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Net Zero Carbon Retrofitting of Existing Buildings – A Bibliometric Study

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Abstract

Carbon emission is a huge challenge for the world to combat climate change and achieve the Paris Agreement targets. To address this challenge, it is important to retrofit existing buildings towards net zero carbon (NZC). Many studies have focused on different aspects of building retrofitting towards NZC. However, a study that systematically examines the knowledge domain of building retrofitting towards NZC is lacking. This study aims to analyze the existing research domain of NZC retrofitting through a bibliometric analysis and provide pathways for future research. Based upon 517 relevant articles identified from Scopus, bibliometric analysis was conducted using the VOSviewer and Gephi software tools. Findings revealed the collaboration networks between authors, countries, organizations, and keywords in this research domain. R.F. De Masi and G.P. Vanoli are the two authors with the highest link strength, while the University of Naples Federico II has the highest number of NZC retrofitting publications. In addition, Italy is the country with the highest number of publications, but China is the most productive country when it comes to both publications and citations combined. "Energy efficiency", "energy saving", "nearly zero energy building", "net zero energy", and "renewable energy" are the most prioritized research areas. Based on identified gaps, future research directions are proposed to include (1) integration of modern technology to simulate NZC retrofitting; (2) optimization of sustainable measures to achieve NZC buildings; and (3)quantification of drivers and benefits of NZC retrofitting. The findings of this study would be useful to researchers, policymakers, and practitioners who are interested in NZC retrofitting.

Keywords

Bibliometric, Collaboration, Existing buildings, Net zero carbon (NZC), Retrofitting.

1. Introduction

Promising to keep the global temperature rising to 1.5 ^{0}C above the preindustrial levels, is one of the major outputs of the 2015 United Nations Paris Agreement (Shubbar et al. 2021). As a result, strong measures are required for decarbonization to keep the global temperature rise to 1.5 ^{0}C (Pedinotti-Castelle et al. 2019). However, the energy crisis and climate change continue to be major issues for humanity's development worldwide (Ascione et al. 2020; Assimakopoulos et al. 2020; Toufeili et al. 2022). The building sector accounts for more than 30% of global energy consumption and carbon emissions, outpacing other key sectors like manufacturing and transportation (Albatici et al. 2016; He et al. 2021; Wang & Holmberg 2015). As a result, the net zero carbon (NZC) building definition has become an innovative way of achieving the zero-emissions benchmark in the building sector (Seo & Foliente 2021).

Even though new building constructions have more concerns about carbon emissions and energy efficiency through various standards (Moran et al. 2020), achieving net zero targets will not be possible without considerable attention to the existing building's carbon emissions and energy performances (Heidari et al. 2022). Hence, there is a vital requirement to reduce the carbon emissions and operational energy from the existing buildings due to their immense contribution to greenhouse gas (GHG) emissions (Abdullah & Alibaba 2017). Currently, building retrofitting is the most cost-effective way to reduce carbon emissions and energy performance in existing buildings (X. Li et al. 2022). Numerous empirical and review studies have been dedicated to the topic of NZC retrofitting of existing buildings. However, despite the existence of such studies, limitations persist in their focus. For instance, Luo (2022) conducted an empirical study primarily examining the economic feasibility of retrofitting measures to reduce energy consumption and carbon emissions. Charles et al. (2019) and Zhu (2014) conducted separate empirical studies focusing on office and educational buildings, respectively, to evaluate the effectiveness of retrofitting measures in achieving zero carbon performance. Additionally, review studies conducted by Aghamolaei and Fallahpour (2023), Liu et al. (2023), and Sun et al. (2023) delved into various aspects such as strategies, policies, and technologies pertinent to transforming existing buildings into NZC. Nevertheless, a systematic review encompassing the entire knowledge domain of NZC retrofitting is still lacking.

Therefore, the purpose of this research is to address this gap by conducting a systematic review of the NZC retrofitting knowledge domain. To achieve this, a quantitative study employing bibliometric analysis was conducted on journal articles. The primary objectives of this study were to identify notable authors, countries, and organizations within this domain and provide an overview of the current state of the field. This paper will commence by discussing the methodology employed in the study, followed by the presentation and analysis of the study's outcomes in terms of publication performance and science maps. Finally, the conclusion will outline the additional work to be undertaken to complement the findings of this study.

2. Research Methodology

This research intends to answer the research question of "What is the current status of NZC retrofitting research?". The most suitable approach to resolve this research question is the analyze co-authorship and the keywords of the existing literature on the NZC retrofitting research domain (Liu & Xia 2015). Co-authorship analysis supports the identification of the best-connected authors within the research domain by revealing the specific elements of the author network as it can link two authors who co-authored the research article (Kumar 2015). In addition, keyword analysis supports identifying the current research status and available research gaps. Therefore, bibliometric analysis is selected for this research as it is a common method that is used to discover the co-authorship network and co-occurrence of keywords within the selected research domain (Castriotta et al. 2019). According to Donthu et al. (2021), a bibliometric analysis is essential for evaluating and visualizing the large amount of unstructured accumulated scientific knowledge within the research domain by acting as the foundation for the broadening of the research domain innovatively and interestingly. Therefore, the methodology of this research was conducted in two stages data collection and bibliometric analysis as shown in the following Figure 1.

