Review Article

Wei Zheng, Muhammad Nasir Amin*, Kaffayatullah Khan, Muhammad Sufian*, and Ahmed Farouk Deifalla

A scientometric review of the literature on the incorporation of steel fibers in ultra-high-performance concrete with research mapping knowledge

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Abstract: In the construction industry, the incorporation of steel fibers in ultra-high-performance concrete (UHPC) is vital for improving its mechanical characteristics. In order to identify the essential factors of UHPC, the literature on the effect of steel fibers on UHPC is reviewed using scientometric methods in this work. The review contains complex processes like knowledge mapping, co-occurrence, and co-citation. In order to analyze the bibliographic data on the impact of steel fibers on UHPC, this study makes use of contemporary methodologies for data processing, mining, analysis, presentation, and visualization. The aim is to provide direction for further research in this area by summarizing the literature. In order to achieve this goal, data from the Scopus database, including publication sources, top authors, keywords, significant publications, and nations contributing the most to the subject, are retrieved and examined. According to the scientometric analysis, the most frequently used keyword is “steel fibers,” “Construction and Building Materials” is the most popular publication source in terms of citations and articles, and China is the top-ranking nation in the industry. Academic scholars can gain from this study’s graphical and quantitative portrayal of the contributing researchers and nations by making it easier to share concepts and form collaborative initiatives. This study also shows that steel fibers can improve the mechanical properties of UHPC but their widespread manufacturing and use are dependent on factors including the fiber content and geometry.

Keywords: steel fibers, ultra-high-performance concrete, mechanical properties, fiber, scientometric analysis

1 Introduction

One of the most basic and commonly used building materials worldwide is concrete [1–3]. However, because of concrete’s inherent characteristics, it has some drawbacks, including poorer resistance against tensile stresses, brittle nature, decreased strain capacity, and less effective resistance to the development and progression of cracks [4–6]. To address these problems, the incorporation of synthetic fibers [7–9], metallic/steel fibers [10,11], natural fibers [12–15], mineral fibers [16–19], *etc.*, in concrete is usually made [20–22] to improve its toughness [23,24]. Figure 1 depicts the broader classification of all the fibers [25]. Ultra-high performance concrete (UHPC) is a solution to the growing demand for strong, long-lasting concrete, which was developed in the 1990s, has remarkable mechanical qualities and an extremely dense microstructure [26].

Higher cement content, superplasticizers (SPs), fibers, silica fume, and other supplementary cementitious materials are all included in the more advanced type of fiber-reinforced concrete known as UHPC. UHPC’s design aims to pack solid materials densely by keeping the water content (w/c) below 0.2 [27]. Because of these characteristics, UHPC has a higher compressive strength of more than 150 MPa [28,29],

*** Corresponding author: Muhammad Nasir Amin**, Department of Civil and Environmental Engineering, College of Engineering, King Faisal University, Al-Ahsa 31982, Saudi Arabia, e-mail: mgadir@kfu.edu.sa
*** Corresponding author: Muhammad Sufian,** Department of Civil Engineering, Southeast University, Nanjing 211189, China, e-mail: drsufian.seu@gmail.com
Wei Zheng: Shanghai Pudong New Area Highway Construction Development Co., Ltd., Shanghai 200000, China
Kaffayatullah Khan: Department of Civil and Environmental Engineering, College of Engineering, King Faisal University, Al-Ahsa 31982, Saudi Arabia
Ahmed Farouk Deifalla: Structural Engineering and Construction Management Department, Future University in Egypt, 11835, New Cairo, Egypt

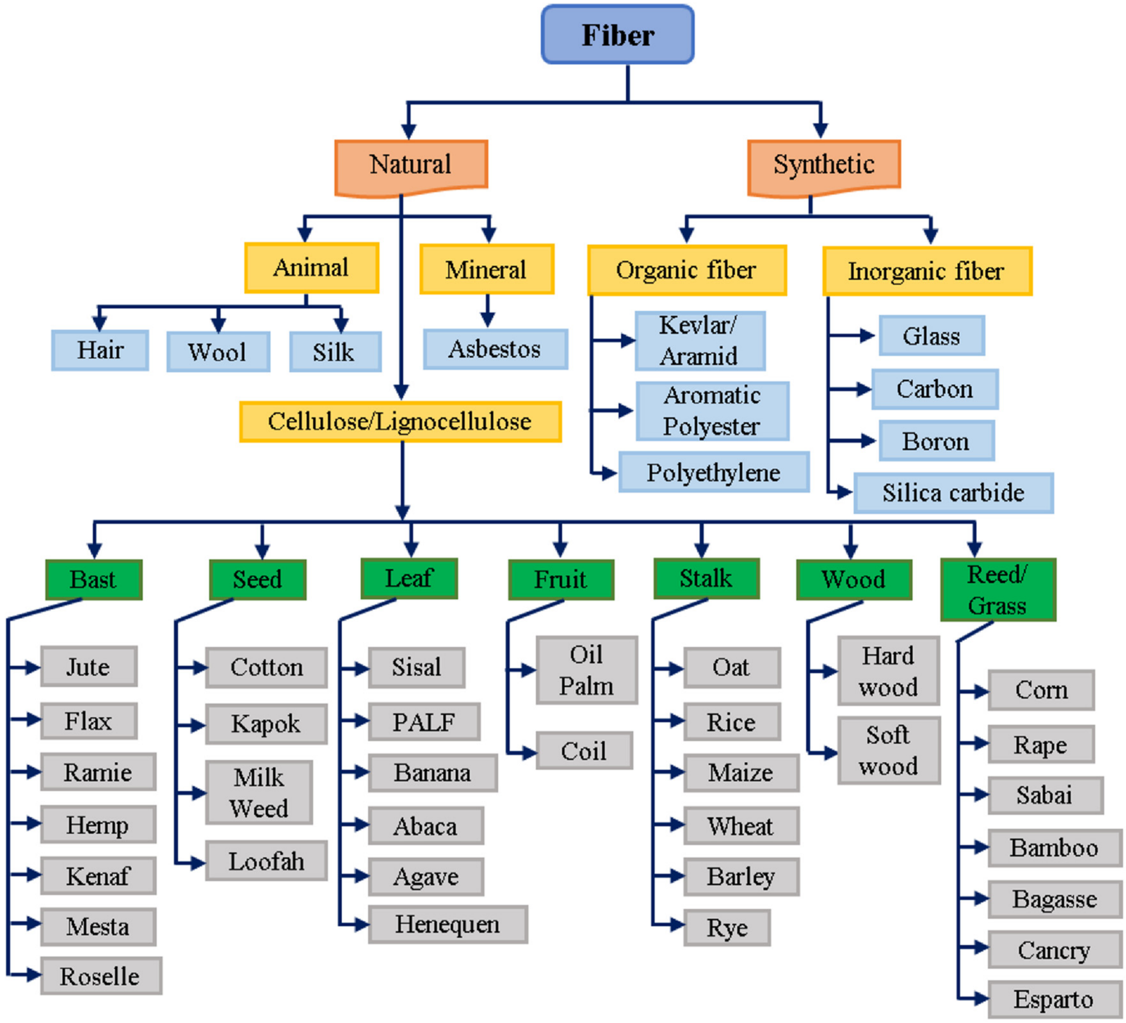


Figure 1: Broader classification of fibers [25].

