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Conversion of organic wastes into biofuel by microorganisms: A bibliometric review

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ABSTRACT

This paper presents a bibliometric research of scientific documents on biofuel production from organic wastes extracted from the Web of Science (WoS) database. Original research and conference proceeding articles published until 2022 year were considered, which resulted in 773 documents. The objective of the study was to track evolutionary nuances and emerging trends of the topic, as well as upgrade knowledge in the area and help formulate scientific policies. The work concentrated on the most productive countries, authors and journals, as well as authors' keywords in documents relating to the biofuel conversion from biomass. The first paper on the field was published in 2004, and the publication number showed increasing trend with over 27% annual growth. The USA, followed by China demonstrated the highest publication and citation number. The thematic map analysis displayed the multidisciplinary nature of the topic, implying that the progress of several research domains is required for this technology. This is the first bibliometric review on biofuel from organic waste by microorganisms in the literature. The investigation results emphasize the need for further research in the area and also highlights the need for higher collaboration.

Introduction

Together with population growth and industrial progress the global energy need has also increased resulting in over-use of fossil fuels. This high use of fossil fuels leads to release of greenhouse gasses (GHG), in particular CO2, which is a key factor in global warming and climate change (Höök and Tang, 2013; Obileke et al., 2020). Fossil fuels were responsible for around 93% of CO_2 emissions worldwide in 2021 (roughly 40% coal, 32% oil, and 21% gas) (Ampese et al., 2022). Consequently, correct management of organic wastes is of particular interest for various industrial sectors in order to fulfill Global Sustainability Goals of the United Nations (United-Nations, 2015). Biomass management and energy conversion technologies are vital to promote sustainable development of bio-economy (Yaashikaa et al., 2020). These environmental concerns rekindled interests in alternative and renewable energy sources as bioenergy. The recovery of bio-energy from organic-waste can uphold the success of economic processes by decreasing the negative effects on the environment and preventing GHG emission (Ampese et al., 2022). Conversion of organic wastes into valuable bioenergy and biochemicals utilizing microorganisms is one of

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the most popular biological processes for bio-waste management and energy recovery (Zamri et al., 2021). In this process, complex organic compounds including proteins, carbohydrates, and lipids are transformed into simple soluble molecules as sugars, amino acids, and fatty acids by a consortium of microorganisms. Consequently, bioenergy and many valuable biochemicals are produced (Ampese et al., 2022; Nguyen et al., 2021). The US Department of Energy describe bioenergy as "renewable energy obtained from organic substances" whereas Food and Agriculture Organization of the United Nations designate bioenergy as "energy produced from biofuels" (Zhang et al., 2021). Bioenergy conversion utilizing a range of biofuels is considered as one of the most prominent alternatives to fossil fuels due to its low carbon dioxide emission. Biofuels can be obtained from renewable energy resources including organic wastes as wheat straw, corn stover, citrus waste and forestry matter (Negro et al., 2018; Stephen and Periyasamy, 2018). Eventually, biofuels are biodegradable and environmentally friendly, contributing to sustainability. Biofuels can be transformed to bioenergy and categorized into four groups based on their organic waste type (Dutta and Chakraborty, 2018). The first group is produced from starch- and sugar- based biomass and vegetable oil; the second group is extracted from algae; the third group biofuel focuses on microalgae genome editing which can process high levels of carbon dioxide (CO_2) for photosynthesis to increase biofuel production. The last biofuel generation is extracted from lignocellulose biomass including various agricultural side streams, as well as forest matter. Despite the wide variety of biofuels including biomethanol, vegetable oils, biodiesel, biogas, bio-oil, and bio-char; bioethanol is by far the most widely utilized biofuel (Balat, 2011). There are various yeast and bacteria strains utilized for bioethanol fermentation from organic waste (Balat, 2011). These microorganisms were successfully used to ferment different bio-wastes including agricultural by-products as wheat straw, corn stover, forestry matter and *Citrus* waste (Mahato et al., 2021; Tan et al., 2012; Tishler et al., 2015).

The bibliometric literature analysis can project popular research topics and gaps in a particular scientific area. This method consists of quantitative and visual procedures to project the impact and dynamics of scientific documents, and to understand the research trends within a specific domain, and provide a holistic overview of the fragmented literature (Pritchard, 1969; Zhang and Yu, 2020). Recently, bibliometric reviews have been widely performed to show the research works and popular topics related to global bioenergy (Ferrari et al., 2020), anaerobic digestion technology (Ampese et al., 2022), and the research evolution of bioenergy under climate change, broadening the perspective of scientists and policymakers for potential research topics and decision-making (Zhang et al., 2021). Therefore, we aimed to elucidate research evolution and trends in bioenergy/biofuel from organic waste by microorganisms utilizing bibliometric analysis. First, we detected all the literature published in the field until 2022 year. Then, bibliometric analysis was performed to shed light on the technological prospects and recent development trends of the topic. Different from the previous reviews which focused on defining and explaining concepts and improvements in a specific domain, the present work aimed detailed analysis of biofuel obtained from organic wastes to describe the major gaps that still need to be explored in the area. Finally, a comprehensive discussion on the challenges facing the topic progress and advancements was performed to promote future research and policy decisions.

Materials and methods

Data extraction

The Web of Science (WoS) database from Clarivate Analytics was our source for bibliographic data extraction, as also utilized in other bibliometric studies to visualize the evolution of literature in the scientific fields (Ali et al., 2022; Jimoh et al., 2022; Obileke et al., 2020; Xie et al., 2020).

