywords shared by the 1st and 2nd subperiod (602) is very low; however, the number of new keywords represents 87%, meaning the relevant development of the research field during this period. However, in the case of the 3rd subperiod, the number of shared keywords increased until 38% and the new ones represents 62%, meaning that although the research field is in continuous development, this period corresponds with the consolidation of knowledge.

Figure 8 shows the thematic evolution maps of the research field in terms of number of documents (Fig. 8a) and average citations (Fig. 8b). In this figure, the dimensions of circles imply the number of documents and average citations. On the other hand, the interconnections among them are related with the thematic area. Thus solid lines mean that the linked themes share the same name (both themes are labeled with the same keywords, or the label of one theme is part of the other theme); however, a dotted line means that the themes share elements that are not the name of the themes; finally, the thickness of the edges is proportional to the inclusion index, which weighs the importance of the thematic nexus (Cobo et al. 2011). In Figure 8, the analysis should point out the following:

- In general terms, in each subperiod the keywords are not the same. In fact, there are only few subsets of keywords that have remained unchanged during two of the subperiods; it is the case of: FOOD-INDUSTRY, FOOD-PROCESSING and WASTEWATER TREATMENT. However, some keywords come from a theme existing in the previous period or some show a strong nexus, for example AMMONIA–NITROGEN or OLIVE OIL–PLANTS OIL, between the first and the second subperiod, or WASTEWATER TREATMENT–FOOD INDUSTRY–FOOD INDUSTRY, along the three subperiods.

