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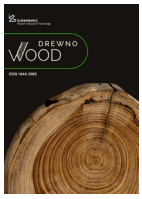

Global Research Trends in Wood Pellets, a Renewable Energy Source: A Bibliometric Analysis

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Due to global warming and climate change, more importance has started to be attached to renewable energy sources as alternatives to fossil fuels. Wood pellets are among the renewable energy sources, and have been the subject of a growing number of studies. Therefore, developments and trends in research on wood pellets can be determined through bibliometric analysis of publications. This study explores the current status and "hot topics" of research on wood pellets using performance analysis and scientific mapping based on publications from 1980–2023. For this purpose, we carried out a bibliometric analysis of 758 publications in the Web of Science database scanned with the keywords "wood" and "pellets". The numbers of publications and citations on wood pellets have grown steadily over the years, with 67% of publications and 89% of citations coming in the last decade. A total of 2,294 authors from 884 organizations and six continents have contributed publications in the field of wood pellets. The University of British Columbia (Canada) and the United States Department of Energy (USA) were the institutions with the most numerous and the most cited publications. Sokhansanj Shahab from the University of British Columbia was the most active and most cited author. The published literature has focused on three topics: biomass, bioenergy, and combustion. As a result, this study will provide a general perspective for future research relating to wood pellets.

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Introduction

Studies on biomass, one of the renewable energy sources, have accelerated in recent years. Considering its great potential and its economically and environmentally advantageous properties, interest in biomass is increasing. Biomass is an important energy source, and is currently the fourth largest energy source globally. Many developed countries see bioenergy as the main energy source of the future (Sungur et al., 2018).

Wood pellets are among the biomass fuels classified as renewable energy sources, and are obtained as a result of drying, grinding, pressing and cooling of wood waste (Zengin et al., 2020). Wood pellets have several advantages over fossil fuels (Saraçoğlu, 2010; Oral, 2022; Saletnik et al., 2022): (1) they are an environmentally

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friendly, economical and high value-added energy source; (2) they produce less carbon emissions than fossil fuels; (3) they offer relatively high energy density and ease of use; (4) they are more favorable in terms of storage and transport, and are more homogeneous in terms of physical and chemical properties; (5) the ash rate of pellets is approximately 10 times lower than that of coal; and (6) they are produced under high pressure without the addition of chemical binders/retainers and have a heating value of approximately 5 KW/h. In addition, wood pellets can be stocked and used by individuals when needed. Therefore, in times of energy crisis, wood pellets have the potential to be a component of energy security (Oral, 2022).

Wood pellets are the fastest growing type of bioenergy feedstock. Global wood pellet production has steadily increased, from about 18 million metric tons in 2012 to 47.586 million metric tons in 2022. According to 2022 data, Europe's wood pellet production is estimated at 24.878 million metric tons, while that of North America is estimated at 13.374 million metric tons. Along with production, growth in wood pellet exports continued in 2022. According to FAOSTAT data, the value of wood pellets exported worldwide in 2022 was US$ 6.343 billion. Approximately 24.3% of the world's total wood pellet exports are from the USA (US$ 1.545 billion), followed by Vietnam (US$ 791 million) and Canada (US$ 532 million).

Wood pellets, as a renewable energy source, are a current subject of interest to scientific researchers. Consequently, the number of scientific articles on wood pellets has increased exponentially. Bibliometric analysis is important in enabling researchers to view this growing number of studies in a systematic manner and to draw up plans for their own research.

Bibliometric analysis is an approach that uses a range of quantitative methods to measure, track and analyze scientific literature. Bibliometric studies analyze and classify bibliographic material by framing representative summaries of existing literature (Donthu et al., 2020; Rojas-Sanchez et al., 2023). With bibliometric research, it can be determined how much work has been done in which areas and in which areas there are deficiencies. Thus, it guides scientists who plan to work in a particular field or subject area (Akıncı, 2020).

In this research, a bibliometric analysis and scientific mapping were made of 758 documents in the Web of Science (WOS) searched with the keywords "wood" and "pellets" and dated from 1980 to 2023. For scientific mapping, VOSviewer software, one of the most popular bibliometric tools, was used. Therefore, based on this research, the hot spots and trends in scientific research on wood pellets over more than 40 years will be summarized.