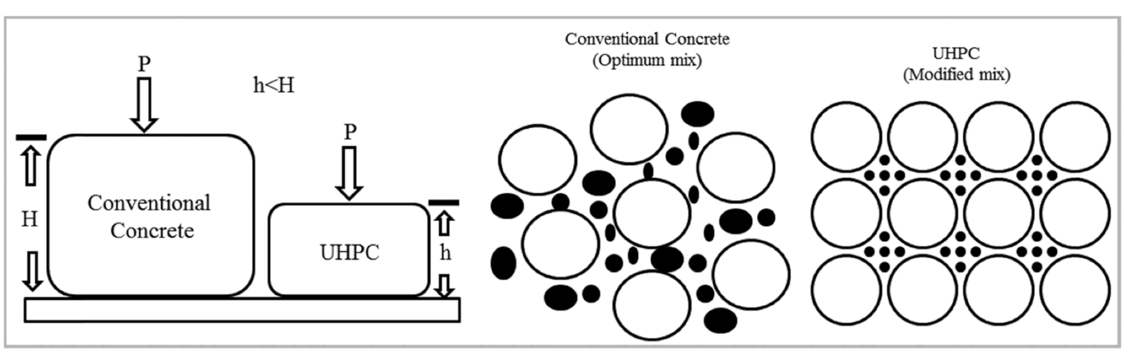


Figure 2: Packing skeleton of conventional concrete and UHPC [36].

almost 3–16 times as much as regular concrete [30,31], high ductility, and energy absorption capacity. The primary definitions state that compressive strength of 150 MPa is recommended for UHPC [28,32–34]. With such superior mechanical properties, UHPC structures are half to two-thirds lighter than conventional concrete without compromising the required load-bearing capacity [35]. Figure 2 depicts the reduced weight and dense particle density in UHPC [36].

Figure 3 depicts the fundamental specifications for UHPC [36]. According to Shi *et al.* [26], the primary factors

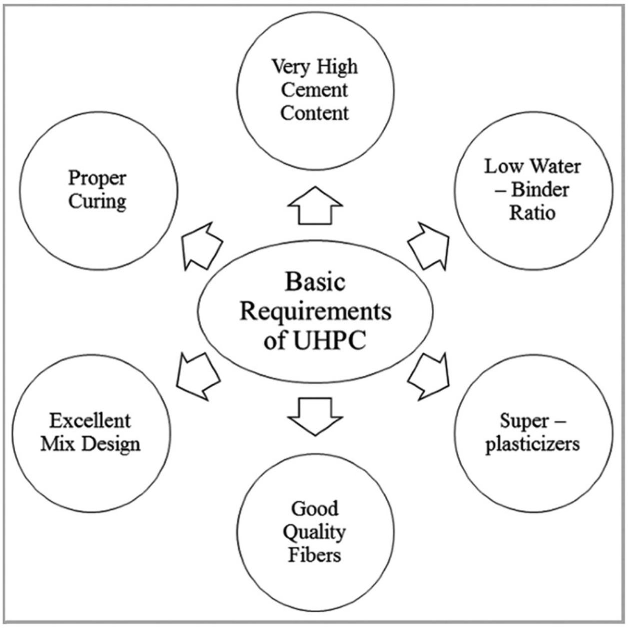


Figure 3: UHPC basic requirements [36].

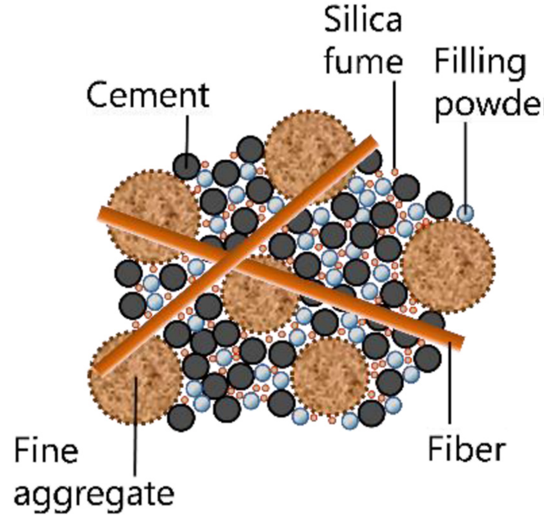


Figure 4: Composition of fiber-reinforced UHPC (not to scale) [52].

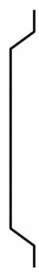
involved in preparing UHPC are reducing porosity, enhancing microstructure, and improving the homogeneity of fresh pastes. With UHPC, the parameters are substantially related to the mix design and raw ingredients. Effects of the addition of additives like rice husk ash [37], silica fume [38], nanoparticles [39,40], limestone powder [41], fly ash [42], *etc.*, further to raw materials in UHPC has been thoroughly examined in a number of research studies. Nowadays, researchers are more attentive toward sustainable supplementary cementitious materials [43–46] and recycled materials [47] for heading toward sustainable development.

The inclusion of fibers in UHPC is crucial for achieving improved mechanical properties [48]. Figure 4 depicts the schematic composition of fiber-reinforced UHPC [49]. The addition of steel fibers to UHPC significantly increased deflection at peak flexural loading and the corresponding strength [50]. Yu *et al.* [51] studied the flowability of UHPC by adding quartz and limestone as replacements and concluded that the flowability reduced as the amount of steel fibers increased.

The four distinct steel fiber forms that are often used in UHPC are depicted in Table 1. Wu *et al.* [53] reported that hooked-end and corrugated steel fibers resulted in reduced UHPC flowability than straight steel fibers due to more friction of aggregates with hooked-end steel fibers compared to other fiber shapes, more mechanical anchoring of deformed steel fibers in the matrix-fiber boding region, and easy bundling of deformed fibers compared to straight fibers [51,54]. The literature reports that adding an SP typically improves the workability of UHPC [26,55]. However, the direct addition of water and SP resulted in the absorption of cement particles by the SP, posing difficulty in achieving effective dispersion during mixing [26]. Hence, literature studies [28,36,46,57–61] suggest a step-by-step method for incorporating steel fibers to increase the dispersion of SP in UHPC. In addition, mixing time also affects how workable steel fiber-reinforced UHPC is. In general, more time and effort must be put into mixing to ensure that the fibers in UHPC are distributed uniformly. Instead, owing to the prolonged mixing time and the formation of air bubbles, the UHPC temperature is increased, which reduces the strength [32,56]. The UHPC mixing duration is typically adjusted between 10 and 20 min, according to the literature.

The objective of this systematic review is to investigate how steel fibers affect important UHPC features. This research focuses on a scientometric analysis of published data from the literature on UHPC reinforced with steel fibers up to 2022. The bibliography, funding, citations, keywords, abstract, and other data from 838 related articles are acquired using the Scopus search engine. VOSviewer tool is then employed to analyze the obtained data. The impact of steel fiber characteristics on the bonding mechanism between UHPC matrix and fibers is explained, including fiber orientation and distribution, pull-out resistance, and bonding zone microstructure. The effects of steel fiber shapes, length, and hybridization on UHPC's mechanical properties, failure mode, durability, and autogenous shrinkage are elaborated.

Table 1: Types and shapes of steel fibers [57–62]

Type of steel fiber	**Straight**				**Twisted**			**Corrugated**		**Hooked end**		
Shape of the steel fiber												
Length of the steel fiber (mm)	6	12	13	30	13	18	30	13	30	13	20	30
Diameter of the steel fiber (μm)	0.16	0.20	0.16/0.20	0.30	0.20	0.30	0.30/0.50	0.20	0.30	0.20	0.25/0.35	0.38

2 Research significance

Since the study of steel fiber-reinforced UHPC, high-strength concrete has been a topic that is urgently needed, as lack of information restricts researchers' ability to conduct new studies and form new partnerships. So, it is important to devise and execute a plan which aids scholars in gathering crucial knowledge from extremely reliable sources. Using a scientometric procedure, which includes using an appropriate software tool to statistically evaluate a vast volume of bibliographic data, is one way to get over this information gap. Scientometric analysis, in contrast to conventional review-based research, may precisely and thoroughly link various aspects of the literature. The authors with the most publications and citations, the co-occurrence of keywords, the major contributing nations, and the highly referenced articles in the research on steel fiber-reinforced UHPC may all be identified using scientometric analysis. This study can offer insightful information about the direction of future research on the subject and the existing state of the field. Young researchers can discuss concepts and techniques and form collaborations with one another with the aid of the statistical and graphical representations of academics and nations in the current work. By encouraging collaborations and knowledge sharing among researchers, the conducted scientometric analysis can help improve research on steel fiber-reinforced UHPC.

