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Scientometric Review of Cement-Less Ultra-High-Performance Concrete: Trends, Innovations, and Future Research Directions

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Abstract

This study presents a comprehensive scientometric review of cement-less ultra-high-performance concrete (UHPC) with the objective of identifying research trends, key contributors, dominant themes, and critical knowledge gaps in this emerging field. A systematic bibliometric analysis was conducted using the Scopus database, from which 59 peer-reviewed journal articles published between 2014 and 2024 were selected following rigorous screening criteria. Scientometric mapping was performed using VOSviewer to analyze publication trends, keyword co-occurrence, leading journals, influential authors, and active research regions. The findings reveal a sharp increase in research output after 2020, reflecting growing interest in geopolymer-based UHPC due to sustainability concerns. Existing studies predominantly focus on mechanical properties, particularly compressive strength and steel fiber reinforcement, while durability-related aspects such as corrosion resistance, fire performance, and long-term structural behavior remain underexplored. Higher sand-to-binder ratios (up to 0.8) were found to improve packing density and mechanical performance, achieving compressive strengths up to 160.7 MPa, while silica fume contents around 30% enhanced compressive strength by approximately 25% and fracture energy by nearly 50%. The novelty of this work lies in being the first dedicated scientometric assessment of cement-less UHPC, providing a quantitative overview of research evolution while systematically highlighting critical gaps and future research directions to support its effective structural application.

Keywords: Scientometric; Geopolymer; Cement-Less; UHPC.

1. Introduction

The manufacturing of Ordinary Portland Cement (OPC), a fundamental component in concrete production, is accountable for approximately 10% of global carbon dioxide (CO_2) emissions. Given that concrete is one of the most exploited sources on Earth, only surpassed by water, the ongoing dependence on OPC will likely escalate CO_2 emissions. To mitigate this environmental impact, researchers have been exploring alternative binders for concrete production. One promising development is geopolymer concrete, which has the ability to act as an alternative to traditional concrete. Geopolymer concrete is a type of concrete that replaces Portland cement. Instead, its binder is produced by the reaction of an alkali with a silica- and alumina-rich source material [1, 2]. When geopolymer concrete is properly designed and fabricated using supplementary cementitious materials, it can achieve similar properties to conventional concrete while significantly reducing the CO_2 emissions associated with OPC production by up to 80%. Additionally, OPC manufacturing not only releases CO_2 but also depletes non-renewable resources such as limestone [3–5].

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Ultra-high-performance concrete (UHPC) is a cement-based material identified for its excellent characteristics, including compressive strength surpassing 150 MPa, excellent tensile deformation, notable toughness, and remarkable durability. The production of UHPC typically involves using a significant amount of OPC with a low water-to-cement fraction, incorporating silica fume (SF), quartz powder, superplasticizers, and steel fibers [6]. Moreover, thermal curing is employed to enhance its performance characteristics [7,8]. However, the extensive use of OPC in UHPC production reduces its sustainability owing to the high energy utilization and carbon releases linked with OPC manufacturing [9,10]. The OPC content in UHPC is approximately three times that of normal OPC concrete, resulting in embedded carbon emissions ranging from 600 to 1300 kg/m³. To enhance the sustainability of construction materials, substituting OPC with alternate low-carbon binders is contemplated as an efficient strategy [11,12]. Geopolymer binders are free from clinker and offer performance similar to or better than OPC [13,14]. Researchers have explored the use of fly ash (FA) [15], ground granulated blast furnace slag (GGBFS) [16], metakaolin [17], and recycled glass powder [18] as geopolymer binders in the presence of alkaline activators like sodium hydroxide [19]. According to Zhang et al. [20], geopolymer binders have the potential to release 60% lower CO_2 than OPC.

Randl et al. [21] stated that up to 45% of OPC may be substituted by supplementary cementitious materials (SCMs) without negatively affecting the mechanical characteristics of UHPC. Additionally, some works have explored the complete replacement of cement utilizing alkali-activated material (AAM) binders derived from GGBFS, metakaolin, and FA to create cement-less UHPC. Ambily et al. [22] produced ultra-high performance geopolymer concrete (UHPGC) utilizing GGBFS and achieved a compressive strength exceeding 170 MPa. Wetzel & Middendorf [23] reported similar capacity by refining the pore composition with the inclusion of SF and metakaolin in slag-based AAM. But the use of an alkaline-activating solution in cement-less UHPC presents several drawbacks due to its high pH, which may cause burns and respiratory issues [24]. Additionally, the price and accessibility of the silicates and hydroxides utilized in the mixture could be problematic [25, 26].

Recently, studies have investigated the potential of mortar, concrete, or UHPC made with binders that completely replace cement. In the existing literature, the terms cement-less UHPC, geopolymer UHPC, and UHPGC are often used interchangeably, although their definitions are not always explicitly stated. In general, geopolymer UHPC or UHPGC refers to UHPC systems in which OPC is fully replaced by alkali-activated binders such as GGBFS, FA, metakaolin, and SF. In this study, the term cement-less UHPC is adopted as an umbrella expression to collectively describe UHPC mixtures that achieve ultra-high mechanical performance without the use of Portland cement, including systems commonly reported as geopolymer UHPC or UHPGC in the literature. This terminology is used to ensure consistency while acknowledging that minor differences may exist in precursor chemistry and activation mechanisms among individual studies. Oinam et al. [27] studied the effect of natural cellulose fibers (NCFs) on the hydration characteristics of cement-less UHPC made with CaO-activated GGBFS. Saturated NCFs were used as internal-curing agents to supply additional water, enhancing the sensitivity of unhydrated parts. The study involved adding NCFs at 0% to 1.5% by weight of the GGBFS plus CaO and evaluating the hydration characteristics using TGA and FTIR analyses. Results indicated that increased NCF content improved the establishment of hydration products, as shown by a rise in the heat of hydration. Microstructural analyses revealed hydration products forming on and near the NCF surfaces, attributed to internal curing. Additionally, the compressive and tensile capacity was either maintained or slightly improved with the incorporation of NCFs.

Lee et al. [28] evaluated how steel fiber shape and aspect fraction affect the bond and tensile characteristics of cement-less UHPC alkali-activated concrete. Hooked-end fibers resulted in the maximum bond capacity, while straight fibers with a length-to-diameter fraction of 97.5 offered the best tensile response, including the highest capacity (12.29 MPa) and strain energy density (55.24 kJ/m³). Straight fibers also improved tensile capacity more effectively than hooked-end fibers. Dahal et al. [16] introduced a novel method for creating cement-less UHPC by activating GGBFS with CaO and using calcium formate (CF) as an accelerator. CaO (5% by weight) activated GGBFS, while CF was added at up to 6% by weight. Findings revealed that CF improved mechanical characteristics up to 5% by weight, with all samples achieving compressive strength over 150 MPa. Tensile coupon tests showed a strain-hardening response analogous to traditional UHPC. Increased hydration products and refined pore sizes enhanced mechanical characteristics, and the life cycle assessment demonstrated closely 70% lower CO_2 emissions when compared to cement-based UHPC. This approach offers a promising route for sustainable UHPC development.

According to Swathi & Vidjeapriya [29], research on UHPC alkali-activated concrete was limited before 2019 compared to normal capacity and high-performance geopolymer concrete. Till now, there has been a notable increase in this domain, focusing on cement-less UHPC using alkali-activated GGBFS, FA, and SF. Qian et al. [30] developed cement-less UHPC and employed steam curing at varying temperatures to ascertain the mechanical, durability, permeability, and microstructure. It was reported that a temperature between 60° and 80° Celsius was critical to obtain the optimum compressive and flexural strength. Wang et al. [31] compared UHPC and cement-less UHPC. They showed that cement-less UHPC demonstrated up to 61.6% greater compressive strength than UHPC while reducing chloride penetration depth by up to 44.8%. Moreover, strength-normalized CO_2 emissions and cost were reduced by up to 86.0% and 33.0%, respectively. Recently, Xu et al. [32] and Aghaee & Khayat [33] employed Convolutional Neural Networks to predict the compressive strength of cement-less UHPC. Yang et al. [34] produced multifunctional UHPC deriving from Tailoring Chemical Reaction Pathways.