Materials and methods

As presented in Fig. 1, scientific publications indexed in the Web of Science database were retrieved on March 13, 2024. First, publications with a combination of "wood" and "pellet" in the title were identified. As a result of the first search, 793 publications were found. Subsequently, publications from the year 2024 were excluded, as well as the following types of publications: meeting abstract, correction, editorial material, news item, book review, data paper, and note. After the filtering process, 758 publications were identified from the years 1980–2023. To enable the analysis of publications with VOSviewer software, they were exported in .txt format. VOSviewer software was used to analyze co-authorship, co-citation, co-occurrence, and themes. VOSviewer is a computer program developed by Van Eck and Waltman (2010) to create, visualize and explore bibliometric maps of studies, and is freely available to users (Van Eck, 2011). In this program, two standard weight attributes are applied: the "links attribute" and "total link strength attribute" (Yu et al., 2020).

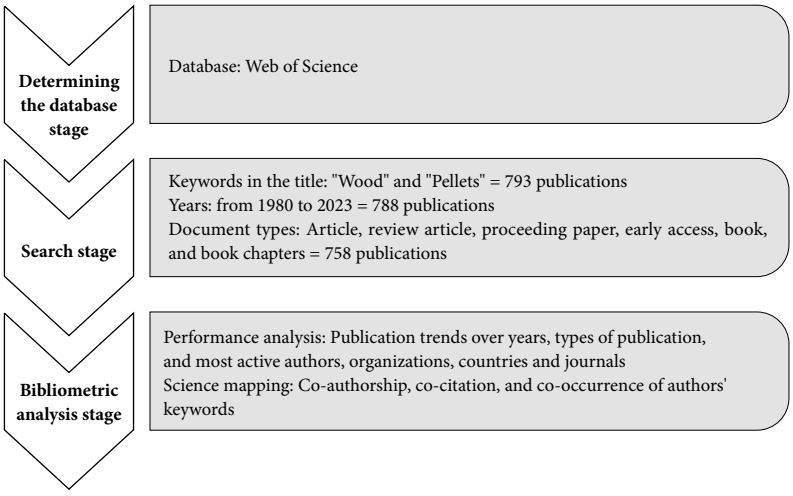

Fig. 1. Stages of research

Results

1. Bibliometric analysis of publications and citations

As a result of the bibliometric query in Web of Science, 758 scientific publications were identified, consisting of 650 research articles, 105 proceeding papers, 19 review articles, and 25 other forms of publications including early access, book chapters, and a book. The oldest of these are publications titled "Wood-pulp fines or corn-silage as roughages in complete rations or a pelleted complete ration for young dairy replacements from birth through 18 weeks of age" and "Wood-pulp fines or corn-silage as roughages in complete rations or a pelleted complete ration for young dairy replacements 18 through 36 weeks of age," published in the *Journal of Dairy Science* in 1980 (Block and Shellenberger, 1980a; Block and Shellenberger, 1980b). Publications relating to wood pellets appeared in 286 journals, with a total of 2,294 authors working for 884 organizations from 75 countries. As presented in Table 2, publications in the field of wood pellets and the number of cited publications have constantly increased over the years. The year with the most publications on wood pellets was 2017 (71 publications), and the greatest number of citations was recorded for 2021 (2,056 citations). In total, there were 15,504 citations to publications in the field of wood pellets, of which 2,294 were authors' self-citations. The most cited publication was "Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets" published in the *Journal of Atmospheric Environment* in 2004, with 377 citations, as indicated in Table 3. Four of the top ten most cited publications were published in the journal *Biomass and Bioenergy*. There are 22 publications that have received more than 100 citations.

In addition, the degree of collaboration reflected in the publications was calculated using the following formula (1) (Subramanyam, 1983):

$$C = \frac{N_m}{N_m + N_s} \quad (1)$$

where:
C is the degree of collaboration in the discipline,
N_m is the number of multi-authored documents,
N_s is the number of single-authored documents.
The C value was calculated as 0.97. The higher the C value, the higher the degree of collaboration.