3 Methods

This study uses scientometric analysis of bibliographic data [62–64] to enumerate its numerous characteristics. The scientometric analysis utilizes scientific mapping, which researchers devise to study bibliometric data [63,64]. There are several articles on considered research areas; hence, the employment of an authentic search engine is essential. The two highly recommended databases, Web of Science and Scopus, are appropriate to achieve the study objective [65,66]. Subsequently, Scopus collects bibliographic data regarding research on UHPC having steel fibers. A search of UHPC with steel fibers on Scopus has given 838 results. Numerous screens are applied to filter out unnecessary data. Figure 5 depicts a comprehensive systematic flowchart of all the stages that were performed, including data retrieval, analysis, and the use of various filters during analysis.

Likewise, the literature has reported multiple studies on this method [67–69]. Using appropriate software, the CSV format stocks the Scopus database for its added assessment. The quantitative assessment and scientific visualization of gathered information are done using the VOSviewer

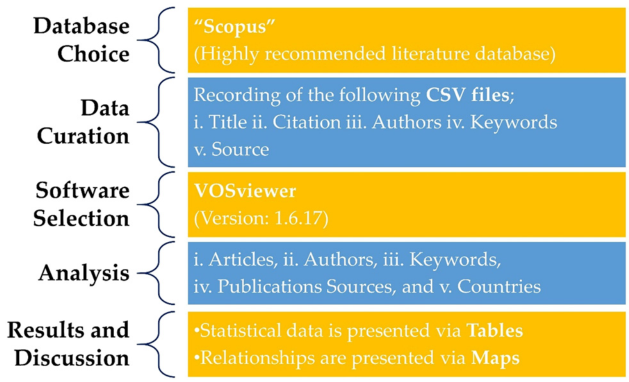


Figure 5: Sequence of the research methods.

mapping tool [70–72]. The succeeding CSV file is then updated on VOSviewer. The valuation of publication sources with frequently applied keywords, the authors with the most citations and articles, the highly cited articles, and the involvement of various countries are performed via scientometric analysis. The numerous features, their interconnectivity, and co-occurrences are established using maps, and the related quantifiable statistics are illustrated via tables. To recognize a specific element in the map, colors are allocated to the groups. Also, unique colors like a rainbow are employed to show density mapping, whereas plasma, rainbow, and Viridis are used for density visualization.

4 Analysis of results

4.1 Relevant subject areas and yearly publications

The evaluation to recognize the highly related research areas is performed using a Scopus analyzer. "Engineering" is the leading documents-generating discipline, with almost 51% of documents, followed by "Materials Science," having 33% of documents (Figure 6). Overall, 89% of the total documents are contributed by these two disciplines. In order to assess the publishing patterns in the study fields under consideration, the Scopus database is also examined (Figure 7). Out of this evaluation, it is extracted that around 78% are journal articles, almost 16% are conference papers, and 3.5% are conference review articles. The annual trend of articles in steel fiber-reinforced UHPC from 2011 up to December 2022 is presented in Figure 8. There has been a gradual increase up to 2016 in the considered research area. However, a significant enhancement in the number of publications on steel fiber-reinforced UHPC is observed from 2016 to 2021. In 2022, the number of publications in the mentioned research area is more than 250 (December 2022). It is pretty motivating to observe that the steel fiber-reinforced UHPC is gaining the attention of researchers as high-strength concrete.

4.2 Sources of publications

The sources of publication are evaluated from bibliographic data by applying VOSviewer. At least. a limit of 10 articles is set for a single source and, in this way, 13 out of 838 article sources have met the specified criteria. Table 2 lists the number of publications and citations from sources containing at least ten articles in the respective domain. The "Construction and Building Materials" is a leading source of publications with 118 articles in the under-studied research area. Following that, the "Engineering Structures" and "Cement and Concrete Composites," 46 and 44 articles, respectively, are the second and third leading publication sources. As far as the number of citations is concerned, the top three leading journals are "Engineering Structures," "Cement and Concrete Research," and "IOP Conference Series: Materials Science and Engineering" with 3,221, 1,713, and 950 citations, respectively, up to December 2022. This evaluation will provide a basis for the forthcoming scientometric analysis of steel-reinforced UHPC research. Moreover, the conventional review studies are insufficient to produce systematic graphs. Figure 9 represents the publication sources' visualization with at least ten papers. The frame dimensions illustrate the source impact on this field of research with respect to document count, showing that the higher the effect, the larger the frame is, as it can be observed that "Construction and Building Materials" has a bigger frame as compared to others representing its higher impact in the steel fiber-reinforced UHPC research area. Three clusters are formed, and each cluster is assigned a different color on the map. The extent of publication source and frequency of co-citations is the basis for cluster formation [73]. The journal clustering is done using VOSviewer, based on their co-citation capacity in published documents. Like in the red cluster, seven journals have frequent co-citations in the same research. Additionally, the distance among clusters represents the linkage among sources of publication. "Construction and Building Materials" is more closely linked with "Materials" than with "IOP Conference Series: Materials Science and Engineering" or "Advanced Materials Research."

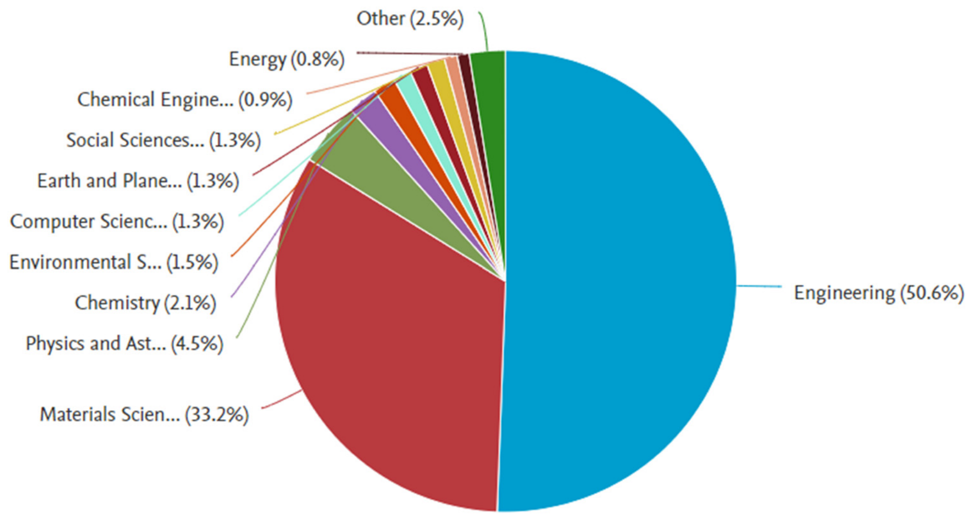


Figure 6: Subject area of articles.

4.3 Keywords

Keywords are necessary in the research to identify the key idea of specific research [74]. Minimum keyword repetition requirements are set at 50. This results in a total of 19 keywords being shortlisted, as shown in Table 3. The three most often used keywords in the research on steel fiber-reinforced UHPC are compressive strength, UHPC, and steel fibers. Figure 10 displays a frequency occurrence map depending on density and links. The size of the frame for a certain keyword shows how frequently it appears, and the frame position shows how frequently it appears with other keywords in articles (Figure 10a). Also, as indicated in the graph, the frame size for leading keywords is noticeably bigger than it is for the other keywords, demonstrating the significance of these keywords for studying research on steel fiber-reinforced UHPC. Clustering is used to show the co-occurrence of terms across several publications. To illustrate the co-occurrence of the terms in published articles, each cluster is given a different color. Four unique groupings are represented by various color shades (Figure 10a). Similarly, many distinctive colors indicate concentrations of keyword density (Figure 10b). Each color is grouped in decreasing density order. The red color has the maximum density, whereas yellow, green, and blue have the lowest densities. UHPC and steel fibers are presented in yellow or red colors, presenting a reflection of their more frequent occurrences. Young scientists would find this conclusion useful in choosing keywords that will make searching for publications relevant to this particular research topic as easy as possible.