Recent experimental studies on cement-less UHPC have primarily focused on optimizing mix design parameters, including the use of alkali-activated binders such as GGBFS, FA, and SF, as well as the role of steel and polymer fibers in enhancing mechanical performance. Several studies have reported compressive strengths exceeding 150 MPa, with steel fiber content and geometry playing a dominant role in tensile strength and fracture behavior. Other investigations have examined the influence of curing regimes, water-to-binder ratios, and sand-to-binder proportions on fresh and hardened properties. While these studies demonstrate the technical feasibility of cement-less UHPC, they are largely conducted at the material level and remain dispersed across different research themes.

Despite these advancements, the existing literature reveals notable gaps. Research efforts are predominantly concentrated on short-term mechanical performance, whereas critical aspects such as durability, fire resistance, corrosion behavior, bond performance with steel reinforcement, and structural response under flexural and shear loading remain insufficiently explored. Moreover, no study has systematically quantified the evolution of research trends, identified dominant contributors, or mapped emerging research directions specific to cement-less UHPC. To address this limitation, the present study adopts a scientometric approach, enabling an objective and quantitative assessment of the existing body of literature. By integrating bibliometric mapping with a focused technical discussion, this work provides a comprehensive overview of research development and identifies priority areas for future investigation.

The remainder of this paper is organized as follows. Section 2 outlines the research significance of cement-less UHPC. Section 3 describes the scientometric methodology, including the data collection process, screening criteria, and bibliometric mapping approach. Section 4 presents the results of the scientometric analysis, covering publication trends, keyword co-occurrence, leading journals, influential authors, and contributing countries. Section 5 provides a detailed technical discussion linking scientometric findings with experimental evidence on mix design, curing regimes, and key material parameters. Section 6 highlights future research directions based on identified knowledge gaps, and Section 7 summarizes the main conclusions of the study.

The concept of producing cement-less UHPC is relatively recent, with significant research emerging primarily over the past five to ten years. Given the distinct advantages of cement-less UHPC compared to traditional cement-based UHPC, it is crucial to explore and identify the areas where further research is required. While cement has a long history and its response in terms of durability, fire, and corrosion endurance has been extensively studied, it is essential to determine whether cement-less UHPC has demonstrated comparable potential in these aspects beyond its mechanical properties. The target of this study is to pinpoint these research gaps in cement-less UHPC to ensure that its full performance potential is realized and optimized.

2. Methodology

This work conducted a scientometric study to review the existing research on cement-less UHPC [35]. The study delivered an in-depth review of the state-of-the-art research issues within this field. The choice to employ a scientometric assessment was driven by the recognition that previous construction studies often indicated that relying exclusively on subjective evaluations could yield inconsistent results. This highlights the need for a more objective and systematic method for reviewing research [36]. Previous research has shown that using scientometric analysis can help mitigate subjectivity and bias [37, 38]. This study seeks to offer a thorough overview and a mixture of research conducted over the past ten years on the subject. To accomplish this, it employs bibliometric data and mapping techniques to quantify research advancements and identify connections between various works, yielding a robust quantitative evaluation.

It is important to note that work on cement-less UHPC is relatively scarce. A thorough scientometric assessment was carried out by searching the Scopus database for studies related to the use of geopolymer binders in cement-less UHPC production. The search was conducted via Scopus because of its massive database of abstracts and citations, making it among the largest and most comprehensive scholarly databases accessible [39]. The search was performed using the keywords ("cement-less" AND "UHPC") OR ("cement-less" AND "UHPC") OR (" geopolymer " AND " UHPC") OR "ultra-high-performance geopolymer concrete" OR "UHPGC").,' yielding a total of 113 documents. Importantly, all of these documents were published after 2014. This means that the concept of cement-less UHPC is still evolving. Furthermore, the filter of "Article" and language of "English" were selected that narrowed down the total number to 79. Table 1 illustrates the search refinement process and the corresponding number of documents. It is noteworthy that several researchers used the word "geopolymer" for UHPC that partially replaced OPC with alternate geopolymer binders. Therefore, the mix design of all 79 documents were carefully checked. Due to the overlapping terminology used in the literature, the initial keyword search yielded a number of false positives, particularly studies in which ordinary Portland cement was only partially replaced by SCMs. To address this issue, a two-stage screening process was adopted. In the first stage, titles and abstracts were manually reviewed to identify studies explicitly claiming full cement replacement or the use of alkali-activated or geopolymer binders in UHPC. In the second stage, the full texts of the shortlisted articles were carefully examined, with particular attention to mix design tables, binder composition descriptions, and experimental methodology. Studies were excluded if any amount of Portland cement was present in the binder system, regardless of replacement level. Only studies employing 100% cement-free binder systems were retained for the final dataset. Thus, a total of 59 articles were utilized for the scientometric review.

Table 1. Scopus database was searched on 31st July 2024

Result Refiner	Boundaries	Number of Documents
Title-Abstract-Keywords	-	113
Year	2014-2024	113
Subject Area	Engineering, Material Science	107
Document Type	Article	80
Language	English	79
Must Fully Replace OPC	-	59

Keywords: Best key word combination for Cement-less UHPC literature search - TITLE-ABS-KEY ("cement-less" AND "UHPC") OR ("cement-less" AND "UHPC") OR ("geopolymer" AND "UHPC") OR "ultra-high-performance geopolymer concrete" OR "UHPGC").

This study relies exclusively on the Scopus database, which was selected due to its extensive coverage of peer-reviewed journals in engineering and materials science, as well as its compatibility with bibliometric analysis tools such as VOSviewer. While other databases, including Web of Science, may contain additional relevant publications, previous studies [35, 36, 38] have shown that Scopus and Web of Science exhibit substantial overlap in high-impact journals within the field of construction materials. As a result, the exclusion of other databases may lead to the omission of a limited number of publications, but is unlikely to significantly alter the identified publication trends, keyword structures, or leading contributors. Nevertheless, future scientometric studies could benefit from multi-database integration to further enhance completeness and cross-validation of results.

After the compilation of the database, a series of analyses were performed to discover different facets of the gathered data. For this purpose, VOSviewer was used, a software tool renowned for its versatility. VOSviewer allows for the creation, visualization, exploration, and presentation of bibliometric data in a clear and accessible manner [40]. From VOSviewer, the data input kind was configured to 'create a map from bibliographic data.' Following that, various constraints were assessed and analyzed, as follows. Figure 1 shows the flowchart of the adopted methodology.