The bibliographic data utilized in the present study was retrieved from the Web of Science (WoS) core collection using the following search string within the document topic field: biofuel* AND (ferment* OR biotransform*) AND ("organic waste*" OR "Citrus waste*" OR "bio-waste" OR "wheat straw*" OR "corn stover*" OR "forestry matter")

Searching within the publication topic field provides results that contain the search strings in document's title, abstract, author keywords, and keywords plus. The Boolean operators (AND and OR) and wildcards were used to detect papers with various combinations of the defined keywords in both singular and plural forms. The search was conducted in August 2022, and the syntax resulted in 773 SCI-expanded original research articles published until 2022. The flowsheet of the bibliometric study is illustrated in Fig. 1.

Bibliometric analysis

Pritchard (1969) pioneered the bibliometric analysis to project article networks based on citations (Pritchard, 1969), following his work, bibliometric and scientometric methods have been widely utilized in the literature (Goodell et al., 2021). Besides measuring scientific production, quality and impact, bibliometrics also describes intellectual, conceptual and social structures of a specific science domain together with its evolution over time. Consequently, bibliometrics intends to portray how specific research domains are structured and how they progressed over time, as well as discover hidden patterns and research gaps (Aria and Cuccurullo, 2017; Forliano et al., 2021). Performance analysis and science mapping constitute the bibliometric method. Briefly, performance analysis shows the impacts of research constituents, whereas science mapping defines the *relationships* between research constituents (Donthu et al., 2021). Performance analysis and science mapping methods composing the bibliometric method were adopted (Noyons et al., 1999), and the bibliometric analysis was performed with bibliometrix package and biblioshiny interface (Aria and Cuccurullo, 2017) available in R language (R Core Team, 2022).

Results and discussions

Publication evolution

The bibliographic data consisted of 773 research articles from 193 sources, published until 2022 year. The average citation per documents was 34.8, and 3147 authors in total were detected among the 773 documents. The collaboration index per document was 5.48, implying that there were 5.48 (on average) authors in each publication. The graph on annual publication shows that the first paper on biofuel from bio-waste was released in 2004 and the number of papers on the area showed 27.23% annual growth over time (Fig. 2). There was a sharp growth of publications after 2007, with publication peaks in 2011, 2014 and 2017. This increase in publication number over time can be attributed to the evolving consciousness of climate change and adverse effects of fossil fuels. The Kyoto Protocol, which was established during the UNFCCC in 1997, aimed to reduce the emission of GHG that contribute to global warming by promoting green technologies for biofuel production (Zhang et al., 2021). Consequently, interest progressed towards low-carbon energy sources like organic-waste. The publication activity was very low during 2004–2007 period because the research topic was still in its infant stage. However, the increase in publication after 2007 can be attributed to the high oil price crisis as well, which fostered a global interest in renewable fuels employment (Perea-Moreno et al., 2019).

Country productivity and collaboration

Table 1 shows the most active countries on bio-fuel production from bio-waste utilizing microorganisms. Evaluating the most active countries provides a better understanding of the research topic and elucidates

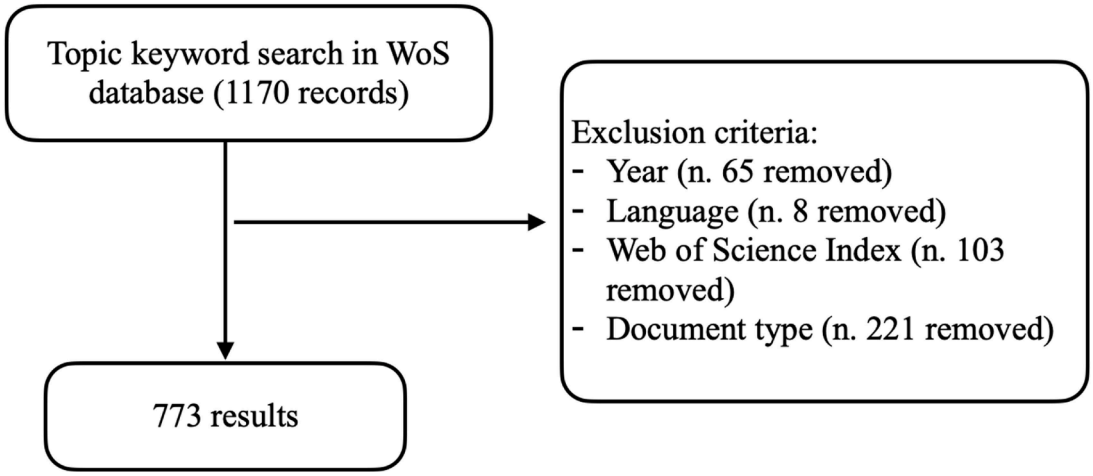

Fig. 1. Flowsheet of the bibliometric study.