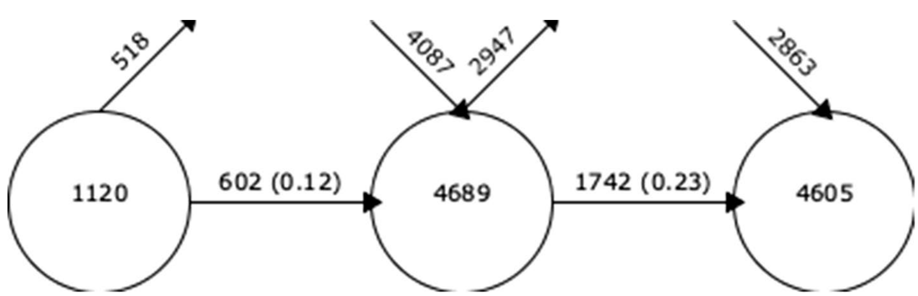


Fig. 7 Overlay graph of the research field

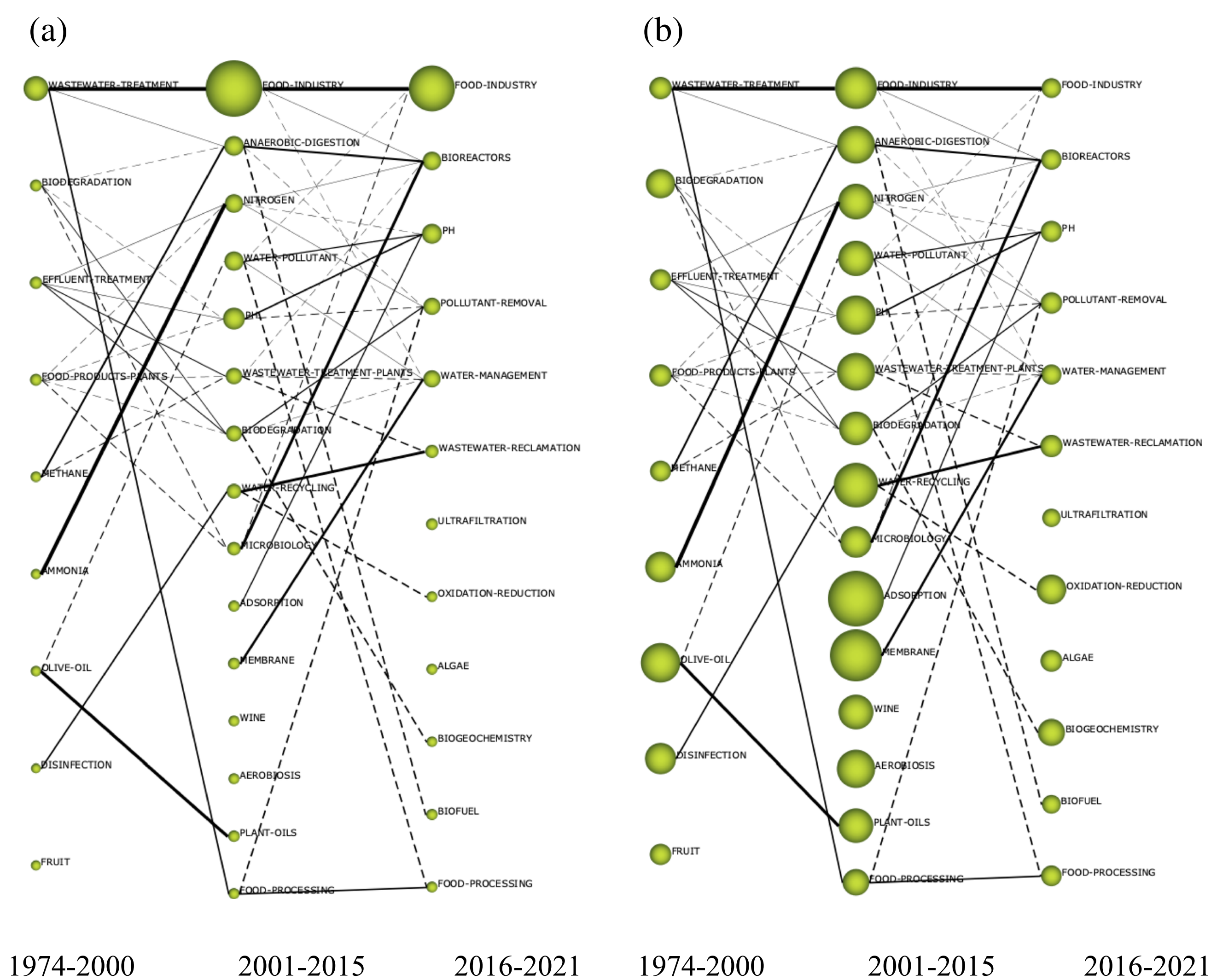


Fig. 8 Thematic evolution map of the research field in terms of (**a**) number of documents and (**b**) average citations

This result means that new topics with their associated keywords appear and others disappear, as it has been discussed in overlay graph.

- It is possible to highlight the great cohesion between some themes, with a higher number of lines connecting them. For example, FOOD-PRODUCTS-PLANTS which is connected with themes related with treatment process and conditions (NITROGEN, PH, BIODEGRADATION and MICROBIOLOGY), or WATER POLLUTANT connected with FOOD INDUSTRY, PH, WATER MANAGEMENT and FOOD PROCESING. However, some themes are not related with the rest, so they are considered very recent in each period and could be considered as the beginning of a new thematic area; this is the case of FRUIT and WINE in subperiods 1 and 2, respectively, or ALGAE and ULTRAFILTRATION in the 3rd one. Besides, dotted line connecting themes as OLIVE OIL–WATER POLLUTANT or FOOD PROCESSING–POLLUTANT REMOVAL means that the themes share elements that are not the name of the themes; however, solid lines connecting themes as OLIVE OIL–PLANT OILS, DESINFECTION–WATER RECYCLING–WASTEWATER RECLAMATION, show that they share the same name.
- It is possible to highlight the low number of documents in themes, except in the case of general ones: WASTEWATER-TREATMENT and FOOD-INDUSTRY. Again, this result can be explained by the breadth of the topic, both in relation to the type of food industry and the different treatments that can be applied to purify its wastewater. In this sense, Fig. 8b shows the higher relevance of OLIVE-OIL and WINE industry, as well as the presence of FRUIT sector, and the higher development of the following treatment technologies to treat wastewater: ADSORPTION, MEMBRANE, ANAEROBIC DIGESTION or OXIDATION–REDUCTION.