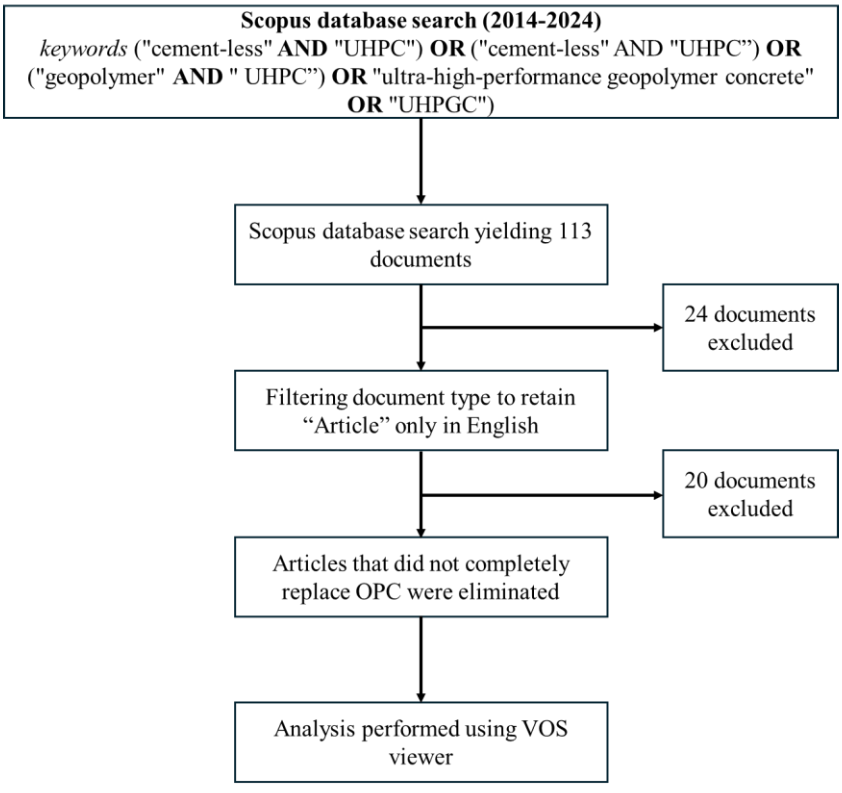

Figure 1. Flowchart of the methodology adopted

3. Findings from Scientometric Review

3.1. Yearly Trend of Publications

The yearly record of publications on cement-less UHPC is shown in Figure 2. Particularly, the years 2022-24 experienced a surge in exploring the potential of cement-less UHPC, with 21 publications each in the years 2022 and 2023. The trend seems to be escalating this year as 20 publications have already been made by researchers at the halfway point of 2024. A potential reason behind this increase lies in the heightened awareness of its optimistic effects on the sustainable environment, besides various other contributive factors. This emphasizes that researchers have identified the need to look for alternate geopolymer binders, given the extremely hazardous-to-the-environment process adopted during the manufacturing of cement. Furthermore, the division of articles by research domains is shown in Figure 3. It may be observed that over 90% of the articles concerning the utilization of cement-less UHPC fall under the categories of Engineering and Materials Science.

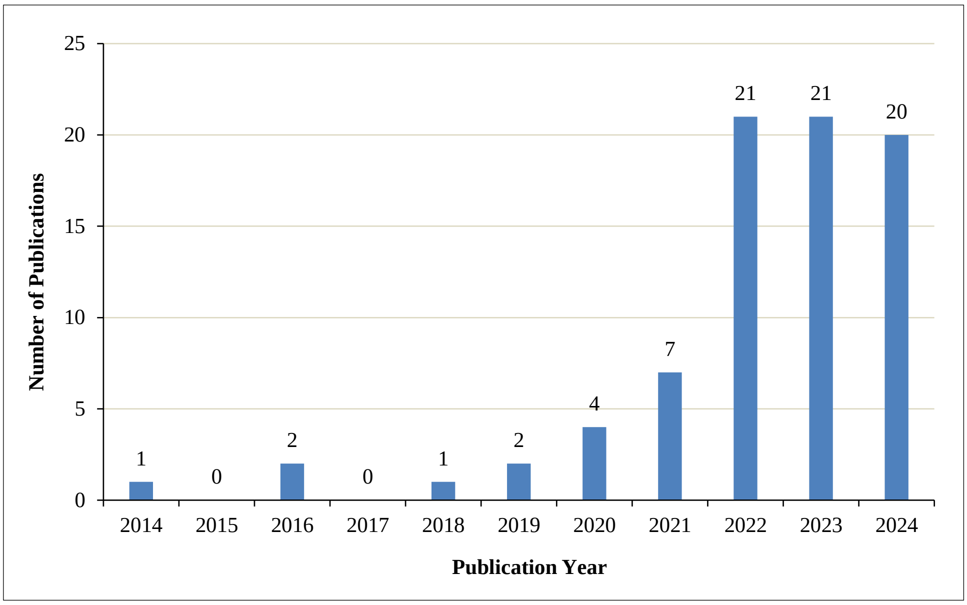

Figure 2. Year-wise number of publications reported on Cement-less UHPC from 2014-2024

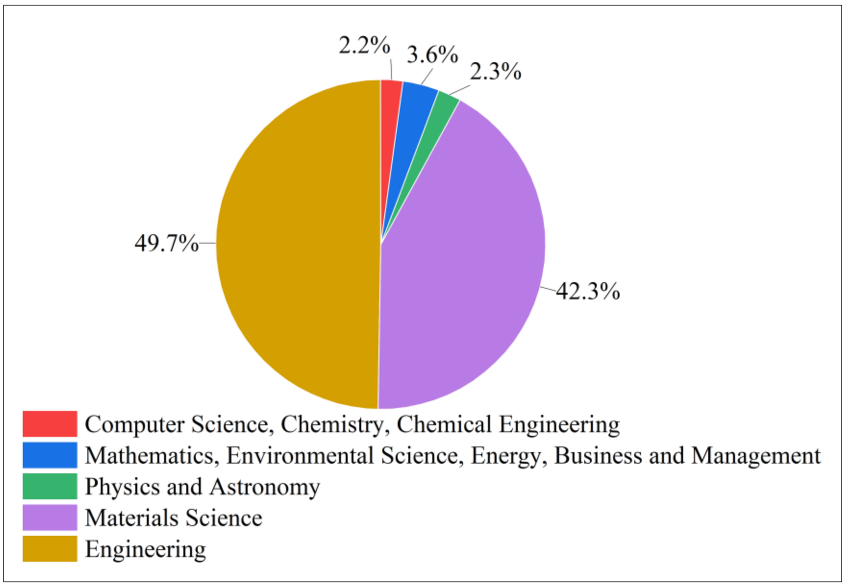

Figure 3. Pie chart expressing the area-wise publications on Cement-less UHPC

The sharp increase in publications after 2020 reflects the growing urgency to reduce carbon emissions associated with conventional cement-based UHPC. This trend coincides with increased global emphasis on sustainable construction materials and the wider acceptance of geopolymer and alkali-activated systems. The sustained publication rate in recent years suggests that cement-less UHPC is transitioning from a niche research topic toward a recognized research domain, although the relatively short publication history indicates that many fundamental aspects could remain unresolved.

3.2. Frequently Used Keywords

Keywords highlight the main theme of a research area, showing what the contents focus on Su & Lee [41]. In this work, the most frequently utilized keywords were recognized from VOSviewer and are listed in Table 2. Notable keywords include geopolymers, compressive strength, steel fibers, and mechanical properties. Previous research on producing cement-less UHPC has usually focused on its mechanical properties. Moreover, the occurrence of steel fibers in mostly used keywords suggests that steel fibers are predominantly used in the production of cement-less UHPC. Furthermore, geopolymer binders like GGBFS and SF have replaced cement in cement-less UHPC primarily. It is noteworthy that so far, researchers have focused on the mechanical properties of cement-less UHPC, such as compressive strength and tensile capacity. Figure 4 presents a pictorial representation of the highly utilized keywords depending on their number of utilizations, frequency, and link strength. The link strength attribute signifies the overall strength of a researcher's co-authorship network with other researchers [40]. The size and position of all nodes indicate their frequency and occurrence, whereas the thickness of the lines connecting the nodes reflects the capacity of their relationships. This visualization proves the frequency of keywords listed in Table 2. As an instance, the keywords "compressive strength," " High Performance Concrete," and " Geopolymers " are more central in the network compared to others. Recognizing the highly utilized keywords in a field aids future researchers in selecting relevant and impactful keywords for their studies. This improves the discoverability and visibility of their study, rendering it more accessible for other researchers to recognize and cite. On one side, the mapping in Figure 4 is representative of the highly focused areas, it also presents useful information on areas in the domain of cement-less UHPC that still lack investigation. For example, the absence of keywords like durability, fire endurance, corrosion resistance, and other keywords related to structural applications of cement-less UHPC presents notable missing applications/properties of cement-less UHPC that still need attention.

