Bibliometric Analysis of Fire Safety Research in Green Buildings 2000-2021

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ABSTRACT
This study creates a bibliometric profile of scientific research on fire safety problems and solution methods in green buildings, which is important for sustainability of built enviroments. The bibliometric method, which analyzes scientific publications quantitatively and visually, is used in scientific studies on fire safety in green buildings (GBFS) between the years 2000-2021 to reveal research areas, trends, and new research needs. Scopus database is used to view scientific publications and VOSviewer Software is used for bibliometric analysis tool. To present the global framework of the research area, 213 articles were seen as a result of the searches in the database. The results show that the studies on GBFS are limited, and the fields of study are focused on materials and chemical engineering sciences. There is a need for architecture and engineering disciplines research related to green building and fire safety designs. The bibliometric analysis findings will provide insight into current research areas and new trends for green building and fire safety design stakeholders and academics.

1. INTRODUCTION
Green buildings, which adopt the sustainability goals in the built environment as a principle, contribute to the creation of healthy, ecological and efficient environments with environmental, social and economic designs in the life cycle process. Green building designs take advantage of many factors such as using climatic data, providing resource, energy and water efficiency, improving indoor quality, using natural materials and recycled or recyclable materials. However, if a fire occurs in a green building, problems may occur that conflict with sustainability goals. Because of this reason, the integration of fire safety in the design stages of green buildings is inevitable for the safety of life and property, the protection of the environment, resources and energy, and the sustainability of social and economic activities. In this study, researches on GBFS problems and solution methods are systematically examined. The bibliometric method is used to reveal general research gaps, trends and research areas related to GBFS.

2. METHODOLOGY
The bibliometric method was used for numerical and visual analysis in the GBFS research subject area. Web of Science and Scopus databases were examined in order to search for scientific studies in the bibliometric analysis process. When bibliometric statistics from Web of Science and Scopus are compared, articles and citations in these databases are highly correlated. Therefore, there will not be significant differences in bibliometric analysis results between these two databases (Archambault et al., 2009). As a result, Scopus was preferred because there are more recent publications on the research.

2.1 Bibliometric analysis method
The bibliometrics method is a science that quantitatively analyzes bibliographic data and offers an effective research opportunity. In bibliometric analysis, the scientific framework of the research is formed by measuring the data about the research topic (Cobo et al., 2011). The bibliometric technology, which has been used extensively in research-based studies in recent years, has been preferred to examine GBFS researches within the scope of the study. As a result of the quantitative and visual analysis of the most productive

researchers in the field of research, countries and authors making high-level contributions, and the relations between studies, research trends and gaps were identified and classified.

2.2 Scopus database survey

The keyword survey in the database should be accurate and complementary to list studies that examine green buildings with fire safety problems without leaving the research area. First of all, it was scanned with different combinations of words such as "fire, "building, green, energy, sustainability" (eg: fire, green, building). Since the displayed publications generally include studies that are out of the scope of the subject, adjusments were made in the keywords.

In order to find data on research limitations, different combinations were created by adding the keywords "green building, green design, sustainable building, sustainable design, energy efficiency" to the phrases "fire, "smoke, combustion, fire spread". Then, the numerical analysis was simplified by choosing the document type as article or review and the language as English in the database. Considering the date the research became widespread, the date range from 1976-2021 was limited to 2000-2021 and as a result, 340 scientific studies were determined (Fig.1). As a result of the removal of branches of science outside the subject area such as chemistry and medicine, 213 articles were obtained for numerical and visual analysis. Bibliometric data obtained from Scopus database were downloaded as "Comma Separated Values" file and related literature was transferred to VOSviewer for scientific mapping.

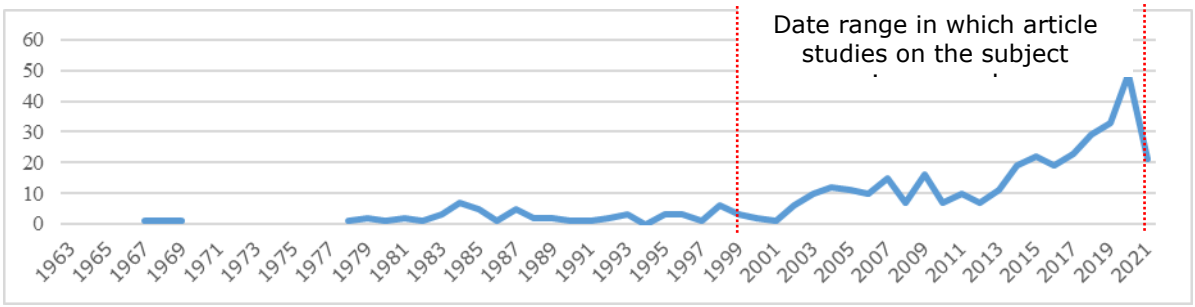

Figure 1. Distribution of articles by years

It is seen in Figure 2 that the studies can be included in more than one discipline due to their interdisciplinary contributions. Engineering was observed as the branch of science that gave the most publications on the research subject with 46.63%. Detailed subject areas analysis was made in the VOSviewer analyzes in the next sections.