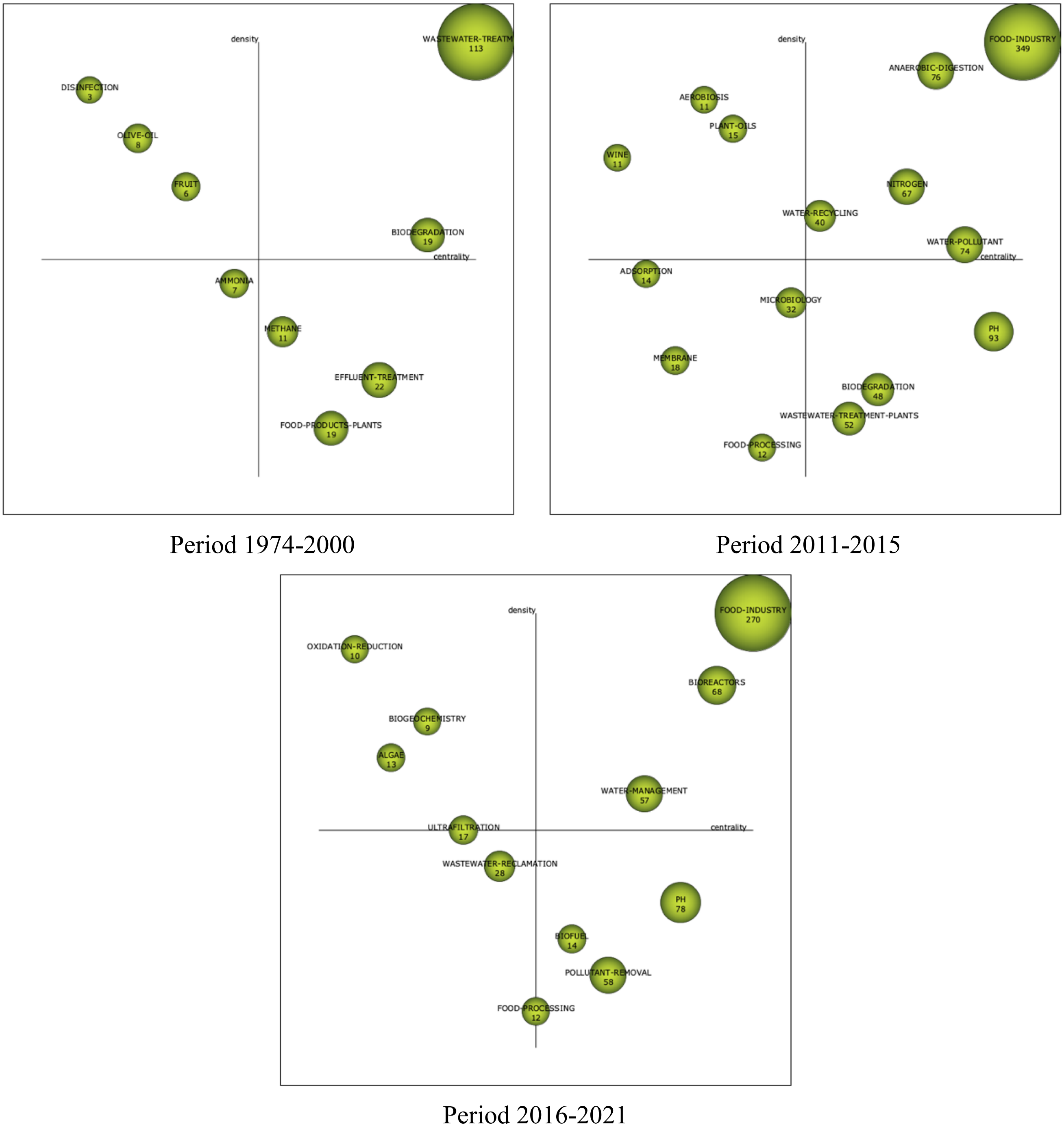


Fig. 9 Strategy diagrams in terms of number of documents published

- **Strategy diagrams**

SciMAT has been used to produce two strategy diagrams for each subperiod to show the evolution of keywords or research topics in terms of number of documents published (Fig. 9) and average citations (Fig. 10) as well as Supplementry Table S1 containing some quantitative and impact measures to analyze each subperiod. In the case of the strategy diagrams, they are divided into four quadrants showing the following four types of research topics (Cobo et al. 2011): motor themes in the upper right quadrant, which are well developed and essential topics in the field; highly developed and isolated themes, in the upper left quadrant, which are highly developed inside but isolated from the other themes and they are specialized topics in outlying areas of