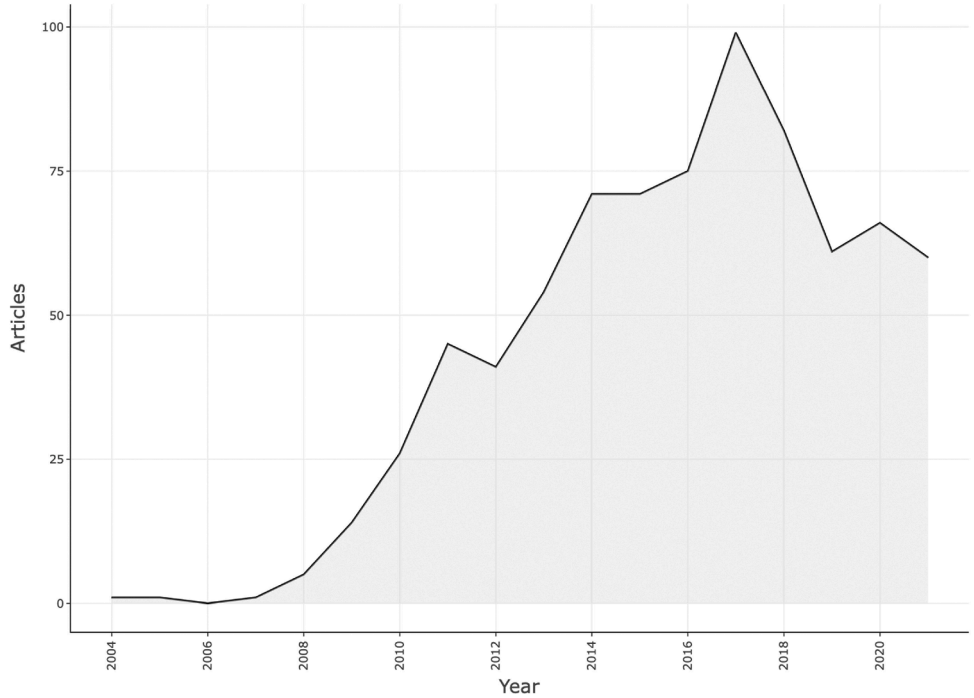

Fig. 2. Evolution of the number of publications related to biofuel production from bio-waste over the years.
Total number of publications and citations per year for research related to bio-waste to bioenergy during 1998–2018.

Table 1
Most productive andim pactful countries.

Countries	Documents	Total citation	Average Article Citation
USA	742	11493	45.43
China	414	3770	23.86
India	89	1093	30.36
Sweden	63	1082	45.08
Brazil	59	732	36.60
Mexico	54	434	22.84
Spain	50	374	22.00

the development reasons of particular type of research. The USA, followed by China were the most productive and impactful countries. These results were according to each author's country affiliation. For example, if ten authors collaborated in a publication under the affiliation of the USA, then the USA will be credited ten times. Hence, we also provided country publication activity based on corresponding author affiliation for better representation of country productivity and collaboration on the topic (Fig. 3a). The USA was the leading country with respect to publications and received citations, followed by the China, India and Sweden (Table 1). Although China had the highest publication and total citation number after the USA, Sweden ranked second based on average article citation, followed by Brazil and India (Table 1). China followed by the USA, Italy and Spain were most productive in anaerobic digestion research for organic waste management and energy recovery (Ampese et al., 2022). Fig. 3a illustrates the frequency of most productive countries according to corresponding author, as well as depicts the ratios of multiple country publications (MCP) and single country publications (SCP). International collaboration is substantial for knowledge and experience share between laboratories to enhance quality standards by bringing together high-skilled researchers (Jimoh et al., 2022; Montoya et al., 2018). Although half of the publications of Sweden,