2. Leading authors, organizations and countries

The top ten countries, organizations and authors producing publications on wood pellets are presented in Table 4. The author with the most publications on wood pellets is Sokhansanj Shahab from the University of British Columbia; his 33 publications have been cited 982 times. The author with the largest number of citations per publication is Junginger Martin from Utrecht University, with 52.71. The only country to produce more than 100 publications in the field of wood pellets is the USA, and there are six countries whose publications have been cited more than 1,000 times. The University of British Columbia has produced 50 related publications, with 1,582 citations, followed by the United States Department of Energy and Oak Ridge National Laboratory. The three organizations that produced the most publications each accumulated more than 1000 citations.

3. Most active journals

A total of 287 journals published papers on wood pellets; of these, 258 published fewer than 5 articles, while 260 publications appeared in the top ten journals. The journal with the most publications in the field of wood pellets was *Biomass & Bioenergy*, with 49 publications, followed by *Fuel*, *Energy & Fuels*, and *Energies*. *Biomass & Bioenergy* was also the most cited journal, with 1531 citations, followed by *Energy & Fuels* and *Fuel*. There are six journals that have been cited more than 500 times. The journal with the largest number of citations per publication was *Atmospheric Environment*, with 106.2 (Table 5).

4. Co-authorship network visualization

Fig. 2A shows a network map of co-authors of relevant publications. On this map, the thicker the line between authors, the stronger the collaboration, while the bigger the node, the larger the number of publications. Each color represents a group. In creating the map, the minimum number of publications of an author was set at 5. It was observed that 45 authors passed this threshold, and the largest connected set consisted of seven authors. As presented in Fig. 2A, the authors are divided into two groups: Cluster 1 (red color, 4 authors), and Cluster 2 (green color, 3 authors). Sokhansanj Shabab, the author with the highest number of publications and total link strength, had the strongest collaboration link with Lim C. Jim.

The minimum number of documents of an organization was chosen as 5, and the network map showing the collaboration of 30 organizations is shown in Fig. 2B. The organization with the highest total link strength is Oak Ridge National Laboratory with 52. The number of its collaborators was 9, and its main collaborator was the University of British Columbia. However, the Swedish University of Agricultural Sciences has the largest number of collaborating organizations in the

Table 1. Main information about publications in the field of wood pellets from 1980 to 2023

Description	Result
Journals	286
Publications	758
Organizations	884
Countries	75
Total citations	15504
Self-citations	2181
Research article	650
Proceeding paper	105
Review article	19
Early access	15
Book chapters	9
Book	1
Authors	2294
Single-authored publications	26
Multi-authored publications	732

Table 2. Annual numbers of publications on wood pellets and annual numbers of citations

Year	Publications	Citations in WOS	Year	Publications	Citations in WOS
1980	2	1	2002	1	5
1981	0	0	2003	4	11
1982	0	0	2004	7	15
1983	0	0	2005	3	23
1984	2	0	2006	4	30
1985	0	0	2007	8	38
1986	1	0	2008	15	72
1987	0	0	2009	17	115
1988	1	0	2010	23	113
1989	1	1	2011	34	244
1990	0	1	2012	30	362
1991	1	1	2013	35	390
1992	0	1	2014	50	609
1993	0	2	2015	51	790
1994	0	1	2016	56	959
1995	0	0	2017	71	1104
1996	1	6	2018	67	1395
1997	3	4	2019	59	1405
1998	1	3	2020	58	1755
1999	0	4	2021	59	2056
2000	1	5	2022	49	1951
2001	2	8	2023	41	1813

Table 3. The 10 most cited publications on wood pellets according to WOS (1980–2023)

Publication title	Journal	Number of citations in WOS	References
Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets	*Atmospheric Environment*	377	Johansson et al. 2004
Factors affecting wood, energy grass and straw pellet durability – A review	*Renewable & Sustainable Energy Reviews*	198	Whittaker and Shield 2017
The European wood pellet markets: current status and prospects for 2020	*Biofuels Bioproducts & Biorefining – BIOFPR*	182	Sikkema et al. 2011
Heating values of wood pellets from different species	*Biomass & Bioenergy*	166	Telmo and Lousada 2011
Effect of wood fuel on the emissions from a top-feed pellet stove	*Energy & Fuels*	166	Sippula et al. 2007
Slagging tendencies of wood pellet ash during combustion in residential pellet burners	*Biomass & Bioenergy*	161	Öhman et al. 2004
Life Cycle Emissions and Cost of Producing Electricity from Coal, Natural Gas, and Wood Pellets in Ontario, Canada	*Environmental Science & Technology*	159	Zhang et al. 2010
An environmental impact assessment of exported wood pellets from Canada to Europe	*Biomass & Bioenergy*	150	Magelli et al. 2009
Wood pellet production costs under Austrian and in comparison to Swedish framework conditions	*Biomass & Bioenergy*	148	Thek and Obernberger 2004
Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: Experimental study	*Applied Energy*	147	Erlich and Fransson 2011