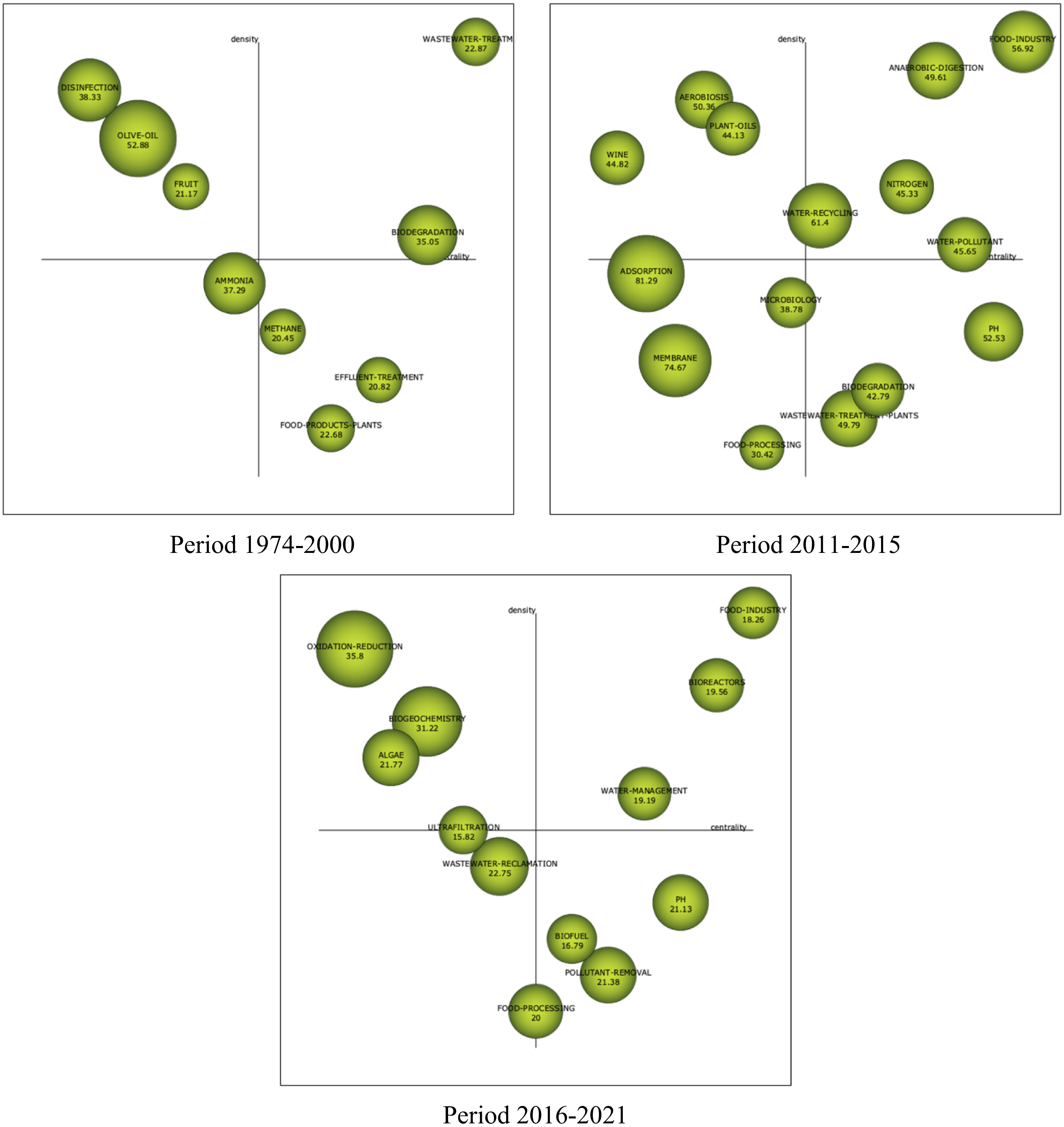


Fig. 10 Strategy diagrams in terms of average citations

the research field; emerging or declining research topics, in the lower-left quadrant, which lack development and relevance, although they may evolve and be relevant or disappear; and finally, basic themes, in the lower right quadrant which are transversal to the scientific field.

