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Fire Resistance of Building Structures and Fire Protection Materials: Bibliometric Analysis

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Abstract: Scientometric analysis using the Scopus database and VosViewer program identified the critical directions of development of this or that field to identify promising technologies and to understand how these achievements affect the practice of design and construction. According to the analytics, the average number of articles per year on the topic of structural fire resistance and flame retardants increased by 18% compared to the previous period, and according to preliminary data, the trend will continue in 2024. Among the most cited papers, studies on composite materials and polymers dominate. Among the most productive researchers in the field of flame retardancy of materials are Hu, Yuan (54 papers), Wang, WeiYong (47 papers), and Jiang, Jian (39 papers). According to Scopus, research papers on this topic have been published in 2175 sources. The leading journal in terms of the number of published papers is Fire Safety with 250 publications, but journals such as *Fire* and *Buildings* of MDPI Publishing are strongly increasing the pace. Chinese researchers are actively studying various aspects of fire resistance of materials and have published 40% of all papers. Keyword analysis revealed a lack of papers on calculation of fire resistance of structures with fire protection means, calculation of fire resistance of composite structures, and 3D-printed structures compared to the number of articles on the reliability (strength calculation) of building structures.

Keywords: scientometrics; bibliometric analysis; buildings; constructions; fire resistance; fire protection; VosViewer

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Academic Editors: Longxing Yu, Shengzhong Zhao and Fang Liu

Received: 23 November 2024
Revised: 22 December 2024
Accepted: 26 December 2024
Published: 30 December 2024

Citation: Gravit, M.V.; Kotlyarskaya, I.L.; Zybina, O.A.; Korolchenko, D.A.; Nuguzhinov, Z.S. Fire Resistance of Building Structures and Fire Protection Materials: Bibliometric Analysis. *Fire* **2025**, *8*, 10. https://doi.org/10.3390/fire8010010

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1. Introduction

Fire is an uncontrolled combustion process that can cause material damage and create a danger to human health and life, the environment, and the interests of society and the state. According to an analysis in the article [1], an average of 3.7 million fires occurred annually between 1993 and 2021.

According to the World Fire Statistics Center's 2023 final report [2], 30% of all fires occur in buildings [3] (20.5% in residences), 7.7% in vehicles, and the remaining fires occur in forests [4] or landfills (landfill fires). The main causes of fires in buildings are related to violations of the rules of operation of electrical equipment, gas equipment, and heat-generating units and installations. In addition, fires can occur due to careless handling

of fire (e.g., smoking or children's mischief), spontaneous combustion of materials, and deliberate arson. Fires occur in both new buildings and historical buildings; for example, the National Museum of Brazil (Rio de Janeiro, Brazil) [5,6], built in 1818, broke out on 2 September 2018.

The fire engulfed three floors of the building. No people were injured, but the building and its rich collection suffered irreparable damage. In 2018, flames engulfed the School of Art in Glasgow, Scotland [7,8]. This building had already burned in 2014. On 15 April 2019, there was a fire in the Cathedral of Notre Dame de Paris (Paris, France) [9,10]. Due to the fire, the spire of the cathedral and one-third of the roof, installed in the 19th century, collapsed.

Twenty-first-century buildings are characterized by varied geometry, large volumes of rooms, heights, open spaces, dynamic and glass facades, etc., which poses additional fire safety challenges [11]. The last decade has also seen a trend toward the construction of underground shopping centers, warehouses, subway lobbies, and parking lots. In such facilities, the evacuation process in case of fire becomes even more complex and challenging. Thus, bold and unique volume-planning solutions pose complex fire safety challenges for engineers and designers. In this regard, the design of buildings must include all necessary fire prevention measures, as well as the ability to effectively control the development and consequences of accidental or deliberate fires. Compliance with fire safety standards in buildings is achieved through the use of active and passive fire protection systems [12].

The safety and comfort of people in buildings directly depend on the ability of building structures to retain their load-bearing and/or enclosing functions under fire conditions. Fire can bring irreparable consequences to the property and health of people both inside and in the vicinity of a burning building. Fire resistance of building structures is ensured through their structural solutions, the use of appropriate building materials, and the use of fire protection means.

Over the past five years, advances in fire safety and fire resistance of structures have been diverse and characterized by varying degrees of sophistication. The article [13] discusses nanotechnology for the production of fire-resistant building materials and structures. For example, silica-based aerogel nanomaterials can be used in translucent windows or vacuum insulation panels, being a highly efficient thermal insulator and fire-resistant barrier [14,15]. The work [16] studies nanosilica, which, when used in translucent structures, can provide a high level of fire protection by creating a blowing layer between two plates of glass.

The use of intumescent agents is becoming increasingly popular in fireproofing building structures due to their advantages such as lightness, environmental friendliness, and odorlessness. Intumescent materials are special coatings that undergo a radical change when exposed to high temperatures, transforming into a dense, porous layer of charred material that provides passive protection against fire by delaying ignition and reducing the rate of combustion [17–19]. They are actively used in lightweight fire-resistant panels [20] and transformable fire partitions [21].

A new engineering wood material, glued laminated timber, has been actively used in construction [22–24]. Buildings made of it are considered high-quality, durable, and fireproof. Cross-laminated timber (CLT) construction is used to create apartments, dormitories, hotels, libraries, schools, offices, commercial buildings, factories, and buildings for multifunctional purposes [25,26].

Given the rapid development of technologies in the field of fire resistance of building structures and means of protection against fire, there is a need to update scientific data and create an analysis with a quantitative assessment of the growth rate of research on this topic.

Scientometrics deals with the quantitative study of science. Scientometrics studies patterns, trends, and potential directions for the development of the field on the basis of statistical processing of an array of articles on the selected topic [27]. It relies on metadata and references. With the development of software and mathematical methods for processing large volumes of data, researchers have the opportunity to form compact, visual, and informative images (network graphs, landscapes, conceptual, cluster, heat maps, etc.) based on a huge number of documents [28,29]). Such visualization of information is necessary for effective assessment and identification of analysis of strengths, current status, and gaps in research.

Scientometric studies are widely used in various scientific fields: education [30], sustainable production [31], construction [32,33], climatology [34,35], medicine [36,37], and marketing [38]. In the field of fire safety, scientometric studies are also taken into account, for example, by the authors of the work [39], who take into account the fire risk—researchers who study the impact of forest fires on the environment. The issues of evacuation of people from a building in case of fire were considered by scientists [40]. In the article [41], a bibliographic analysis is made, according to the authors "All available technologies and strategies for fire prevention and mitigation", but exactly the issues of fire resistance and fire protection are practically not covered.