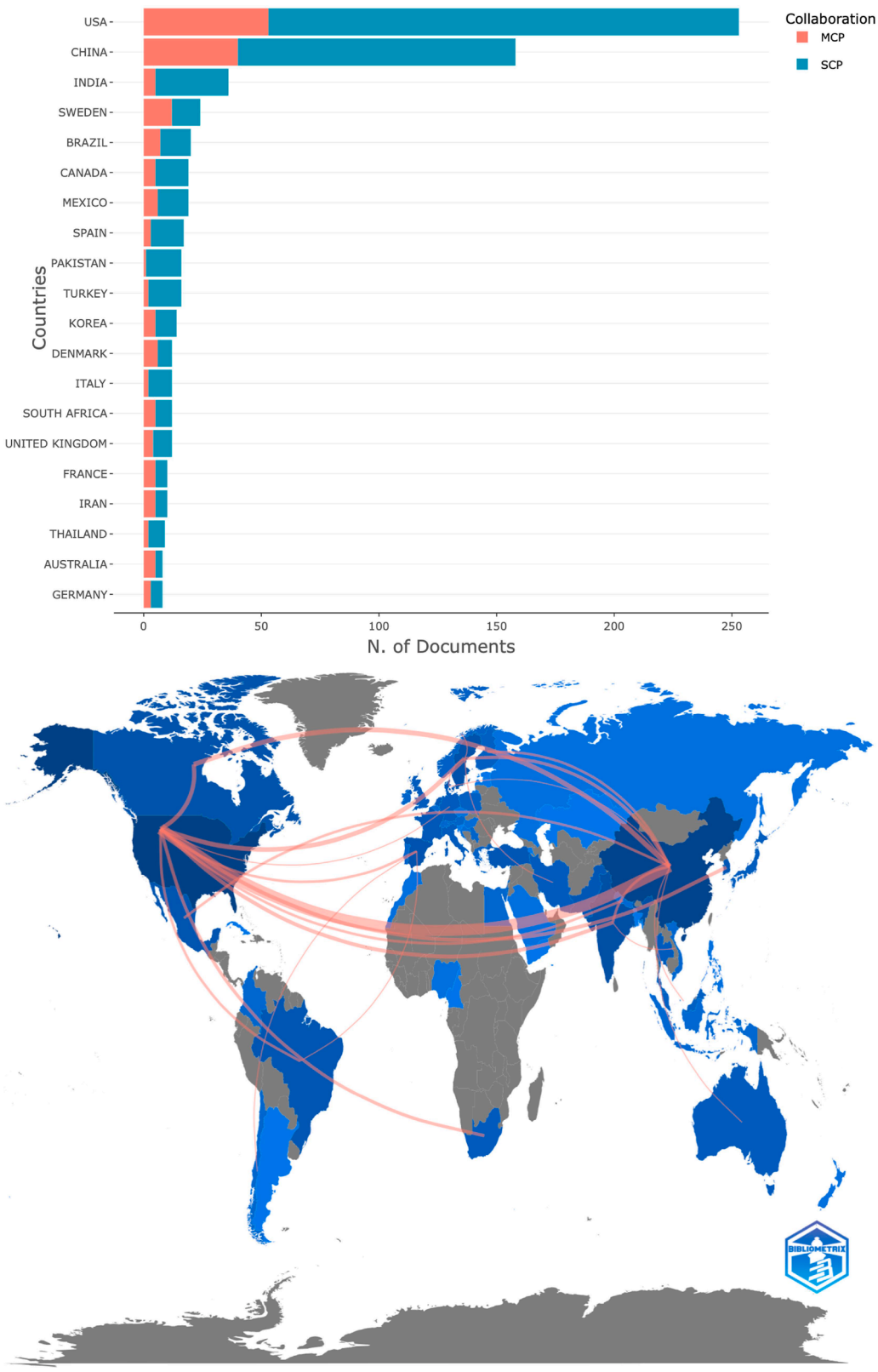

Fig. 3. (a) International collaboration on biofuel from biowaste by microorganisms based on corresponding author country. SCP: single country publication, MCP: multiple country publication. **(b).** Collaboration world map on biofuel from bio-waste by microorganisms. The color concentration is proportional to publication number. Collaboration threshold set for ≤ 3 papers.

Denmark, France and Iran were in collaboration with other countries, the top countries doing research on the field generally showed single-country publication rather than international collaboration. Only Australia had higher multiple country publication ratio (Fig. 3a). The world map on publication number and collaboration was set for at least 3 collaborative papers (Fig. 3b). The USA and China which are the most productive countries on the topic showed the highest collaboration frequency with each other (Fig. 3b). The second highest publication rate was among China and Canada, followed by USA and Sweden, USA and Canada, USA and India, USA and Korea, China and Sweden, etc. (Fig. 3a).

Most productive journals and research fields

The literature on the topic is associated with several research areas, such as Energy Fuels, Biotechnology Applied Microbiology, Agriculture and Chemistry (data not shown). This fact showed that research on biofuel from bio waste by microorganisms comprises several areas and eventually indicates its multidisciplinary features. A bibliometric study on anaerobic digestion technology illustrated various disciplines collaboration tendency as well (Ampese et al., 2022). Although the core consisted of six journals with *Biotechnology for Biofuels* followed by *Bioresource Technology, Biomass & Bioenergy, Industrial Crops and Products, Bioenergy Research, Applied Biochemistry and Biotechnology* (Fig. 4a); our bibliographic data collection was published in over 190 journals which implies the emerging and high popularity of this scientific field. Despite *Biotechnology for Biofuels* had the highest publication number, *Bioresource Technology* Journal had a slightly higher H-index impact (data not shown). Fig. 4b presents the *Biotechnology for Biofuels* and *Bioresource Technology* journals as the most outstanding, and the closest relationship occurs with the keywords pretreatment, enzymatic hydrolysis, biofuels, bioethanol, corn stover and fermentation. This graph displays the multidisciplinary nature of the biofuel from bio-waste by microorganisms' studies, implying that the improvement of several research domains is required for this technology. The co-occurrence analysis of keywords can be a useful tool to popular research topics and frontiers (Ye et al., 2020). Fig. 5a displays the clustering of the 50 most used author keywords. In this type of graph, the colors represent different sub-groups, and the sub-group generation depends on the relation degrees of the actors, thus resulting in closely related group members. In general, the most used keywords in the bibliographic data collection ranked according to the strongest relationship were pretreatment, enzymatic hydrolysis, fermentation, ethanol, bioethanol, biofuels, and biomass. Similar words which explain a similar concept grouped together among the 50 most frequent keywords resulting in four clusters. Pretreatment, enzymatic hydrolysis, fermentation and ethanol were the most apparent keywords within the red cluster; whereas biofuel, biomass and corn stover were the most prominent keywords in the blue cluster. The plot suggests the relevant procedures to valorize bio-wastes and allow formulating technological routes to produce biofuel utilizing microorganisms. The major steps of bioethanol production from cellulose are: pretreatment, hydrolysis, fermentation and product distillation. Optimizing the pretreatment process in cost-effective way is one of the major challenges in biofuel production (Balat, 2011). There are different types of hydrolysis. Enzymatic hydrolysis is advantageous when converting lignocellulose to glucose. The enzymatic hydrolysis success depends on many factors including structural parameters of the substrate (Dutta and Chakraborty, 2018). The supernatant (i.e. sugars) from the enzymatic hydrolysis of lignocellulose can be fermented to bioethanol through microorganisms (Keshwani and Cheng, 2009). Fig. 5b illustrates a thematic map clustering of the author's keywords in accordance with the relationship and development degree of the scientific domains. The thematic map consists of four parts, which are motor themes, basic themes, emerging or declining themes and, very specialized/niche themes. Each bubble on the plot represents a network cluster, and the bubble size is proportional to the cluster word occurrences. Biofuel, ethanol and lignocellulose forming the green bubble constitute the motor-themes, which means that this network of words (or these research topic) are prominent and have a good progress. On the contrary, the group of pretreatment, enzymatic hydrolysis and lignocellulosic biomass; wheat straw, biodiesel and anaerobic digestion; as well as biofuel, corn stover and cellulosic ethanol are considered basic themes, which are substantial for the research area but are not well-improved. We can say that they have low density and high centrality, and require further research. Together with scientific development of these subfields, they can move towards to motor-themes. Optimization of pretreatment and enzymatic hydrolysis processes are considered as major challenges in biofuel production (Adsul et al., 2020; Balat, 2011). Recent scientific works showed that anaerobic digestion is not largely implemented for bioenergy conversion from biomass because of poor methane production due to operational problems and procedure inconsistancy (Kumar and Samadder, 2020; Serrano et al., 2021). Saccharification, cellulase and xylanase form Emerging/Declining themes. Fermentation, biomass and butanol; bioethanol, biorefinery, simultaneous saccharification and fermentation; as well as steam explosion, fungi and bagasse consisted the niche themes corresponding to highly developed and isolated topics. Conversion of cellulose through saccharification and fermentation is a main procedure for ethanol production from bio-waste. Optimizing saccharification conditions of biomass can improve biofuel generation (Kucharska et al., 2020). Citation number is one of the most important measures in a scientific area showing the most impactful, studied, and advanced topics regarding the research field.