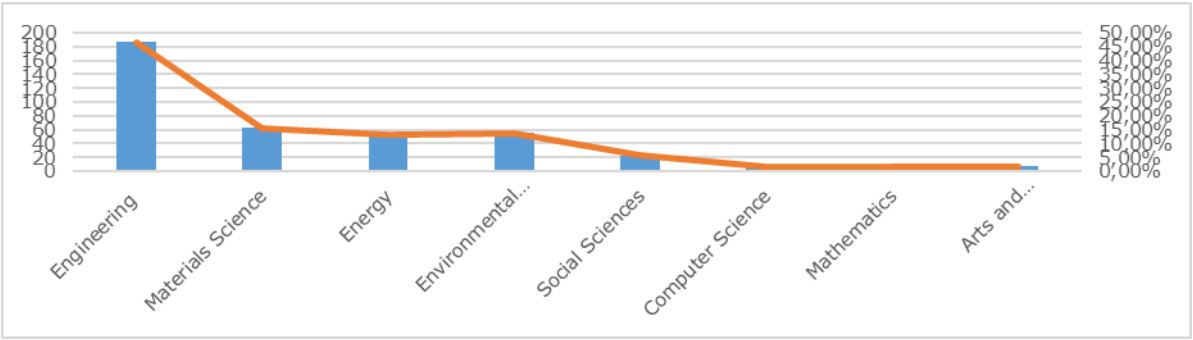

Figure 2. Distribution of articles by science

2.3 VOSviewer Software

Van Eck and Waltman developed the VOSviewer text mining tool at the Leiden University Science and Technology Research Center in 2010 to analyze and visualize bibliometric

networks. Networks of journals, researchers and publications with VOSviewer; co-citation, bibliographic matching, co-author relations and co-existence or co-occurrence of words used in the document are examined (van Eck & Waltman, 2010).

The size of nodes and fonts in VOSviewer network visualization represent the frequency of occurrence of keywords. The number of links distributed from a node indicates the citation frequency, and the nodes with more links represent qualified fields (journal, article, country, etc.) in the subject area. In addition, since the position of a node in the network visualization is determined by the frequency of occurrence, the number of citations and its connections with other nodes, the nodes in the center of the network are critical for analysis.

3. BİBLİOMETRİC ANALYSİS FİNDİNGS

Literature data about GBFS obtained from Scopus database and transferred to VOSviewer are visualized as source journal, keywords, co-author, citation and countries.

3.1 Main Journals Publishing GBFS Research

Identifying scientific journals that publish articles on the research topic and receive high citations allows to follow academic developments and innovations on the subject. A minimum of 3 articles for publication and a minimum of 5 citations are determined in a journal. 17 of 120 journals publishing research articles are as seen in Figure-3. Identifying scientific journals that publish articles on the research topic and receive high citations allows to follow academic developments and innovations on the subject. A minimum of 3 articles for publication and a minimum of 5 citations are determined in a journal. 17 of 120 journals publishing research articles are as shown in Figure 3.