Innovative 3D-printed structures have not been investigated for fire resistance, and in [42], the authors argue that polymer-based materials lack the fire resistance required for many spaces and buildings. More research in advanced materials and additive manufacturing is needed to improve structural strength, fire resistance, and cost-effectiveness. The paper [43] concludes that all investigated materials belong to class A1fl (regarding combustibility) according to EN ISO 1182:2020 standard, but the issues of fire resistance of structures have not been investigated.

The aim of this paper is to analyze the publications from the Scopus scientific database since 2019 that present research on structural fire resistance and fire protection, to identify trends and authors with the maximum number of publications and research centers and to explore the interrelationships between different research groups and institutes. The advances presented in this paper can provide a detailed and comprehensive understanding of the current state of research in structural fire resistance—not just research on fire safety, risk reduction, and building safety, but specifically on fire resistance and fire protection—as means to increase the required fire resistance improvement limits of building structures and products (ducts, cable structures, and equipment).

2. Data Collection Methods

In this study, Scopus (database, launched by the academic publisher Elsevier as a competitor to the older Web of Science in 2004) was used for bibliometric analysis to provide comprehensive, scientifically rigorous, and reliable data. The Scopus scientific database contains abstracts and citation information of peer-reviewed scientific literature with built-in tools for tracking, analyzing, and visualizing data. It brings together more than 78 million records obtained directly from publishers and updated regularly. It is one of the most important citation indices, which was developed by Elsevier in 2004 [44,45].

The study used VOSviewer version 1.6.20. The authors searched for publications on 23 September 2024, and in the interval from 1 January 2019 to 23 September 2024 (the last five years). The following keywords were used: fire resistance, Fire protection, Fireproofing, Passive Fire Protection (PFP), Intumescent coatings, Fire retardant compositions, and Fire-resistance rating. The search selected 10,235 documents for analysis. These data were saved in text format for ease of import and subsequent literature analysis.

The VOSviewer software [46] was used for visualization, clustering, and qualitative analysis of networks based on publication metadata. VOSviewer is a universal tool for bibliometric scientific mapping (scientific mapping). It provides the ability to spatially represent how disciplines, scientific fields, authors, as well as author groups, organizations, etc., reinforce each other [47]. Bibliometric maps were built based on the following parameters (units of analysis): authors write about fire resistance of building structures and fire protection; organizations involved in research on fire resistance of building structures and fire protection (affiliated authors publish); countries involved in research on fire resistance of building structures and fire protection (territorial affiliation of organizations); keywords of authors presented in publications on fire resistance of building structures and fire protection.

3. Results and Discussion

3.1. Publication Analysis

A total of 10,235 documents were analyzed. Figure 1 shows the distribution of scientific literature from the beginning of 2019 to 23 September 2024, by the number of publications per year in the field of fire resistance of building structures and fire protection equipment. The graph was compiled using Scopus tools for bibliometric analysis.

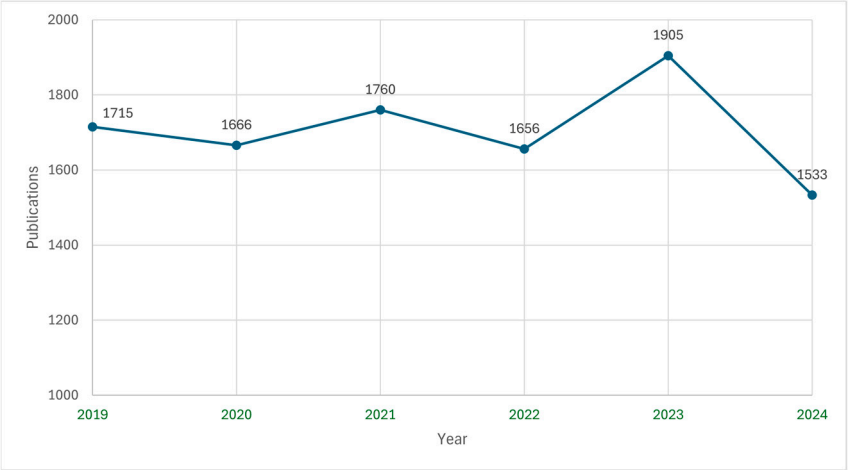

Figure 1. Number of publications for each year from 2019 to 23 September 2024.

From the graph in Figure 1, it can be noted that the number of publications annually exceeded 1600, and in 2019–2022, the annual number of publications was in the range of 1650–1750, and in 2023, there was a significant surge in scientific publications, which is also explained by the increase in the number of specialized conferences and the influence of traditional conferences (for example, conferences such as the International Conference on Structures in Fire, SFPE Engineering Solutions Symposium, the Fire Safety Event, and others). Conferences are held in a hybrid format, which allows delegates to attend in person or remotely. It is worth noting that the hybrid format, which became widespread during the coronavirus period, also led to an increase in the number of conference participants, including due to the logistical ease of participation.

The number of publications in 2023 on the selected topic is 1915 (an increase of 18%). More than 1000 publications were published in the first half of 2024, so it can be assumed that by the end of 2024, the number of works will correspond to the achievement of 2023. This trend indicates an increase in attention to research in the field of fire resistance of structures. Table 1 shows the 10 most popular scientific publications with the maximum number of citations. The articles are selected by keywords according to Section 2 without specifying the scope of study.

Table 1. Top 10 most cited articles on the research topic.