According to strategic diagrams (Figs. 9, 10) and quantitative measures (Supplementry Table S1), the analysis should point out the following per subperiod:

- Subperiod 1974–2000:

  - Two motor themes are identified: WASTEWATER-TREATMENT, with the higher number of documents, although not in the average citations, and BIODEGRADATION with only 19 documents, besides, WASTEWATER-TREATMENT shows a high centrality and density, meaning the high level of interaction of this research theme with other ones and a high level of development measuring the internal cohesion of all the links between the keywords describing the topic (Cobo et al. 2011), respectively. In the case of BIODEGRADATION, the low value of density shows that, although it is an essential theme in the field, it had a low internal cohesion between the keywords.

- Three well-developed but isolated themes have been identified: DISINFECTION, OLIVE-OIL and FRUIT, all of them with a low number of documents, but OLIVE-OIL shows the higher value in the case of average citations.
- Only AMMONIA is included in the lower-left quadrant, meaning that it is an emerging or declining theme, but a relative high average citations with only 7 documents.
- Three themes are transversal or basic to the scientific field: METHANE, EFFLUENT-TREATMENT and FOOD-PRODUCTS-PLANTS, all of them with a relative low number of documents and an average citation around 21.

- Subperiod 2001–2015:

  - The number of motor themes increases in this subperiod, including FOOD-INDUSTRY with the higher number of documents, although the average citations is lower than other ones. Other themes included in these categories are ANAEROBIC-DIGESTION, NITROGEN, WATER-POLLUTANT and WATER-RECYCLING, showing the importance of some treatments as well as the reuse of treated water.
  - Three well-developed but isolated themes have been identified: AEROBIOSIS, WINE and PLANT-OILS. The last two themes consist of identifying in the two last one industrial sectors that are developing techniques to reduce water pollution.
  - Emerging themes, with a relative number of documents but a high average citations are ADSORPTION, MICROBIOLOGY and MEMBRANE showing the development of new technologies to treat wastewater.
  - WASTEWATER-TREATMENT-PLANTS, BIODEGRADATION and pH are in the lower-right quadrant. In fact, the evolution of the research has made that motor themes in the previous subperiod have evolved to basic or transversal themes.

- Subperiod 2016–2021:

  - The number of motor themes in this subperiod includes again FOOD-INDUSTRY with the higher number of documents, although the average citations is lower than other ones. BIOREACTORS theme appears as a motor theme as a consequence of the increase of research in these new technologies.
  - Four well-developed but isolated themes have been identified: OXIDATION–REDUCTION, BIOGECHEMISTRY, ALGAE and ULTRAFILTRATION, which correspond to developing techniques to reduce water pollution.
  - Only WASTEWATER-RECLAMATION is in the lower-left quadrant, meaning that the field is consolidated and, in this period, they are not emerging.
  - BIOFUEL, POLLUTANT-REMOVAL and pH are in the lower-right quadrant, identifying basic and transversal themes not developed. In the case of FOOD-PROCESSING, it has evolved going toward declining sectors.

- Finally, in general terms, although there are some differences between the number of documents per themes, the average citation is more homogeneous for all the subperiods, meaning that the interest on these themes was similar and that the evolution of the research in the field has progressed in a homogeneous way.

Findings and discussion

A scientometric evaluation was conducted on published documents about food industry wastewater treatment research to identify the leading sources, authors, countries and documents of publications, and research themes, all of which constitute this study's aims. Generally, it was noticed that the research on food industry wastewater treatment is well developed and has risen a maturity level including different technologies, beginning by biological and physicochemical treatments until more recent ones as membrane and bioreactors technologies. Worth to mention, there is a shortage in executing agro-food wastewater treatment in the developing countries, due to the cost-intensive nature of treatment processes, energy requirements and financial limitations (Hafeez et al. 2021). The current global research is oriented to developing new technologies and adapting the existing ones for sustainability. An ideal strategy to cut the costs would include the use of environmentally friendly techniques, meanwhile producing value-added products as an option of investment. For example, a comprehensive review by Barbera et al. (2013) indicated several benefits of treated agro-food wastewater in irrigation of appropriate plants, because of its richness in nutrients which positively impact soil fertility. Another track is the use of agro-food wastewater sludge in the construction field such as in concrete mixtures (Rabie et al. 2019), light concrete (Mojapelo et al.