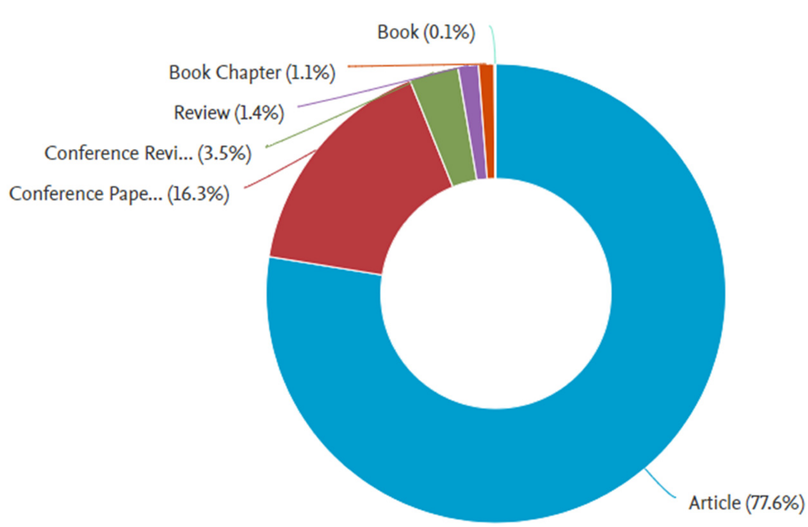


Figure 7: Different kinds of publications on the relevant academic topic.

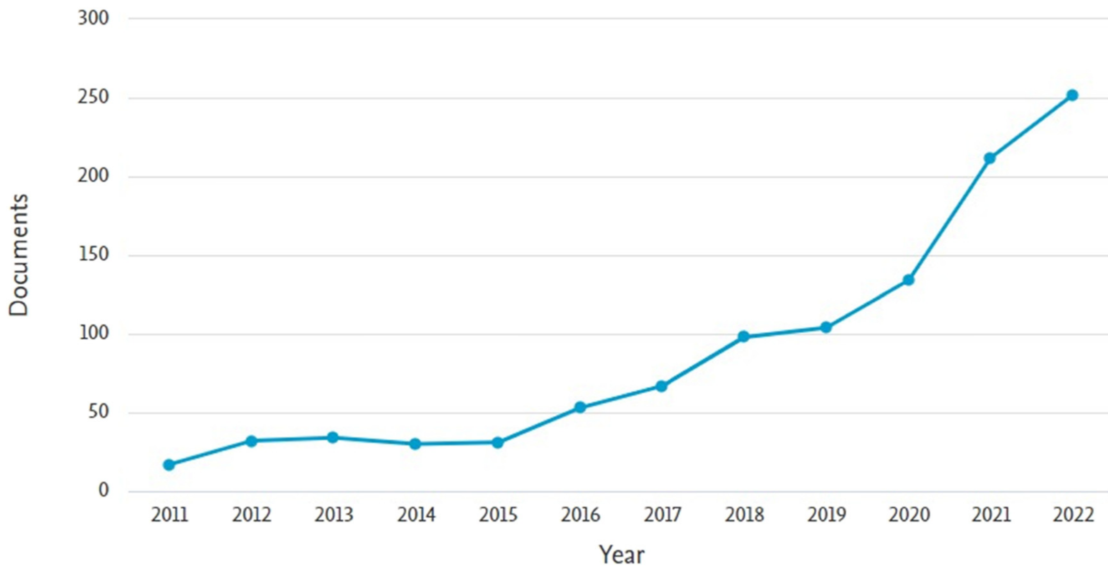


Figure 8: Annual publication trend of articles.

Table 2: Sources of articles with at least ten publications in the same field of study

S/N	Publication source	Number of publications	Total number of citations
1	Construction and Building Materials	118	908
2	Engineering Structures	46	3,221
3	Cement and Concrete Composites	44	26
4	IOP Conference Series: Materials Science and Engineering	28	950
5	Materials	28	112
6	Composite Structures	19	480
7	Journal of Building Engineering	19	72
8	Composites Part B: Engineering	18	234
9	Cement and Concrete Research	14	1,713
10	Journal of Materials in Civil Engineering	11	67
11	Structural Concrete	11	82
12	Advanced Materials Research	10	35
13	ACI Structural Journal	10	149

4.4 Authors

The citations of an author depict his impact on a specific research field [75]. Here, the least articles threshold of a particular author is set as more than 10. Table 4 illustrates that 20 authors meet the criteria of more than 10 minimum relevant publications with the quantum of their articles and corresponding citations relevant to steel fiber-reinforced UHPC, as explored by employing VOSviewer on bibliographic data. An author's credibility is difficult to know by considering all the factors, like overall citations, number of articles, average citations, *etc.*, at once; instead, their ranking may be evaluated against each factor distinctly/individually. Accordingly, it is extracted by the analysis that Yoo D.Y., Wang J., and Wu C. are the three leading authors with 44, 26, and 24 publications, respectively. Wille K. has 1,744 citations, followed by Yoo D.Y, with 1,158 citations, and Khayat K.H. has 716 citations in the research field of steel fiber-reinforced UHPC. Figure 11 shows the connection between researchers with ten publications. It is concluded by performing this analysis that there is significant interconnectivity among authors, in terms of citations, who are researching steel fiber-reinforced UHPC.

4.5 Documents

Regarding authors, the significance of a particular article in a specific field of research is demonstrated by the number of citations it receives. The articles with the highest citations are considered pioneers in a specific field.

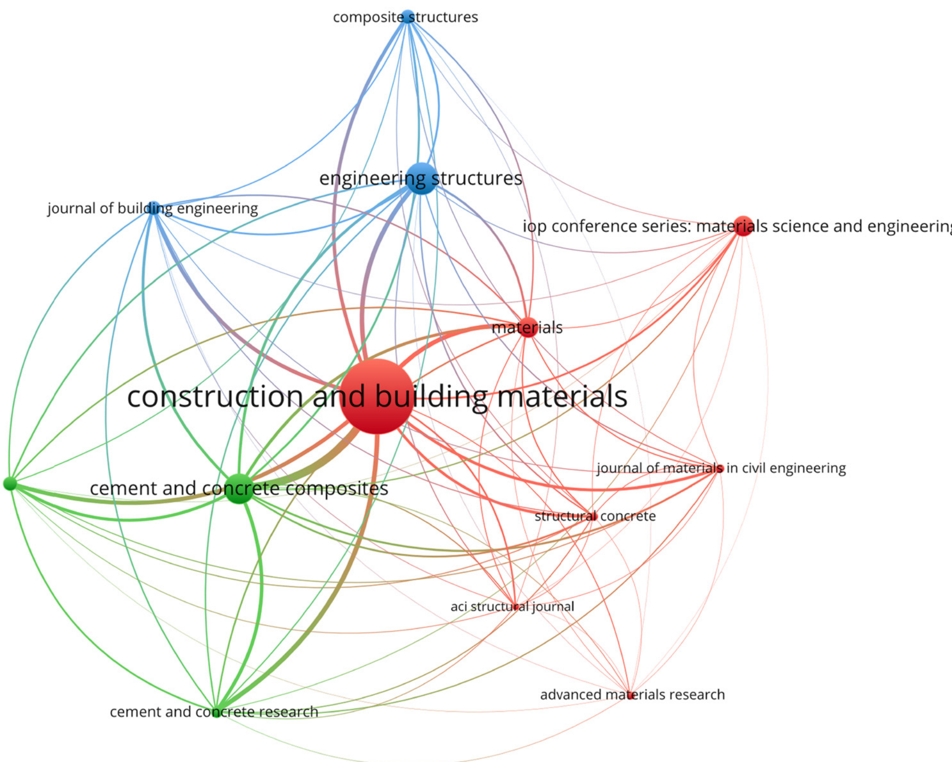


Figure 9: Scientific representation of the sources of publications with at least ten articles in the same field of study.