area of wood pellets, with 10 organizations. In recent years, the most active organizations have been North Carolina State University, Technical University Wien, and Technical University Denmark.

Publications in the field of wood pellets have been produced by authors from six different continents. The minimum number of documents of an author was chosen as 5, and the largest set of connected countries consists of 37 countries. As presented in Fig. 2C, the five countries with the highest number of publications, number of citations and total link strength were the USA, Canada, Germany, Sweden and Italy; the total link strengths of these countries are 101, 72, 51, 49 and 43, respectively. The USA and Sweden are the countries that collaborate the most with other countries in studies on wood pellets, with 17 links. The USA had the strongest collaboration with Canada, while Sweden had the strongest collaboration with the USA. The most active countries in studies of wood pellets in recent years have been Egypt and Brazil.

5. Co-citation network visualization

Another important analysis is the co-citation analysis of the publications. In co-citation analysis, a link is created between two publications if they were cited by the same study. It is one of the most effective and common tools used to identify studies of central importance in scientific research in a specific field (Zitt and Bassecoulard, 1994). In Fig. 3A, a network map of the most frequently co-cited references in the wood pellets literature is presented. The network map was created with 31 references that were cited at least 20 times from a total of 19,107 cited references. The most frequently cited references in the wood pellets

Table 4. The ten authors, countries and institutions with the most publications related to wood pellets

Authors	**Number of publications**	**Number of citations in WOS**
Sokhansanj Shahab	33	982
Bi Xiaotao	30	773
Lim Choon Jim	23	786
Melin Staffan	19	846
Junginger Martin	14	738
Hopke Philip	11	259
Jandacka Jozef	10	99
Toscano Giuseppe	9	304
Holubcik Michal	9	98
*Lau Anthony K.	8	145
*Scherer Viktor	8	69
*Berghel Jonas	8	190
*Yazdanpanah Fahimeh	8	66
Countries	**Number of publications**	**Number of citations in WOS**
USA	141	3355
Sweden	85	3152
Canada	80	2538
Germany	59	1321
Italy	50	1324
South Korea	40	460
England	35	1226
Poland	35	205
Finland	32	854
People's Rep. China	32	837
Organizations	**Number of publications**	**Number of citations in WOS**
University of British Columbia	50	1582
United States Department of Energy	43	1418
Oak Ridge National Laboratory	34	1201
Swedish University of Agricultural Sciences	23	565
Utrecht University	16	687
Delta Research Corporation	14	485
Umea University	14	696
University of Georgia	14	296
University System of Georgia	14	296
*Clarkson University	12	265
*Karlstad University	12	337
*North Carolina State University	12	234

*Equal number of publications

Table 5. The ten journals with most numerous and most cited publications on wood pellets

Journal	Number of publications	Journal	Number of citations in WOS
Biomass & Bioenergy	49	Biomass & Bioenergy	1531
Fuel	42	Energy & Fuels	1105
Energy & Fuels	37	Fuel	993
Energies	33	Applied Energy	599
Fuel Processing Technology	22	Fuel Processing Technology	533
Renewable Energy	19	Atmospheric Environment	531
Applied Energy	17	Renewable & Sustainable Energy Reviews	394
Energy	17	Biofuels Bioproducts & Biorefining Journal	385
Renewable & Sustainable Energy Reviews	12	Energy	243
Forest Products Journal	12	Renewable Energy	235