2018), mortar (Darvish et al. 2020), ceramic (de la Casa et al. 2021), epoxy (Rizal et al. 2019) and in manufacturing interlock bricks (Erdogmus et al. 2021; Limami et al. 2021).

The wide variations in properties of different agro-food effluents are a major reason that makes treatment in the centralized networks impracticable and cost prohibitive. On local levels, the impact can be even greater because inefficient treatment contributes to more than 50% of the organic pollutants released in the water bodies (Wu et al. 2015). The decentralization approach can be the best option for small industries; and it has been linked to wastewater sustainability (Parkinson and Tayler 2003). Based on our current analysis of article mapping, emerging technologies related to coagulation/electrocoagulation/ultrasonic processes (Moradi et al. 2021), hybrid constructed wetlands (Shukla et al. 2021) and microbial inoculation in treatment systems (Nzila et al. 2016) are being developed to meet the needs of decentralized treatment. The research involved the performance optimization of technologies, the dynamics and mechanism of treatment processes, the removal of a specific pollutant, etc., while there is a lack of quantitative methods to systematically summarize the agro-food wastewater treatment literature. It is difficult to understand the research hotspot and future research trends in this field from an application perspective. The following section in this review is concerned with discussing the knowledge gaps related with application of the evolved technologies in agro-food wastewater treatment and the cogeneration of valuable by-products.

Chemical coagulation/electrocoagulation/ultrasonic processes

The principle of electrocoagulation is similar to that of chemical coagulation/flocculation, with the basic difference being the coagulant delivery route. Metal salts or polymers are used in the chemical technique to dissolve in water, causing colloidal particles to cluster and form flocs, whereas metal electrodes are electrochemically dissolved in electrocoagulation. (Moussa et al. 2017).

The major disadvantage of the electrocoagulation technique is the formation of a passive layer on the electrode surface over time. The combination of the ultrasonic with electrocoagulation significantly increases the pollutant removal. Ultrasonic waves create high-pressure points inside the solution during the cavitation phenomenon. This results in the breakdown of sediments produced at the electrode surface and the generation of large quantities of radical species to remove contaminants (Moradi et al. 2021).Various studies demonstrate their applications in the treatment of wastewater from agro-food related industries, including oil (An et al. 2017), sugar mill (Chaudhary and Sahu 2013), slaughterhouse (Asselin et al. 2008), baker's yeast (Kobya and Delipinar 2008), dairy (Tchamango et al. 2010) and others (Moradi et al. 2021).

The development of a more systematic approach to the coagulation reactor design, operation and modelling behavior in order to predict the performance prior to actual operation, on a large scale, are the primary challenges that must be solved (Holt et al. 2005). Another issue that must be addressed is to evaluate the performance of electrocoagulation units operating in continuous flow mode, for industrial applications (Moussa et al. 2017). Moradi et al. (2021) provided a detailed analysis of the field's significant successes and explain the major disadvantages, as well as ideas for prospective research alternatives that might improve the technology and broaden its range of applications. In electrocoagulation reactors, Holt et al. (2005) identified an interlinked relationship between three "basic technologies" of electrochemistry, coagulation and flotation. These are substantially responsible for an efficient electrocoagulation process.

Coagulation, both chemical and electrical, generates large quantities of waste sludge, that contains organics removed during effluent treatment, and metal complexes, specifically aluminum or iron, resulting from the electrodes used in the electrocoagulation. The potential applications of the sludge have yet to be thoroughly investigated, with just a few research on sludge valorization in specific fields having been done. Among these valorizations: the use of sludge as fertilizers (García et al. 2013), pigments for ceramic manufacturing (Un and Ozel 2013), bricks for construction materials (Weng et al. 2003), absorbents for phosphate removal (Golder et al. 2006) and catalysts in photo-Fenton process (Samy et al. 2020). The comprehensive review by Rajaniemi et al. (2021) highlights the existing sludge valorization studies with a focus on the quality of sludge produced from the effluents of electrocoagulation processes and the future research needs.

The dried sludge was employed as a partial substitute for sand in structural concrete, up to 7.5 percent replacement; moreover, wastewater was used as a curing medium (Mojapelo et al. 2021). The unit weight of the concrete reduced, as the sludge concentration increased, which was due to the sludge's lower density. Furthermore, the addition of sludge additive to brick preparations has lowered the pH of the mixes, leading to highly porous bricks with superior thermal characteristics and reduced mechanical compressive strength were produced. (Limami et al. 2021). A significant number of research studies (de la Casa et al. 2021) have investigated the recycling of olive industry wastes for the production of ceramic materials. These wastes can act as pore-forming agents and have lowered the density of ceramic.