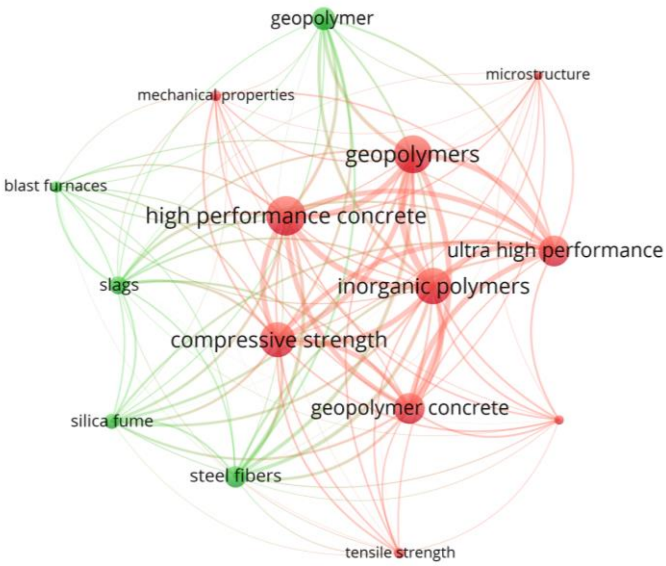

Figure 4. Scientometric mapping of the most commonly occurring keywords related to Cement-less UHPC

Table 2. Top 15 mostly occurred words in title, abstract, and keyword

No.	Keywords	Number of Occurrences	Total Link strength
1	Geopolymers	42	283
2	Inorganic Polymers	41	277
3	High Performance Concrete	44	275
4	Compressive Strength	39	253
5	Geopolymer Concrete	34	247
6	Ultra-High Performance	34	244
7	Steel Fibers	24	162
8	Geopolymer	26	138
9	Silica Fume	17	137
10	Slags	20	134
11	Ultra-High Performance Geopolymer Concrete	11	90
12	Blast Furnaces	13	87
13	Mechanical Properties	12	86
14	Tensile Capacity	12	79
15	Microstructure	10	68

The dominance of keywords related to compressive strength, steel fibers, and mechanical properties indicates that research on cement-less UHPC remains primarily material-driven. In contrast, the limited occurrence of keywords related to durability, fire resistance, corrosion performance, and structural applications highlights significant research gaps. This imbalance suggests that while early studies have focused on demonstrating feasibility and strength potential, the long-term performance and practical implementation of cement-less UHPC in real structures have not yet been sufficiently addressed. Although the keyword co-occurrence analysis presents cumulative frequencies, examination of publication years associated with highly recurrent keywords reveals a clear temporal evolution of research focus. Early studies (2014–2017) predominantly emphasized feasibility-related terms such as geopolymer, compressive strength, and alkali-activated materials, reflecting efforts to demonstrate ultra-high-strength potential without Portland cement. From 2018 onward, keywords related to steel fibers, fracture behavior, and microstructure became more prominent, indicating a shift toward performance enhancement and reinforcement efficiency. In more recent years (2021–2024), emerging keywords such as sustainability, packing density, sand-to-binder ratio, and durability-related properties have shown increasing occurrence, suggesting a gradual transition from proof-of-concept studies toward optimization and application-oriented research. This temporal progression highlights the maturation of cement-less UHPC research and underscores the need for future studies focusing on long-term performance and structural implementation.

3.3. Top Publication Journals

Assessing a journal's effect within a particular domain assists researchers in locating the most credible information and enables researchers to recognize journals that are well-suited for publishing their work [42]. The joint link strength of a scholarly source to other peer-reviewed sources, including its quantity of published articles and citation number, together reflect the journal's overall effect. The journal of Construction and Building Materials published 15 articles related to cement-less UHPC, demonstrating a total link strength of 302. It is noted that despite publishing the highest quantity of articles, Construction and Building Materials is placed third in terms of total citations achieved. The journal of Cement and Concrete Composites demonstrated 621 citations with four articles, followed by the journal Case Studies in Construction Materials with five articles and 342 citations.

Journals with the most publications are graphically networked in Figure 5. The node size associated with each journal is indicative of the number of publications related to this field. Greater nodes, like those for Construction and Building Materials, Cement and Concrete Composites, and Journal of Building Engineering, specify a greater impact and influence in this particular research area. Clusters are created by examining the domain of research channels or the frequency of their co-references in scholarly works [43]. The links connecting the research resources indicate the quantity of documents in the current research area that attribute co-citations [44]. A greater link strength between two nodes signifies that the journals are often referenced together within the same academic publication. Additionally, the closer the two nodes are to each other, the more often they have been cited together. In this case, the journals seem to be equidistant.

Figure 5. Scientometric mapping of sources based on the number of articles published

The concentration of publications in journals such as Construction and Building Materials and Cement and Concrete Composites reflects the materials-oriented nature of current research on cement-less UHPC. However, the relatively lower presence of structural engineering journals suggests that the transition from material development to full-scale structural application is still limited. This observation further reinforces the need for future studies focusing on reinforced members, structural behavior, and design-oriented investigations. The discrepancy between publication volume and citation impact observed among journals highlights an important distinction between research quantity and influence. Journals such as Cement and Concrete Composites achieve high citation counts despite publishing fewer articles on cement-less UHPC, which can be attributed to their strong emphasis on fundamental material science, high selectivity, and publication of conceptually influential studies that are widely cited across related fields. In contrast, journals with higher publication volumes often serve as broader dissemination platforms, accommodating a wider range of experimental investigations with varying citation lifespans. This pattern suggests that while high-output journals play a critical role in advancing and diversifying the field, high-impact journals disproportionately shape research directions by publishing fewer but more influential contributions (see Table 3).

Table 3. List of journals with at least three articles on Cement-less UHPC

No.	Sources	Document	Citation	Total Link strength
1	Construction and Building Materials	15	244	302
2	Journal of Building Engineering	8	175	209
3	Case Studies in Construction Materials	5	342	181
4	Cement and Concrete Composites	4	621	149
5	Structures	3	92	65

3.4. Top Contributing Authors

In this section, a list of authors with a minimum of five publications on cement-less UHPC is discussed, as shown in Table 4. Based on the analysis, 15 authors passed this threshold. The top three authors with the most publications were Xu Shenchun, Liu Jian, and Wu Chengqing with 10, 8, and 8 publications, respectively. Xu Shenchun has notable works on the development of mix design of cement-less UHPC using alkaline activators [45], exploring experimental and numerical bond behavior between cement-less UHPC and steel reinforcement [46], exploring the endurance of cement-less UHPC against sodium sulfate attack [47], experimental and numerical studies on the response of multi-layer protective slabs made with cement-less UHPC [48], and investigating the behavior of cement-less UHPC against contact projectile penetrations [49] and contact explosions [1, 50]. The works by Liu Jian focused on experimental study on the impacts of heating and cooling on the mechanical characteristics of cement-less UHPC subjected to elevated temperatures [51], and 3D meso-scale modeling of cement-less UHPC with ceramic ball coarse aggregates, subjected to high-velocity projectile impacts at normal incidence. It is noted that these three authors co-authored many publications and, therefore, are ranked among the top authors. The author Abdellatief Mohamed also worked on the mechanical performance, microstructural analysis, and ecological assessment of cement-less UHPC [52], studied the fresh properties of cement-less UHPC [53], and utilized industrial wastes for its production [54].