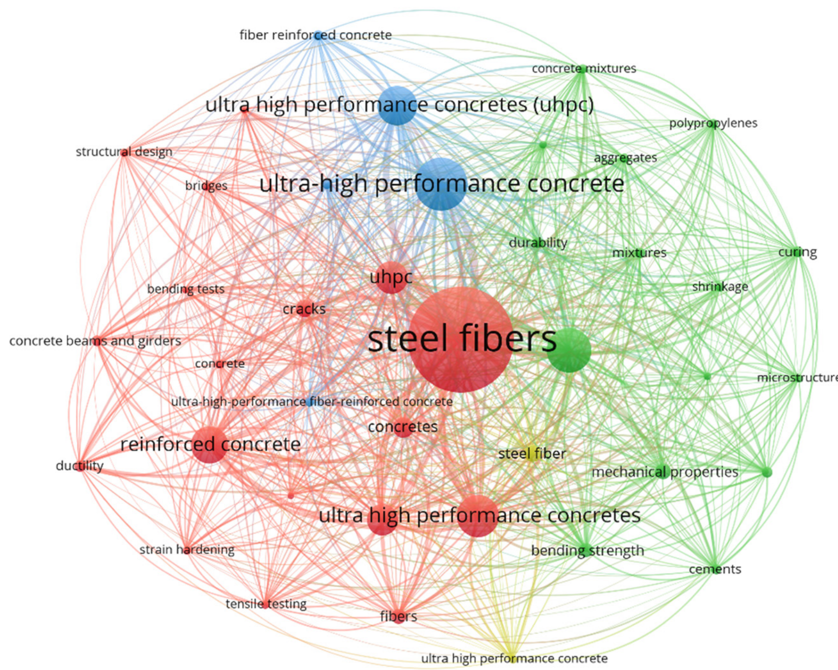
Table 3: Leading 19 frequently employed keywords in the steel fiber-reinforced UHPC research

S/N	Keyword	Occurrences
1	Steel fibers	645
2	UHPCs	302
3	Compressive strength	248
4	UHPCs	233
5	UHPCs	218
6	Reinforced concrete	204
7	UHPCs	179
8	Tensile strength	171
9	Concretes	108
10	Cracks	88
11	Steel fibers	83
12	Mechanical properties	78
13	Fibers	74
14	Bending strength	72
15	Ductility	59
16	Concrete beams and girders	54
17	Silica fume	53
18	Durability	52
19	Curing	51

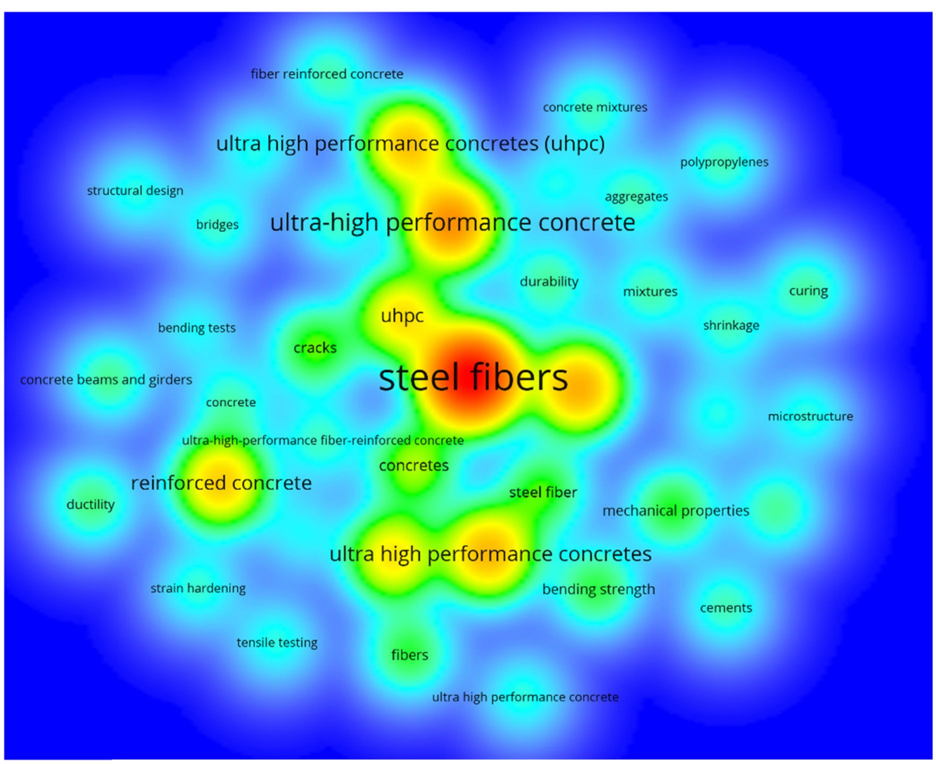
Figure 12 shows the citations based on inter-related articles' scientific visualization and density concentration for publications in the steel fiber-reinforced UHPC research area. The citations based on inter-related publications extracted from VOSviewer are shown in Figure 12a. The frame dimensions in the case of a specific article are directly related to the influence of that particular article in the steel fiber-reinforced UHPC research. Additionally, the increased density concentrations for the citation-based leading publications are revealed from the density mapping shown in Figure 12b.

4.6 Countries

Among different countries in the world, some countries have contributed more publications in steel fiber-reinforced UHPC research than others, and those contributing countries are focused on producing more articles. For bibliophiles to evaluate the enthusiastic nations' contributions to the study of steel fiber-reinforced UHPC, a methodical plot has been developed. This analysis sets the limit of the least articles from one country as 10. The 17 countries that meet the set criteria are listed in Table 5. It is observed that China, the United States, and South Korea are among the three leading countries that have produced 337, 150, and 96 publications, respectively. Additionally, the United States received 4,273 citations, followed by China, having 3,671



(a)



(b)

Figure 10: Analysis of the keywords: (a) scientific visualization and (b) visualization of density.

Table 4: Authors having more than ten publications in steel fiber-reinforced UHPC research

S/N	Author	Number of publications	Total number of citations
1	Yoo D. Y.	44	1,158
2	Wang J.	26	274
3	Wu C.	24	559
4	Li J.	23	512
5	Liu Z.	19	266
6	Liu J.	18	308
7	Khayat K. H.	17	716
8	Fehling E.	15	319
9	Gao X.	15	360
10	Kim S.	14	321
11	Zhang Y.	14	122
12	Fang Z.	13	90
13	Huang H.	12	212
14	Kim D. J.	12	546
15	Shi C.	12	683
16	Yang J.	12	63
17	Su Y.	11	409
18	Wille K.	11	1,744
19	Wu Z.	11	696
20	Xu S.	11	75

citations, and South Korea, has 2,220 citations. In Figure 13, the citations based on inter-connected countries are mapped in addition to the visualization of density concentration. The considered research field relevant article-based influence of a particular country is represented by the dimensions of the respective frame (Figure 13a). Likewise, it is revealed from Figure 13b that countries with the most publications depict higher density. The statistical and graphical output representation for participating countries will aid young scholars in forming scientific collaborations, establishing joint projects, and exchanging innovative concepts and methods. Academics from different nations interested in researching steel-reinforced UHPC may collaborate with relevant field experts to benefit from their expertise.