As the first step of data collection, Scopus is selected as the database for this research since it is well established (Chadegani et al. 2013) database and it contains a huge number of scientific publications rather than other databases like Web of Science (Zhao et al. 2019). The keywords used for the search of articles need to be carefully arranged due to their significant impact on the results of the research study (Norouzi et al. 2021). Hence, a search string was developed after reviewing the recent publications on the NZC retrofitting domain. Finally, all the keywords were connected using "AND" and "OR" Boolean operators and started to search the literature using "TITLE-ABS-KEY".

As the last step of data collection, the identified publications were refined according to the publication year, article type, subject areas, and language in order to have the best input for the analysis.

After refining the identified publications, they were imported to the VOSviewer software for the bibliometric analysis. Since there is a huge number of publications on NZC retrofitting, it is very complex to conduct manual bibliometric analysis and VOSviewer is a free and common platform used for bibliometric analysis (van Eck & Waltman 2014). Further, the authors detailed that VOSviewer is user-friendly and supports the Scopus databases. After that Gephi was used to visualize the analyzed data as it is a user-friendly software to visualize, analyze and explore the graphs in bibliometric analysis (Bastian et al. 2009). Therefore, VOSviewer and Gephi were used in this research to analyze and visualize the identified literature.

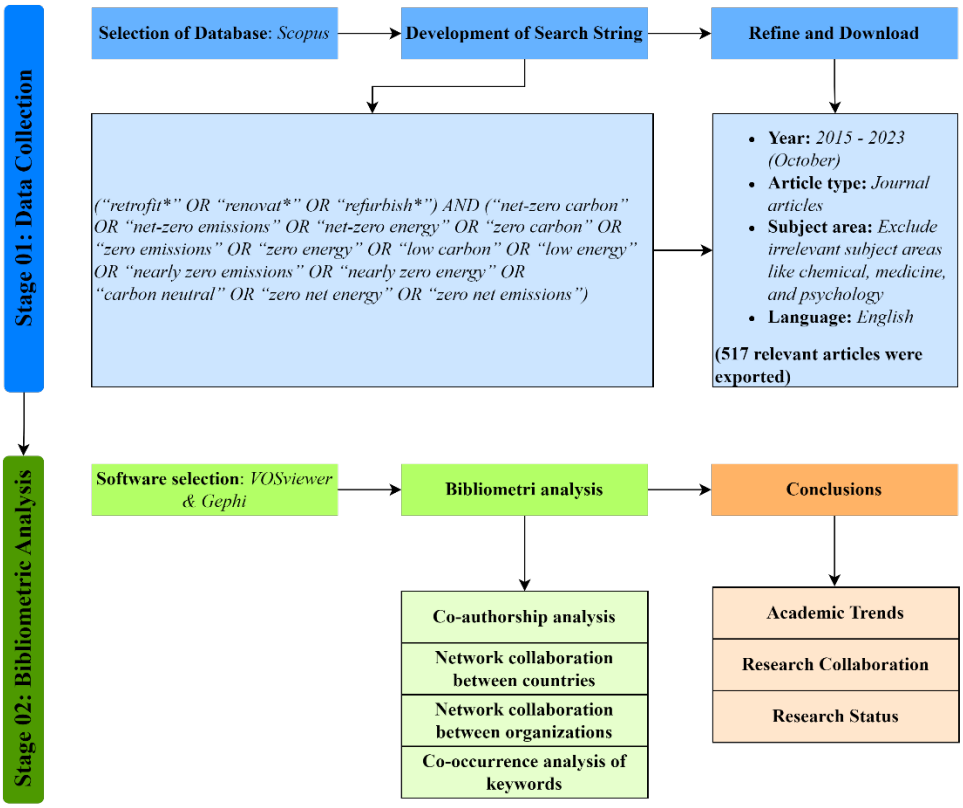

Figure 1. Research methodology

3. Findings and Discussion

This section presents a comprehensive discussion on the co-authorship analysis of the NZC retrofitting research domain and the co-occurrence analysis of keywords. The insights derived from these analyses may be helpful for new researchers who are seeking assistance from specialized groups and experts in the NZC retrofitting research domain.

3.1 Co-authorship Analysis

The major benefit of conducting a co-authorship analysis is to determine the academic collaboration within the research domain (Liu et al. 2005). Hence, it can reveal the patterns of collaboration between two or more authors. Before starting the co-authorship analysis, the minimum number of documents of an author needs to be included. In this case, the minimum number of documents was set as 3, and then from a total of 1720 authors only 71 (4.13%) authors met the threshold and Gephi was used to visualize it as shown in Figure 2.

In Gephi, the different color nodes represent the author collaboration clusters and the node size shows the publications with the author in the research domain. The thickness of the lines (edges) shows the closeness of the authors. However, according to Figure 2, most of the clusters have maintained the collaboration within the cluster or stayed individually

while only a few clusters have maintained a collaboration with different clusters. Therefore, it indicates that future researchers need to be encouraged to perform in the domain of NZC retrofitting by creating more collaborations with domain experts.