Table 4. Top contributing authors on Cement-less UHPC

No.	Authors	No. of Articles	Citation	Average Citation	Total link strength
1	Xu, Shenchun	10	234	23	2795
2	Liu, Jian	8	220	27	2484
3	Wu, Chengqing	8	197	25	2294
4	Su, Yu	7	213	30	2220
5	Pyo, Sukhoon	6	27	4	673
6	Yuan, Pengcheng	6	102	17	1559
7	Abdellatief, Mohamed	5	133	27	462
8	Dai, Jian-Guo	5	280	56	2114
9	Huang, Bo-Tao	5	301	60	2532
10	Lao, Jian-Cong	5	301	60	2532
11	Li, Jun	5	190	38	1681
12	Liu, Zhongxian	5	178	36	1640
13	Oinam, Yanchen	5	27	5	626
14	Tahwia, Ahmed M.	5	225	45	344
15	Xu, Ling-Yu	5	301	60	2532

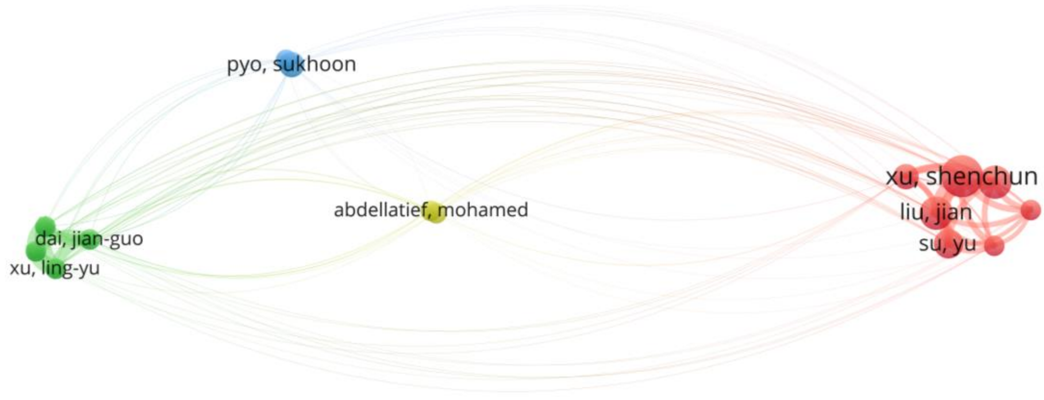

Figure 6. Scientometric mapping of authors with at least five publications on Cement-less UHPC

3.5. Top Cited Articles

In this section, articles on cement-less UHPC with a minimum of 50 citations are presented, as shown in Table 5, where a link refers to a connection or correlation between two entities [40]. The work Liu et al. [55] received 217 citations and examined the impact of steel fiber and SF on the mechanical and fracture characteristics of cement-less UHPC. Four levels of steel fiber (0%, 1%, 2%, and 3%) and four SF contents (5%, 10%, 20%, and 30%) were evaluated. Results showed that growing steel fiber improved the mechanical and fracture performance but reduced workability, while SF's effects were more complex: 10% increased flowability but decreased mechanical performance, whereas 20% and 30% enhanced it. Additionally, empirical equations for predicting elastic modulus did not accurately estimate cement-less UHPC values, though some formulas for splitting tensile capacity were applicable. Liu et al. [56] received 174 citations and developed cement-less UHPC by reducing its brittleness using various steel fibers. Testing included straight fibers with numerous aspect fractions and deformed fibers, focusing on flowability, compressive strength, and flexural response. Increased fiber content and smaller diameter enhanced mechanical capacity, but flowability decreased. Straight fibers were more effective than corrugated ones, and a new predictive model for cement-less UHPC showed better accuracy than previous ones.

Wetzel & Middendorf [23] received 149 citations and optimized cement-less UHPC using GGBFS, potassium waterglass, and potassium hydroxide. SF and metakaolin enhanced packing density, while quartz sand and powder were used as aggregates. Results showed that increasing SF improved rheological properties, achieving a water-to-binder (W/B) fraction below 0.25. The material's compressive strength was comparable to UHPC, and substituting some slag with metakaolin reduced capillary porosity. Good workability was achieved without superplasticizers by adjusting SF levels. The work by Ambily et al. [22] has been discussed in the Introduction. Aisheh et al. [57] examined cement-less UHPC with micro silica, GGBFS, polypropylene fibers, and steel fibers. The findings showed polypropylene fibers improved mechanical properties when combined with steel fibers, while steel fibers alone reduced capacity but enhanced durability. Kathirvel & Sreekumaran [58] developed cement-less UHPC with GGBFS and SF, activated with sodium hydroxide and sodium silicate. The study assessed the impact of varying GGBFS and SF levels, quartz powder, and steel fibers on flow and compressive strength. Results showed that these additions significantly improve capacity, with SF, quartz powder, and steel fibers playing key roles. Statistical analysis confirms that experimental results align with predictions and that UHPGC is more sustainable compared to traditional cement concrete. Lao et al. [59] noted that the presence of straight steel fibers caused significant tensile strain hardening of cement-less UHPC. Increasing the FA-to-GGBFS fraction and steel fiber content improved tensile capacity, with ductility between 0.35% and 0.55% and minimal crack widths of 10–20 μm. SEM analysis confirmed a strong bond between the cement-less UHPC matrix and steel fibers, providing a solid basis for designing cement-less UHPC with enhanced tensile properties.

Tahwia et al. [60] evaluated the impact of waste materials on cement-less UHPC. Ten specimens incorporated crushed glass (CG), ceramic (CC), and crumb rubber (CR) at volumes of 7.5%, 15%, and 22.5% as partial substitutes for fine aggregate. Flowability, setting time, and mechanical properties were measured, and microstructure and porosity were evaluated using SEM and Mercury intrusion porosimetry (MIP). Findings showed that while 7.5% CC and CR reduced mechanical and microstructural properties, increasing CG content improved them. Mousavinejad & Sammak [61] developed cement-less UHPC with GGBFS, SF, and steel and polypropylene fibers. Results revealed that polypropylene fibers improved the mechanical and durability characteristics when combined with steel fibers, though replacing steel fibers with polypropylene fibers decreased mechanical capacity but enhanced durability. Results reported that the current passing reduced when polypropylene fibers were combined with steel fibers compared to steel fibers alone. Tayeh et al. [62] produced mixtures using polypropylene fibers at 4 volume fractions (0%, 0.75%, 1.75%, and 2.75%) and 5 levels of microsilica (0%, 7.5%, 15%, 25%, and 35%) based on the total binder mass. Results indicated that adding 15% microsilica initially degraded the mechanical properties of cement-less UHPC, but improvements were observed with higher microsilica levels. polypropylene fibers significantly enhanced the mechanical characteristics, and a 2.75% polypropylene fibers content effectively mitigated the decline in properties caused by 15% microsilica. Xu et al. [45] investigated how sodium silicate stiffness, FA, GGBFS, Si/Al fraction, Ca/(Si + Al) fraction, and steel fiber affect the flowability and mechanical response of cement-less UHPC through flowability, compression, and flexure tests. Results showed that higher sodium silicate stiffness, GGBFS, and Si/Al fraction negatively affected flowability, while FA improved it. Compressive and flexural capacity of cement-less UHPC initially improved with greater sodium silicate stiffness, FA, GGBFS, and Ca/(Si + Al) fractions, but then decreased beyond certain levels.