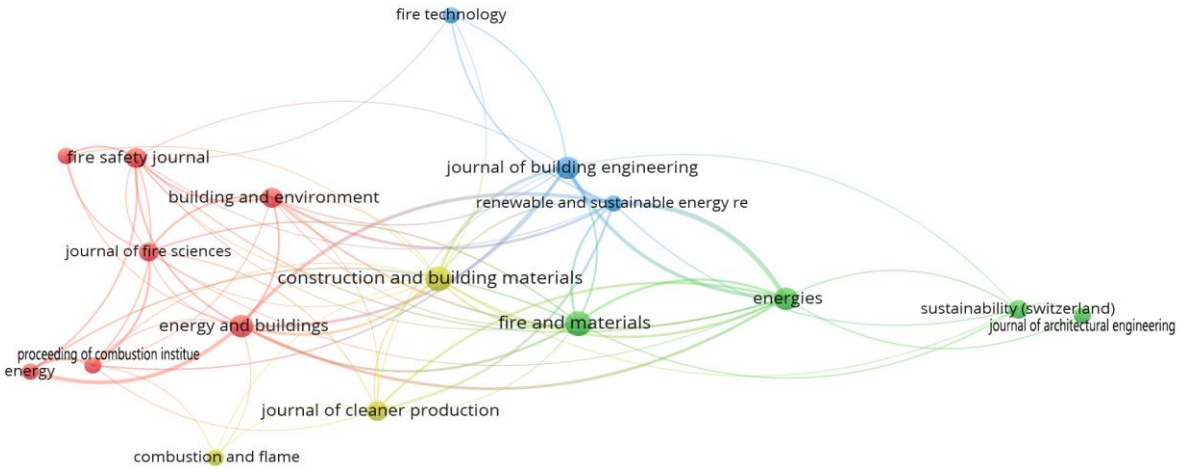

Figure 3. Network visualization of main journals

Table 1 contains the numerical data of the network visualization in Figure 3. The link in the table shows the number of links of a journal with other journals, and the total link weight shows the total number of links with other journals. The total number of citations is the total number of citations received from other articles; The average number of citations refers to the number of citations per article in a journal. Normalized citation shows the citation potential of recently published articles, while average normalized citation shows the citation trend of articles with a new publication year. According to Table-1 and Figure-3, the journals that contributed the most to the research topic are Construction and Buildings Materials and Energy and Buildings.

Table 1. Numerical data network visualization of main journals

Journal	*Link*	*Total link*	*Number of articles*	*Number of citiations*	*Normalized citation*	*Average citation*	*Avarage normalized citation*
Construction and Building Materials	14	45	7	212	7.8109	30.2857	1.1158
Fire and Materials	11	37	7	34	4.2346	4.8571	0.6049
Energies	11	78	6	32	4.1136	5.3333	0.6856
Energy and Buildings	12	71	6	343	17.8178	57.1667	2.9696
Journal of Building Engineering	11	64	6	22	7.0381	3.6667	1.173
Building and Environment	10	30	5	116	6.2499	23.2	1.25
Fire Safety Journal	12	24	5	54	3.7681	10.8	0.7536
Journal of Cleaner Production	9	25	5	78	6.2061	15.6	1.2412
Journal of Fire Sciences	9	21	4	27	1.2584	6.75	0.3146
Sustainability (Switzerland)	6	9	4	1	0.4133	0.25	0.1033
Applied Energy	4	8	3	80	7.6328	26.6667	2.5443
Combustion and Flame	4	4	3	47	2.4199	15.6667	0.8066
Energy	4	30	3	13	1.8267	4.3333	0.6089
Fire Technology	4	7	3	7	2.5159	2.3333	0.8386
Journal of Architectural Engineering	2	3	3	22	1.7171	7.3333	0.5724
Proceedings of The Combustion Institute	9	24	3	62	6.5534	20.6667	2.1845
Renewable and Sustainable Energy	10	84	3	292	10.7499	97.3333	3.5833

Spearman correlation analysis was used to analyze statistical data on the level and strength of the relationship between citation numbers and normalized citation numbers. A strong positive correlation was found between citation numbers and normalized citation numbers ($r=0.817$, $p<0.0001$) (Fig. 4). As a result, a strong correlation was found between the number of citations of a journal and its average annual impact (normalized citation).

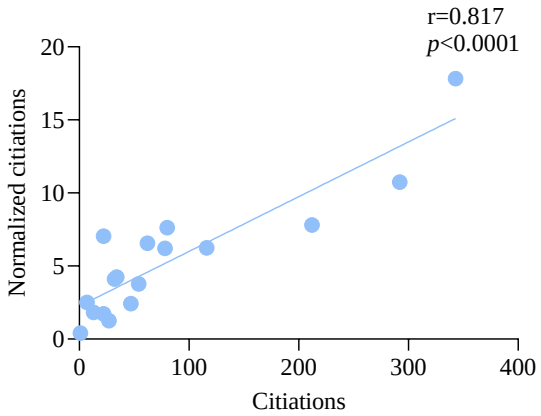

Figure 4. Correlation graphic between the number of citations and the normalized average citation

3.2 Countries Active in GBFS Research

GBFS problems and solution methods are a global problem due to sustainability goals. However, the level of importance given to the problem by countries differs. For the country network analysis, the limitations of publishing at least 3 articles and getting at least 20 citations were determined and 15 countries linked from 45 countries were displayed on the network visualization. (Fig.5).