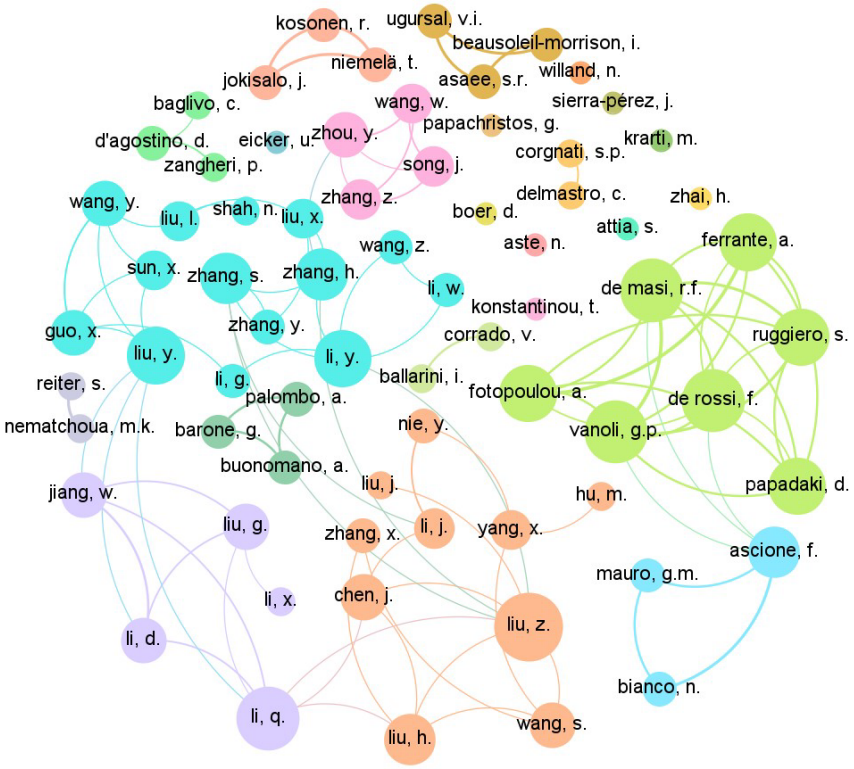

Figure 2. Visualization of collaboration among authors

Table 1 is used to represent the authors whose total link strength is above 10. According to Table 1, "R.F. De Masi" and "G.P. Vanoli" have a total link strength of 22. Both authors have collaborated on highly cited papers related to energy efficiency in buildings. Further, both authors have collaborated on the research studies conducted on the base of retrofitting educational buildings, and hospital buildings as well as deciding cost-optimal methods for historic building refurbishments. Rather than these two authors, the other authors in Figure 2 also have collaborated in the different research studies related to the domain of NZC retrofitting. The availability of 4.13% of authors of more than three publications in the NZC retrofitting research domain needs to be considered because it demonstrates the domain's popularity among the authors which needs to be increased in the future to achieve NZC buildings. Hence, this analysis is useful for the new researchers to identify the research gaps in the NZC retrofitting domain by creating new collaborations.

Table 1. Quantitative measurements of authors in the NZC retrofitting research domain.

Rank	Author	Publications	Links	Total Link Strengths	Avg. Publication Year
1	De Masi, R.F.	5	7	22	2021
2	Vanoli, G.P.	5	7	22	2021
3	Ferrante, A.	5	6	19	2020
4	Fotopoulou, A.	5	6	19	2020
5	Ruggiero, S.	4	6	19	2021
6	Papadaki, D.	3	6	17	2021
7	De Rossi, F.	3	7	15	2020
8	Ascione, F.	2	5	10	2021

3.2 Network Collaborations between Countries

The co-authorship analysis of the VOSviewer software can be further used to analyze the collaboration between countries based on their academic contributions to the NZC retrofitting research domain. After setting the minimum number of documents and the citations of a country as 5 and 2 respectively, 31 out of 72 countries met the threshold. The resulting collaboration network was visualized using Gephi, as depicted in Figure 3.