No.	Title	Author	Journal and Publisher	Year	Citation Frequency
1	A review of lithium ion battery failure mechanisms and fire prevention strategies [48]	Wang Q., Mao B., Stoliarov S.I., Sun J.	Progress in Energy and Combustion Science, Elsevier	2019	1000
2	Fiber-reinforced polymer composites: Manufacturing, properties, and applications [49]	Rajak D.K., Pagar D.D., Menezes P.L., Linul E.	Polymers, Multidisciplinary Digital Publishing Institute (MDPI)	2019	979
3	A review of natural fiber composites: properties, modification and processing techniques, characterization, applications [50]	Gholampour A., Ozbakkaloglu T.	Journal of Materials Science, Springer Nature	2020	583
4	Recent progress of reinforcement materials: A comprehensive overview of composite materials [51]	Rajak D.K., Pagar D.D., Kumar R., Pruncu C.I.	Journal of Materials Research and Technology, Elsevier	2019	550
5	Polymer composite materials: A comprehensive review [52]	Hsissou R., Seghiri R., Benzekri Z., Hilali M., Rafik M., Elharfi A.	Composite Structures, Elsevier	2021	524
6	Amazonia as a carbon source linked to deforestation and climate change [53]	Gatti L.V., Basso L.S., Miller J.B., Gloor M., Gatti Domingues L., Cassol H.L.G., Tejada G., Aragão L.E.O.C., Nobre C., Peters W., Marani L., Arai E., Sanches A.H., Corrêa S.M., Anderson L., Von Randow C., Correia C.S.C., Crispim S.P., Neves R.A.L.	Nature, Springer Nature	2021	440
7	Durability of ultra-high performance concrete—A review [54]	Li J., Wu Z., Shi C., Yuan Q., Zhang Z.	Construction and Building Materials, Elsevier	2020	344
8	Physical and functional characteristics of foam concrete: A review [55]	Raj A., Sathyan D., Mini K.M.	Construction and Building Materials, Elsevier	2019	334
9	Interface decoration of exfoliated MXene ultra-thin nanosheets for fire and smoke suppressions of thermoplastic polyurethane elastomer [56]	Yu B., Tawiah B., Wang L.-Q., Yin Yuen A.C., Zhang Z.-C., Shen L.-L., Lin B., Fei B., Yang W., Li A., Zhu S.-E., Hu E.-Z., Lu H.-D., Yeoh G.H.	Journal of Hazardous Materials, Elsevier	2019	329
10	Construction of multifunctional boron nitride nanosheet towards reducing toxic volatiles (CO and HCN) generation and fire hazard of thermoplastic polyurethane [57]	Wang J., Zhang D., Zhang Y., Cai W., Yao C., Hu Y., Hu W.	Journal of Hazardous Materials, Elsevier	2019	302

The most cited work is by Wang Qu, Mao B., Stolyarov S.I., and Sun Jian [48], which discusses potential measures to prevent fires in lithium-ion batteries. A large number of works from Table 1 are devoted to composite materials, polymers, and their properties, including their ability to resist fire. Two works are devoted to innovative ultra-thin

nanosheets that have a barrier effect on the spread of fire. When testing these structures in a cone calorimeter, a significant decrease in the peak heat release rate, peak smoke generation rate, peak CO, and CO_2 formation rate (49.7% and 51.7%) was recorded [56]. Analysis of different countries.

According to the scientific database Scopus, scientists from 135 countries studied fire resistance of building structures and fire protection equipment between 1 January 2019 and 23 September 2024. Figure 2 shows a graph showing the leading countries that have written scientific papers on the selected topic.

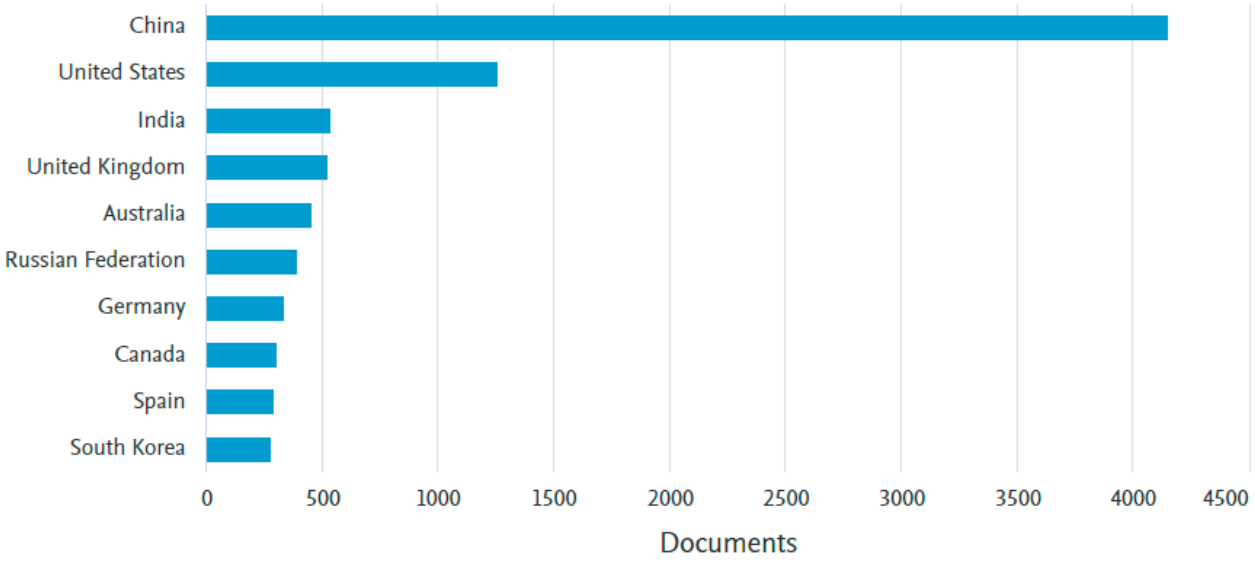

Figure 2. Top 10 countries by number of publications in the field of fire resistance of building structures and fire protection means.

China ranks first in the research field in terms of the number of publications by country. China published 4148 articles, accounting for 40% of all publications, followed by the United States with 1254 articles. Together, these two countries published more than half of all scientific articles on the research topic. The country partnership map illustrates the frequency of collaboration between different countries (Figure 3). Scientists from China, the United States, India, the Russian Federation, and Germany participate in international scientific research most frequently. In terms of collaboration, China and the United States not only collaborate with many countries but also have the strongest collaborative relationships with each other. For example, researchers from China and the United States jointly conducted an extensive experimental study on the effect of elevated temperature on the thermal properties and mechanical properties of fly ash-based geopolymer paste [58]. Scientists from India and Singapore also jointly studied the fire retardancy of geopolymers [59]. Researchers from Germany and Switzerland in their work [60] considered struvite mineralization as an environmentally friendly solution for obtaining fire-retardant wood. Each joint study of a particular scientific aspect leads to the emergence of new knowledge.

Figure 3 also provides a timeline that helps to understand in which year a particular country was more active in writing scientific papers on the fire resistance of building structures and fire protection means. For example, scientists from Cyprus began studying this topic quite recently (2023–present) [61–63]. Also, most of the papers of Argentine scientists were written at the beginning of the studied period (2019–2020) [64,65].