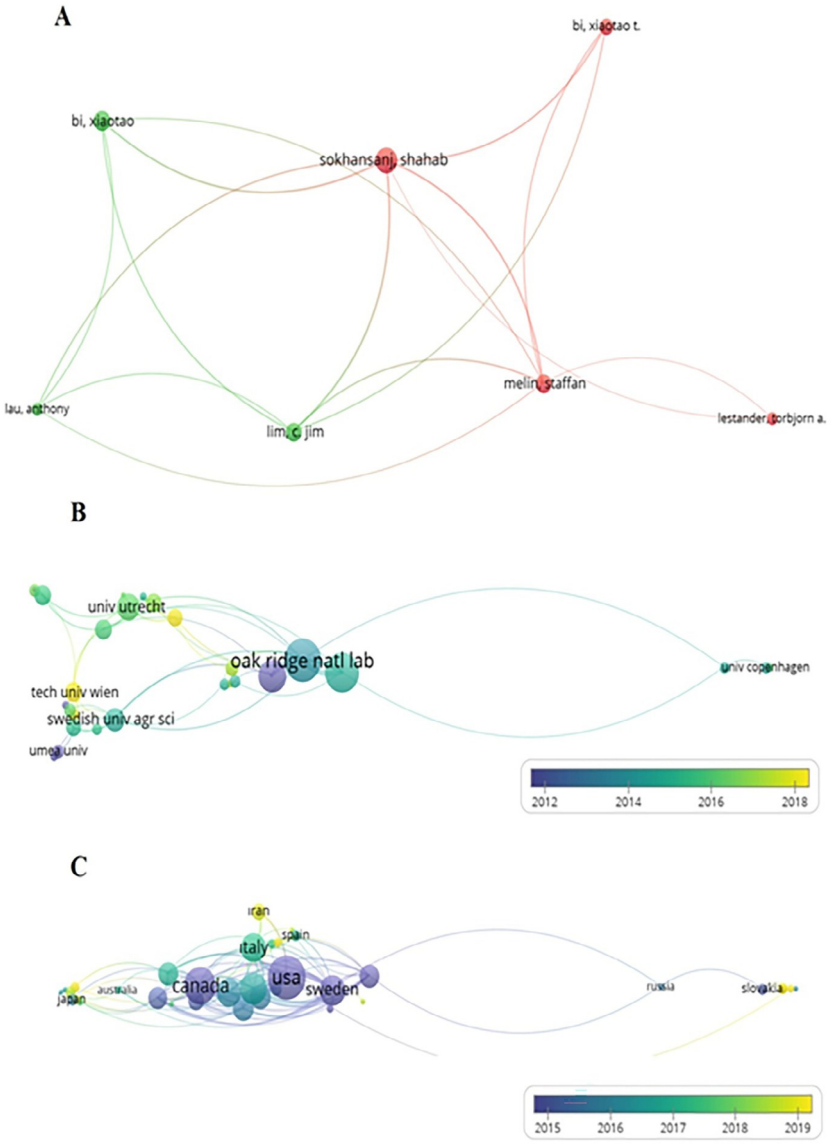

Fig. 2. Co-authorship maps of authors (A), organizations (B), and countries (C)

literature formed three clusters: Cluster 1 (red color, 16 references), Cluster 2 (green color, 8 references), and Cluster 3 (blue color, 7 references). The reference with the highest total link strength (171) was the study titled "Emission of hexanal and carbon monoxide from storage of wood pellets, a potential occupational and domestic health hazard" published by Svendberg et al. (2004) in *Annals of Occupational Hygiene*, followed by the papers of Svendberg et al. (2008) and Kuang et al. (2008). Interestingly, the three publications with the highest link strengths are all published in the journal *Annals of Occupational Hygiene*, whereas the total link strength of the study published by Kaliyan and Morey (2009) in *Biomass and Bioenergy*, which has the highest number of citations, is not very high.

While preparing their studies, researchers primarily refer to scientific publications published in field journals. Therefore, it is very important to determine the most referenced journals in a field. For this purpose, an analysis of co-citation of sources was conducted (Fig. 3B). With this analysis, co-cited journals in the bibliographies of publications in the field of wood pellets are identified. The network map was created with 75 journals that were cited at least 30 times from a total of 9,158 journal citations. The journal with the highest number of citations (1641) and total link strength (30,425) is *Biomass & Energy*, followed by *Fuel*, *Energy Fuel* and *Full Process Technology*. The journals with the strongest co-citation links with *Biomass & Bioenergy* were *Fuel* and *Energy Fuel*, although it had such links with 73 different journals. The impact factor of the journal in 2022 was 6, and it is ranked Q1 in the agricultural engineering category according to 2022 JCR data. In terms of impact factor, *Biomass & Bioenergy* is ranked second out of 14 journals in the agricultural engineering category.