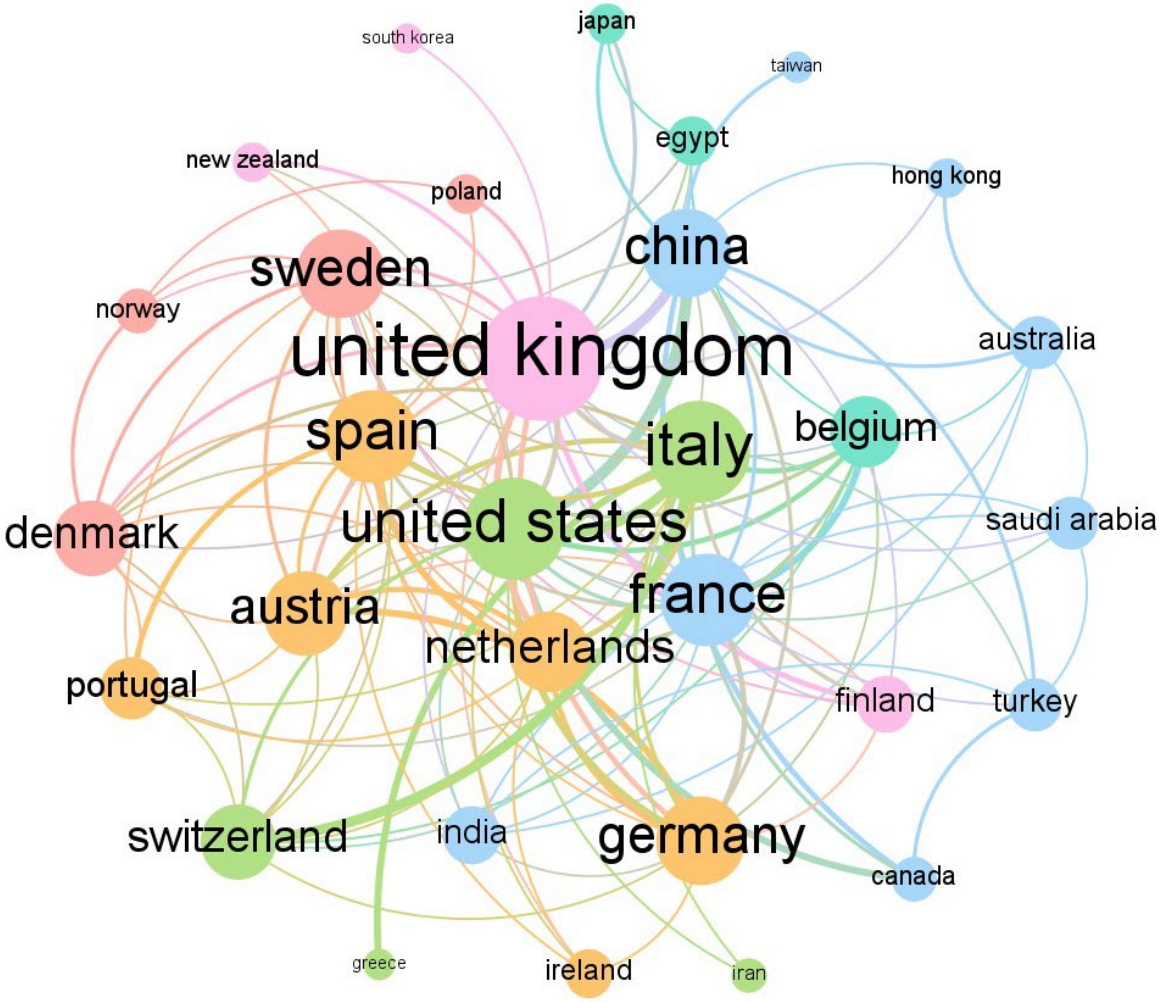

Figure 3. Visualization of collaboration among countries

Based on the node sizes depicted in Figure 3, Italy, China, the United Kingdom, the United States, and Spain have published more articles in the NZC retrofitting research domain. This observation suggests that these countries have created collaborative networks on a global scale, indicating their pivotal role in fostering the worldwide advancement of NZC research domain. Thick lines between two nodes represent the close connection between the respective countries while nodes of same color indicate a close collaboration between them. Accordingly, China and the United Kingdom, China and the United States, Italy and the United States, and Italy and Spain followed close collaboration links. Furthermore, in terms of publication output in NZC retrofitting research domain, Italy and China are emerged as the two leading countries.

However, only the number of publications cannot be considered to have academic decisions on the knowledge base. According to Meho (2007), the influence of citation is the best way for new researchers to assess the contribution of articles in a research domain. The average citation is the ratio between total citations and the total publications which can be affected by highly cited papers due to the early publications. However, average normalized citations avoid that issue by representing that the publication is obtaining additional citations for a year (Jin et al. 2019). Therefore, Table

2 represents the most productive 31 countries in the NZC retrofitting research domain according to the decelerating order of average normalized citations.

Table 2. Quantitative measurements of countries in the NZC retrofitting research domain.

Rank	Country	Publications	Total Citations	Avg. Citations	Avg. Publication Year	Avg. norm. Citations
1	Iran	8	168	21.00	2021	2.35
2	Norway	11	297	27.00	2020	1.94
3	South Korea	8	67	8.38	2022	1.81
4	Turkey	9	82	9.11	2021	1.75
5	Japan	7	101	14.43	2021	1.64
6	Canada	21	383	18.24	2019	1.44
7	Beljium	13	219	16.85	2021	1.33
8	Sweden	11	231	21.00	2020	1.29
9	Australia	18	456	25.33	2020	1.29
10	France	17	274	16.12	2020	1.27
11	Austria	10	155	15.50	2020	1.27
12	China	83	915	11.02	2022	1.20
13	Germany	21	310	14.76	2020	1.18
14	Egypt	6	86	14.33	2020	1.06
15	United Kingdom	78	1602	20.54	2020	1.01
16	Italy	94	1651	17.56	2020	1.00
17	Finland	15	332	22.13	2019	0.99
18	Switzerland	14	201	14.36	2021	0.98
19	United States	51	751	14.73	2020	0.86
20	Netherland	24	325	13.54	2020	0.84
21	New Zealand	5	101	20.20	2020	0.83
22	Saudi Arabia	5	33	6.60	2021	0.83
23	Greece	13	188	14.46	2020	0.82
24	Portugal	10	173	17.30	2019	0.78
25	Ireland	10	148	14.80	2020	0.66
26	Poland	13	115	8.55	2021	0.65
27	Spain	40	493	12.33	2020	0.65
28	Hong Kong	5	72	14.40	2020	0.63
29	India	12	148	12.33	2020	0.59
30	Denmark	10	104	10.40	2021	0.54
31	Taiwan	5	48	9.60	2019	0.38

