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Review article

A bibliometric analysis of carbon and water footprints in renewable energy: The post-COVID-19 landscape

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ABSTRACT

The recent energy crisis in Europe has underscored the urgent need for renewable energy sources to meet growing energy demands and mitigate environmental impacts. This study investigates the Carbon Footprint (CF) and Water Footprint (WF) associated with renewable energies, considering the effects of COVID-19. Data was sourced from Scopus documents published after 2019, using keywords such as "carbon footprint ", "water footprint ", "renewable energies" and "COVID-19."

Recent research increasingly focuses on the interplay between energy, environment, and water. Using data extracted from the Scopus database on countries, keywords, highly cited publications, and trending research topics, the bibliometric software VOS viewer has been employed to evaluate bibliographic entries. The findings reveal that the United States leads in the volume of publications within this field, with significant research also originating from China, the United Kingdom, and European Union countries. Among the 1834 articles analyzed, keywords associated with environmental impact, climate change, sustainable development, and fossil fuels were frequently linked to our search terms.

This paper synthesizes literature on the correlation between CF and WF, identifies prevalent themes, and outlines potential directions for future research in this domain. The study addresses the urgent need for sustainable energy solutions amidst the ongoing energy crisis in Europe. The goals are to provide a comprehensive analysis of the impacts of renewable energy specially the environmental impacts, while highlighting the most researched areas and emerging trends in the field, and identify potential gaps in the existing literature to suggest areas for future research.

1. Introduction

To provide clear guidance to the reader on the objectives of this paper, it is essential to explain and describe some of the key research topics. This chapter aims to offer insights into these subjects, thereby highlighting the focus of the paper. The transition to renewable energy sources is paramount in mitigating climate change and fostering sustainable development. the role of renewable energy sources is crucial promoting sustainability [1]. By reducing greenhouse gas emissions [2] and mitigating environmental damage, these energy sources offer significant benefits, though they also present certain challenges. However, governments and corporations face substantial financial hurdles in advancing renewable energy initiatives [1]. Fossil-based energy consumption, policy uncertainty, and population dynamics are primary barriers to renewable energy development [3]. These insights provide policymakers and practitioners with critical information to devise effective strategies for promoting renewable energy [4].

The recent energy crisis in Europe [4] has underscored the urgent need for renewable energy sources to meet growing energy demands [5] and ensure environmental sustainability. Currently, the European Union (EU) imports nearly 60% of its energy, highlighting a critical lack of strategic energy autonomy [6,7]. This dependency not only threatens the EU's energy policy objectives but also exacerbates public and private debt and inflation, destabilizing the energy market. While diversifying gas imports from Russia [8], mitigates some risks, reliance on multiple third-party suppliers introduces new vulnerabilities. High fossil fuel prices could accelerate the shift to renewable energy [9], but short-term investments in alternative fossil fuels and energy price caps may undermine the green transition [6,7], additionally, among G20 nations from 1995 to 2020 The impact of the transition to renewable energy and environmental technology innovations on achieving carbon-neutrality goals [10] and emission reduction, has been remarkable [11,12].

Furthermore, the review highlights the crucial role of renewable energy in achieving the United Nations' Sustainable Development Goal

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7 (SDG 7) by 2030, which aims to provide affordable energy access, expand renewable energy use, improve energy efficiency, and enhance international cooperation for clean-energy research and infrastructure. Despite progress, the world is falling short due to the influence of the fossil-fuel industry and political resistance. Integrated efforts, informed by scientific research, are essential to overcome economic and political barriers and promote sustainable development globally (The International Journal of Science, 2023). Moreover, the COVID-19 pandemic has had a profound impact on the energy sector. In 2019, several EU member states risked missing their renewable energy targets due to a lack of proactive policies [13–15]. The pandemic has disrupted these advancements but also created opportunities for growth in renewable energy investment, which is crucial for long-term sustainability [14,16,17]. However, the volatile political and economic conditions pose significant challenges to the development of renewable energy technologies. The pandemic-induced decline in oil prices offers a mixed outlook, with potential boosts in energy demand and economic expansion on one hand, but heightened risks to the renewable energy sector on the other [13,18].

The recent widespread adoption of some renewables such as solar energy supports the energy sector and creates employment opportunities [19] contributing to economic and environmental sustainability. However, further development is needed to ensure long-term sustainability and decarbonization [20,21].

Assessing the environmental impact of energy systems is vital in this context. The carbon footprint (CF) and water footprint (WF) are critical metrics for evaluating the sustainability of energy sources [22]. While CO2 emissions from fossil fuel use are a primary concern, a comprehensive evaluation should consider all sources of emissions and water usage [22–24]. Renewable energy technologies offer pathways to reducing these impacts [14,25]. However, the heavy reliance on water for electricity generation poses additional risks, particularly in regions with severe water stress [22,26,27]. In contrast, fossil fuels being replaced by renewable energy technologies some of them may come up with higher water usage [22,28]. so Evaluating energy-related water usage adds another layer of complexity to the feasibility of 100% renewable energy systems [13,29].

The transition to renewable energy is gaining momentum, driven by the need to reduce greenhouse gas emissions. Life cycle assessment (LCA) methodologies are crucial for calculating greenhouse gas emissions and establishing foundations for carbon neutrality in order to debilitate the climate change momentum [30,31] In summary, the more renewable energy usage [32,33], the adoption of green energy, and the reduction of CF and WF are essential for mitigating climate change [34–37]. This study aims to emphasize the importance of transitioning from fossil fuels to renewable energy by analyzing the CF and WF studies, and understanding the impact of the COVID-19 pandemic on these metrics using bibliographic analysis through VOS viewer software.

2. Literature review

Aiming to emphasize the renewable energy usage normalization in routine [32], Mr. Simon Perry, have investigated the use of renewable energy on a small scale, e.g., in residential areas, hospitals, or small factories, and call this locally integrated energy sector (LIES), The study focuses on the transition from carbon-based fuels to renewable energy sources for reducing greenhouse gas emissions. It proposes the use of micro-cogeneration, combined heat and power generation, and renewable energy technologies like reciprocating engines, Stirling engines, and fuel cells for localized heating and cooling. Integrating renewable energy with fossil fuels to meet the needs of small industries, households, businesses, and social institutions results in lower carbon emissions than the exclusive use of fossil fuels.

In order to achieve carbon neutrality, it is crucial to calculate and analyze one's carbon footprint; The LCA methodology has proven to be an essential scientific tool in establishing the foundation for calculating greenhouse gas emissions [30]. A study conducted by Paul Wolfman used a hybrid LCA methodology to calculate the economic carbon footprint of seven electricity generation technologies in varying renewable energy scenarios in Australia. The study employed a bottom-up approach through process analysis (PA) and a top-down approach through input–output analysis (IOA). The results indicate that renewable energy technologies can significantly reduce Australia's greenhouse gas emissions, including indirect emissions throughout the technology's life cycle. This highlights the importance of renewable energy as a crucial option for mitigating climate change [31].