Table 5. List of published articles on Cement-less UHPC with a minimum of 50 citations

No.	Document	Citations	Links
1	Liu et al. [55]	217	1
2	Liu et al. [56]	174	1
3	Wetzel & Middendorf [23]	149	8
4	Ambily et al. [22]	118	0
5	Aisheh et al. [57]	105	1
6	Kathirvel & Sreekumaran [58]	98	0
7	Lao et al. [59]	81	2
8	Tahwia et al. [60]	77	0
9	Mousavinejad & Sammak [61]	71	1
10	Tayeh et al. [62]	64	1
11	Xu et al. [45]	58	1

3.6. Countries with Most Research on Cementless-UHPC

Table 6 presents countries with a minimum 5 articles in this domain. It was observed that the authors with the most publications in this domain were Chinese. This is reflected in Table 6 where the largest number of documents belonged to China at 29. This was followed by Australia and Egypt with 14 and 9 publications, respectively. Figure 7 shows the scientometric mapping of countries that participated the most in articles on cement-less UHPC.

Table 6. Countries that participated most considering articles on Cement-less UHPC

No.	Country	Document	Citation	Total link strength
1	China	29	1022	1821
2	Australia	14	530	1351
3	Egypt	9	311	544
4	South Korea	6	27	477
5	Iran	5	118	196
6	United States	5	172	917

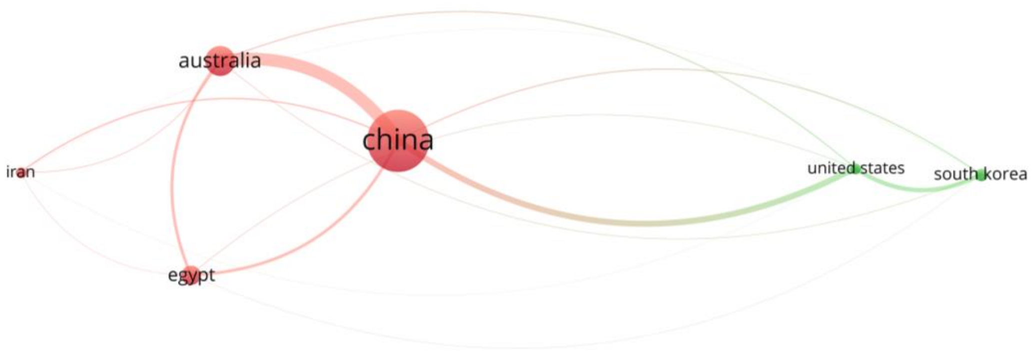

Figure 7. Scientometric mapping of countries that contributed most in terms of articles on Cement-less UHPC

The strong contribution from China and Australia reflects national research priorities related to sustainable construction and industrial by-product utilization. Countries with significant steel production and slag availability appear to be more actively involved in cement-less UHPC research. However, the limited participation from developing regions suggests potential opportunities for expanding research considering local materials and region-specific sustainability challenges.

4. Discussion on Cement-Less UHPC

4.1. Mix Design

Cement-less UHPC is typically produced using a specific mix design that replaces traditional Portland cement with AAMs. The binders commonly utilized in cement-less UHPC include GGBFS, FA, and metakaolin. These binders are activated with alkali solutions like sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), or their potassium counterparts. Aggregates, including fine materials like sand and quartz powder, are incorporated into the mix. To enhance performance, steel fibers and polypropylene fibers may be added. The mix design is carefully proportioned, typically with a low W/B fraction to achieve high capacity and durability. The mixing process involves high-energy mixers to ensure a uniform blend, followed by curing under controlled conditions to develop the desired properties. Table 7 provides mix designs adopted for cement-less UHPC by various researchers. It is observed that the most used binders are GGBFS, SF, and FA, whereas most of the authors used steel fibers to produce cement-less UHPC. The important point is the W/B value that ranges from 0.20 to 0.36. This extremely low W/B fraction is really important to achieve the dense packing required for UHPC. Earlier research in this area has utilized a two-part system involving alkali mixture. Some studies also used a binary binder structure, replacing FA or metakaolin with GGBFS. Because of GGBFS's latent hydraulic reactivity, an alkali-based activator is necessary to achieve efficient bonding.

Table 7. Mix designs for Cement-less UHPC adopted by various researchers

Reference	Binder	Activator	W/B Fraction	S/B Fraction	Fiber Type	Fiber (%)	Compressive Strength (MPa)
Liu et al. [55]	GGBFS, SF, FA	Na_2SiO_3, K_2CO_3	0.30	0.83	BF, StF	2, 1	< 120
Liu et al. [56]	GGBFS, SF, FA	NaOH, Na_2SiO_3	-	-	StF	0.6, 1.2, 1.8	153
Wetzel & Middendorf [23]	GGBFS, SF, MK	NaOH, KOH, K_2SiO_3, Na_2SiO_3	0.25	-	-	-	141.6-178.6
Ambily et al. [22]	GGBFS, FA, SF	NaOH, KOH, K_2SiO_3, Na_2SiO_3	0.32	1.5, 1.0	StF	1, 2, 3	131.5-170.4
Aisheh et al. [57]	GGBFS, MS	NaOH, Na_2 SiO_3	-	0.73-0.74	PF, StF	0.25, 1-2.25	
Kathirvel & Sreekumaran [58]	GGBFS, SF	NaOH, Na_2SiO_3	-	1.2	StF	1-2	100-150
Lao et al. [59]	GGBFS, FA, SF	Na_2SiO_3,WG	0.2	0.65	StF	2-4	162-22
Tahwia et al. [60]	GGBFS, SF	KOH, Na_2 SiO_3	0.35	1.34	StF	1-3	90-160
Mousavinejad & Sammak [61]	GGBFS, SF	NaOH, Na_2 SiO_3	-	0.73	StF, PF	2, 0.25	112-150
Tayeh et al. [62]	GGBFS, FA, MS	NaOH, WG	0.34	-	PF	0-2.75	155-180
Xu et al. [45]	GGBFS, FA, SF	NaOH, waterglass	0.32	-	StF	1-2	83-160

Note: SF, FA, MK, and MS stand for silica fume, fly ash, metakaolin, and micro silica, respectively; BF, StF, and PF stand for basalt fibers, steel fibers, and polypropylene fibers, respectively; W/B is the W/B fraction, and S/B is the sand-to-binder fraction; and WG stands for waterglass.

The observed variability in mix design parameters across studies reflects the absence of a unified design philosophy for cement-less UHPC. Unlike conventional UHPC, where optimized particle packing and standardized cementitious compositions are well established, cement-less UHPC [63] relies heavily on the reactivity of alternative binders and the chemistry of activators. This dependence results in a narrow workable range for water-to-binder ratios and sand-to-binder fractions, making the mix design highly sensitive to minor compositional changes. Consequently, the reported high compressive strengths are often achieved under tightly controlled laboratory conditions, which may limit direct scalability to field applications.

4.2. Effect of Curing Conditions

Zhang et al. [64] selected 3 common curing methods for enhancing cement-less UHPC, including ambient, standard, and hybrid curing, to explore their impacts on the material characteristics of cement-less UHPC. In ambient curing, samples were kept in laboratory environments after removing molds until the testing day. In standard curing, specimens were maintained at 20 ± 2°C with a relative humidity over 95% till the test day. In hybrid curing, samples were initially placed in a steam-curing tank at 90°C for 48 hours after removal from molds, then transferred to the ambient environment for the remainder of the curing period. As illustrated in Figure 8, the presence of steel fibers did not influence the impact of the curing regime. Notably, compressive strength at three days under hybrid curing can reach the capacity attained after 28 days of standard curing. Similarly, the flexural capacity of cement-less UHPC after hybrid curing was exceptionally greater than other curing regimes, as illustrated in Figure 8-b. Zhang et al. [64] studied pore structure alteration under these curing regimes. It was shown that the cumulative pore volume under the hybrid curing regime was the least. As a result, maximum microstructural compactness was observed under hybrid curing.