According to Table 2, Iran, Norway, and South Korea have the highest average normalized citations in the research domain. But those countries have fewer publications. However, Italy and China have maintained the highest number of publications as well as citations. In addition, China and South Korea have recently published articles in the research domain. Overall, China is the most productive country in terms of publications and collaborations. Therefore, it can be concluded that China is making great efforts to create NZC buildings by retrofitting the existing building stocks.

3.3 Network Collaboration between Organizations

VOSviewer software additionally serves to address co-authorship and the organization's contribution in the research domain of retrofitting the existing buildings towards NZC. The minimum number of documents and citations of an organization was set as 2 for the analysis. Then out of 1136 organizations, only 48 organizations met the threshold and Gephi was used to visualize it as in Figure 4.

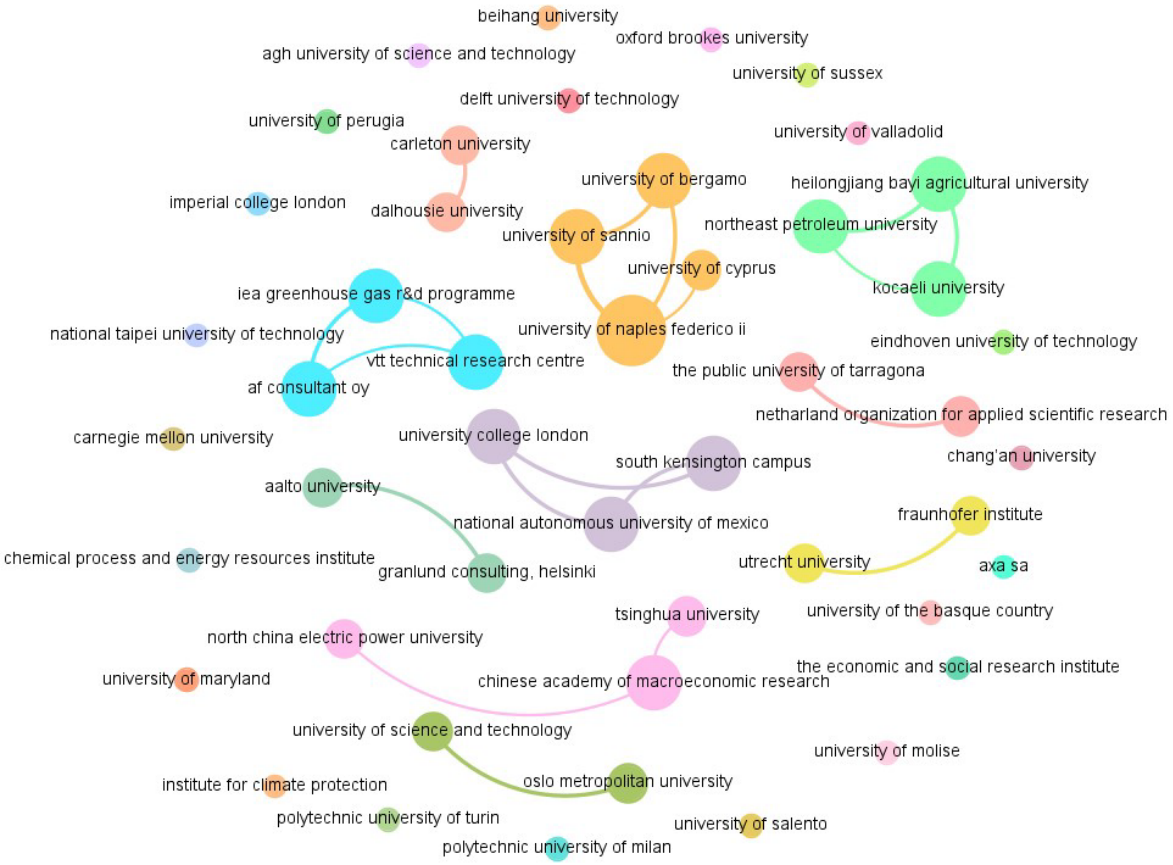

Figure 4. Visualization of collaboration among organizations

Figure 4 reveals that, the University of Naples Federico II in Italy has the highest number of publications in the research domain. In addition, it has maintained more collaborations than the other organizations. This observation, along with the collaborative network depicted, highlights Italy's prominent role in terms of publication output and citation count within the research domain. Therefore, the Figure shows that the organizations within the country have higher collaboration than the organizations outside the country. In addition, most of the organizations stay alone without making any collaborations with other organizations. Hence, in order to effectively promote scientific academic knowledge and to develop productivity, close collaborations need to be created with various organizations across different countries. So, this study suggests that there is a vital to encourage researchers from diverse organizations to facilitate improved collaboration among various entities which will enhance the academic productivity within the domain.