Ruchi Tyagi, the author of the Indian Renewable Energy Act, proposes several plans to reduce carbon emissions and carbon footprint through renewable energy. The National Renewable Energy Advisory Group (NREA), the Renewable Energy Corporation of India (RECI), and the government are collaborating to explore power generation methods. To support these efforts, the National Renewable Energy Policy (NREP), Renewable Energy Resource Assessment (RERA), Technical Standards and Testing, Manufacturing and Skill Development have been considered. Additionally, the Economic and Financial Framework has been established, including the National Renewable Energy Fund, State Green Fund, and Distributed Renewable Energy Applications [38].

Bengochea conducted a study on the relationship between CO2 emissions and renewable energy supply in EU-15 countries from 1990–2004. The study found that an increase in carbon emissions is positively correlated with an increase in renewable energy supply. Furthermore, CO2 emissions serve as an indicator of the need to accelerate the adoption of green energy and the level of penetration of renewable energy sources in the medium term [39].

A study conducted by M.A. Russo aimed to evaluate the impact of COVID-19 on energy, environment, and costs in Portugal. The findings indicated that during the peak of population mobility restrictions in Spring, there were positive impacts on most sectors, including reduced energy consumption, lower emissions, and associated costs. Transport-related activities experienced the most significant positive impact, followed by services, industry, agriculture, and fisheries, with less energy consumption, lower emissions, and reduced carbon footprint. [34]. M. Maktabifard conducted an assessment of strategies to reduce the carbon footprint (CF) of municipal wastewater treatment plants (WWTPs). The study identified energy consumption, sludge management, and wastewater treatment as the most significant factors affecting the total CF [35].

Speaking about water footprint, Analyzing the influence of the energy sector on water consumption in Europe, Gibran Vita suggests that employing renewable energy sources could substantially decrease water consumption related to energy production. The study also highlights the importance of analyzing the water-related effects of new power infrastructure, such as hydropower, and the benefits of establishing transmission connections between different regions [36].

Alena Lohrmann conducted a study on the water footprint assessment for the European energy sector during the shift to 100% renewable energy. The study utilized various research methods such as data collection and database, analytical approach for current water footprint assessment, scenarios, and estimation of the water footprint of the energy sector. The research revealed that the transition to a 100% renewable electricity system could decrease energy-based water consumption in Europe by up to 28.3% by 2050. The water footprint of thermal power plants is also expected to decrease significantly to 1.6% in 2050 under the "Region" scenario. However, the study also highlighted potential bottlenecks that could lead to an increase in energy-related water consumption during the transformation of the energy system [37].

On the other hand, it also has to be noted that by examining the projected impacts of different energy scenarios on water availability and consumption in EU30 countries, specifically focusing on Romania, Germany, and Spain, the results reveal that while some technologies of renewable energy such as CSP, bioenergy and geothermal

energy can offset water usage, the adoption of CCS technologies can substantially increase freshwater usage. These findings imply that low-carbon technologies present alternative risks and that the renewability of renewable energy sources with regard to water resources is not absolute [40].

Achieving sustainability has become a central goal, with developed nations adopting pro-environmental interventions to curb emissions, particularly in the air transportation sector [41]. Eco-friendly innovations and environmental taxes significantly mitigate pollution, while smart city policies in China encourage green innovation [42]. Market-based tools and carbon trading schemes have dual benefits, reducing emissions and boosting employment [43]. The pursuit of green economic development is essential, with economic policy uncertainties impacting carbon emissions efficiency [44].

Furthermore, this has to be noted that Temperature variations significantly impact urban electricity consumption, emphasizing the need for effective demand management [45]. Achieving carbon neutrality by 2050 or 2060 requires a focus on technology and renewable energy for energy efficiency, with the manufacturing sector playing a crucial role in reducing greenhouse gas emissions [46]. Integrating eco-friendly innovations, market-based tools, and smart city policies, alongside addressing economic policy uncertainties, are essential for environmental sustainability [46,47]. These strategies provide a comprehensive foundation for policymakers to promote renewable energy and achieve carbon neutrality.

3. Methodology

Modern techniques for research evaluation have been applied in this study. The Elsevier Science SCOPUS database was used to determine the intended outcome. A descriptive and statistical assessment of a field, topic, or idea is called a bibliographic analysis, and it is used to monitor advancement and pinpoint areas of strength and weakness for the future. Elsevier Science SCOPUS is an excellent and thorough reference. Furthermore, the greatest database for reviewing and analyzing a variety of papers is Elsevier's Scopus. Numerous investigators have employed this database for examination.

Keywords were chosen based on their relevance to the research topic, including "carbon footprint", "pandemic", "corona and energy and Europe and carbon", "corona and renewable and energy and carbon and emission", "renewable energy", "water footprint", and "COVID-19". These specific search terms ensured comprehensive coverage of the subjects of interest, considering their occurrence in titles, abstracts, and keywords in Scopus. Variations of these keywords with asterisks were used to enhance search accuracy.

This report employs a systematic methodology and bibliographic analysis utilizing VOSviewer software to investigate current research on diverse subjects. It also points out areas requiring more research to ensure these technologies are used as effectively and successfully as possible. This work aims to explore the relationships between different articles, their volumes of publication, and their corresponding timestamps. This is for individuals interested in learning more about scientific issues about the water and carbon footprint, energy, sustainability, and its relation to COVID-19.

Only articles, book chapters, and conference papers that included these keywords were considered, focusing on publications from 2019 onwards to reflect the latest trends and research developments, particularly in the context of the COVID-19 pandemic. VOS viewer software was utilized for keyword analysis and co-citation analysis, examining the relationships and strength of links between keywords, aiding in identifying significant connections. Our approach involved the strategic application of these keywords to attain relevant results, effectively narrowing down our search to retrieve information pertinent to our research objectives.

It indicates possible areas for additional research activity by highlighting the regions with research gaps and those with few published papers. The article emphasizes the crucial function of data mining in article research by facilitating a thorough understanding of the connections between several topics. Moreover, the following lists possible study topics for this discussion that may be explored in the future. Peer-reviewed papers are not the only sources included in the study. The first step in gathering the needed data and conducting the necessary research in this sector is to locate all of the publications that have been published on this topic up to the end of 2023. Our search methodology entails the strategic application of specific keywords to attain relevant results. This approach allows us to effectively narrow down our search, and only retrieve information that is pertinent to our research objectives.