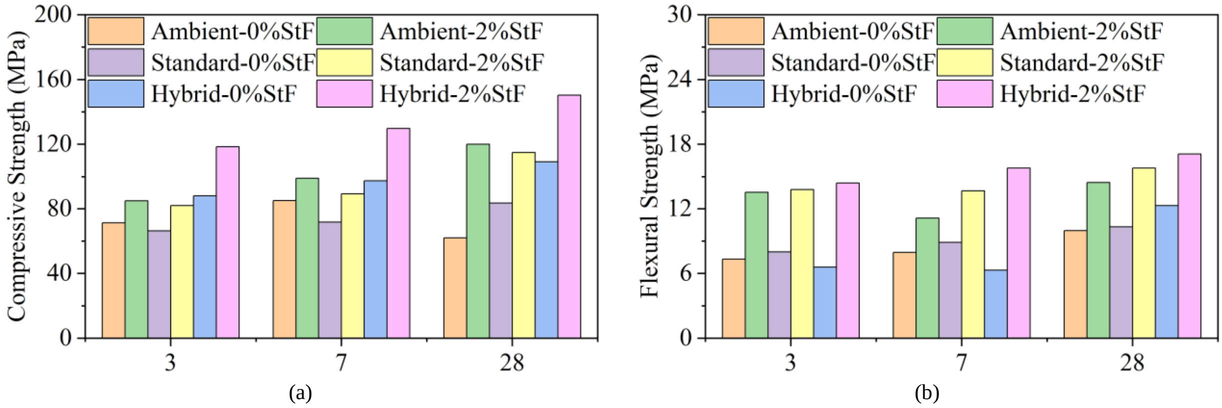

Figure 8. Impact of curing regimes on mechanical characteristics of Cement-less UHPC: (a) compressive strength, and (b) flexural capacity [64]

Tahwia et al. [60] explored the effect of curing on compressive strength utilizing four main conditions: water, ambient, heat curing at 80 degrees Celsius for 24 hours, and autoclave curing at 90 ± 5 degrees Celsius for 48 hours. In ambient curing, specimens were kept in the ambient environment in the laboratory. Specimens were cured for a 28-day period in both water and ambient curing. After this period, some air-cured samples were transferred to an oven at 80°C for 24 hours, while the remaining samples were kept in an autoclave to assess the effects of temperature on the compressive strength of cement-less UHPC. Heat and autoclave curing methods significantly enhanced compressive strength. The capacity is affected by the binder response, curing method, and the reaction between steel fibers and the matrix. Autoclave curing, in particular, enhanced the geopolymerization magnitude and microstructure of the concrete [60]. Higher curing temperatures lead to increased compressive strength, with thermal curing improving capacity by 6.35% and autoclave curing by 10.42% compared to ambient conditions, and by 9.45% and 14.43% related to normal curing, as shown in Figure 9.

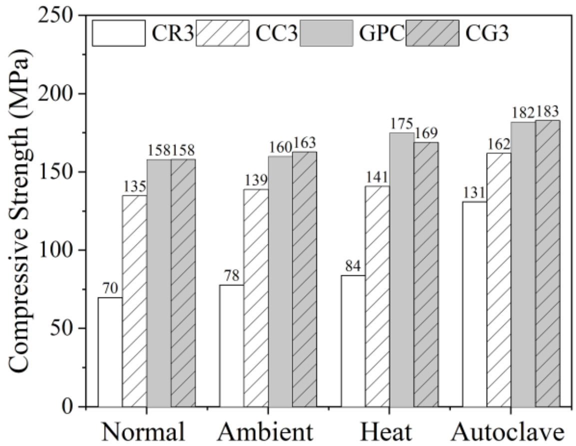

Figure 9. Impact of four different curing conditions on compressive strength of Cement-less UHPC [60]

Liu et al. [56] employed 2 different curing regimes in their work: steam curing at 80°C and standard curing at 20°C. The particular stages of the curing conditions were as follows: First, samples were pre-cured inside the molds for 24 hours at a laboratory room temperature of 20°C and a relative humidity (RH) of 65 ± 5%, covered with a plastic film to prevent water loss. Then, the specimens were taken out of molds and cured in two ways: (1) standard curing, where specimens were kept in a room at 20 ± 1°C and RH of 100% for another 27 days, and (2) steam curing, where specimens were cured in steam at 80 ± 1°C for 24 hours. For cement-less UHPC reinforced with 6-mm long plain steel fibers, curing using steam usually enhanced both compressive and flexural capacity related to 28-day curing at standard curing. Nonetheless, the magnitude of this improvement differed depending on the kind and dimensions of the steel fibers used.

The impact of heat curing on the compressive strength is summarized in Table 8. Zhang et al. [64] performed a hybrid curing, i.e., an additional ambient curing that followed the initial heat curing at 90° for 48 hours. It is seen that the compressive strength after hybrid curing improved by 31.16% over that of standard curing. The works by Tahwia et al. [60] and Liu et al. [56] reported the improvement after heat curing by up to 13.31% and 5.73%, respectively. It is noted that the impact of heat curing is limited to 14%, unless a hybrid curing is adopted. The difficulty in employing heat curing at large-scale manufacturing of cement-less UHPC cannot be ignored. Therefore, ambient curing can be adopted in practical applications, as the difference is limited to 14%.

Table 8. Impact of heat curing on the compressive strength of Cement-less UHPC

Reference	Heat Curing Parts		Improvement in Compressive Strength Over Standard Curing (%)
	Initial	Subsequent	
Zhang et al. [64]	Heat curing at 90° for 48 hours	Ambient curing till testing	31.16
Tahwia et al. [60]	Heat curing at 80° for 24 hours	None	13.31
Liu et al. [56]	Heat curing at 80° for 24 hours	None	5.73

The pronounced influence of heat and hybrid curing on early-age strength development can be attributed to accelerated geopolymerization and enhanced dissolution of aluminosilicate phases. Elevated temperatures promote the formation of a denser reaction product network, reducing capillary porosity and improving load transfer between the matrix and fibers. However, the marginal long-term strength gains observed beyond certain curing thresholds suggest that excessive thermal curing may primarily accelerate early reactions rather than fundamentally alter ultimate reaction products. This finding highlights the need to balance performance enhancement with practical and energy-related constraints.

4.3. Effect of W/B Ratio

Zhang et al. [65] studied the impact of moisture magnitude on the macro-characteristics, hydration process, and micro-process of the fabricated cement-less UHPC. The hydration process of the fabricated cement-less UHPC was cautiously studied. It was observed that reducing the W/B ratio increases the chain length and hydration magnitude of the polymer. When the W/B value is about 0.30, the magnitude of hydration goes up to 62.58%, and the longest molecular chain length of the polymer is approximately 4.74. The microstructure tests indicated that a lower moisture content results in a more compact structure. Specifically, the porosity is 3.32% with a W/B ratio of 0.29, compared to 3.99% with a ratio of 0.32. The experimental findings demonstrated that both the fresh performance and macroscopic mechanical characteristics of cement-less UHPC improve at lower moisture content, with the compressive strength at 28 days reaching a peak of 118 MPa at a W/B ratio of 0.30. Bahmani & Mostofinejad [66] found that the mechanical characteristics of cement-less UHPC can be significantly increased by decreasing the W/B fraction. Specifically, reducing this ratio from 0.4 to 0.25 yielded an improvement in compressive strength from 70 MPa to 200 MPa, an enhancement of about 130 MPa. This improvement was also observed in cement-less UHPC reinforced with polyethylene fibers, where decreasing the W/B ratio from 0.38 to 0.26 led to a tensile strain increase of approximately 39%. Enhancing the W/B ratio raises the amount of unreacted water in the SCM and reduces the intensity of the alkaline activator, resulting in a decreased concentration of alkali activator and less interaction among alkaline ions and metal cations in the mineral powder. This slows the reaction speed and leads to a reduction in compressive strength. The impact of W/B ratio on the initial setting time and compressive strength is shown in Table 9. Zhang et al. [65] noted an enhancement of 15 minutes in the initial setting time as the W/B ratio was enhanced from 0.28 to 0.32. Huang et al. [67] reported a similar increase of 4 minutes as the W/B ratio enhanced from 0.20 to 0.25.