5 Discussions

UHPC is a modern cementitious composite with greatly improved mechanical properties compared to regular cementitious concrete [76]. Discontinuous fiber reinforcement is a crucial component of UHPC. Concrete can benefit from the

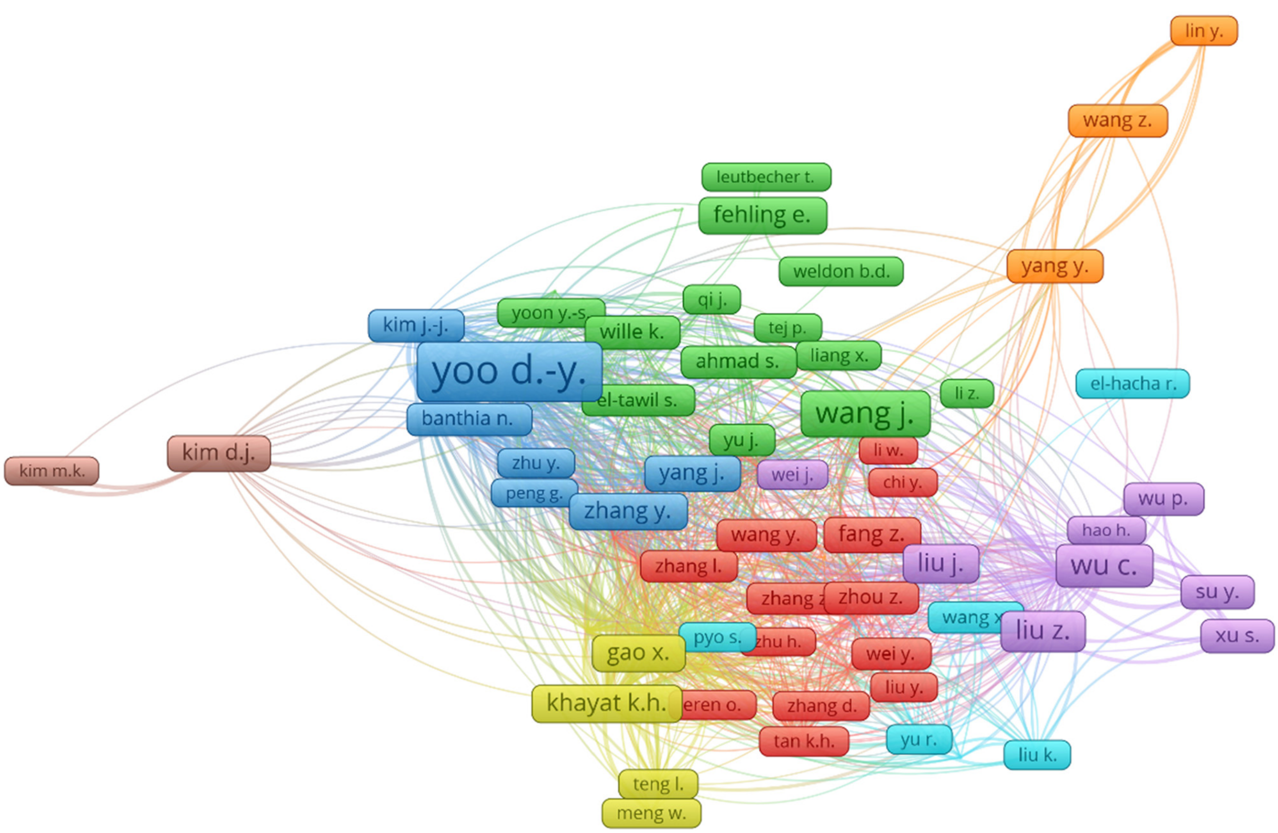


Figure 11: Scientific visualization of authors.

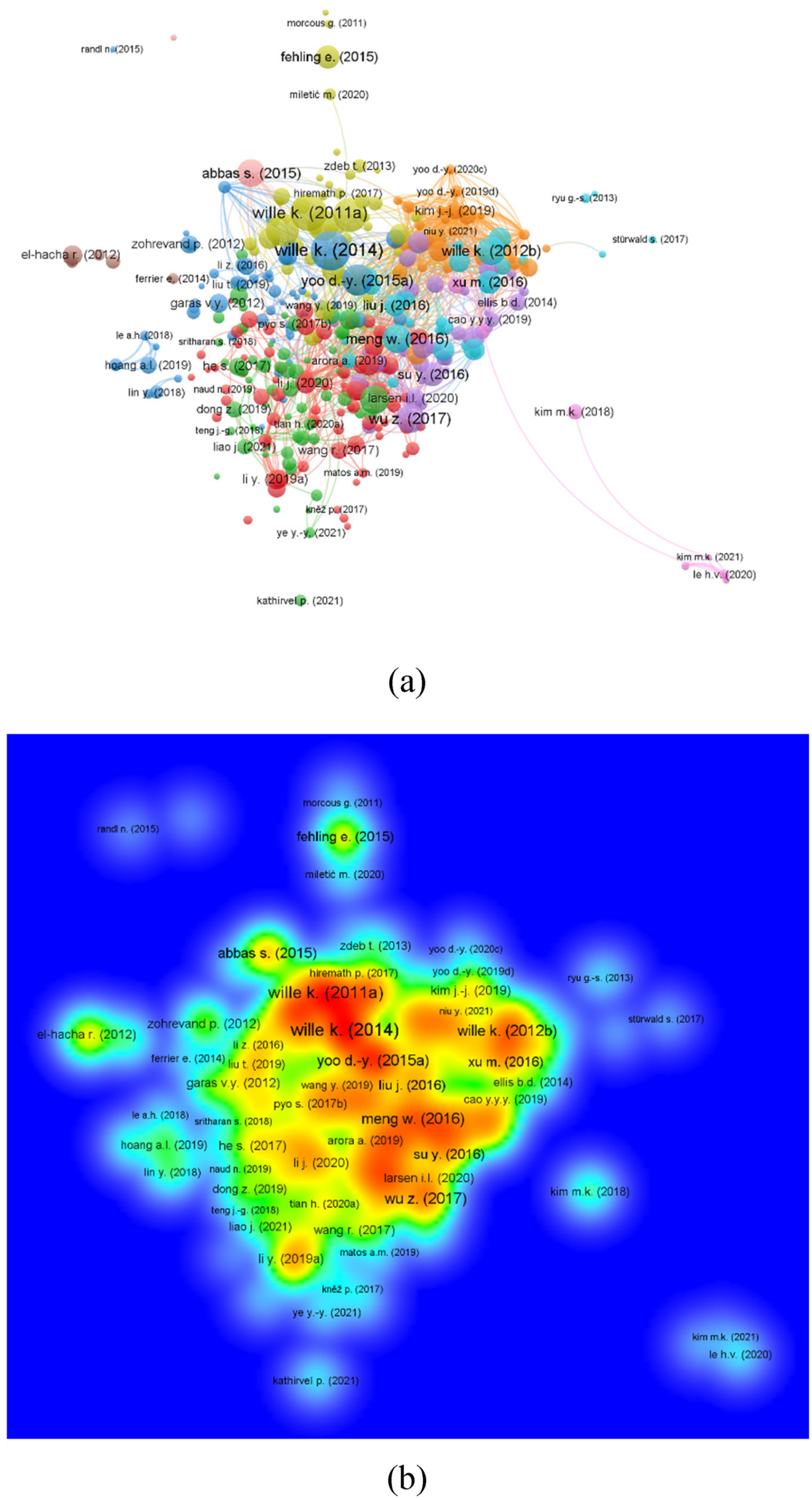


Figure 12: Scientific mapping of publications that have been published in the associated field of study: (a) connected articles based on citations and (b) the number of linked articles.

Table 5: Leading countries having more than ten published articles

S/N	Country	Number of publications	Total number of citations
1	China	337	3,671
2	United States	150	4,273
3	South Korea	96	2,220
4	Germany	59	434
5	Canada	49	835
6	Australia	48	983
7	Czech Republic	22	147
8	Viet Nam	21	381
9	Austria	20	109
10	Hong Kong	17	141
11	Saudi Arabia	17	182
12	Taiwan	15	322
13	United Kingdom	15	318
14	Iraq	13	39
15	Singapore	13	290
16	Iran	12	76
17	Turkey	11	72

addition of fibers in several ways, including increased energy absorption and significant tensile strength. When designing a UHPC mix, flexural and compressive strengths are crucial mechanical elements that are evaluated to determine ductility and strength. However, there is brittleness in UHPC that needs to be addressed. The strength and ductility of UHPC have been reported to improve by the addition of evenly distributed steel fibers having more tensile strength. In the literature, this type of concrete is frequently referred to as steel fiber-reinforced UHPC [77]. An important characteristic of UHPC that is often assessed in comparison to conventional concrete is its compressive strength [78]. The compressive behavior of UHPC having steel fibers does not significantly differ from that of normal concrete. The much increased stiffness and compressive strength of UHPC, however, make it stand out. A number of variables, such as the materials, mix design, fiber content, and curing procedure, affect the compressive strength of UHPC [78]. Researchers have published a number of studies on the increased compressive strength of UHPC reinforced with steel fibers [53,54,79–88]. Additionally, by incorporating steel fibers into UHPC, structural integrity can be attained by transferring load across cracks via crack bridging [89]. According to the literature, UHPC's flexural tensile strength typically increases as the fiber content increases [90–93]. According to numerous research studies, longer steel fibers can enhance UHPC's flexural strength by more than 20% [60,92–96].