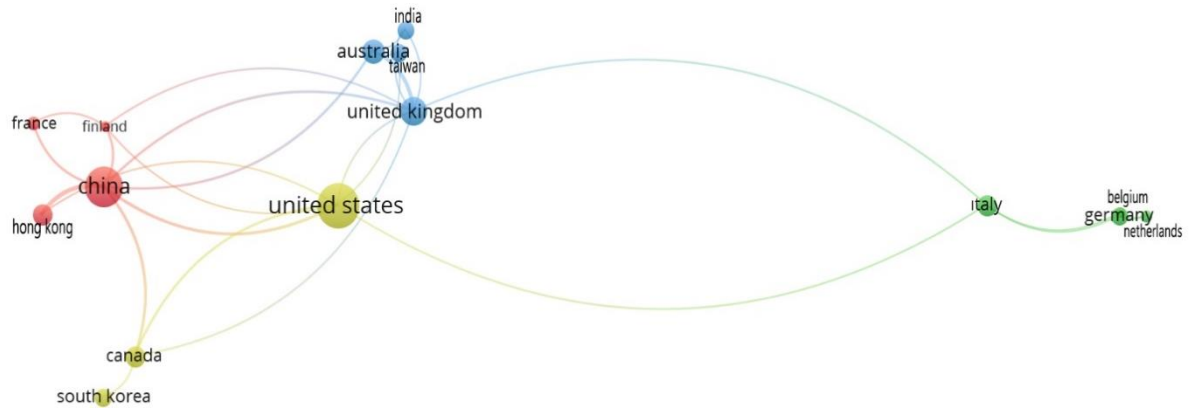

Figure 5. Network visualization of countries

The United States of America (USA), which has a large node and high connection strength in the network image, is the country that contributes the most to the research topic with 51 articles. Research in the USA is focused on material analysis and energy efficiency. In some studies, energy efficiency, structural properties, environmental effects and fire performance of low-value wood construction materials such as cross laminated timber, wooden wall panels were investigated (eg.; (Hafez & Tajvidi, 2020; Khavari et al., 2016; Laguarda Mallo & Espinoza, 2015; Mohammadi & Ling, 2017)). In other studies, thermal values, energy and fire performance and chemical properties of shell and insulation materials were investigated. In these studies, the energy performance and environmental effects of shell elements and insulation materials with different chemical properties were investigated, and fire safety was not the primary research target. (eg.; (Dvorak, 2009; Kalhor & Emaminejad, 2020; Knowles, 2004; Rathnayake et al., 2020; Suzuki & Manzello, 2021)). In some studies, energy efficiency, structural properties, environmental effects and fire performance of low-value wood construction materials such as cross laminated timber, wooden wall panels were investigated. (eg.,(Chang et al., 2003; Forrest et al., 2020; Lstiburek, 2005; Woods, 2007)). In addition, some articles examined the explosion at the World Trade Center in 2001 and the subsequent fire in terms of mechanical, chemical and human health. (eg.,(Baum & Rehm, 2005; Bažant & Verdure, 2007; Tao et al., 2008)). Articles in China found more studies examining green buildings in the context of fire safety than in the USA. Articles in China have examined the fire and thermal performance of materials and smoke propagation within the building. In China, besides the studies examining the energy and fire performance of insulation materials produced with organic, inorganic, plastic-based, cement-reinforced or nanofiber fibers, (eg.,(Huang et al., 2015; Jiang et al., 2014; Kumar et al., 2020; Ma, Tu, Cheng, et al., 2018; Ma, Tu, Ding, et al., 2018; Qian et al., 2018)), articles were found in the field of chemical engineering, dealing with the chemical properties of the material. (eg.;(Jia et al., 2021; Wang et al., 2019; Xiao et al., 2020)). Another research area in China was the air currents formed by temperature and pressure differences in the building through experimental and computational fluid dynamics. These studies were often covered by the same authors. (eg.;(C. L. Chow et al., 2004; W. K. Chow & Chow, 2005; W. K. Chow & Gao, 2008; W. K. Chow & Zhao, 2011; Mckeen & Liao, 2019)). Few articles have examined the efficiency and fire hazards of active energy generating systems. (eg.;(Feng et al., 2019; Ju et al., 2018)).

3.3 Productive Researcher Analysis

Co-author network connections enable the identification of academics writing articles on GBFS. As a result of selecting the minimum number of articles published by an author of 3 and number of citations 10, 19 authors were displayed. (Fig. 6). The authors were divided into 8 clusters according to their citation and collaborative relationships on the network visualization. The citation network relationship between only 2 clusters showed that the number of linked and internationally networked articles was limited.