Most influential documents

Table 2 displays the 10 most cited documents in the biofuel from bio-waste utilizing microorganisms' research. Balat (2011) "Production of bioethanol from lignocellulosic materials via the biochemical pathway: a review" had the highest citation number (815 citations) followed by Klein-Marcuschamer et al. (2012) "The challenge of enzyme cost in the production of lignocellulosic biofuels" (624 citations) (Table 2). Despite Kaparaju et al. (2009) "Bioethanol, biohydrogen and biogas production from wheat straw in a biorefinery concept" ranked third with respect to total citation number, Fu et al. (2011) "Genetic manipulation of lignin reduces recalcitrance and improves ethanol production from switchgrass" showed higher total citation per year (Table 2). In a nutshell, these most cited papers illustrated some main characteristics of biofuel production from bio-waste, which provided adequate information for the application of the procedures at industrial level. They depicted the most important operational factors, reactor types, process circumstances, and major biomass kinds used for biofuel generation.

Collaboration network

The author collaboration network graph is generated as follow: (i) each author is represented by a node/circle in the map; (ii) a link is formed when two authors co-occur in one document; and (iii) the co-occurrence number between authors is described as edge weight (Peng et al., 2017). The social network analysis conducted on the collaboration amongst the most influential 30 scientists mapped seven clusters after removing isolated nodes that have no relationship with other nodes (Fig. 6). The size of node is represented by its degree, which means that if an author collaborates with many other authors, the representing node size will increase accordingly. Wiring thickness is defined by the strength/frequency of the co- occurrence, that is, higher collaboration rate thicker connection between nodes. The red cluster consisting of five authors is the densest one, with Dale and Balan being the most actively collaborating within the network. Network density impacts information spread. Higher density means better interaction and dissemination of knowledge (Wang, 2008). This author subnetwork was generally collaborating on pretreatment technologies for biofuel