3.4 Keywords Analysis

Keywords play a significant role in indicating the current research focus within the research domain. According to C. Z. Li et al. (2022) the network of keywords and their analysis support to identification of the major research areas and offer a thorough understanding of their interrelationships. The minimum number of occurrences of a keyword was set as 5 and the words with the same meaning such as "building refurbishment" and "building retrofitting", "BIPV" and "building integrated photovoltaics" and "LCA" and "life cycle analysis" were integrated through a thesaurus file. Then out of 1715 keywords 50 keywords met the threshold and it was visualized using Gephi as in Figure 5.

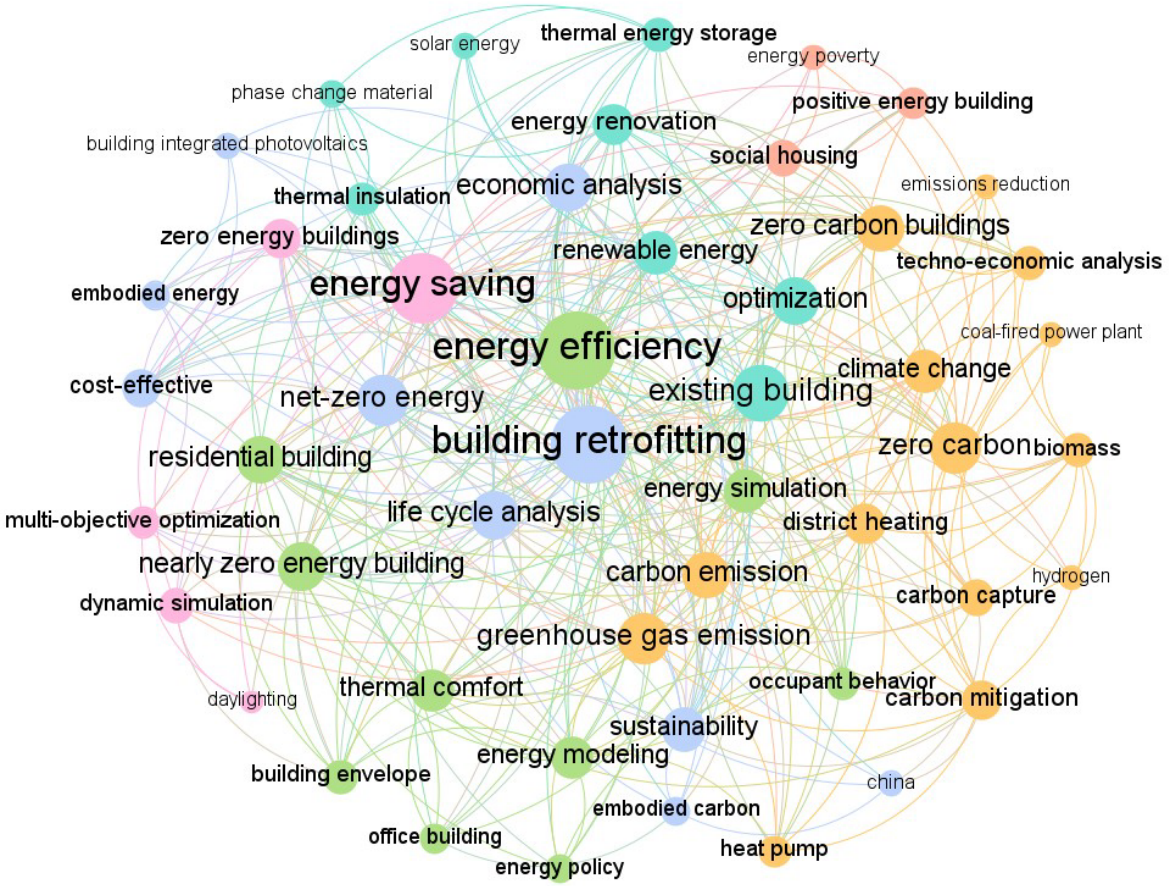

Figure 5. Visualization of the keywords co-occurrence

In Figure 5, the size of the node denotes the number of occurrences of a keyword while the thickness of the line denotes the closeness between the keywords. Accordingly, “building retrofitting” (119 times) and “energy efficiency” (112 times) are the frequently appearing keywords. This finding ensures that building retrofitting is mostly a concern for the researchers to reduce the adverse impacts of climatic changes by reducing the energy consumption and the carbon emission from the existing building stock. Further keywords show that zero-carbon buildings and zero-energy buildings have taken considerable attention within the research domain in order to control the energy consumption and carbon emission to mitigate the adverse environmental effects. Since existing buildings are responsible for more carbon emissions from their operational energy, the term “energy” is highlighted among the keywords using various terms such as energy efficiency, energy saving, net-zero energy, energy simulation and renewable energy. In addition, the use of terms such as residential buildings, office buildings, and social housing represent that it is needed to consider building types before deciding to retrofit toward NZC as the energy consumption and carbon emissions may differ with the building type. Moreover, key words represented the availability of different retrofitting measures along with their implementing benefits and deciding methods.