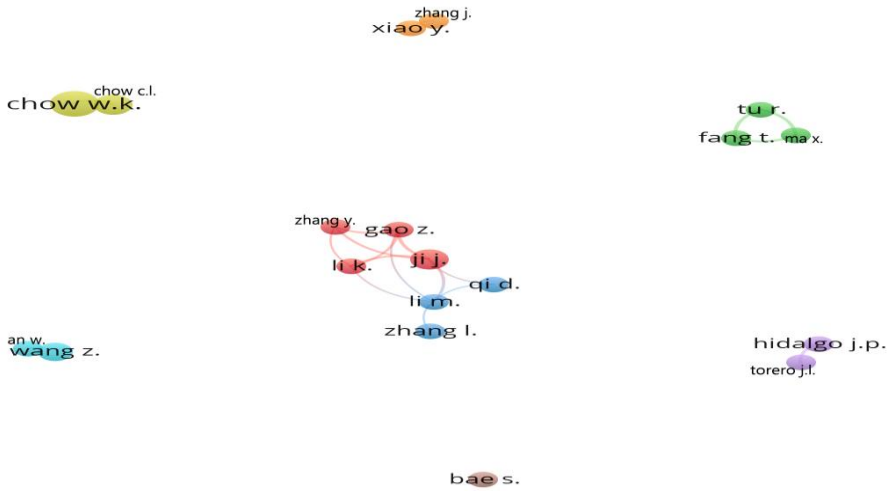

Figure 6. Network visualization of authors

Table 2 contains the numerical analyzes of the author's network map. Accordingly, Chow. W.K and Chow C.L. have made significant contributions to the subject of research and studies in China. These authors investigated smoke emissions from air currents in the building using computational fluid dynamics. (eg.,(C. L. Chow et al., 2004; W. K. Chow, 2004; W. K. Chow & Chow, 2005; W. K. Chow & Zhao, 2011).

Table 2. Numerical data network visualization of researcher

Author	*Link*	*Total link*	*Number of articles*	*Number of citiations*	*Normalized citation*	*Average citation*	*Avarage normalized citation*
Chow w.k.	1	3	8	175	15.2421	21.875	1.9053
An w.	1	1	3	79	5.6429	26.3333	1.881
Ji j.	5	10	5	67	6.7605	13.4	1.3521
Li m.	5	6	3	56	7.4282	18.6667	2.4761
Chow c.l.	1	3	5	52	4.9819	10.4	0.9964
Wang z.	1	1	4	50	7.8664	12.5	1.9666
Zhang l.	1	1	3	42	6.5842	14	2.1947
Gao z.	4	8	3	39	4.3939	13	1.4646
Li k.	4	6	3	34	3.683	11.3333	1.2277
Zhang y.	3	5	3	33	12.303	11	4.101
Fang t.	2	6	3	28	2.5455	9.3333	0.8485
Ma x.	2	6	3	28	2.5455	9.3333	0.8485
Tu r.	2	6	3	28	2.5455	9.3333	0.8485
Hidalgo j.p.	1	3	3	27	3.3826	9	1.1275
Torero j.l.	1	3	3	27	3.3826	9	1.1275
Zhang j.	1	1	3	23	3.0539	7.6667	1.018
Qi d.	2	2	3	20	5.0435	6.6667	1.6812
Bae s.	0	0	3	16	2.2532	5.3333	0.7511
Xiao y.	1	1	3	15	1.3636	5	0.4545

Spearman correlation analysis was used to analyze statistical data on the level and strength of the relationship between citation numbers and normalized citation numbers, number of articles. A strong positive correlation was found between the number of citations and the number of articles ($r=0.604$, $p<0.006$). There was also a strong positive correlation between citation numbers and normalized citation numbers ($r=0.764$, $p<0.0001$) (Fig.7). As a result, it has been determined that there is a direct relationship between the number of citations of the authors and the average annual effect of their articles (normalized citations) and the total number of articles.

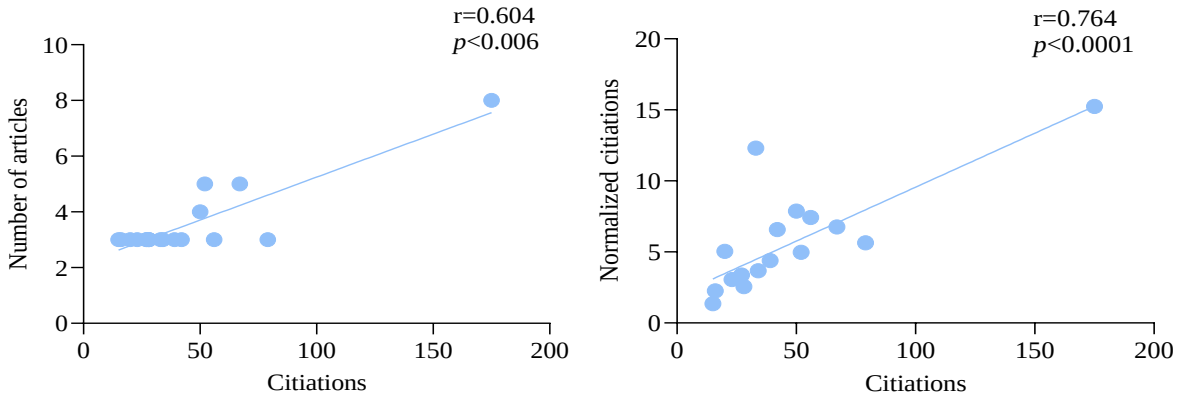

Figure 7. Correlation graphic between the number of citations and number of articles, the normalized average citation.