We employed the "Water, Carbon, Footprint, Renewable Energy, COVID-19" and its modifications to find titles. Concerning the standards we set, keywords can be thought of as filters. For example, the terms "water" and "energy" must be used throughout the text, although the word "sustainability" is not strictly required. The quantity of resulting articles can vary depending on how these filters' settings are changed. Various search combinations were employed and evaluated to identify the most accurate and comprehensive outcomes. This analysis was conducted on a sample of publications from the year 2019, which included abstracts, author keywords, journals, year of publication, number of citations, and author information. The primary focus was on examining air-wise, triple, and quadruple linkages in water, carbon, footprint, energy, and COVID-19, in addition to any relevant subjects directly related to our research, all of which were incorporated into this collection of articles. We used Scopus's sophisticated search tool to narrow the study's scope to the quadruple linkage and related topics. This required making the use of essential terms like "water", "carbon", "footprint", "Renewable energy", and "COVID-19", and synonyms for them in the title and keywords mandatory. This procedure establishes the groundwork for deriving significant conclusions and rendering trustworthy decisions in various industries. The references were retrieved, relevant keywords were identified, and synonymous terms were excluded from the inventory after minor adjustments to scrutinize the authors' framing of their research. The literature, research articles, and countries under investigation by the authors were analyzed and ascertained.

The theoretical rationale for selecting these variables is based on their significant relevance to the core research themes of environmental impact and sustainability. Data Screening Process. It is a useful exercise to evaluate the extent to which this body of literature has progressed in integrating concepts and methodologies from diverse disciplines and research domains to investigate the interrelationships between the terminologies employed in the literature. To achieve this objective, a network diagram displaying the co-occurrence of noun phrases extracted from the abstracts was constructed. Noun phrases refer to a sequence of one or more words in a sentence that culminates in a noun and is preceded by either another noun or an adjective. Such an approach facilitates a more comprehensive understanding of the interrelatedness of the concepts explored in the literature. As demonstrated, various studies have been carried out by researchers considering energy, water, and carbon emissions, some of which have relations with COVID-19.

The outcome of the bibliographic study of 1834 was presented and analyzed: the graph Fig. 1. The presents the outcome of a bibliographic analysis conducted using data extracted from scholarly articles and research papers. where a minimum number of occurrences of a keyword is at least 39 where 74 meet the threshold out of 10 912 keywords, which 35 of them are left after filtering and combining some of them. The total strength of links with other keywords was computed, and the keywords with the highest total strength of links were chosen. As can be seen from the charts exported from the Vos viewer software, using various search terms with Scopus, it is evident that the carbon footprint, water footprint, COVID-19, and European Union are mainly linked

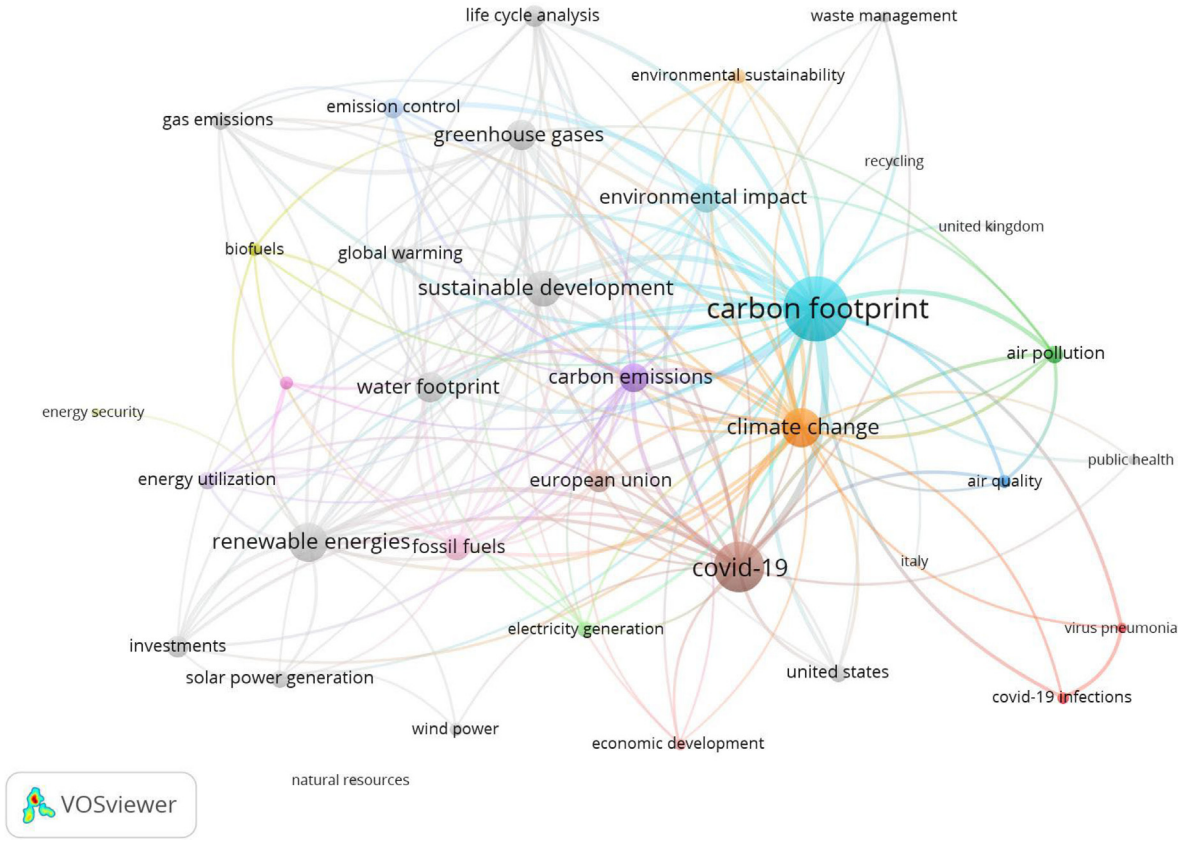

Fig. 1. Keywords map with precise classification.

in many areas, such as climate change, air pollution, and sustainable development.

By structuring our methodology and detailing our approach, we aim to improve the transparency and reproducibility of our research, providing a clear path for future studies in this crucial area.

3.1. Trends

Assessing the trend of the number of citations of the collected data helps us to recognize the author's goal in publishing or the growth rate of article usage. After examining the related articles, it can be seen that the most significant number of articles was published between 2020 and 2022. These articles were published between 2019 and 2023, with most of them being published between 2020 and 2022. In the articles, the term 'carbon footprint' was the most commonly used keyword. This information is presented in the Table 1. The word COVID-19 is in second place in the high rankings. Another point worth mentioning is that the number of citations has increased since the start of the study (2019), as has the number of articles. This behavior proves that interest in carbon and water FP, renewable energies, and COVID-19 has increased.

Notably, the recent energy crisis in Europe has heightened the urgency for renewable energy development to achieve strategic energy autonomy. The crisis has driven up fossil fuel prices, presenting an opportunity for a green transition but also posing risks if short-term fossil fuel investments overshadow renewable initiatives. This trend is reflected in the surge of publications and citations related to CF and WF, signifying a growing focus on environmental impacts in response to the crisis.