6. Keyword analysis and trending topics

Fig. 4A depicts an analysis of the co-occurrence of keywords listed by the authors in publications on wood pellets. In this analysis, the minimum number of occurrences of a keyword was 5, and 76 keywords passing this threshold were identified from a total of 1,827 keywords. The keyword that appeared most was "wood pellets" (total link strength 207), which has a strong link to biomass and bioenergy. In addition, this keyword had connections with 61 different keywords. The other keywords with total link

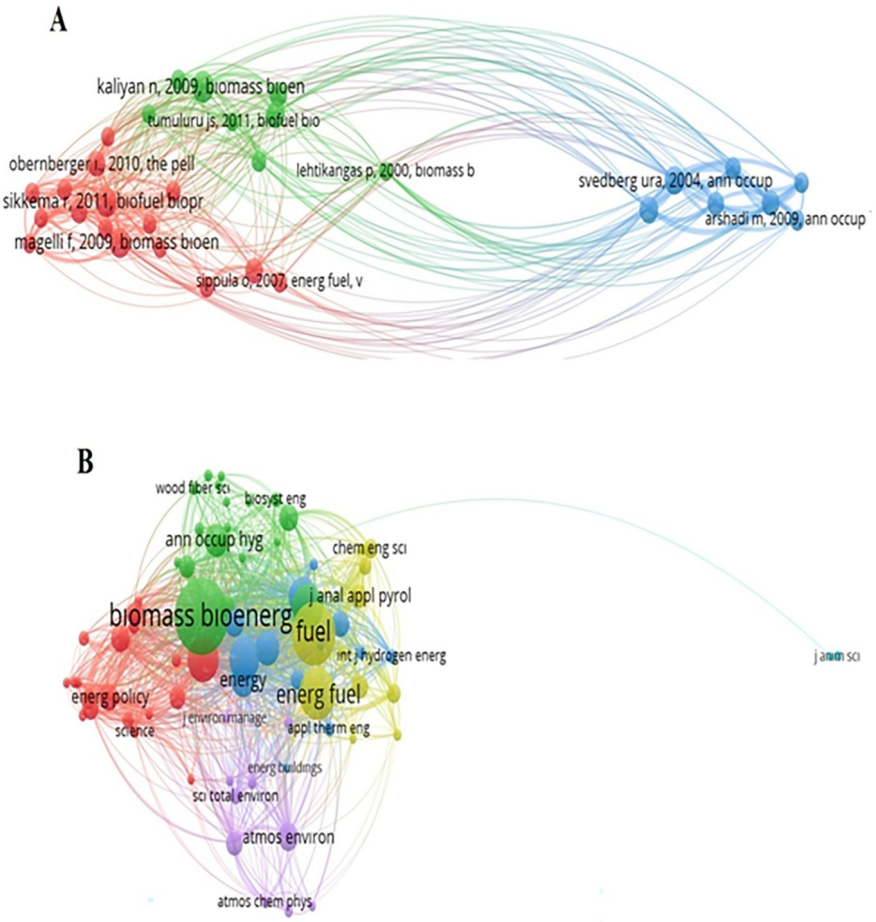

Fig. 3. Co-citation maps of references (A) and sources (B)