Hybrid constructed wetlands

One of the most common options for agro-food wastewater treatment is constructed wetlands, (CWs) (Varma et al. 2021). These engineered systems are designed to mimic the natural processes (soils, wetland vegetation and the associated microbial communities) to support wastewater treatment at minimum energy requirements. Several hybrid systems, consisting of different vertical—and horizontal-flow stages, are used for treating agro-industrial wastewater. The vertical-flow (VF) CWs achieve high organic matter removal efficiency and high nitrification rates, and the horizontal-flow (HF) CWs accomplish high denitrification rates (Sultana et al. 2015). To address the issue of low DO concentrations, Wang et al. (2018) combined VF CWs with tidal flow methods that improve oxygen delivery.

At the pilot scale, CWs were mainly used as a polishing stage; thus, prior-treatment technologies are essential to reduce the high loads of suspended solids and organic matter in the agro-industrial wastewater. The previous studies have used biological, physical and chemical processes as a prior stage to lower the load of solids (Stefanakis 2018). The biological pre-treatment phases in the majority of literature involved either simple settling basins or stabilization lagoons, which may achieve significant removal rates of suspended solids and organics (Sultana et al. 2015).

Prior-treatment is usually adapted to the criteria of each wastewater. A sludge digestion step is frequently included in the treatment of fruit juice wastewater to remove suspended lignocellulose fibers and organic loads. (Serrano et al. 2011). Meat processing wastewaters that contain high loads of proteins and fats are mainly treated with biological treatment, such as up-flow anaerobic sludge blanket UASB reactors, to reduce both organic and nitrogen loads (Aziz et al. 2019). The main treatment stages for olive mill and other cooking oil products involve advanced treatment methods including electrocoagulation (Abdulla et al. 2019), electrochemical oxidation (Grafias et al. 2010) and biological trickling filters (Tatoulis et al. 2017) to lower toxic phenol concentrations. However, the chemical processes, such as electrochemical oxidation generated toxic intermediate compounds in the agro-food wastewater which was only partially removed in the CW system (Grafias et al. 2010). Similarly, coagulation increase pH of the wastewater to above 8, which cause toxicity to the CW vegetation (Del Bubba et al. 2004).

Microbial inoculation in treatment systems

To improve CW performance for agro-food wastewater treatment, specific design and operation parameters should be enhanced, including CW design, vegetation type, media type and microbial inoculation (bioaugmentation) with microorganisms. As reviewed by Engida et al. (2021), great bacterial diversity of Firmicutes, Actinobacteria and Bacteroidetes groups exist in CWs. They concluded that vertical flow CWs favor aerobic microbes and have higher removal efficiency for organic carbon and ammonium, while horizontal sub surface flow systems favor anoxic and anaerobic microbes. Therefore, the use of hybrid CW designs to enhance the activity of the targeted group would better optimize performance.

Baek et al. (2020) have proved the amendment with magnetite additions and external voltage, alone and in combination, as effective strategies to enhance anaerobic digestion process of dairy wastewater. In our previous work, we have augmented industrial wastewaters with specific bacterial strains to accelerate the mitigation of high COD loads (El-Shatoury et al. 2014), phenols and oils (Abdulla et al. 2019) and heavy metals (Abdulla et al. 2018). These strains could be potential microorganisms for accelerating the biotreatment. At the molecular level, the capacity to synthesize bioremediation enzymes is often carried on large pieces of DNA plasmids. The presence of degradation abilities on plasmids has an important environmental implication, as plasmid transfer in these cases might be responsible for the spread of the degradation genes between other microorganisms in the biofilter matrix. The recent review of (Garbisu et al. 2017) shows that plasmid-mediated bioaugmentation requires considerably more study for a better selection of donor bacterial strains and supporting plasmids. An open research area is to gain a thorough understanding of indigenous microbial populations and the environmental variables that influence plasmid uptake and expression of catabolic genes.