Out of 1834 articles analyzed, more than 200 were freely accessible, with environmental sciences, technology, and energy journals dominating the field. Most articles were original research, complemented by review articles, book chapters, and conference contributions. Utilizing VOSviewer software, we examined keywords' connections, revealing 'carbon footprint' with a total link strength of 1875 and frequent usage since 2019. The keyword "COVID-19" and themes like sustainable development and water footprint were also prominent.

3.2. Characteristics

The journals all offer hybrid access. All journals have some things in common with the others. Of the total of 1834 articles, more than 200 are freely accessible. In first place are the environmental sciences, and in second and third place are the fields of technology and energy, which have the most to do with the research objective. These journals account for more than 60% of the articles in the carbon and water footprint area. Of the 1834 articles in this section, about 70% are articles, and the rest are review articles, book chapters, and conference contributions.

According to Table 1, it contains information about the keywords extracted from the VOS viewer software in a bibliographic way. This method involved checking all keywords with standard links to search topics, removing words with a low reputation count and keeping keywords with a high reputation count.

According to Table 2 provides comprehensive data on countries that have researched and published articles on CF and WF renewable energy and COVID-19. All the countries in this table have played a significant role in this research area and have cooperated with at least one other country mentioned in the table. This high level of cooperation between these countries highlights the importance and relevance of this hot topic. A country's influence on the topic increases with the number of links it has with other countries in the table. Furthermore, the more articles a country publishes, the more "documents" it has.

Table 1
Common keywords for the search subject.

keywords	Links	Total link strength	Occurrences
Carbon footprint	35	1875	584
Water footprint	35	613	183
Covid-19	35	1077	399
European union	35	534	130
Sustainable development	35	913	238
Environmental sustainability	35	323	66
Environmental impact	35	828	181
Carbon emissions	35	726	174
Greenhouse gases	35	872	188
Fossil fuels	35	630	146
Climate change	35	1064	270
Electricity generation	35	312	76
Global warming	34	378	81
Air pollution	34	408	80
United states	34	351	84
Life cycle analysis	34	504	112
Economic development	34	214	50
Renewable energies	33	860	269
Gas emissions	33	441	88
Emission control	33	445	102
Energy utilization	33	345	84
Recycling	33	162	38
Air quality	32	292	57
Bio fuels	32	227	52
Waste management	32	218	49
Investments	32	396	117
Economic and social effects	32	244	52
Italy	31	136	31
Solar power generation	30	292	24
Covid-19 infections	29	224	44
Virus pneumonia	29	211	41
United Kingdom	28	172	40
Energy security	28	126	34
Public health	27	192	42

Table 2
Countries included in the search topic.

Countries	Links	Total link strength	Documents
Australia	28	12 207	79
Austria	28	9727	29
Canada	28	5120	50
Czech Republic	28	4147	28
Denmark	28	6450	28
Finland	28	4953	19
France	28	8397	51
Germany	28	14 798	105
Greece	28	4977	28
Ireland	28	4168	29
Italy	28	14 555	123
Norway	28	5674	27
Poland	28	5126	65
Portugal	28	3575	30
Russian Federation	28	4104	38
Spain	28	12 729	106
Sweden	28	7036	28
Switzerland	28	10 831	41
Tunisia	28	1642	12
Turkey	28	4606	57
Ukraine	28	1380	14
United Kingdom	28	23 003	206
Netherlands	27	9254	65
Romania	27	1646	27
Belgium	26	6291	34
Slovakia	26	657	12
United States	28	24 187	225
China	28	19 638	183

3.3. Table analysis

Looking at the tables, we see three describing topics. For example, links give information about the number of connections for each keyword for a link number of 35, which means that the keyword is connected to all of the 35 keywords in Table 1. Total link strength gives information about the intensity of connections with the effect of several reputations for keywords. For example, in Table 2. the United Kingdom has a total link strength of 23 003; this means that this country has published lots of papers cooperating with other countries in the European Union, China, the United States, and Singapore and has published more than 200 documents in Table 1. By Looking at the keyword "Carbon Footprint", with a total link strength of 1875, it is understood that this keyword has been continuously used in articles published since 2019 and has occurred more than 500 times in the articles since then. The table shows that the first 12 topics have the highest links, equal to 35. This means that they are the most connected topics commonly published, with connections with all of the 35 keywords.

It also has to be noted that the topics Carbon Footprint, COVID-19, sustainable development, and Water Footprint, which contain our focus on the previously published articles' relation and link strengths, are among the most relevant topics to be studied recently, noticing the years of publication in Fig. 2. The first 12 keywords are almost the most frequently used among all 35. The other five topics, including global warming, air pollution, United States LC analysis, and economic development, are connected to all of the keywords mentioned in the articles shown in Table 1 with total links of 34 and 504 maximum link strength, which shows that these topics are commonly used in the area of CFP and WFP and renewable energies considering the COVID-19 pandemic.

The critical word "renewable energies" is the most common topic in the yellow third row with 33 links. Its link strength is noticeable, which shows its importance and the impact of COVID-19 on this field of study. Checking Table 1, it has to be noted that all of the 35 keywords have at least 27 connections with each other with a minimum link strength of 27 and minimum occurrences of 31. All the keywords in Table 1 are the most common among the 1834 articles from which the data was extracted using the Scopus database.

4. Results

4.1. Keywords analysis

The analysis of the coincidence of the two articles examines the keywords of the articles. The map in the Fig. 1 illustrates that author from different countries, in this specific study area, have dealt with various topics related to this theme. The authors' keyword analysis which is pictured in Fig. 1 would help researchers identify a topic's main challenges and advances. The presence of two keywords in close proximity suggests a stronger relationship between them in articles. This can help identify important themes and topics within the text. The number of documents containing both terms determine the relationship between them. The authors' keywords are usually not a part of the article's title.

Figs. 1 and 2 illustrate the keywords that were analyzed to identify the most critical topics in CF, WF, Renewable Energies, and COVID-19. The VOS viewer software is utilized to sort out words based on their frequency of occurrence. The words carbon, water footprint, and energy appear frequently, with some words removed due to similarity and repetition in all articles. The recent energy crisis in Europe has underscored the urgent need for renewable energy development. High fossil fuel prices and geopolitical tensions have spurred interest in renewable energy sources, as reflected in the surge of publications and citations related to CF and WF. This behavior indicates increased interest in CF, WF, renewable energies, and the pandemic's impact. Out of 1834 articles analyzed, more than 200 are freely accessible, with environmental sciences, technology, and energy journals dominating the field. Most articles were original research, complemented by review articles, book chapters, and conference contributions. Utilizing VOS viewer software, we examined keywords' connections, revealing 'carbon footprint' with a total link strength of 1875 and frequent usage