Table 3 is used to illustrate the quantitative impacts of the keywords. In Table 3, keywords have been ranked according to their occurrences. Even though “building retrofitting”, “energy efficiency” and “energy saving” are the top-ranked keywords according to the occurrences, “China”, “embodied energy” and “embodied carbon” are at the top three levels according to the average normalized citations by showing their impacts on the research domain. Accordingly, it is clear that China has made huge efforts to convert its existing buildings to NZC while comparing with the collaborations among countries. In addition, embodied carbon and embodied energy are two main factors that need to be considered before implementing selected retrofitting measures for the existing buildings.

Table 3. Quantitative measurements of keyword co-occurrences

Rank	Keyword	Occurrences	Avg.Pub.Year	Avg. Citations	Avg. norm. Citations	Rank	Keyword	Occurrences	Avg.Pub.Year	Avg. Citations	Avg. norm. Citations
1	Building retrofitting	119	2020	17.83	1.05	26	Climate change	11	2020	17.91	1.15
2	Energy efficiency	112	2020	15.21	0.89	27	Dynamic simulations	11	2021	8.00	1.05
3	Energy saving	57	2020	15.74	0.97	28	Energy renovation	9	2020	12.22	0.64
4	Nearly zero energy building	38	2020	20.92	1.05	29	Social housing	9	2020	12.44	0.79
5	Existing building	35	2020	23.46	1.20	30	Building envelope	8	2020	10.25	0.47
6	Zero carbon	33	2020	14.33	0.92	31	Embodied carbon	8	2021	19.75	1.56
7	Net zero energy	32	2020	19.75	1.12	32	Heat pump	8	2021	5.50	0.46
8	Sustainability	28	2020	17.11	1.02	33	Multi-objective optimization	8	2021	22.13	1.39
9	Renewable energy	27	2021	11.89	1.01	34	Occupant behavior	8	2019	26.75	1.04
10	Residential buildings	24	2020	16.71	0.86	35	Office building	8	2019	16.13	0.76
11	Life cycle analysis	23	2021	13.52	1.30	36	Building integrated photovoltaics	7	2021	22.29	1.51
12	Economic analysis	22	2021	13.86	1.19	37	Coal-fired power plant	6	2020	19.17	1.43
13	Greenhouse gas emission	22	2020	16.09	1.15	38	Embodied energy	6	2020	25.33	1.71
14	Optimization	22	2020	17.86	1.21	39	Energy policy	6	2019	32.67	1.08
15	Carbon emission	21	2021	22.43	1.45	40	Hydrogen	6	2022	7.67	0.73
16	Zero carbon buildings	20	2020	17.65	1.22	41	Positive energy building	6	2020	14.17	0.71
17	Cost-effective	18	2019	28.78	1.36	42	Solar energy	6	2021	7.33	0.75
18	Carbon capture	16	2020	19.13	1.01	43	Thermal energy storage	6	2021	21.00	1.36
19	District heating	15	2021	11.27	0.78	44	China	5	2019	37.40	2.58
20	Zero energy buildings	15	2020	22.80	1.25	45	Daylighting	5	2021	8.60	0.68
21	Thermal comfort	14	2020	15.71	0.73	46	Emission reduction	5	2021	12.00	1.01
22	Biomass	13	2020	12.77	0.56	47	Energy poverty	5	2019	17.60	1.02
23	Energy simulation	13	2020	21.92	1.24	48	Phase change material	5	2021	19.20	1.13
24	Energy modeling	12	2021	10.50	0.77	49	Techno-economic analysis	5	2022	3.00	0.49
25	Carbon mitigation	11	2021	6.00	0.43	50	Thermal insulation	5	2021	12.60	1.19

The VOSviewer software has analyzed keywords under six clusters by denoting them in different color nodes as in Figure 5. However, the clusters formed by software do not represent the accurate cover of the topics in the NZC retrofitting research domain. Therefore, referring to the topics of the papers and through an initial review of the domain, the keywords were classified into eight subcategories as in Figure 6. Hence, that will be beneficial for future researchers to gain an initial understanding of the enhancing areas of the NZC retrofitting research domain. In addition, researchers can use this figure to identify the research gaps in the domain of converting existing buildings to NZC. As a result, innovative studies can be developed to achieve the NZC from the existing building stock in order to reduce the adverse climatic impacts and environmental pollution by mitigating carbon emissions.