Pull-out test (single) results used to establish bonding qualities indicate relationships with the UHPC production process, steel fiber form, content, orientation, and distribution [97]. On a microscopic scale, Figure 14 illustrates the interfacial transition zone (ITZ) of conventional concrete with UHPC, as reported by Mishra and Singh [36]. For UHPC to function properly overall, the bonding and pull-out behavior of the steel fibers within the matrix is essential. Several elements, including the steel fibers' characteristics, the UHPC matrix's chemical composition, and the curing conditions, have an impact on the bonding between the steel fibers and the matrix. To withstand tensile loads and prevent the pull-out of the steel fibers from the matrix, the binding strength between the steel fibers and the UHPC matrix is essential. A valuable tool for examining the microstructure and bonding properties of the steel fibers in UHPC is the scanning electron microscope (SEM). The SEM images in Figure 15 demonstrate a strong connection between the steel fiber and the concrete matrix around it, demonstrating how this bond can reduce stress concentrations and prevent the material's internal deterioration, thereby improving mechanical properties. Steel fibers used in UHPC have a rough surface with tiny protrusions, which enhances the mechanical interaction between the fibers and matrix as seen in SEM images of the fibers. The steel fibers are evenly dispersed throughout the UHPC matrix, resulting in a dense and homogenous microstructure, as seen in SEM images. The area where the characteristics of both materials are altered as a result of bonding is known as the ITZ, which is situated between the fibers and the surrounding matrix [98,99]. The ITZ exhibits a complex microstructure as seen in SEM images, with cementitious paste adhering to the fiber surface and steel fibers partially embedded in the matrix. The bonding and pull-out behavior of the steel fibers in UHPC are greatly influenced by the ITZ.

Every day, more scientists are gaining interest in UHPC research and commercial applications. UHPC still has drawbacks, such as a lack of internationally recognized design codes, unclear structural capabilities for extended usage, and a lack of knowledge of material categorization techniques, even though it has achieved recognition in many nations. The design of thin, lightweight buildings is the key to maximizing their use [30], in addition to low maintenance, a smaller environmental impact, and lower costs overall [101,102]. Steel fiber-reinforced UHPC is frequently used in bridge deck overlays, bridge columns, and bridge beams [103–105]. Moreover, it is employed in the construction of various types of infrastructures, including retaining walls, roadways, and tunnels [106]. Moreover, steel fiber-reinforced UHPC is used in architectural applications such as façades, cladding, and decorative panels due to its superior strength and durability [107,108]. Because of its outstanding durability and wear resistance, steel fiber-reinforced UHPC is

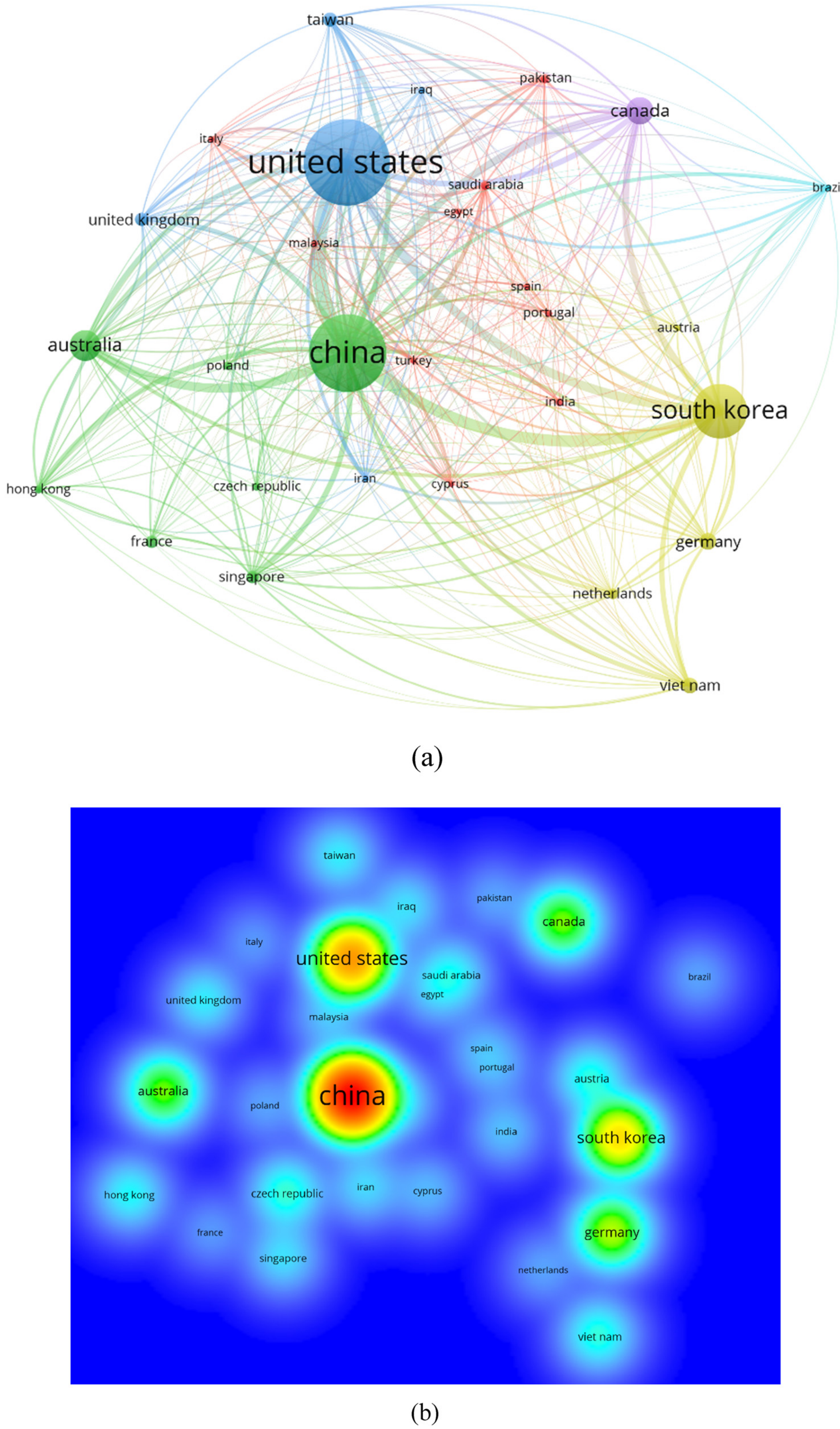


Figure 13: (a) Scientific network and (b) density visualizations of the nations involved in the relevant fields of study.