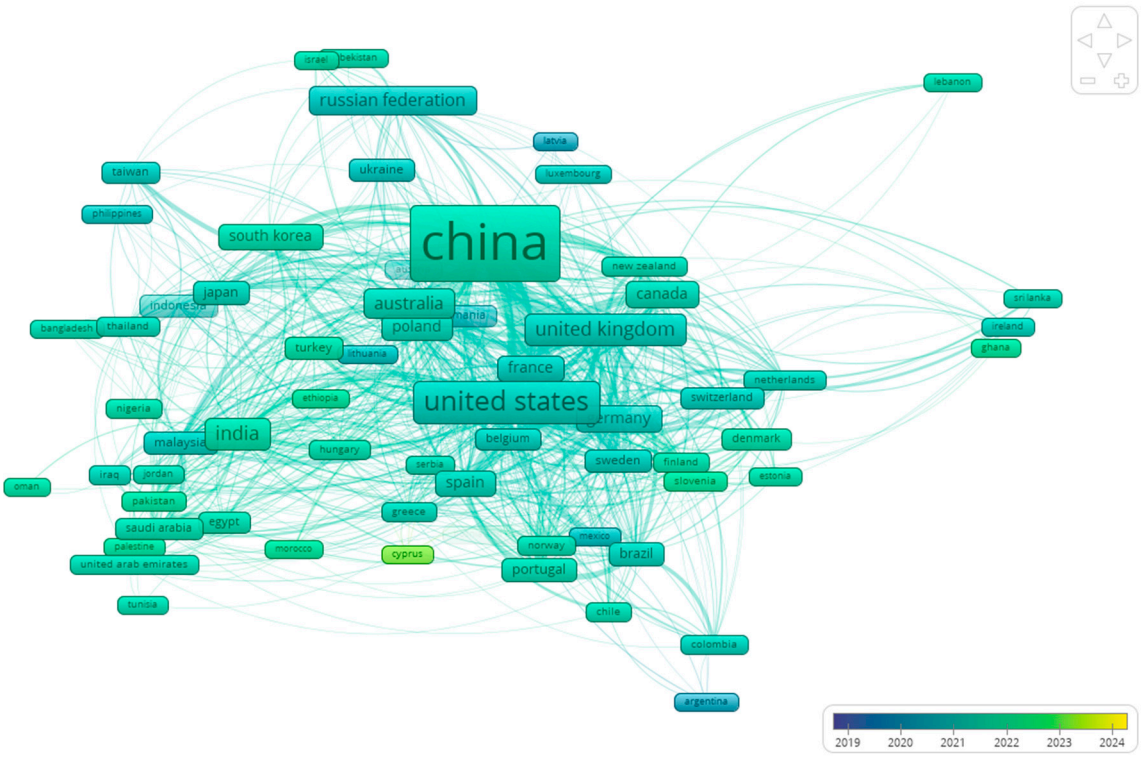

Figure 3. Scientific map of the partnership of countries.

3.2. Analysis by Different Authors

The significant annual increase in scientific papers on the study of fire resistance of building structures and fire protection indicates a high level of activity of scientists in this area of research. According to the graph in Figure 4, obtained using Scopus analysis tools, the leader in the number of publications is Hu Yuan. According to Scopus data, from 2019 to 23 September 2024, he wrote 54 articles on the selected topic. Wang WeiYong, who has 47 works, follows him. Jiang Jian occupies third place in the number of articles, with 39 works. In terms of the number of articles, the author closest to this one is Mahendran Mahen, who has written 38 articles.

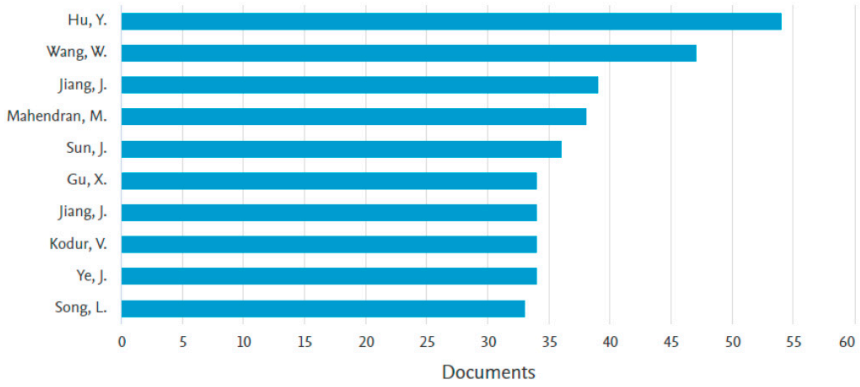

Figure 4. Top 10 authors by number of publications in the field of fire resistance of building structures and fire protection means.

Leading authors working in the field of fire resistance of building structures and fire protection products have different specifics and directions. Hu, Yuan (University of Science and Technology of China, Hefei, Anhui) mainly deals with flame-retardant polymers [66], and he is particularly interested in suppressing the smoke toxicity of polymers during combustion [67–69]. Wang, WeiYong (Chongqing University, Chongqing, China) specializes

in studying the properties of high-strength steels (e.g., Q960 [70], Q460 [71], Q355 [72]) and steel members at elevated temperatures [73,74]. Jiang, Jian (China University of Mining and Technology, Xuzhou, China) studies the destruction of steel structures after a fire [75,76] and actively studies the flame-retardant properties of superabsorbent polymers [77,78], as well as the post-fire behavior of steel structure joints [79–81]. Mahendran, Mahen (Queensland University of Technology, Brisbane, Australia) actively studies the behavior of lightweight, thin-walled steel structures under thermal influence [82–84]. Sun, Jun (Beijing University of Chemical Technology, Beijing, China) and Gu, Xiaoyu (Beijing University of Chemical Technology, Beijing, China) are researching the reduction of fire hazards in polymers [85,86] and fire-resistant textiles [87,88]. Jiang, Juncheng (Nanjing Tech University, China) studies intumescent flame-retardant coatings [89–91] and the application of nanomaterials for fire protection including lithium-ion batteries. [92,93]. Kodur, Venkatesh (Michigan State University, East Lansing, MI, USA) investigates high-stress concrete and fiber concretes under elevated temperatures and, in principle, cement and concrete research [94,95]. Ye, Jihong (China University of Mining and Technology, Xuzhou, China) researches cold-formed structures [96], tunnelling [97], and other structures. Song, Lei (University of Science and Technology of China, Hefei, China) specializes in chemical additives for fire retardants and building materials [98].

It is important to note that these scientists not only publish their research but also actively interact with colleagues by participating in conferences and seminars and publishing their research results in reputable scientific journals. The interaction of authors and different academic communities can reflect the preservation, accumulation, and transfer of knowledge in a scientific field. Collaboration between researchers contributes to the development of a discipline and increases scientific productivity. Mapping the authors of scientific publications in the study area reveals numerous collaborative relationships (Figure 5). Of the 922 authors with five or more publications, 762 authors are involved in recurring collaborations.