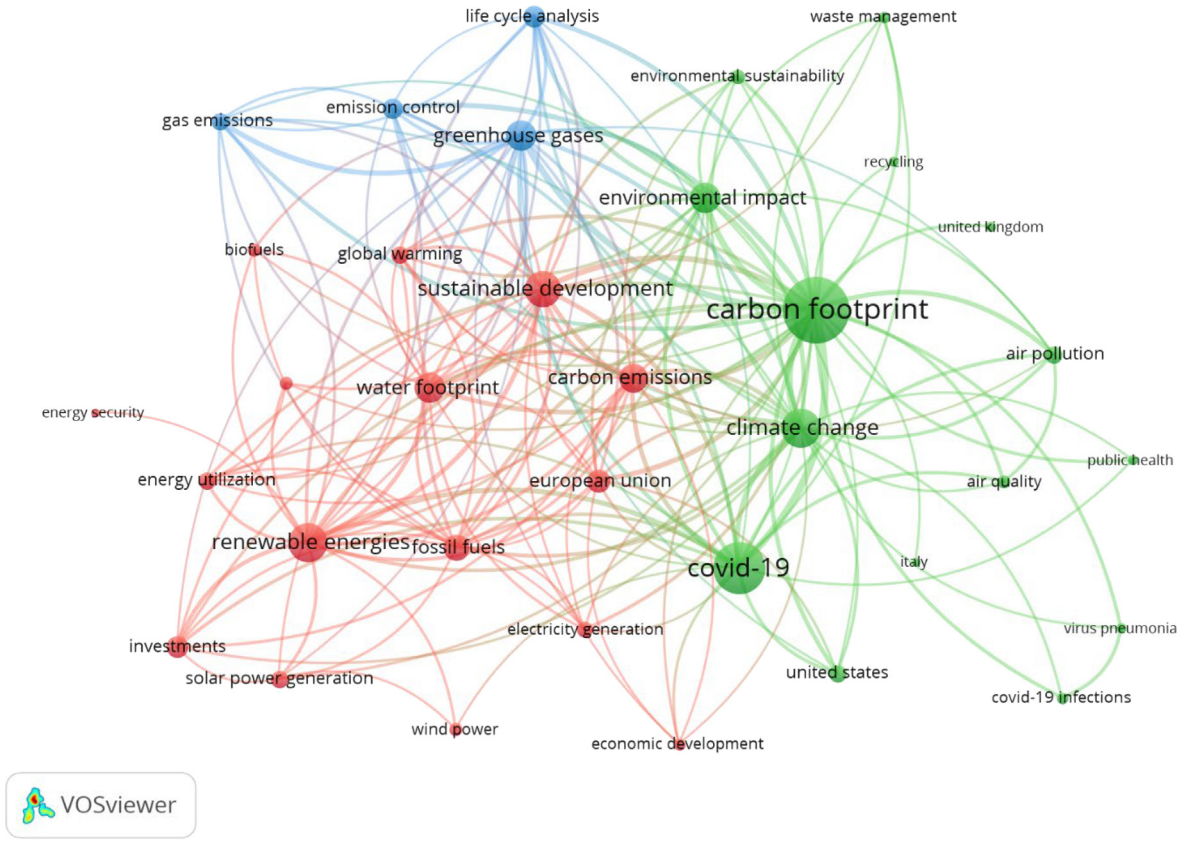

Fig. 2. Keywords map with resolution 1.

since 2019. The keyword "COVID-19" and themes like sustainable development and water footprint were also prominent. As anticipated, CF is one of the most common words that authors use. The connection between water, renewable energies, carbon, COVID-19, and the European Union depends on sustainability for many reasons, such as saving and using resources wisely, reducing climate change impacts, promoting fairness and human rights, enhancing adaptability, and comprehensive solutions. The connection between water, renewable energies, carbon, and the environment requires sustainability for effective management. Life cycle analysis (LCA) is another frequently used concept. LCA reveals and explains the intricate relationships between emissions, water, and energy. For example, it can show the amount of water needed to generate specific energies. LCA can support more effective and eco-friendly resource utilization by finding out where water and energy production are wasteful and damage the environment through carbon dioxide production; LCA can enhance technology, systems, and behavior. Water and energy security is the third most common topic for authors, and it falls under the security category. Water, energy, and the environment are linked in terms of security, and a risk to any of them can have a domino effect on the rest. To manage these resources sustainably, this nexus must be considered, and policies must be developed that reflect these connections to guarantee the stability and safety of all elements. The well-being of ecosystems can deteriorate due to environmental instability, which can then affect the security of water and energy. For example, cutting down trees can interfere with water flows, harm water availability, and add to climate change, which endangers other elements. On the other hand, it can be a source of biofuel as a renewable energy resource. All of the topics in the table are related to each other. This suggests that water and emissions have been the primary concern of the authors' studies and that it is essential to consider water, carbon, and its associated problems when examining the nexus of water, energy, and the environment. Moreover, the papers published in WCFP have a solid connection to renewable energies like solar and wind power. Countries like the United Kingdom have strong research collaborations, publishing extensively on these topics, demonstrating the interconnectedness and importance of global cooperation in addressing the energy crisis and promoting renewable energy solutions. The emphasis on CF and WF research highlights the critical need for sustainable practices amid the energy crisis.

4.2. Co-occurrence map of key themes

The keyword simultaneity map is studied by limiting all words in the articles to having a minimum link strength of 15 and a maximum link strength of 1000. After the screening process, only 35 out of the original 74 words were retained. The words that referred to the research methodology were eliminated through manual screening. This map displays the most common subjects of authors for studies in the area of the Carbon and Water footprint in Europe, having a perspective on COVID-19. The map in Fig. 1 can also help to examine the connections among different topics. The nodes in this map have sizes that reflect the frequency of that word in the articles. The bigger the circle, the more often the word is used. The lines that link the nodes have thicknesses that show the strength of the relation between two terms, which means the number of summaries that include both terms. The connection between two nodes is stronger when the line between them is shorter. Nodes that are closer to each other are more likely to be mentioned in the same article. In addition, VOS viewer identifies clusters of nodes in a network based on their thematic similarity. A cluster is a group of items on the map that share a common theme or topic. When using VOS viewer to analyze bibliometric networks, clusters are identifiable as separate groups. The number of clusters can be determined by adjusting the resolution parameter, with a higher resolution resulting in more clusters. Each node in the network is assigned to only one cluster, which is depicted using different colors by VOS viewer.