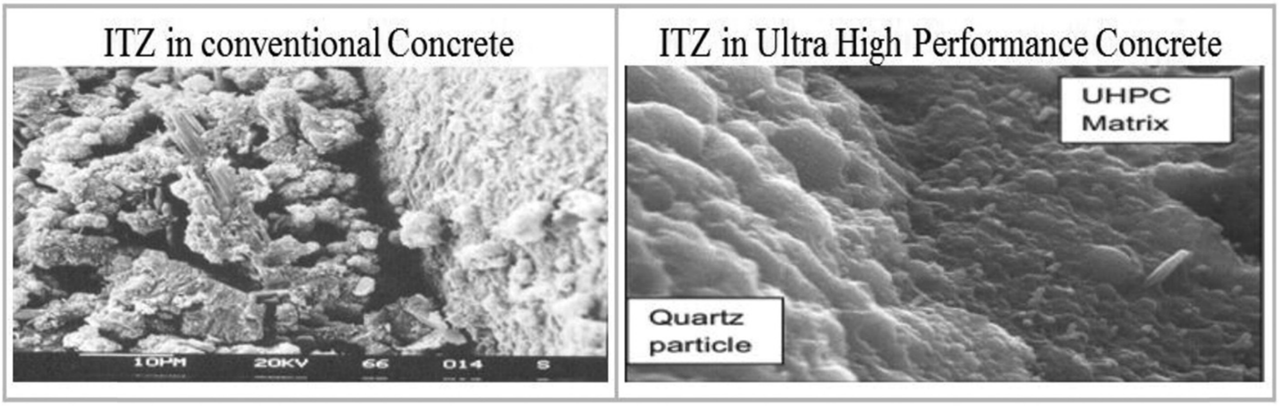


Figure 14: SEM images for conventional concrete and UHPC ITZ [36].

widely utilized in industrial flooring applications [109]. Additionally, because of its great strength and capacity to bear impact and blast loads, steel fiber-reinforced UHPC is suitable for building blast-resistant structures [110,111]. Moreover, to increase a building's resilience to earthquake loads, steel fiber-reinforced UHPC is also employed during seismic retrofitting [112,113]. Moreover, due to its strong resistance to corrosion, steel fiber-reinforced UHPC is widely employed in the building of marine constructions including ports, harbors, and offshore platforms [114,115]. Overall, the superior characteristics of UHPC having steel fibers make it an ideal material for numerous civil engineering structural applications in the field of construction.

The variety of fiber composition, combination, shape, orientation, and distribution may be responsible for the complexity of UHPC structural design. Steel fibers might also be responsible for the higher costs and carbon footprints of UHPC. Hence, expanding knowledge of the impacts of steel fibers on UHPC is essential for developing widely used UHPC applications and standard design standards. The existing typical review literature, such as review-based manual studies, is insufficient for connecting various aspects of the literature precisely and comprehensively. However, in this systematic review, mapping bibliographic data and its statistical analysis on the steel fiber-reinforced UHPC research. In this method, researchers who have published the most articles and received the most citations in the field of steel fiber-reinforced UHPC are identified, along with the keywords that are most frequently used, more related articles contributing countries, more related articles producing journals, and the most viable researchers. The assessment of keywords shows that the compressive strength of UHPC with the addition of steel fibers is mainly investigated for achieving the high strength of UHPC. Likewise, the highest contributing countries in under-studied research areas are categorized by the literature with linkages based on citations. This analysis will help academics collaborate to progress research in this domain.

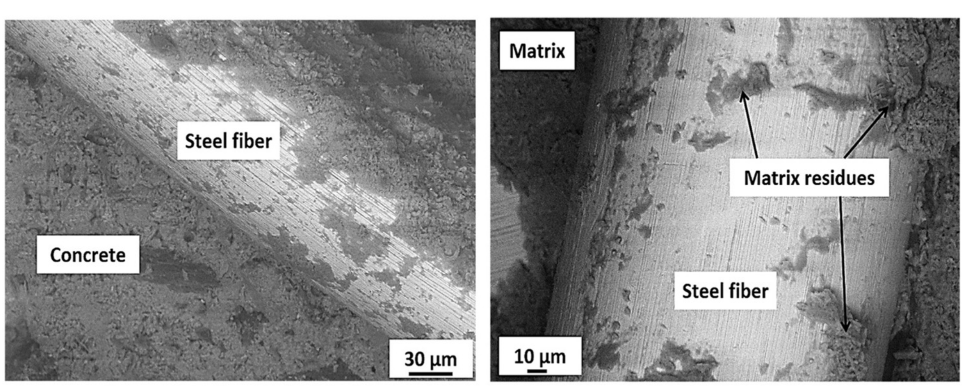


Figure 15: SEM images of steel fiber bonding with the concrete matrix [100].

6 Conclusions

Current developments in scientific communication methods have sparked the development of novel bibliometric measures, which establish reliable value scales through mathematical and statistical research. These measures make it possible to evaluate the number of research contributions made by various individuals, organizations, countries, and groupings. The main aim of this study is to perform the scientometric analysis of the existing literature on steel fiber-reinforced UHPC using a database of 838 papers that were collected from Scopus and reviewed with VOSviewer software. This study arrives at a number of conclusions.

- The top three journals in this field, with 118, 46, and 44 articles, are “Construction and Building Materials,” “Engineering Structures,” and “Cement and Concrete Composites,” respectively, according to a review of pertinent articles on steel fibers in UHPC. As of December 2022, Engineering Structures, Cement and Concrete Research, and IOP Conference Series: Materials Science and Engineering have the most citations overall, with 3,221, 1,713, and 950 citations, respectively.
- The most often employed keywords for studies on UHPC with steel fibers, according to an analysis of keywords, are compressive strength, UHPC, and steel fibers. This evaluation also demonstrates that the key objective of research in UHPC with steel fibers has been to produce high-strength concrete.
- In the field of steel fiber-reinforced UHPC research, 27 researchers have written more than ten papers, according to an analysis of their authorship. Yoo D.Y., Wang J., and Wu C. are the three authors who have published the most, with 44, 26, and 24 publications, respectively. The author with the most citations overall in the steel fiber-reinforced UHPC research is Wille K., with 1,744, followed by Yoo D.Y. with 1,158, and Khayat K.H. in the third place with 716.
- According to a ranking of the top countries for steel fiber-reinforced UHPC research, at least 10 articles have been contributed by 17 different countries. With 337, 150, and 96 papers, China, the United States, and South Korea, respectively, have published the most relevant publications. The United States leads all other countries in the number of citations with 4,273, followed by China with 3,671, and South Korea with 2,220.
- Steel fiber-reinforced UHPC is a versatile material with superior mechanical properties that makes it suitable for a variety of applications in the construction industry, including, bridge deck overlays, beams, columns, blast-resistant structures, seismic retrofitting of buildings, marine structures, and industrial flooring.
- It has been shown that the strength and ductility of UHPC can be enhanced by the addition of evenly distributed steel fibers with higher ultimate elongation and tensile strength. This results in better material properties, such as a higher energy absorption capacity and substantial tensile strength. A key factor in the bonding and pull-out behavior of the steel fibers in UHPC is the ITZ.
- A number of factors, including fiber content, mix design, and supplementary cementitious materials, have an effect on the development and applications of steel fiber-reinforced UHPC. Unfortunately, knowledge of factors like toughness, steel fiber hybridization, life cycle assessment, bonding process, and life cycle cost analysis is lacking. As a result, more investigation and thorough research into steel fiber-reinforced UHPC are required.

7 Future recommendations

By utilizing the scientometric analysis to evaluate keywords and the related literature, this study highlights the potential future directions of UHPC reinforced with steel fibers. After conducting a scientometric analysis on UHPC reinforced with steel fibers, the study suggests the following possibilities for future research in this field:

- Taking into account the establishment of several standards for UHPC, comparative studies between various suggested standards will be beneficial for scientific discussions for associating the novel research with existing ones while maintaining all other factors constant [116].
- A detailed and precise analysis of the bonding mechanism between steel fibers and the UHPC matrix is required in order to comprehend the mechanical properties of UHPC for structural applications.
- Carbon, mineral, and synthetic fibers, in addition to steel, have particular effects on the performance of UHPC. Thus, adding such fibers to enhance UHPC performance in accordance with their characteristics needs to be investigated.
- Further study on improving the bonding process between fiber and matrix by treating fibers chemically and physically is strongly encouraged.
- To stop the development and progression of cracks in UHPC, the idea of steel fiber hybridization [117] that combines steel fibers of various lengths and shapes should be further investigated.
- It is also advised to use Artificial Intelligence-based Machine Learning methodologies for designing steel fiber-reinforced UHPC in an effort to conserve natural resources and use less energy, money, and time. This enables the

optimization of a number of variables, such as the fiber length, form, content, mix design, w/c ratio, and the supplementary cementitious material contents [118,119].
- Last, but not the least, it is also necessary to comprehend life cycle cost analysis and life cycle assessment before steel fiber-reinforced UHPC can be applied following large-scale manufacture.

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