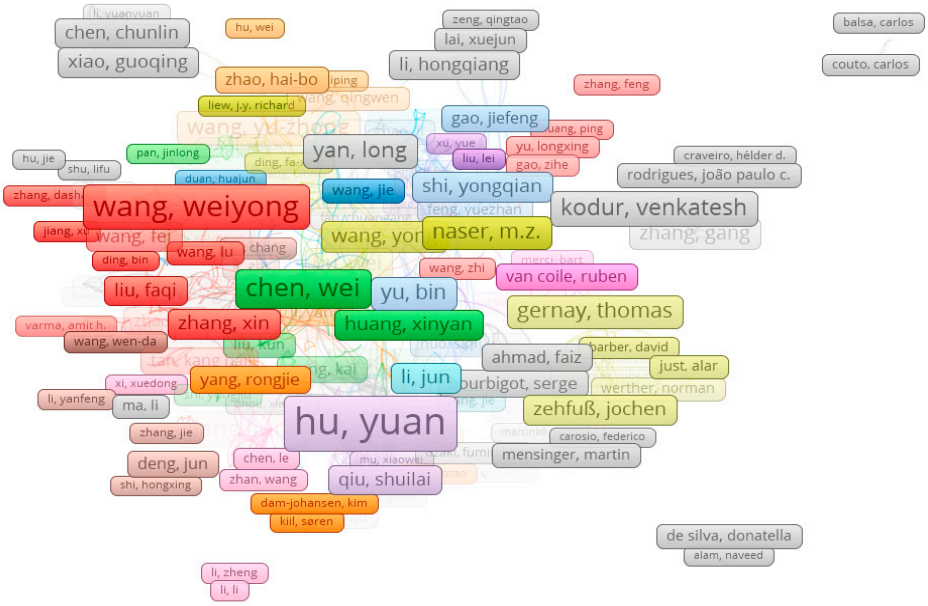

Figure 5. Scientific map of co-authorship from 30 clusters.

VosViewer generated 30 clusters by co-authorship, each consisting of at least five authors. Removing this restriction leads to 113 clusters, the composition of which can be represented by a single researcher. The cluster has its own color. The most active researchers in each cluster are highlighted in a larger font.

The cluster headed by Hu, Yuan published the largest number of documents—64 pcs. This cluster included 28 researchers. The association of authors that gave the second result in the number of published documents is the cluster with the leader Wang, WeiYong. The team of 54 researchers published 46 scientific papers. The scientific group headed by scientist Chen, Wei published a total of 37 documents. The third scientific group includes 47 scientists.

Mahendran Mahen, who published 38 documents, is absent from the scientific co-authorship map since, during the analyzed period, he collaborated with fewer than five other researchers. Accordingly, his cluster of co-authors was not taken into account in this distribution.

It follows from the previous point that Chinese researchers carried out more than 40% of scientific papers, therefore, the scientific map of authors (Figure 5) mainly presents the names of scientists from China. For a more detailed consideration of the remaining scientific connections, an additional map of scientific co-authorship was formed (Figure 6). This science map also has the limitation of connecting to more than five disabled researchers.

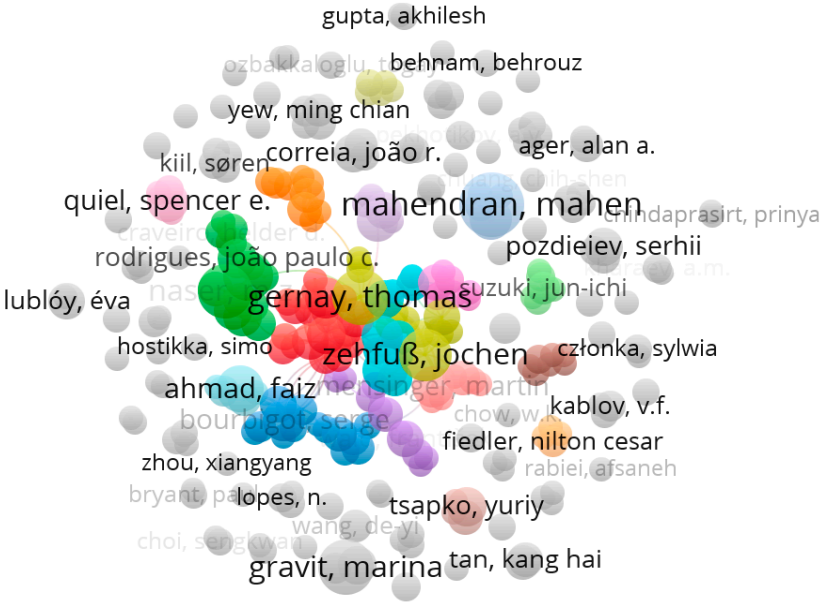

Figure 6. Scientific map of co-authorship of researchers (sample without Chinese researchers).

According to the scientific map (Figure 6), the most productive authors are Mahendran, Mahen from Australia, Gernay, Thomas from the USA, Zefuss, Jochen from Germany, Gravit, Marina from the Russian Federation, Joao Paulo C. Rodrigues (Portugal), and others. Prof. Mahen Mahendran mainly studies cold-formed steel structures and thin-walled structures. Gernay, Thomas is mainly engaged in research on the fire resistance of wooden, concrete, and light steel structures [99,100]. Zefus, Jochen is engaged in the thermal conductivity of concrete [101], gypsum plasterboards [102], etc. Gravit, Marina studies transformable fences [11,21] and thermal insulation coatings [103] under hydrocarbon fires. Joao Paulo C. Rodrigues studies the fire resistance of tunnels with reinforced concrete structures, steel structures, and thin-walled structures [104,105]. Andrea Lucherini explores indoor fires, different fire regimes, and fire protection products, including intumescent coatings [101]. If, for comparison, the authors are sorted only by articles with the keyword "fire resistance," then the number of authors, according to Scopus, is 3974 units. The VosViewer program sorted the authors and selected only those who wrote at least five articles; there were 66 such authors. The graph of the relation of these authors is presented in Figure 7.

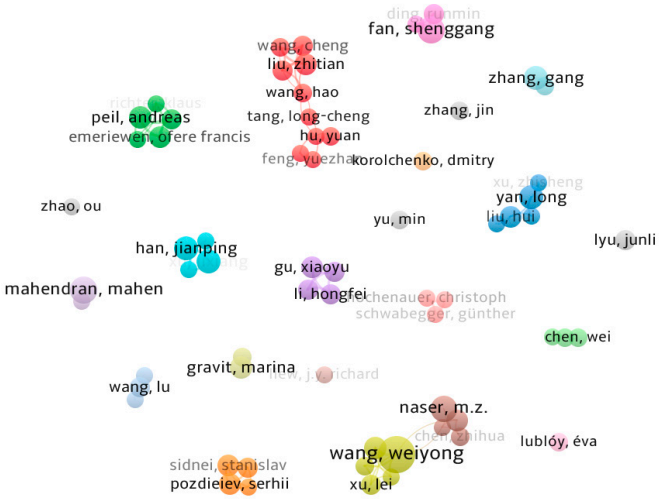

Figure 7. Scientific map of the relationship between authors for the keyword "Fire resistance".