3.4 Highly Cited Articles

As a result of limiting the minimum number of citations to 25 in 213 articles, 24 articles were visualized (Fig. 8). From Figure 8, it was seen that the link network was weak and the number of clusters was high among the articles. This situation gives an idea about the low rate of influence among qualified studies about the research and the abundance of research areas of the articles.

Figure 8. Network visualization of articles

The highly cited articles generally investigated the chemical, energy efficiency and fire resistance properties of the insulation materials preferred to provide the thermal comfort level in buildings. While the highly cited studies in Table 3 were mostly in the field of materials engineering within the scope of the analysis of building materials (Colangelo et al., 2016; Huang et al., 2015; Schiavoni et al., 2016; Stec & Hull, 2011), there were also studies that included materials and chemical engineering disciplines together (Guo et al., 2018; Patnaik et al., 2015; Wang et al., 2019; Wicklein et al., 2015).

Table 3. Numerical data network visualization of articles

Yazar	*Title*	*Field*	*Citation*
Wicklein B. vd.	Thermally insulating and fire-retardant lightweight anisotropic foams based on nanocellulose and graphene oxide	Material and Chemistry	641
Schiavoni S. vd	Insulation materials for the building sector: a review and comparative analysis	Material and Enviromental	282
Stec A.A. vd.	Assessment of the fire toxicity of building insulation materials	Fire Engineering and Material	128
Patnaik A. vd.	Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies	Material and Chemistry	115
Pinto J. vd.	Characterization of corn cob as a possible raw building material	Material, Chemistry and Envriomental	75
Colangelo F. vd.	Recycled polyolefins waste as aggregates for lightweight concrete	Material and Enviromental	59
Huang Z.vd.	Proportioning and characterization of portland cement-based ultra-lightweight foam concretes	Material	58
Mallo M.F.vd.	Awareness, perceptions and willingness to adopt cross-laminated timber by the architecture community in the united states	Architecture and Enviromental	53
Jiang.l.vd	Correlation study between flammability and the width of organic thermal insulation materials for building ex. walls	Fire Engineering and Material	53
Guo.W.vd	Nano-fibrillated cellulose-hydroxyapatite based composite foams with excellent fire resistance	Fire Engineering, Chemistry and Material	45
Fisk.w.j.vd	Review of some effects of climate change on indoor environmental quality and health and associated no-regrets mitigation measures	Mechanical engineering	42
Lachance.J.vd	Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure	Hydrogen energy and technology	41
Chow.W.K.	Wind-induced indoor-air flow in high-rise building adjacent to vertical wall	Fire Engineering	40
Wang.D.vd.	Cyclotriphosphazene-bridged periodic mesoporous organosilica-integrated cellulose nanofiber anisotropic foam with highly flame-retardant and thermally insulating properties	Material and Chemistry	39
Chow.W.K.	Fire safety in green or sustainable buildings: application of the fire engineering approach in hong kong	Fire Engineering	36
Prasad.K.vd	Coupled fire dynamics and thermal response of complex building structures	Fire Engineering	35
Rudge J.	Coal fires, fresh air and the hardy british: a historical view of domestic energy efficiency and thermal comfort in britain	Energy and Architecture	31
Luther.W.vd	Fds simulation of the fuel fireball from a hypothetical commercial airliner crash on a generic nuclear power plant	Physics and Energy	30
Asimakopoulou E.K.vd.	Fire safety aspects of pcm-enhanced gypsum plasterboards: an experimental and numerical investigation	Mechanical engineering and Material	28
Matthews E.C.vd.	A critical analysis of hazard resilience measures within sustainability assessment frameworks	Enviromental	28
Chow.W.K.vd.	Thermal stresses on window glasses upon heating	Fire Engineering	27
Chow.W.K.vd	Evacuation with smoke control for atria in green and sustainable buildings	Fire Engineering and Architecture	27
Bournas D.A.	Concurrent seismic and energy retrofitting of rc and masonry building envelopes using inorganic textile-based composites combined with insulation materials: a new concept	Material and Earthquake Engineering	26
An.W.vd.	Thermal and fire risk analysis of typical insulation material in a high elevation area: ınfluence of sidewalls, dimension and pressure	Fire Engineering, Architecture	26

3.5 Keyword Analysis

Keywords describe the focus of a particular article and give researchers an idea of the scope, purpose and methods of research (Su & Lee, 2010). There were 650 keywords in GBFS research, and with the limitation of using a word at least twice, 70 words in 11 clusters were encountered (Fig.9).