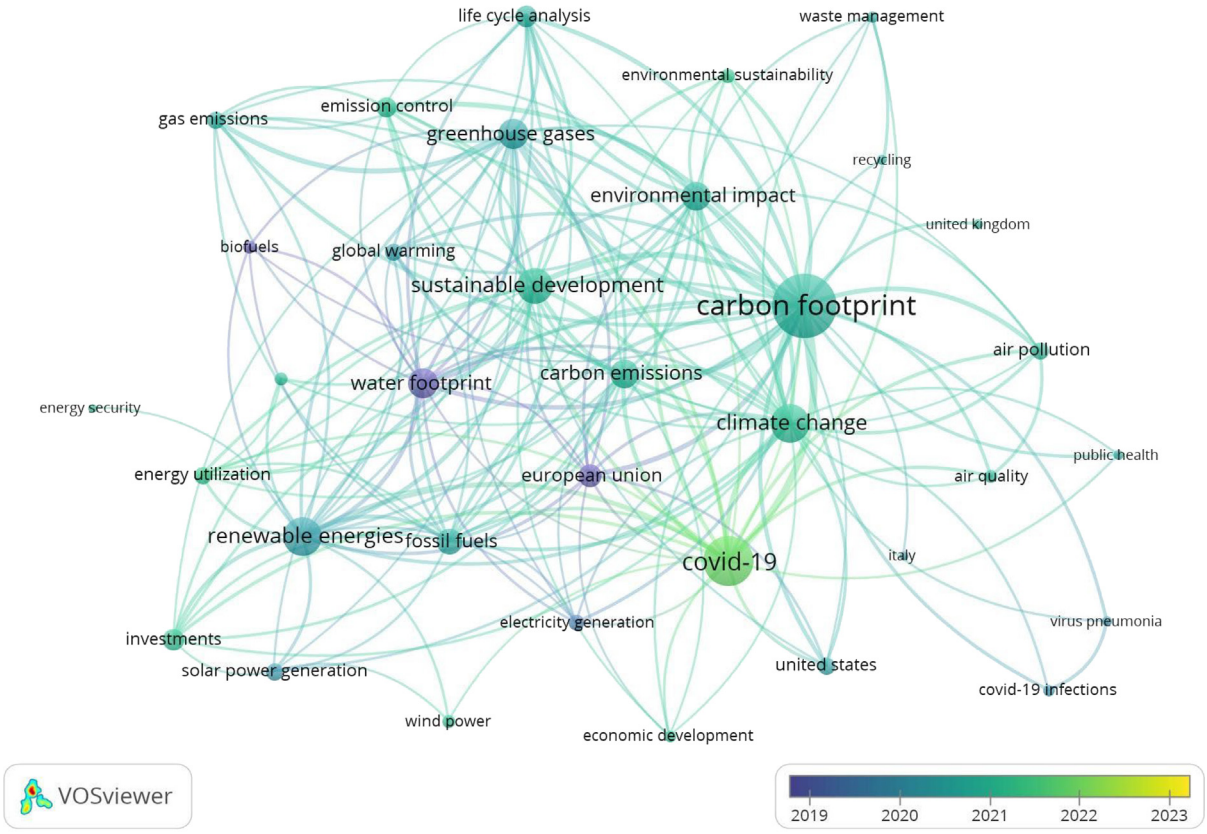

Fig. 3. Keywords overlay visualization map.

As discussed above, Carbon emissions depend heavily on sustainable development. Therefore, researchers have focused on "environmental impact" and "climate change". This cluster also covers renewable energies such as solar and wind power. As shown in Fig. 2 the theme of the clusters describes the connections between carbon footprint, water footprint, and covid-19. Looking at Fig. 2, It is observed that the water footprint in the red cluster has the most vital connection to the carbon footprint in the green cluster. Also, the "water footprint" in the red cluster is vital to the visualization network. The blue cluster focuses on "greenhouse gases", and it contains terms such as "gas emissions", "emission control", and "LCA". The red and blue clusters have a common theme of renewable energies. Carbon footprint is the basis of the green cluster. It also covers topics such as "climate change", "covid-19", and "environmental impact". The red cluster's theme is "renewable energies". Examples of terms that refer to "renewable energies" are investment in solar power generation and wind power. "COVID-19" in the green cluster has the most vital link to "carbon footprint" and "climate change".

Looking at the overlay visualization map in Fig. 3 The color of the nodes on the map gives the information about the year of publication. The weight of an item is indicated by the size of the circles. A bigger circle denotes more articles related to that topic. The subjects shaded in blue and purple were initially given priority by researchers but later required further attention. Words in green have grown more common lately and could be popular topics soon. The density view makes the map's structure and critical areas easier to comprehend.

The density view assigns colors to nodes based on their density. The density of nodes depends on how many and heavy the items around them are. The node's color shifts to red when it has more nodes close to it and less distance from it. as shown in Fig. 4, Keywords have colors that reflect their frequency, words with a stronger connection to the CFP, WFP, and COVID-19 turn red. Red indicates hot topics. Fig. 4 reveals that the subjects marked in green or located far away from the red dots have relatively fewer associated articles. Therefore, these areas may present opportunities for new research.

4.3. Geographical distribution of research

This section explores how nations interact in water, energy, carbon, and the environment. This study relies on all the articles that have discussed the links between water, Renewable energy, carbon, and the covid-19. Moreover, this section also analyzes the distinctive articles that have appeared in the CF and WF fields. This figure illustrates how countries collaborate through their joint authorship of articles. This study focuses on countries that have published at least three articles. There are 39 such countries out of 275. The number of articles is indicated by the circle size in the Fig. 5.

Fig. 5 shows that America, England, and China have the most articles. America leads at 35% of global publications on renewable energy [3]. The link between the two items is shorter and thicker when the two countries have a stronger relationship. America and England also collaborate the most with other countries, in addition to the number of articles. Researchers can use co-authorship among countries to learn about current collaborations and find experienced collaborators. The color scheme used also indicates the level of cooperation between countries in terms of publishing with each other. It is also evident that Europe has done most of the research on this subject. The Fig. 5. displays the frequency map of each country's published articles and reveals that the European Union has the most papers on the triple aspects of CF WF and COVID-19. It also exhibits the nations that engage in the highest level of collaboration with other countries. It demonstrates the number of joint projects a country participates in for publishing articles. It has to be noted that, The United States holds the top position with more than 200 international collaboration initiatives.

Fig. 6 depicts each country separately along with the year of their involvement and interest in the research field. This figure provides