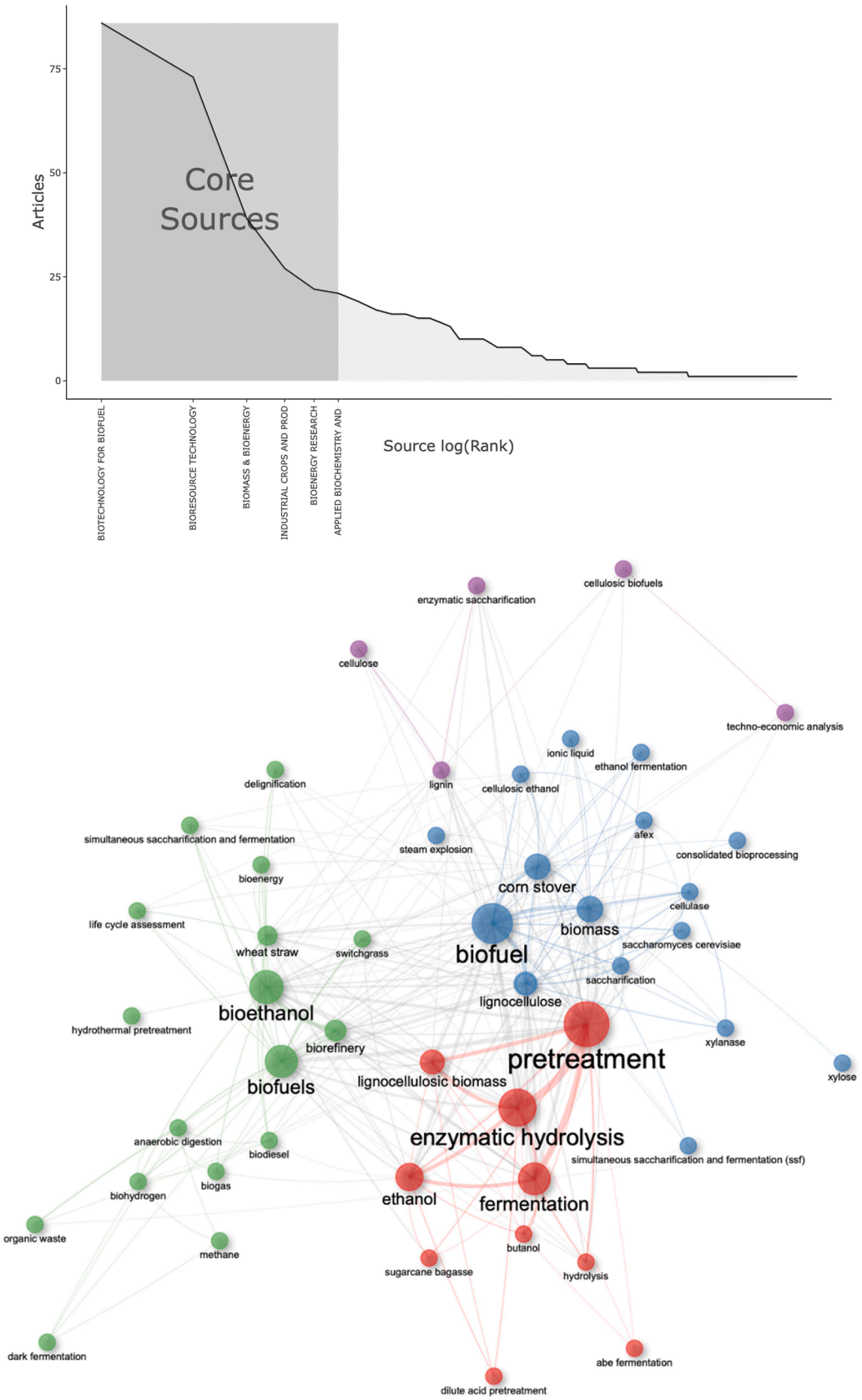

Fig. 4. **(a)** Most productive journals on biofuel from bio-waste by microorganisms literature. **(b)** Three-fields plot showing relationship between top 15 authors, author's keywords and journals.

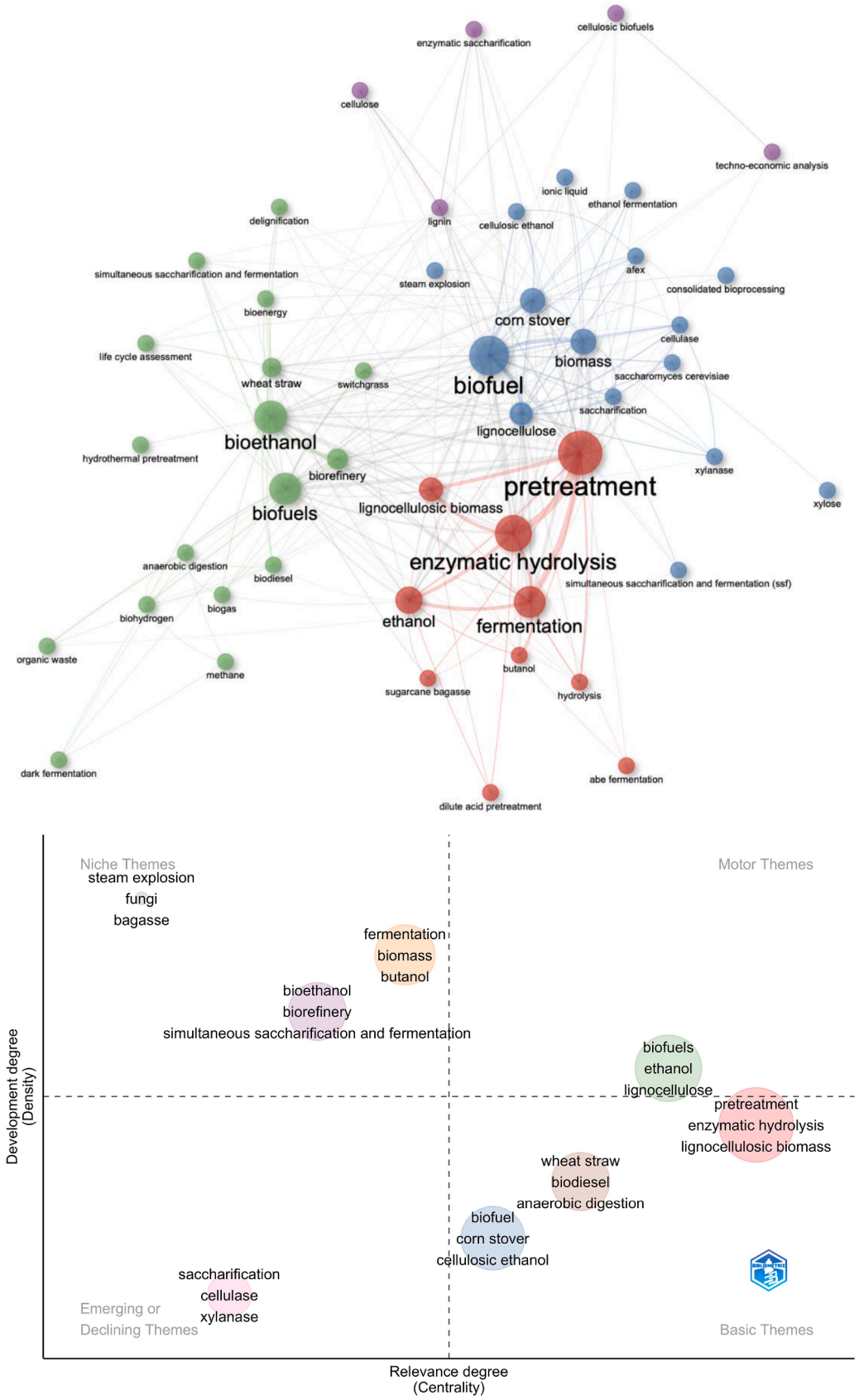

Fig. 5. **(a)** Clustering of the 50 most used author keywords. (**b**). Thematic map on author keywords.