3.3. The Journals

According to Scopus, research articles on the topic were published in 2175 sources. Table 2 presents the top 10 journals ranked by the number of publications on the topic, including journal category, CiteScore, highest percentile, and rank. These metrics are used to analyze the professional status and impact of journals in the field, providing researchers with references to the literature.

Table 2. Top 10 journals publishing articles on the research topic.

No.	Journal, Publisher	Number of Articles on the Research Topic	Journal Category	CiteScore 2023	Highest Percentile	Rank
1	Fire Safety Journal, Elsevier	250	Engineering (Building and Construction); Physics and Astronomy (General Physics and Astronomy); Engineering (Safety, Risk, Reliability and Quality); Chemistry (General Chemistry); Materials Science (General Materials Science)	5.7	79% 47/223 Building and Construction	Q1
2	Fire Technology, Springer Nature	226	Engineering (Safety, Risk, Reliability and Quality); Materials Science (General Materials Science)	6.6	82% 36/207 Safety, Risk, Reliability, and Quality	Q1
3	Construction and building materials, Elsevier	217	Engineering (Civil and Structural Engineering); Engineering (Building and Construction); Materials Science (General Materials Science)	13.8	96% 13/379 Civil and Structural Engineering	Q1
4	Engineering structures, Elsevier	166	Engineering (Civil and Structural Engineering)	10.2	92% 30/379 Civil and Structural Engineering	Q1

Table 2. *Cont.*

No.	Journal, Publisher	Number of Articles on the Research Topic	Journal Category	CiteScore 2023	Highest Percentile	Rank
5	Journal of Building Engineering, Elsevier	152	Engineering (Architecture); Engineering (Building and Construction); Engineering (Safety, Risk, Reliability and Quality); Engineering (Civil and Structural Engineering); Engineering (Mechanics of Materials)	10.0	99% 1/189 Architecture	Q1
6	Journal of constructional steel research, Elsevier	140	Engineering (Building and Construction); Engineering (Civil and Structural Engineering); Materials Science (Metals and Alloys); Engineering (Mechanics of Materials)	7.9	86% 30/223 Building and Construction	Q1
7	Materials, Multidisciplinary Digital Publishing Institute (MDPI)	135	Physics and Astronomy (Condensed Matter Physics); Materials Science (General Materials Science)	5.8	73% 114/434 Condensed Matter Physics	Q2
8	Polymers, Multidisciplinary Digital Publishing Institute (MDPI)	134	Materials Science (Polymers and Plastics); Chemistry (General Chemistry)	8.0	81% 77/408 General Chemistry	Q1
9	Fire and materials, John Wiley & Sons	129	Materials Science (Metals and Alloys); Chemistry (General Chemistry); Materials Science (Electronic, Optical and Magnetic Materials); Materials Science (Ceramics and Composites); Materials Science (Polymers and Plastics)	4.6	75% 44/176 Metals and Alloys	Q1
10	Thin-Walled Structures, Elsevier	98	Engineering (Mechanical Engineering); Engineering (Building and Construction); Engineering (Civil and Structural Engineering)	9.6	92% 52/672 Mechanical Engineering	Q1

These journals make significant contributions to the field and demonstrate strong academic engagement. As can be seen from Table 2, it is impossible to establish clear boundaries between "fire resistance" and "fire protection". Although it would seem that fire resistance is exclusively the field of construction and structures, and fire protection is the field of materials science, nevertheless, fire protection is needed to ensure fire resistance. Therefore, when a scientist deals with fire resistance, and it is not enough, it is necessary to choose the appropriate fire protection.

Notable among the journals is Fire and Buildings, published by the Multidisciplinary Digital Publishing Institute (MDPI), which has shown rapid growth in the number of published articles and citations over the past 5 years (Figures 8 and 9). Fire ranks second in Q2 in the following categories: Forestry, Safety Studies, Safety, Risk, Reliability and Quality,

Construction, Environmental Sciences (Miscellaneous), and Earth and Planetary Sciences (Miscellaneous) (CiteScore 2023 = 3.1). Buildings ranks first in Q1 in the Architecture category and second in Q2 in the Buildings and Structures and Civil and Structural Engineering categories (CiteScore 2023 = 3.4).

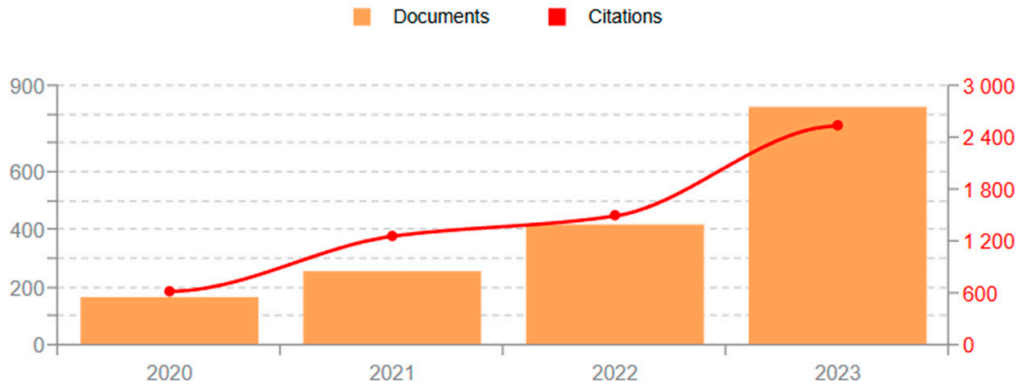

Figure 8. Number of articles and citations of the journal "Fire", MDPI.