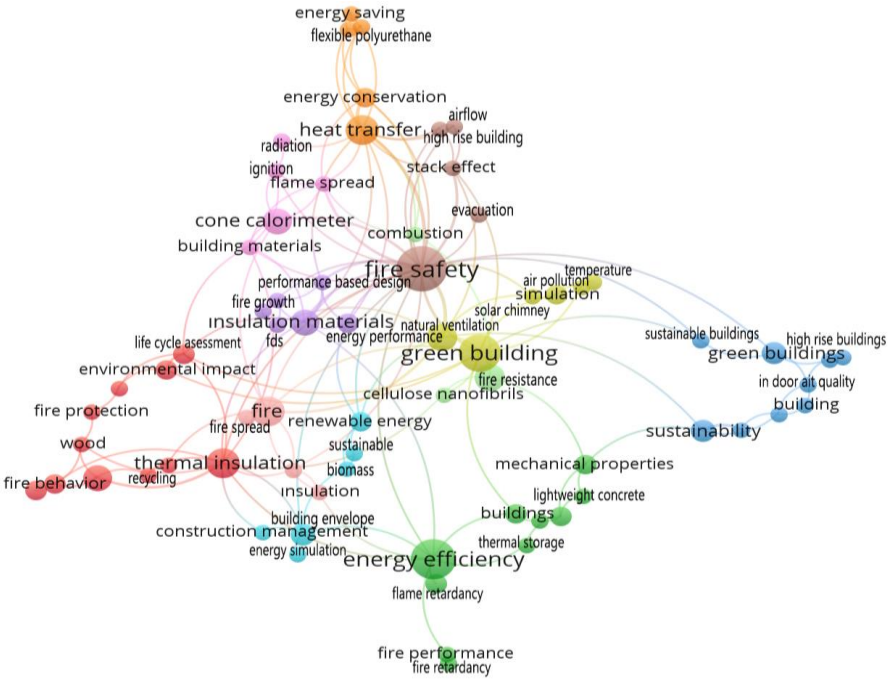

Figure 9. Network visualization of keywords

Fire safety is the most common keyword with 16 views in articles. Keywords such as stack effect, airflow, high rise building, which are in the same cluster as fire safety, give an idea about the impacts of natural air currents on fire safety. Keywords such as natural ventilation, air pollution, and tempeture in the same cluster as the other high-occurrence green building show that this cluster focuses on studies on indoor comfort levels in green buildings.

To expand the keywords determined by the author, the frequently used words and phrases in the titles, abstracts and keywords of the articles were examined. Accordingly, 176 words were viewed with the limitation of at least 5 occurrences out of a total of 6483 words in the title, abstract, and keywords and VOSviewer's classification of related words. By removing the words that will not be needed in the analysis such as end, europe, engineer, door, view, person, 118 words are mapped in Figure 10.