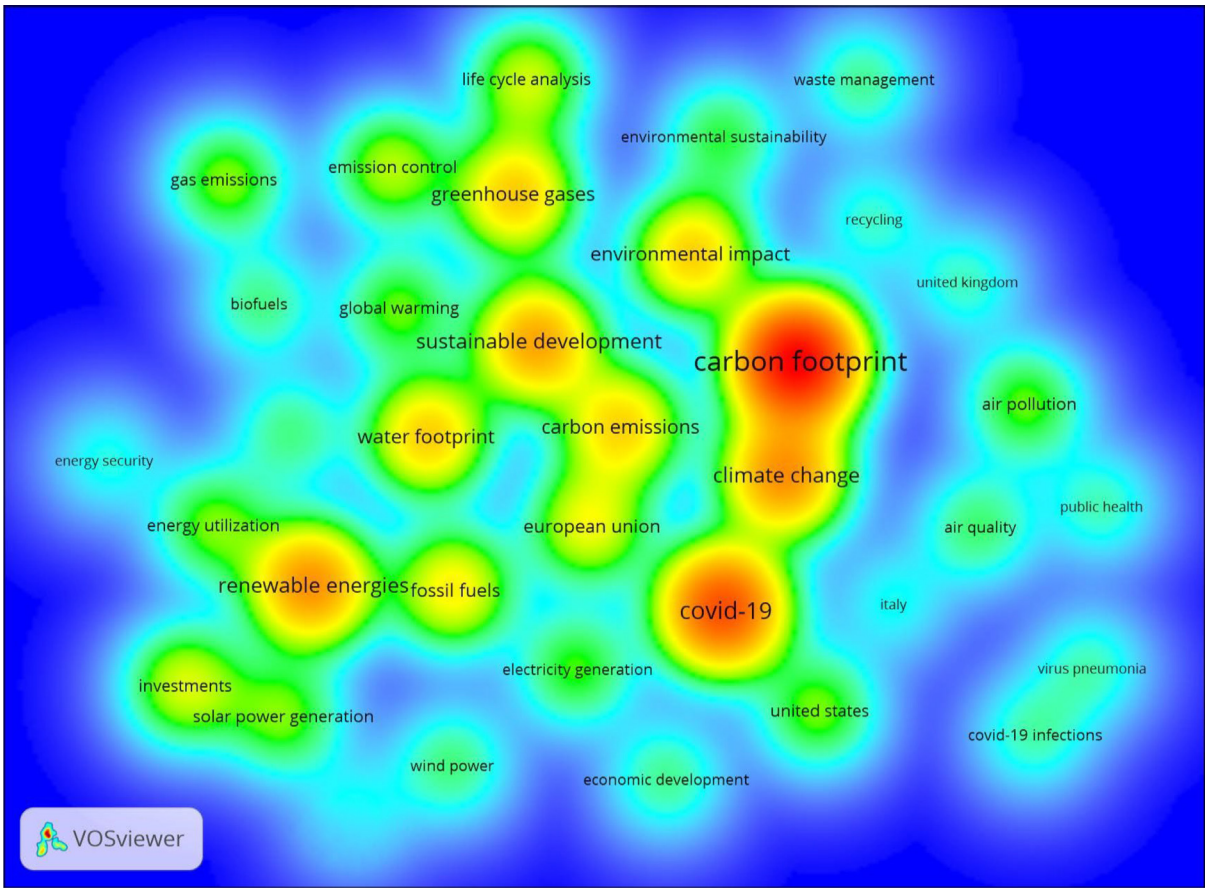

Fig. 4. Keywords density map.

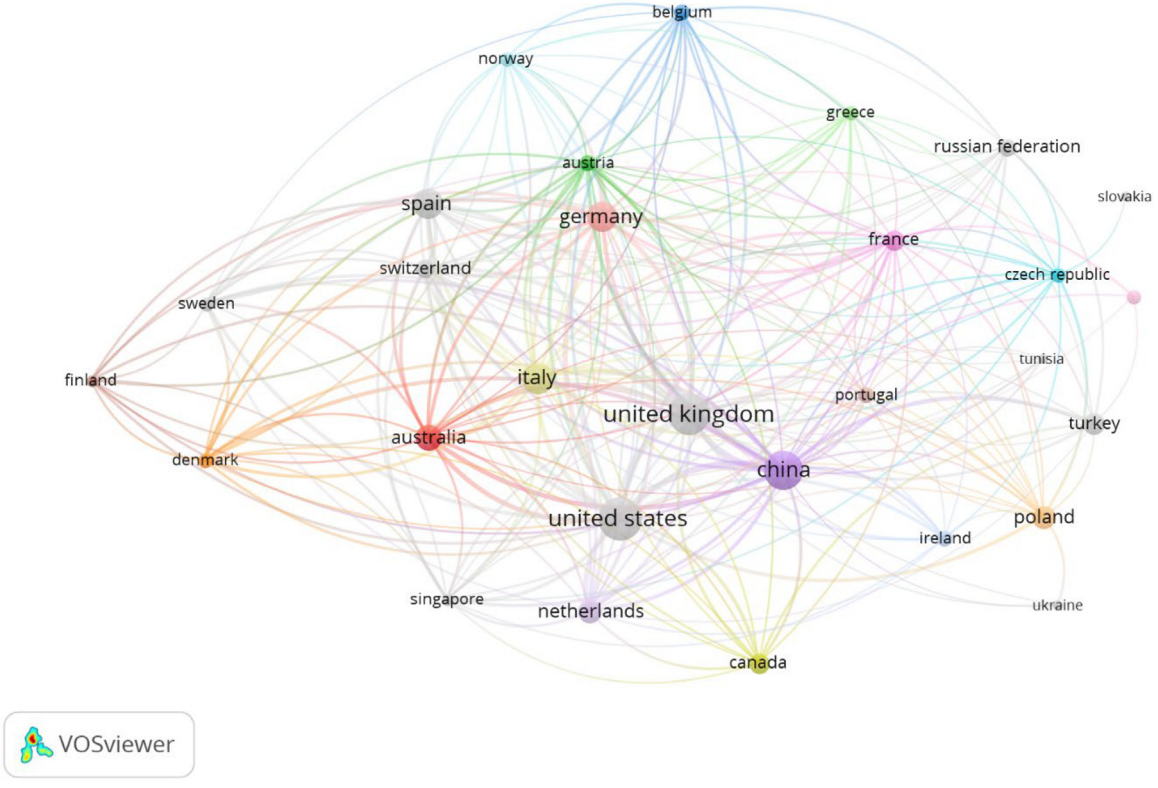

Fig. 5. Countries map.