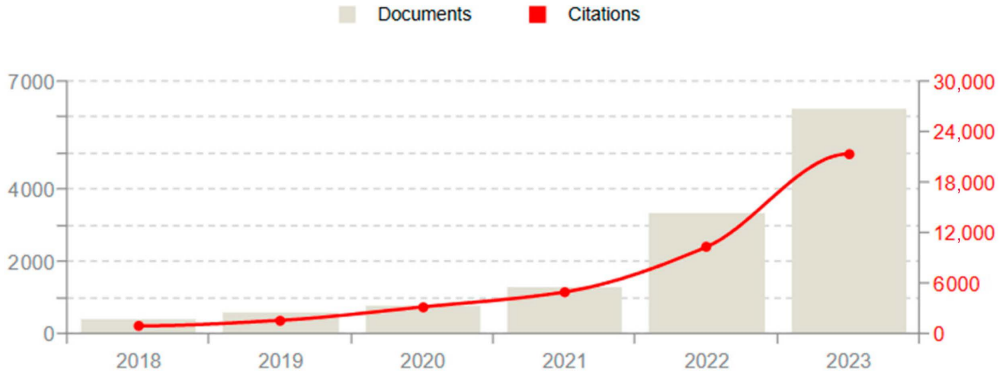

Figure 9. Number of articles and citations of the journal "Buildings", MDPI.

3.4. Keywords

Keywords or phrases reflect the main content of the study. The array of publications for scientometric analysis was selected based on keywords. According to the authors, the following keywords and phrases reflect the main content of studies on fire resistance of building structures and fire protection means: Fire resistance, Fire protection, Fire protection, Fire protection compounds, Passive fire protection (PFP), Intumescent coatings, Fire protection compounds, Fire resistance. In the presented scientometric study, keywords were extracted from 10,235 publications, and their number is 55,530. To create a scientometric map and further analysis, a limitation was set on the minimum number of occurrences of a word or phrase—at least 50 times. A total of 487 such words were found. Some keywords with the same meaning, such as "fire" and "fires", "fireproof" and "fire retardants", "fire-resistance" and "fire resistance", "forest fire" and "forest fires", "tree" and "trees", were combined. Common and trivial words were excluded from consideration, including "article", "human", "people", "property", "lakes", "safety", "water", "animal", "animals", "adult", "male", "female", "design", "mechanical", "accidents", "thermal", "air", "wind", "optimization", "review", "morphology", etc. Thus, a total of 463 keywords were selected for further study. The identified keywords are presented in Figure 10.

Figure 10. The scientific map of keywords.

The most frequently used keywords were: fire resistance (3980 mentions), fire protection (3473 mentions), fires (3447 mentions), fire extinguishers (1239 mentions), fire protection (1189 mentions), smoke (948 mentions), compressive stress (566 mentions), combustion (555 mentions), thermal insulation (536 mentions), reinforced concrete (523 mentions). Further analysis revealed five clusters of keywords (Table 3).

Table 3. The clusters of keywords.

Cluster	Title	Keywords with the Highest Connection Strength
1 (red)	Modeling the behavior of fire-resistant building structures during a fire	There are 179 words in total, of which the most frequently used are: fire resistance, temperature, finite element method, numerical methods, compressive strength, reinforced concrete, abaqus, etc.
2 (blue)	Fire-protective coatings and their chemical composition	There are 135 words in total, of which the most frequently used are: smoke, coatings, flame retardant, scanning electron microscopy, thermogravimetric analysis, nanoparticles, silica, aerogels, wood, etc.
3 (green)	The impact of fire on the environment, forest fires	There are 149 words in total, of which the most frequently used are: fire protection, fires, environmental protection, wildfire, forestry, climate change, controlled study, forest, ecosystem, animals, etc.

These clusters can be taken as differentiating thematic areas of scientific research on fire resistance of structures and fire protection means.

From Figure 10, it follows that among the array of selected publications, the most common terms are “fire resistance” and “fire protection”. Keyword analysis revealed a lack of papers on flame retardants, calculation of fire resistance of composite structures, and 3D-printed structures. The rating and position of these terms in the set of articles with

the keyword "building" is presented in Figure 11. Moreover, in this case, the terms "fire resistance" and "fire protection" are not lost against the background of other keywords, but "architectural design", "energy efficiency", "construction industry", "sustainable management", and "building blocks" are used more often.

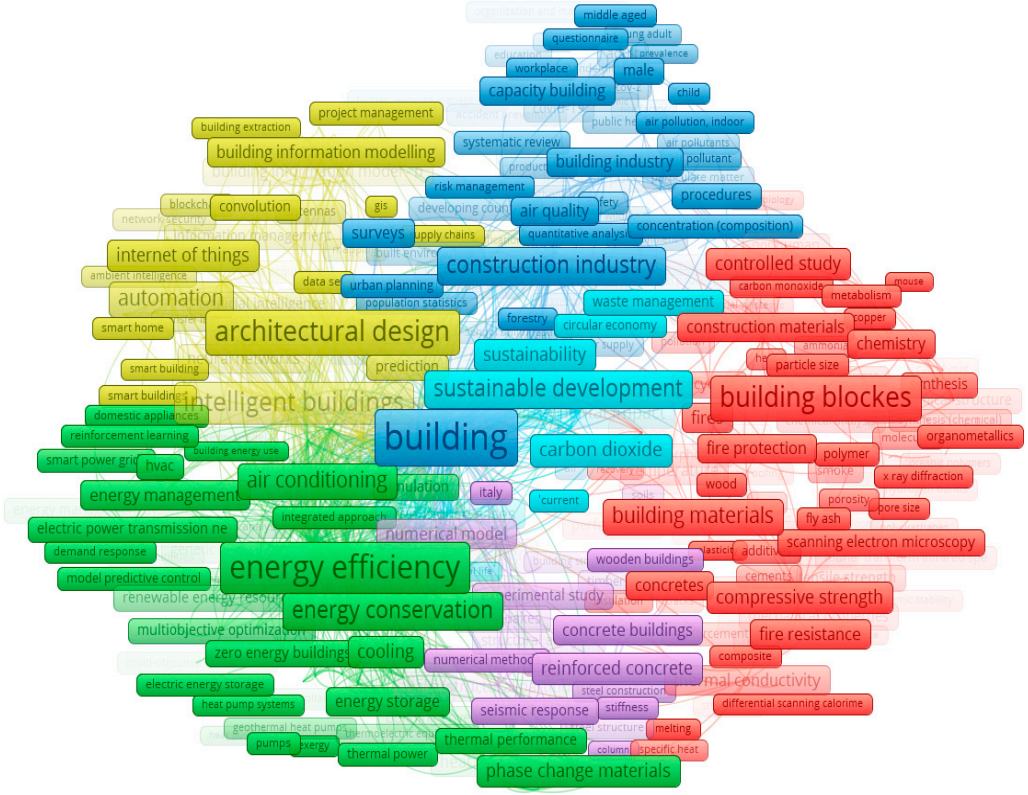

Figure 11. The scientific map of keywords for studying the position of the terms "fire resistance" and "fire protection" in the field of construction.

Figure 11 clearly shows that both the keywords "fire resistance" and "fire protection" represent parts of the huge cluster "building blockes".