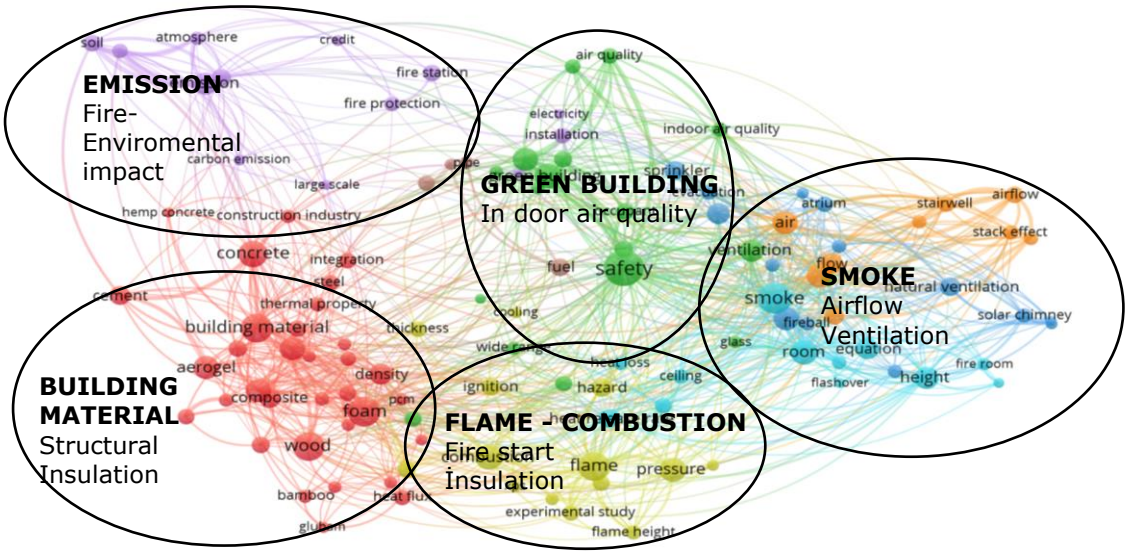

Figure 10. Network visualization of general keywords

Clusters showing the links of using together 118 words in general keyword search are listed in Table-4. Cluster analysis represents a set of very useful exploratory techniques that can be interpreted the problem and study areas of the articles. For example, the studies in the cluster, which is shown with red knots in Figure-10 and contains the highest number of words, examined structural elements (steel, wood, composite) and wood-based building materials (bamboo, laminate vb.) in the context of fire performance and energy efficiency. In order to have an idea about the research trend in the last few years, the keywords used in the years 2019-2021 were shown in red in Table 4. These studies included innovations in mechanical systems and building materials.

Table 4. Keyword cluster analysis

Cluster	*Keywords*	*Field*
1	Foam, wood, building material, concrete, aerogel, fire resistance, thermal conductivity, density, composite, cement, fire performance, mechanical property, timber, insulating material, cross laminated timber, heat flux, steel, energy efficient building, thermal property, bamboo, composite foam, cone calorimeter, elevated temperature, flame retardancy, phase change material, fire behaviour, glue laminated bamboo, hemp concrete	**Building material** Structural material Insulation material Wood containing material
2	Safety, green building, ventilation, exposure, occupant, air quality, flame retardant, health, indoor air quality, ventilation system, glass, stakeholder, water wall system	Building envelope element In door ventilation design
3	Simulation, sustainable building, natural ventilation, sprinkler atrium, evacuation, solar chimney, fireball, power, computational fluid dynamic, atria, tunnel, solar radiation	Building day light design,
4	Flame, combustion, pressure, hazard, ignition, polystyrene, experimental study, fire hazard, thickness, flame height mass loss rate, cooling, mechanical ventilation, xps	Insulation material Mechanical ventilation design
5	Emission, climate change, fire station, soil, installation, carbon, fire protection, atmosphere, carbon emission, credit, sustainable development, large scale	Enviromental impact evaluation
6	Smoke, room, height, equation, heat release rate, experimental result, ceiling, heat loss, smoke layer, fire room, natural ventilation shaft	Indoor smoke spread
7	Air, high rise building, flow, heat transfer, airflow, stairwell, stack effect, heated room, window	Indoor smoke spread High rise building
8	Fuel, environmental impact, pipe, optimum insulation thickness	Enviromental impact evaluation Insulation material

4. CONCLUSIONS

In this study, research trends and deficiencies were determined by analyzing the literature data on GBFS visually and numerically. As a result of keyword searches to find studies examining green buildings in the context of fire safety, only 213 articles were found on the research topic. Because of this reason, there is a need for research that deals with a fire safety design, which is extremely important for the continuity of sustainable built environments, together with green building designs. After the data was transferred to VOSviewer, scientific journal, country, productive author, qualified article, keyword and text keyword analyzes were carried out. The analyzes helped to establish the infrastructure of the research subject by hosting interdependent or independent data. The findings, evaluations, and recommendations obtained through bibliometric and correlation analyzes are summarized below:

- Construction and Buildings Materials, Energy and Buildings, Fire and Materials are the journals that contribute the most to the research field quantitatively. Correlation analysis showed that there is a strong relationship between the citation numbers of these journals and their annual citation potential.
- The USA and China are the countries that contribute the most to the research topic. Articles in the USA generally examine the energy efficiency, fire resistance and chemical properties of insulation materials. Articles in China cover numerical and

experimental analyzes of smoke propagation inside buildings. The contribution of W.K. Chow and C.L. Chow authors to studies in China is high.

- The highly cited articles generally cover the chemical properties of insulation materials, which are preferred for the level of thermal comfort in buildings, their contribution to energy efficiency and fire resistance. There are many studies in materials and chemical engineering sciences.
- Keyword analyzes, which give an idea about the fields of study and the methods used, show the scope of the researches. While the most preferred work area is insulation materials, there are also studies on structural elements and wood-based building elements. In addition, energy efficiency and environmental effects, natural and mechanical ventilation designs are also included in a limited number of research topics.

Research on GBFS basically covers the energy efficiency, thermal comfort level, fire resistance, and chemical properties of the material. The contribution of green building design stakeholders, architects, and related engineers to scientific studies is insufficient. Also, in green building designs, there is a need to develop solution strategies for fire safety in interior design, shell design, heating, and cooling system design, and develop integrated fire safety design approaches in green building designs.

As a result, research findings and results will guide future scientific research for academicians working on green building design and fire safety design. It will also be a thought-provoking analysis of the need to focus on fire safety for green building design stakeholders.

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