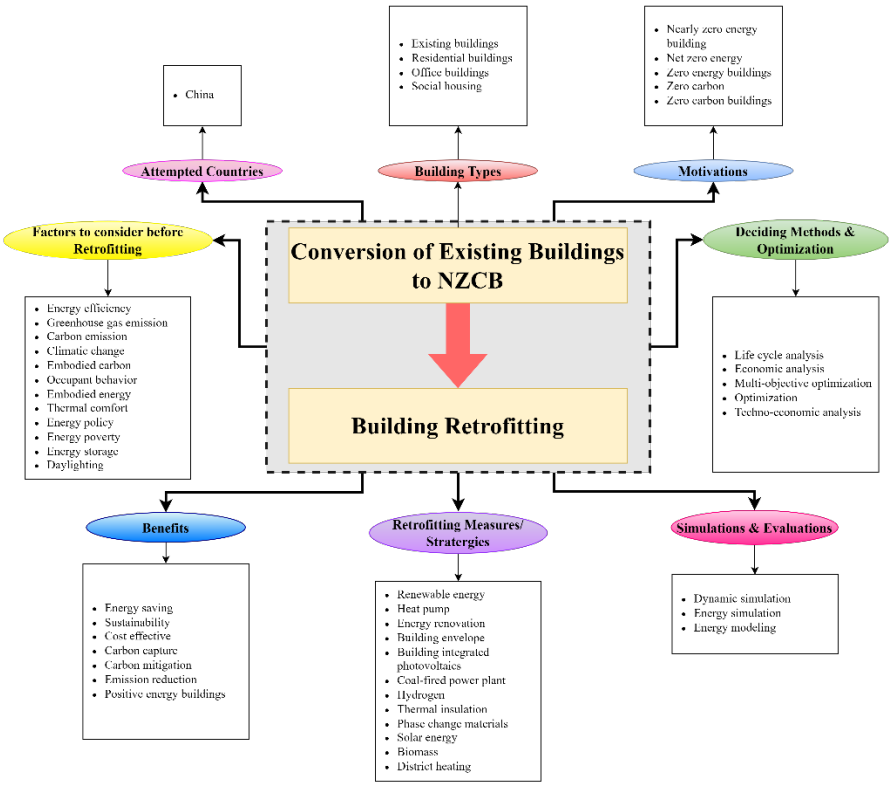

Figure 6. Categorization of keywords

6. Conclusions

NZC retrofitting is the most suitable and effective method to convert the existing buildings into NZC as a solution to mitigate the adverse climatic effects and environmental pollution due to huge carbon emissions and to achieve the Paris Agreement targets. Even though there are various research conducted based on energy savings and reduction of carbon emissions, the concept of NZC retrofitting remains under-explored. Therefore, this study attempts to improve the knowledge base on the NZC research domain through bibliometric analysis as a support for future research activities. The VOSviewer and Gephi software were employed for this study to conduct bibliometric analysis. The review was conducted based on 517 relevant articles published between 2015 and 2023 (October). Finally, articles were used to analyze the co-authorship to identify the productive authors, countries, and organizations within the domain and analyzed the co-occurrence of keywords to identify the current status of research within the domain.

The co-authorship analysis revealed distinct author clusters that were relatively isolated while only a few clusters with interconnections. Remarkably, the authors “R.F. De Masi” and “G.P. Vanoli” have maintained the highest link strength indicating more collaborations. In relation to organizations, the University of Naples Federico II in Italy emerged as the organization with the highest number of publications. Moreover, it indicates that there are more collaborations among the organizations within Italy compared to collaborations with organizations outside the country. Further, while analyzing the countries, Italy stood out as the country with highest number of publications. However, China acts as the most productive country by maintaining both publications and citations showing significant contribution to the domain.

Overall, the analysis demonstrates that the collaboration between the authors and the organizations of NZC retrofitting research domain is very low and it needs to be improved through future research activities. While developing the collaborations, that will be supported to share the knowledge and the experiences of various authors to accelerate the retrofitting process towards NZC. Further, collaborations between organizations will support the sharing of various facilities with developed technologies which can be implemented for the retrofitting of existing buildings to NZC. Therefore, the authors and the institutions should make attempts to develop collaborations through various research

grants and university exchange programs. In addition, participating in conferences, webinars, and workshops will also help to improve the collaborations within the research domain.

The analysis of keyword co-occurrence in the NZC retrofitting research domain revealed the significant trends and emerging research areas within the domain. Accordingly, identified keywords were categorized into eight categories: (1) attempted countries, (2) building types, (3) motivation, (4) benefits, (5) factors to consider before retrofitting, (6) retrofitting measures, (7) simulation and evaluation, and (8) deciding methods and optimization. This categorization provides valuable inputs to the NZC retrofitting research domain highlighting the key areas focused within the domain. Based on the keywords analysis, it is evident that implementation of modern technologies such as Digital Twin and Artificial Intelligence is still lacking within the domain. The availability of different retrofitting measures and the different building types indicate the necessity of optimization methods to select the most suitable retrofitting measures for the different building types. Therefore, the findings of this study will be valuable for future researchers to identify the research gaps as well as for practitioners and policy makers to make collaborations with various countries and organizations to implement the concept of NZC retrofitting. .

However, there are limitations to this study. The study only selected the articles consisting of the developed search string and the articles without those keywords that have significantly contributed to the research domain are not included in this study. In addition, only the Scopus database was selected for this study and the selected articles were limited to the publications between 2015 and 2023 (October). Apart from those limitations, the findings from the study may contribute to both theoretical and practical implementation. The findings from the co-authorship analysis can be used by upcoming researchers as well as currently available researchers within the domain to create collaborations with various organizations and authors. Further, the research students can use the findings to participate in various conferences and apply for research grants. In addition, the co-occurrence of keywords can be used to enhance the research interest towards the NZC retrofitting. Therefore, research students can use these data for their upcoming research to identify the research gaps available in the NZC retrofitting domain. Hence, this study will be a valuable addition for the researchers to enhance the research network within the NZC retrofitting research domain.

Acknowledgements

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