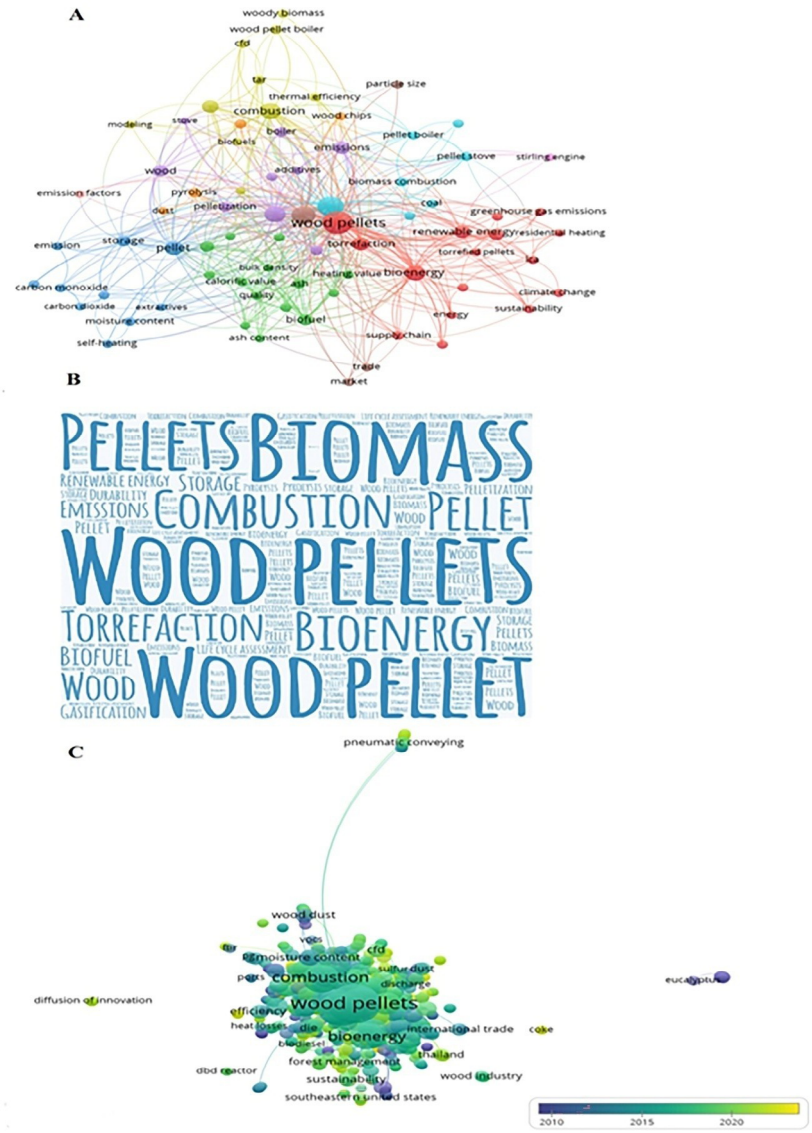

Fig. 4. Co-occurrence of keywords (A), word cloud (B), and trending topics in wood pellets in 2010–2023 (C)

strengths of more than 100 were "biomass", "wood pellet" and "combustion". A word cloud was also created to show the frequency of the keywords which occurred more than 10 times (Fig. 4B). After the keyword "wood pellets", the most frequently used authors' keywords other than the search keywords were "biomass", "wood pellet", "combustion", "pellets" and "bioenergy". Fig. 4C indicates which keywords have appeared more in studies on wood pellets in recent years. The dark colors represent old topics, whereas the lighter colors represent recently discussed topics. Trending topics in recent years include micro computed tomography, peanut shells, spent coffee grain, sugarcane leaves, levoglucosan, phthalates, lignocellulosic anaerobic digestion residues, marine plastic wastes, refuse plastic fuel, tars, diesel, renewable energy sources, sustainable energy, solar drying, co-pyrolysis, woodchips, biofuel pellets, quality pellet, carbon oxides, and lignin bridges.

Discussion

Due to factors such as global warming, climate change, and environmental pollution, the demand for wood pellets as an alternative to fossil fuels is constantly increasing. In recent years, there has been a noticeable increase in the number of academic publications focusing on wood pellets, reflecting a broader interest in renewable energy solutions. This trend can be attributed to several interconnected factors, most notably the global urgency of addressing climate change and reducing greenhouse gas emissions (IPCC, 2021). As countries seek alternatives to fossil fuels, wood pellets have emerged as a promising bioenergy source, often promoted as a carbon-neutral option when produced and consumed sustainably (Berndes et al., 2016). For example, pellets produced from agricultural residues help reduce greenhouse gas emissions (Rodino et al., 2024). Beyond environmental concerns, issues

of energy security, economic viability, and the role of sustainable forest management also contribute to the expanding body of literature (Dwivedi et al., 2014; Lamers et al., 2014). However, evaluating this research in terms of quality and quantity and obtaining valuable information about the studies will be beneficial for future researchers.