Table 2
Top 10 most cited articles in the Web of Science database ordered by total citation number (TC).

#	Author(s)	Title	Year	Journal	TC	TC/Y
1	Balat	Production of bioethanol from lignocellulosic materials via the biochemical pathway: a review	2011	Energy Conversion and Management	815	67.92
2	Klein-Marcuschamer et al.	The challenge of enzyme cost in the production of lignocellulosic biofuels	2012	Biotechnology and Bioengineering	624	56.73
3	Kaparaju et al.	Bioethanol, biohydrogen and biogas production from wheat straw in a biorefinery concept	2009	Bioresource Technology	494	35.24
4	Fu et al.	Genetic manipulation of lignin reduces recalcitrance and improves ethanol production from switchgrass	2011	Proceedings of the National Academy of Sciences	477	39.75
5	Kim and Dale	Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel	2005	Biomass and Bioenergy	385	21.39
6	Binder and Raines	Fermentable sugars by chemical hydrolysis of biomass	2010	Proceedings of the National Academy of Sciences	355	27.31
7	Chaturvedi and Verma	An overview of key pretreatment processes employed for bioconversion of lignocellulosic biomass into biofuels and value added products	2013	3 Biotech	270	27.00
8	Lau and Dale	Cellulosic ethanol production from AFEX-treated corn stover using Saccharomyces cerevisiae 424A(LNH-ST)	2009	Proceedings of the National Academy of Sciences	264	18.86
9	Qureshi et al.	Production of butanol (a biofuel) from agricultural residues: Part I – Use of barley straw hydrolysate	2010	Biomass and Bioenergy	252	19.38
10	Minty et al.	Design and characterization of synthetic fungal-bacterial consortia for direct production of isobutanol from cellulosic biomass	2013	Proceedings of the National Academy of Sciences	248	24.80

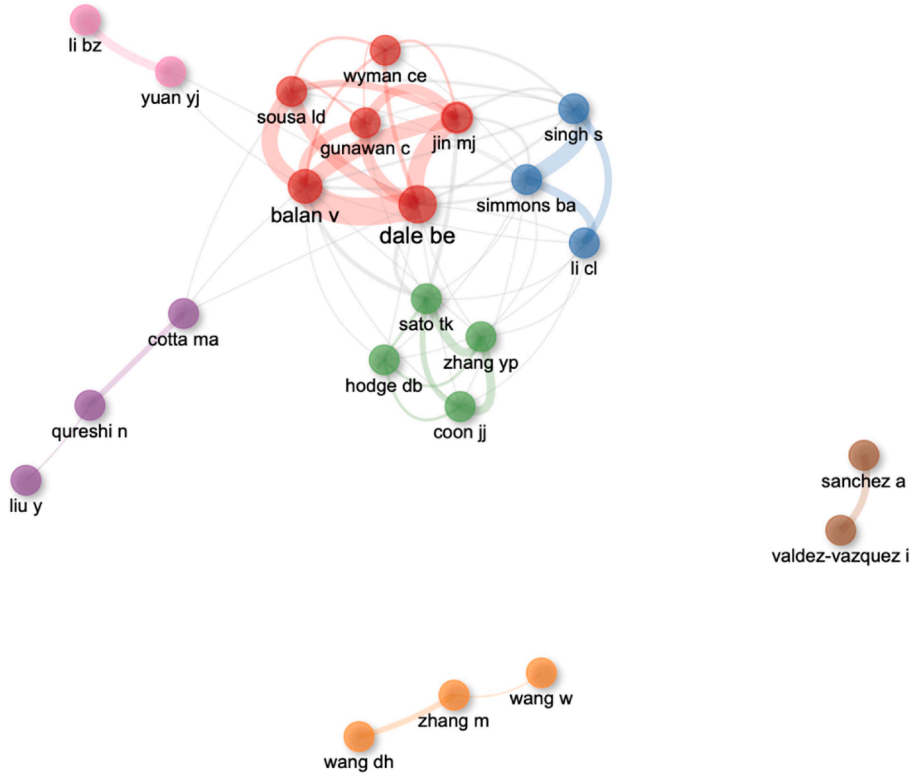

Fig. 6. Collaboration network analysis among the most productive 30 authors.

production. The green cluster was the second biggest sub-network including the authors Sato, Hodge, Zhang and Coon. This group of authors was collaborating on microbial fermentation for biofuel production. These results show the electiveness of these networks and encourage more researchers to be involved on the topic. On the other hand, there are still many opportunities for future collaboration between researchers to promote knowledge dissemination and sharing.