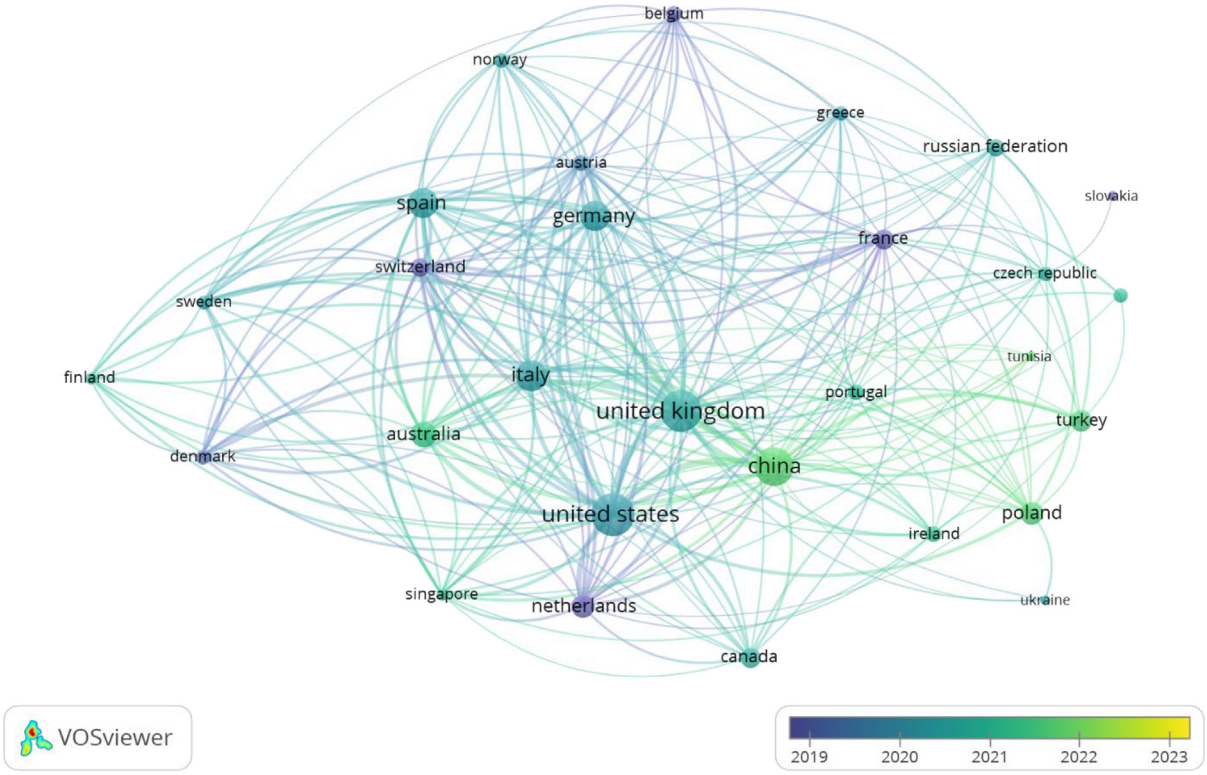

Fig. 6. Countries overlay visualization map.

insight into which country has played a significant role in research and article publication. The color code of the nodes and countries indicates their interest in participating and their recent contribution to the research. It is evident that Turkey, Poland, China, and Australia have recently shown interest in this research topic and have been publishing articles on it.

The analysis presented in Fig. 7 explores each country's weight on the research topic, based on 1739 research articles covering this area extensively. It also shows the citation frequency for each country by the color intensity. The darker the country's color, the higher its participation in the CF, WF, and COVID-19 research domains. The closer the countries get to each other, the more interactions they have. The leadership of these countries in the water-energy-carbon nexus research can be attributed to several factors. The U.S. and the UK have robust policy frameworks and significant investments in renewable energy and sustainability initiatives. For instance, the U.S. has implemented the Inflation Reduction Act, which aims to accelerate the transition to clean energy. Similarly, the UK's Net Zero 2050 Strategy outlines ambitious targets for reducing carbon emissions and promoting sustainable practices. China, on the other hand, has been focusing on the water-energy-carbon coupling coordination model to address its high energy consumption and unevenly distributed water resources. The country's 30/60 Climate Ambitions highlight its commitment to achieving carbon neutrality by 2060 and peaking carbon emissions by 2030. These policy frameworks and national commitments have created an environment conducive to research and innovation in the water-energy-carbon nexus, leading to a higher number of publications from these countries.

5. Conclusion

The ongoing energy crisis in Europe highlights the need for strategic energy autonomy and the development of renewable energy policies. High fossil fuel prices present both a challenge and an opportunity for accelerating the green transition. This crisis has driven home the necessity of integrating renewable energy sources to mitigate environmental impacts, such as carbon and water footprints, and to enhance energy security.

Extensive research has been carried out in the past regarding the interconnectedness between water and energy, as well as between carbon and water, resulting in a vast collection of literature that explores topics related to the nexus of water and energy. Several research studies have explored the interconnections between water, carbon, energy, and the environment in both dual and triple nexus scenarios. Our study involved a comprehensive review of previously published articles to identify recurring themes, highlight areas that show potential for future research, and conduct a bibliometric analysis of international collaboration patterns in relation to carbon, energy, water, environment, and COVID-19. The bibliometric analysis revealed the leading countries in this field, showing that researchers in these countries appreciate the importance of the CFP and WFP and their relation with COVID-19. Examined the author's keywords to discover the main themes discussed with the CF and WF. The topics that were mentioned the most include "sustainable development", "renewable energies", "greenhouse gases", and "environmental impact". The CFP and WFP have received less attention on political and economic aspects than the water-energy-food (WEF) nexus. A remarkable feature of research in this area is the importance of renewable energy and its link to the field. Other important covering topics are "energy security", "wind power", "recycling", and "waste management". We used the density view to find the topics less popular than the main themes.

Researchers who are interested in conducting research within the framework of CF and WF may find these topics appealing:

- The impacts of climate change on water supply, food security, energy systems, and ecosystems are significant. Developing strategies that can adapt and become resilient to these changes is crucial. Such strategies include investments in infrastructure that

Fig. 7. Countries density map.

can withstand climate change, promoting sustainable management practices for land and water resources, and shifting towards low-carbon energy sources.

- The water, food, energy, and environment systems are all intertwined, making the nexus complex and intricate. It is imperative to adopt integrated policymaking and management approaches to manage this system effectively. This entails aligning policies across various sectors, establishing governance structures that span multiple sectors, and fostering collaboration among diverse stakeholders.
- Examining the policies and economic incentives that have been introduced in Europe to promote renewable energy and reduce carbon emissions during and after the pandemic.
- How the pandemic has affected public perception and behavior towards renewable energy and sustainability.
- Analyzing how international research collaborations have influenced advancements in carbon emission reduction technologies and policies.
- Exploring how international research collaborations contribute to innovative solutions for sustainable water resource management.
- Environmental Policy Development through Cross-Border Research; Examining the impact of international research collaborations on the development and implementation of effective environmental policies.
- Exploring the Impact of COVID-19 on Energy Security and Recycling Practices in Europe: A Pathway to Sustainable Recovery.

In conclusion, this study emphasizes the need for robust policy recommendations and actionable solutions to enhance environmental sustainability. Based on the findings drawn from the conducted research in this field, prioritizing investments in renewable energy sources, such as solar and wind power, is essential for mitigating carbon emissions and enhancing energy security. Implementing stricter emission control regulations will address environmental impact and climate change. Encouraging international collaborations for knowledge and technology sharing, particularly benefiting developing nations, and integrating carbon and water footprint considerations into national development plans for a holistic approach to resource management is crucial. Promoting recycling and waste management practices supports sustainable development, and sustained funding for research is vital to uncover new insights and drive innovative solutions. The policy implications are directly correlated with the findings of this research and discussed investigation areas, grounded in critical themes identified through our bibliometric analysis, such as sustainable development, renewable energies, and environmental impact. These recommendations provide clear and constructive solutions, ensuring the policy suggestions are both actionable and directly tied to our findings, enhancing the overall quality and impact of the study.

CRediT authorship contribution statement

Khashayar Fardnia: Writing – original draft, Visualization, Software, Resources, Methodology, Formal analysis, Data curation. **Hossein Yousefi:** Writing – review & editing, Visualization, Supervision, Project administration. **Mahmood Abdoos:** Writing – original draft, Supervision, Software, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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