Approximately 75% of the publications on wood pellets have been produced in the last decade. The present study is the first published bibliometric analysis of the literature on wood pellets. Since pellets are a form of biomass energy, that is, a fuel originating from renewable energy, bibliometric studies in the fields of bioenergy and renewable energy can be compared. Ferrari et al. (2020) performed a bibliometric analysis on the themes of biomass and bioenergy via the Scopus database. Similarly to our study, they found that publications per year in the bioenergy subject field have grown. Also, Rosokhata et al. (2021) made a bibliometric analysis of publications on renewables, and examined a total of 2000 registered studies on WOS. They indicated that the majority of publications were produced after 2010. There are other analyses showing that studies on biomass, bioenergy, renewable energy, the properties of pellets, trade in pellets, and the quality control of pellets have gained in importance in recent years (Mao et al., 2018; Kamperidou, et al., 2018; Schön et al., 2019; Szyszlak-Bargłowicz et al., 2020; Yuan et al., 2022; Kamperidou, 2022; Helal et al., 2023; Seminario-Cordova and Rojas-Ortega, 2023; Kut and Pietrucha-Urbanik, 2024; Waragai, 2024).

The analysis by country shows that eight of the ten countries that conduct the most research on wood pellets are in North America and Europe. In a study on renewable energy sources by Jabeen et al. (2021), it was found that research collaborations occurred especially in the USA and European countries. North America is one of the most important wood pellet producing regions. Nine of the ten largest wood pellet exporting countries are North American and European. Therefore, it has been determined that there is a significant relationship between the numbers of publications from particular countries and their levels of wood pellet production and exports.

Regarding the scientific journals contributing the most to the literature on wood pellets, it has been observed that wood pellet studies are published in journals in the fuel and energy areas, with high impact factors, such as *Biomass and Bioenergy*, *Fuel*, *Energies*, *Renewable Energy*, and *Applied Energy*. In other bibliometric studies on bioenergy, biomass energy and renewable energy, Azevedo et al. (2019), Perea-Moreno et al. (2019), Zhang et al. (2021), Sertolli et al. (2022), Obileke et al. (2022), and Yuan et al. (2022) found that studies on these subjects were published in journals in the energy area with high impact factors, and the results are similar to those obtained in this study.

Conclusions

This research provides an objective overview of the literature on wood pellets. In general, the bibliometric analysis indicates that studies on wood pellets are multidisciplinary in nature and have developed especially in recent years. Based on 758 academic publications on wood pellets produced between 1980 and 2023, it was found that the number of publications on this topic increased steadily, with 2018 being the year with the largest number of wood pellets publications.

Authors use citations in academic publications to demonstrate to their readers that the material they write has previously been scientifically proven, and citations reflect the quality of a publication. In total, there were 15,504 citations to publications in the field of wood pellets, and 22 publications in this field received more than 100 citations. The ten most frequently cited publications were written by a total of 42 authors from 12 different countries. The most cited publication was produced by six authors from Sweden. The majority of publications in this field are produced by two or more authors.

When the author addresses of publications on wood pellets were analyzed, it was observed that the researchers were mostly from the USA, Sweden, and Canada.

The bibliometric analysis in this study showed that studies on wood pellets were generally published in energy and fuel journals, and that there were not many studies on this topic in forest products journals. Overall, the impact factors of the journals publishing the most studies on wood pellets are quite high.

In the analysis of co-occurrence of keywords, the keyword "wood pellets" was most frequently used together with the words "bioenergy" and "biomass". Additionally, studies on wood pellets are generally conducted in the energy fuel, engineering, science technology, environmental science, and agriculture subject areas; there are 89 studies on wood pellets in the agriculture area.

The present research is limited to the Web of Science database. Other relevant databases such as Scopus, Pubmed and Medline have been excluded. New researchers are therefore also able to perform analyses of relevant research, especially in the Scopus databases, and to compare the results with those of this study. Moreover, studies can be carried out using different software programs such as Citespice, Gephi, Bibeexcel, Scimat, and Biblioshiny to visualize the data obtained in bibliometric analyses.

There have been previous bibliometric analyses of studies on biomass, bioenergy and renewable energy, but there are no existing reports on the bibliometric evaluation of wood pellet studies. The present study thus fills a gap in the literature. It may also provide guidance to researchers planning to study wood pellets in the future.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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