3.5. Frontiers, Trends and Directions

In reviewing the literature, keywords and research directions of scientists dealing with fire resistance and, consequently, fire protection, the authors identified several main trends that represent certain research clusters. Obviously, the purpose of such works is to ensure regulatory requirements for structures and the application of appropriate fire protection, or vice versa, to assess the impact of real fires and evaluate the possibility of using structures and fire protection means, or its minimization, or justification of its absence. Table 4 presents the main research directions and their brief description.

Material science tasks on the application of fire protection means without reference to the subject area of construction, without practical significance of the final product (required fire resistance of a structure or reduction of fire hazard of a building material), but only with recommendations for further prospects of application are considered in the journals "Polymers", "Glass and Ceramics", "Materials", "Molecules", "Nanomaterials", and similar journals. The concept of "fire resistance" in such articles ends with the study of oxygen index and thermal analysis of polymers or compositions and is not related to structures and finished products.

Table 4. The main directions of research in the field of fire resistance and fire protection.

No	Subject of the Study	Summary of the Aims and Objectives of the Study	Methods of Defense
1.	Equipment and transportation with lithium-ion batteries	Inspection of transportation facilities and structures of construction sites of parking lots. Protection of equipment from rapid fire.	Active systems and passive fire protection in the form of covers, hoods, blankets made of ceramic fabrics, basalt fibers, and mineral wool.
2.	Wooden structures (including CLT and LVL)	Mechanical tests, fire resistance tests	Various types of impregnations, paints, gypsum board, etc.
3.	Structures of reinforced concrete	Investigations of concretes with different aggregates fiber concretes (metal and polypropylene fibers)	Fire resistance study. Fire protection is rarely used for reinforced concrete (if the functionality of the building is changed).
4.	Polymer composite structures	Mechanical tests, fire resistance tests	Surface fire protection (as for steel) and introduction of flame retardants inside the composite matrix.
5.	3D printing structures (additive technologies)	Mechanical tests, fire resistance tests	Surface fire protection (as for steel) and introduction of flame retardants inside the 3D matrix.
6.	Lightweight steel structures	Mechanical tests, fire resistance tests	Intumescent fire protection in the form of basalt fiber meshes and rolls.
7.	Glass structures	Mechanical tests, fire resistance tests. Investigations of gel-fill for flame retardant glasses.	Use of active defense; passive defense is not used.
8.	Calculation of fire risks and calculation of fire resistance and therefore the application of fire protection	Site fire scenarios and the impact of a real fire on structures are defined.	CFD-modeling is used to identify locations with fireproofing and where it may not be applied.
9.	Cable products, cable ducts and vents	Fire resistance tests	Non-combustible materials (mineral wool, basalt, cement boards, etc.).
10.	Filling expansion joints and holes in structures	Fire resistance tests	Use and development of fire-resistant cords, cushions, doors, gates, hatches, curtains, fire plugs.
11.	Effects of structural fire protection products on humans and the environment	Investigation of gas formation and toxicity of products during fire tests	In most cases, flame-retardant products made of non-combustible materials are used, while combustible ones are tested for fire exposure according to various parameters.
12.	Exterior walls, facades, and other enclosing structures	Mechanical tests, fire resistance tests flame spread tests, flammability tests, etc.	The wide range of structural and material combinations and modeling are used to predict fire hazard reduction.
13.	All types of structures under different temperature effects. Field simulation modeling (CFD) for an indoor fire.	Investigation of structures under different fire regime impacting structures (hydrocarbon and jet combustion, smoldering fire regime, cryogenic effects, arctic and other climates, indoor fires).	Special development of fireproofing materials for special (non-standard) fire regimes. Research of intumescent compositions, including smoldering mode.
14.	Numerical modeling of the behavior of structures with fire protection.	Fire simulation and model building in programs using the finite element method. Predicting the behavior of structures.	All types of structures are used, and the thermal conductivity and heat capacity of fire-retardant materials, including intumescent formulations, are investigated.

4. Conclusions

Scientometrics conducts the study of science by quantitative methods and studies the evolution of science through multiple measurements and statistical processing of scientific information (number of scientific articles published in a given period of time, citations, etc.).

With the help of the Scopus database and VosViewer program, a scientometric study of countries, scientists, and research areas in the field of fire resistance of structures and fire retardants was carried out. The overall objective of this study was to identify the results of research on fire resistance of structures and buildings. The authors identified the names and array of researchers in this field based on 10,235 publications from 2019 to 23 September 2024.

As a result of the study, the following conclusions can be drawn:

(1) The research frontrunners are authors presenting research on composite materials, fire protection of lithium-ion batteries, and fire protection of structures in various types of fire. Many articles are devoted to geopolymers, while it is found that 3D-printed structures have been little investigated for fire resistance.

(2) The scientometric analysis identified countries and leaders in terms of number of publications. According to Scopus, from 2019 to 23 September 2024, the top three are Chinese scientists: Hu Yuan, Wang WeiYong, and Jiang Jian. China published 4148 papers, accounting for 40% of all publications.

(3) According to Scopus, scientific papers on this topic have been published in 2175 sources. The journal that published the largest number of papers on the studied parameters (250 pieces) is the Fire Safety Journal. Journals such as Fire and Buildings show a rapid increase in publications and are realistically projected to achieve a high ranking in the coming year.

(4) It was found that there was a significant spike in scientific publications for the main keywords in 2023: "fire resistance" and "fire protection" (the average number of articles per year increased by 18%). According to preliminary data, in 2024 the number of publications will not be less than in 2023.

The authors predict that the problems of fire resistance of structures will become even more relevant, and more and more scientists will be interested in research in this area.

Author Contributions: Conceptualization, M.V.G.; methodology, M.V.G.; software, I.L.K.; investigation, O.A.Z.; resources, Z.S.N.; data curation, D.A.K.; writing—original draft preparation, I.L.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Science and Higher Education of the Russian Federation within the framework of the state assignment No. 075-03-2022-010 dated 14 January 2022 and No. 075-01568-23-04 dated 28 March 2023 (Additional agreement 075-03-2022-010/10 dated 9 November 2022, Additional agreement 075-03-2023-004/4 dated 22 May 2023, Additional agreement 075-03-2024-004/1 dated 5 February 2024), FSEG-2022-0010 (accessed on 23 November 2024).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors express their deep gratitude to the Scientific and Technological Complex "Digital Engineering in Civil Engineering" (St. Petersburg, Russia) and personally to N.I. Vatin for assistance and analysis of materials. The authors also apologize if the study did not mention any authors on the topic.

Conflicts of Interest: The authors declare no conflicts of interest.

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