Most used keywords and research trends

Keywords are phrases that represent the underlying research aspect of a literature. Consequently, keyword analysis enables mapping research hot topics and helps detect research direction and gaps in a specific scientific field (Jimoh et al., 2022; Xiang et al., 2017). The word cloud displayed biofuel as the most frequently used author keyword followed by pretreatment, enzymatic hydrolysis, ethanol, fermentation, corn stover, and lignocellulosic biomass with other notable keywords as biorefinery, saccharification, butanol, anaerobic digestion, afex, biohydrogen, and steam explosion (Fig. 7). We can infer that optimization studies on pretreatment and enzymatic hydrolysis for biofuel production through fermentation were among the popular research topics and corn stover was the most largely used organic waste. Conversion of biofuel from bio-waste strongly depend on the microbial community applied (Ampese et al., 2022; Gannoun et al., 2016). Besides, this biological

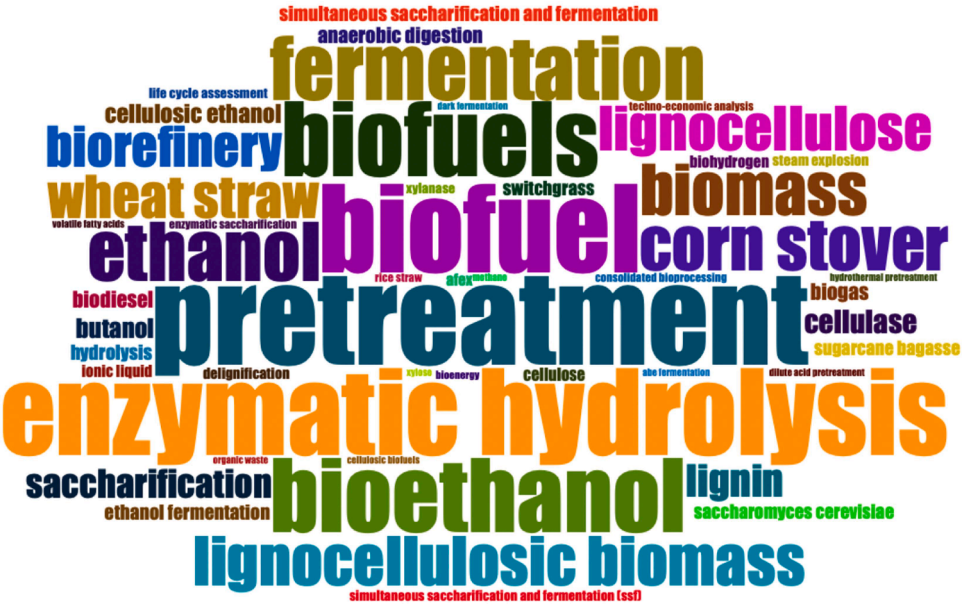

Fig. 7. Word-cloud representing most frequent author's keywords.

process is affected by several other variables including operational parameters, growth factors, and organic waste type (Van et al., 2020).

The major steps in the biomass to biofuel production are: pretreatment, enzymatic hydrolysis, and fermentation of sugars. Pretreatment and enzymatic hydrolysis processes are considered as major cost-centers and optimizing these processes in cost-effective way is one of the major challenges in biofuel production (Adsul et al., 2020; Balat, 2011). There are different types of hydrolysis. Enzymatic hydrolysis is advantageous when converting lignocellulose to glucose. The enzymatic hydrolysis success depends on many factors including structural parameters of the substrate (Dutta and Chakraborty, 2018). Major obstacles in large-scale production of ethanol are the enzyme costs and the inability of a single microbial species to produce all enzymes necessary for an efficient hydrolysis (Adsul et al., 2020). Therefore, research on reducing enzyme cost for ethanol production have been attempted. These studies include designing optimal enzyme blends, having certain enzyme ratios from various microbial sources for efficient hydrolysis of the bio-waste (Soleimani and Ranaei-Siadat, 2017; Victoria et al., 2017). However, the underlying mechanisms of this process still remain unclear. Biofuels will definitely contribute to the decarbonization of the environment and enable appropriate bio-waste control and energy conversion for sustainable progress of bioeconomy. The cellulosic ethanol demand will increase over the years, despite problems related to cost-effective hydrolysis (Adsul et al., 2020). It is assumed that future research will be able to optimize pretreatment and enzymatic hydrolysis for specific types of bio-wastes. Also, the number of scientific works related to the circular economy and the industrial processes related to bio-waste management is expected to increase, considering the growing market demands for sustainable commodities.

Conclusion

This bibliometric study illustrated the research hot topics and gaps on biofuel production from bio-waste by microorganisms, and provided an updated knowledge in the area. The bibliometric analysis projected a lack of information related to biomass management in industries for bioenergy conversion as a pathway for sustainability. The main potential progress stands in the optimization of pretreatment and enzymatic hydrolysis processes for a large-scale yield of ethanol as a profitable biowaste management system for bioenergy production. These improvements will be within the framework of circular economy, and to support this evolution, it is vital to investigate also the economic aspects of biofuel conversion from bio-waste by microorganisms at the pilot and industrial level. It is assumed that future research will be able to optimize pretreatment and enzymatic hydrolysis processes for specific types of organic wastes. In a nutshell, the studies on biofuel production from bio-waste by microorganisms are multidisciplinary, implying that the progress of several scientific areas are required for this topic to evolve. Besides, by integrating the knowledge on biomass characterization, pretreatment and enzymatic hydrolysis with appropriate process modeling and optimization practices biofuel yield could be increased. Thus, biofuel production from bio-waste by microorganisms could be a profitable and sustainable waste management procedure.

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CRediT authorship contribution statement

Melekşen Akın: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – original draft. **Elena Bartkiene:** Validation, Writing – review & editing, Visualization. **Fatih Özogul:** Validation, Writing – review & editing, Visualization. **Sadiye Peral Eyduran:** Validation, Writing – review & editing, Visualization. **Monica Trif:** Validation, Writing – review & editing, Visualization. **José M. Lorenzo:** Validation, Writing – review & editing, Visualization. **João Miguel Rocha:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Data curation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that there are no potential conflicts of interest regarding the research, authorship and publication of this manuscript.

Data availability

Data will be made available on request.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

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