With the recent advances of membrane reactors in wastewater treatment (Al-Asheh et al. 2021), the ability to keep microbial consortia in bioreactors has been enhanced substantially, which should lead to better performance and better quality effluents. However, increasing interest in bioaugmentation ought to be assessed by full-scale data which, to date, is still very scarce. The immobilization techniques can give rise to higher enzymatic rates by achieving higher concentrations and even promoting conformational changes (Bouabidi et al. 2018). This idea could be further investigated to enhance bioaugmentation strategies by cell-to-cell contact in the flocs and biofilms of the treatment system. An equivalent procedure is to encase bacteria into droplets, allowing each droplet to work as an individual microbioreactor, not limited by the suitability of the conditions expressing the enzyme of interest, thus permitting conditions that would be detrimental to most living organisms (Bar Oz et al. 2018; Taly et al. 2007). The recently studied groups of nitrogen metabolizing microorganisms, such as ammonia oxidizing *Archaea*, comammox, heterotrophic nitrifiers and anammox bacteria could be a favorable choice for encapsulation (Wang et al. 2021).

However, development of novel composite encapsulation materials is needed to meet the requirements of stability, permeability and sustainability.

Nowadays, nanotechnology is an emerging area of research with considerable potential. Nanomaterials have been extensively used for rapid or cost-effective cleanup of wastes (Salem and Fouda 2021). Their benefits of application in wastewater treatment are derived from the nanoparticle characteristics: enhanced reactivity, surface area, subsurface transport and/or sequestration characteristics (Brar et al. 2010). As a practical application, engineered nanomaterials could also become water contaminants. There are concerns regarding the use of persistent nanoparticles that they may reach human bodies through the food web. Thus, new methodologies are required for nanomaterials evaluation and for establishing adequate criteria for risk assessment.

Single-cell analysis (SCA) will be crucial for elucidating cellular diversity and heterogeneity (Ou et al. 2021; Wang et al. 2020). A deeper knowledge at the single-cell level (considering the biochemistry and toxicity mechanisms of pollutants), also complemented at the microbial community level, is still needed to understand the success and key factors controlling bioaugmentation under real operation conditions. It seems evident that a close interaction between engineering and biotechnology approaches is essential to promote higher removal efficiencies. It is also essential that the design of the bioreactor supports the transfer from laboratory to full-scale operation. Finally, suitable models that are applicable at all scales and capable of predicting the dynamics of microbial populations under varying conditions must be developed.

Conclusion

This research summarized the present state of the art in agro-food wastewater treatment by utilizing a massive data mining technique of scientometric evaluation of the literature and in-depth discussion of the results. With the increased publication size, researchers face an information overload that may hamper productive research efforts and academic collaboration. The scientometric computational tool enables researchers to obtain critical data from the most reliable sources.

Based on a bibliometric review of 48 years of the agro-food industry wastewater treatment research (1974–2021), the findings could provide useful information about this field as follows:

- The scientometric study showed the top 10 publishing sources, led by Bioresource Technology and Water Science and Technology journals.
- The most frequently used keywords in the literature were clustered around the themes: general wastewater treatment, physical/chemical process and biotechnology.
- Among 31 countries that works together in this research field, Spain had the highest publication and citation counts, while Egypt was the only African country in the average normalized citations ranking (standing at the 4th position).
- Scientometric analysis showed a high recognition for the research themes related to membrane techniques and advanced oxidation processes for agro-food wastewater treatment while the adsorption has appeared only in the average normalized citations, indicating an emerging research trend.

Finally, gaps in the agro-food wastewater research were highlighted, and recommendations for future study were made. Through the proposed scenario, and others that will be developed, science can empower the benefits of: (1) on-site quality enhancement of AF wastewater at low costs, in comparison with the current advanced techniques (2) tailored microbial consortium that can fit with the treatment techniques and accelerate the various treatment processes and (3) introduction of measures to ensure the sustainable use and management of AF wastewater and its related wastes as sources of value-added products according to the circular economy paradigm and the tasks of Sustainable Development Goals.

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Data availability All data generated or analyzed during this study are included in this article and its supplementary information file.

Declarations

Conflict of interest The author declares no potential conflict of interest to report.

Consent for publication The authors confirm the consent for publication.

Human and animal rights This article does not contain any studies with human or animal subjects.

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