Table 9. Effect of W/B ratio on the compressive strength and initial setting time of Cement-less UHPC

Reference	W/B Fraction	Compressive Strength (MPa)	Initial Setting Time (minutes)
Zhang et al. [65]	0.28	114.46	12
	0.32	107.75	27
Huang et al. [67]	0.20	97.53	13
	0.25	89.45	17
Wetzel & Middendorf [23]	0.25	200.00	-
	0.40	70.00	-

4.4. Effect of Sand/Binder Ratio

Kim et al. [68] ranged sand-to-binder (SB) ratios from 0.16 to 0.80 in cement-less UHPC. The packing density and compressive strength of the cement-less UHPC increased with the SB fraction up to 0.8, reaching a maximum density of 0.79 and a compressive strength of 159 MPa at this fraction. Additionally, tensile performance improved with a higher SB fraction, with the best results being a tensile capacity of 10.1 MPa, an ultimate strain of 0.83%, with a strain energy density of 55 kJ/m³. Kim et al. [69] utilized SB fractions of 0.32 and 0.64. At a SB fraction of 0.64 along with 2% steel fibers, the compressive strength of Cement-less UHPC was reported at 159.6 MPa. This compressive strength was significantly reduced to 121.1 MPa when the SB fraction decreased to 0.32 in the presence of 2% polypropylene fibers. Kim et al. [68] found that the tensile performance of cement-less UHPC with steel fibers is strongly influenced by the bond capacity among the fibers and the mixture. Increasing the silica sand quantity improves the frictional bonding, leading to enhanced tensile capacity and strain capacity. Cement-less UHPC containing 2% steel fibers and an SB fraction of 0.8 demonstrated the optimum response. In summary, for cement-less UHPC strengthened with plain steel fibers, a greater S/B fraction (reaching 0.8) has demonstrated efficiency in increasing the compressive and tensile capacity, as well as tensile deformation. On the contrary, for cement-less UHPC strengthened with PE fibers, a smaller SB fraction positively influences tensile behavior. This validates that the effect of SB fraction on the strain-hardening tensile response of Cement-less UHPC depends on the kind of reinforcing fibers. It is seen in Figure 10 that the impact of SB fraction on the compressive strength of cement-less UHPC is significant, as observed from R^2 values in excess of 0.80.

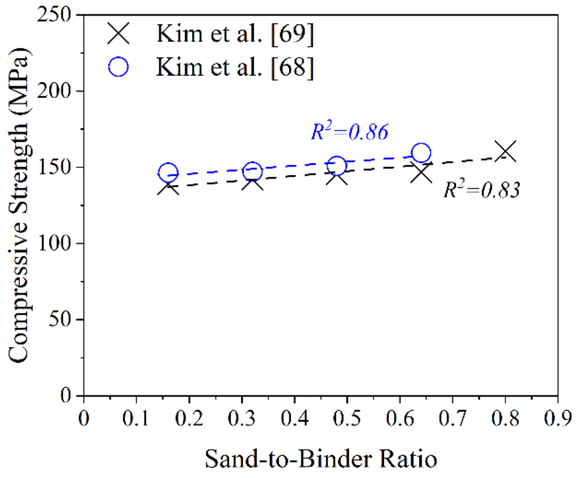

Figure 10. Effect of SB fraction on compressive strength of cement-less UHPC reported

The improvement in mechanical performance at higher SB ratios can be attributed not only to enhanced particle packing but also to improved fiber–matrix interaction. Increased sand content enhances surface roughness and frictional resistance, which strengthens fiber pull-out behavior and contributes to strain-hardening responses. However, this effect is highly dependent on fiber type and geometry, indicating that optimal SB ratios must be selected in conjunction with reinforcement strategy rather than as an isolated parameter.

4.5. Effect of Fiber Ratio

Lao et al. [59] used steel fiber ratios of 2%, 3%, and 4%. The SB ratio was 0.65, whereas the W/B ratio was 0.20. GGBFS, SF, and FA were used as binders, whereas silica sand was utilized as fine aggregate. The increase in fiber fraction from 2% to 3% and 4% improved the compressive strength by 11.2 MPa and 22.8 MPa, respectively. For a 4% steel fiber ratio, significant enhancements in tensile strength were observed. Liu et al. [55] increased steel fiber ratios from 0% to 4% with increments of 1%. The W/B ratio was 0.32, whereas the SB ratio was 1.0. GGBFS, SF, and FA were used as binders. The mixture's flowability in the absence of steel fibers was 271 mm. Increasing the steel fiber magnitude to 3% reduced the flowability to 190 mm, corresponding to a reduction of 30.2%. The decrease in flowability was more pronounced beyond the steel fiber content of 2%. The presence of fibers formed a structural skeleton that impeded the slump of the fresh mixtures. Moreover, as the fiber content rose, the total specific surface area of the fibers increased, resulting in some of the solution being occupied. The quantity of steel fibers positively influenced the compressive strength and stiffness of cement-less UHPC. In the absence of fiber reinforcement, the mean compressive strength and stiffness were 101.4 MPa and 25.8 GPa, respectively. With 1% steel fibers, the compressive strength and stiffness increased to 108.5 MPa and 27.6 GPa. At 2% fiber content, they further increased to 127.5 MPa and 29.0 GPa. The highest values were observed with 3% fraction, reaching 155 MPa and 31.4 GPa, being 53% and 22.2% greater than values obtained in the absence of steel fibers, respectively.

Liu et al. [56] also increased steel fiber ratios from 0% to 3%. Standard and steam curing regimes were adopted and compared. The compressive strength at 3% steel fiber ratio showed a 56.8% and 67.1% increase in compressive strength of standard and steam-cured cement-less UHPC. For a steel fiber fraction of 3%, the flexural capacity increased by 434.1% under standard curing and 189.4% under steam curing. Aisheh et al. [70] used straight steel fibers of fractions ranging from 0% to 3%. GGBFS, FA, and micro silica were used as binders. The W/B ratio was 0.30. The flow diameter decreased from roughly 175 mm to 155 mm, 150 mm, and 125 mm in cement-less UHPC mixes with 0%, 1%, 2%, and 3% steel fiber ratios. The compressive strength and elastic modulus increased by 53% and 22% at 3% steel fiber ratio, compared to cement-less UHPC without steel fibers. The splitting tensile capacity improved by 15% and 43% at 2% and 3% steel fiber ratios. As shown in Figure 11, the compressive strength shows a positive trend with the fiber content. However, it must be noted that the improvement in compressive strength is not solely dependent on the fiber content, as observed from the different slopes of improvement in Figure 11. The SB ratio used by Aisheh et al. [70] and Liu et al. [55] was 1.0, whereas an SB ratio of 0.65 was utilized by Lao et al. [59]. It is vital to observe that all these studies utilized GGBFS, FA, and SF as geopolymer binders, whereas steel fibers were used for reinforcement. Therefore, it is vital to observe that the SB fraction offers a significant role in determining the improvement in compressive strength imparted by the increase in fiber content.

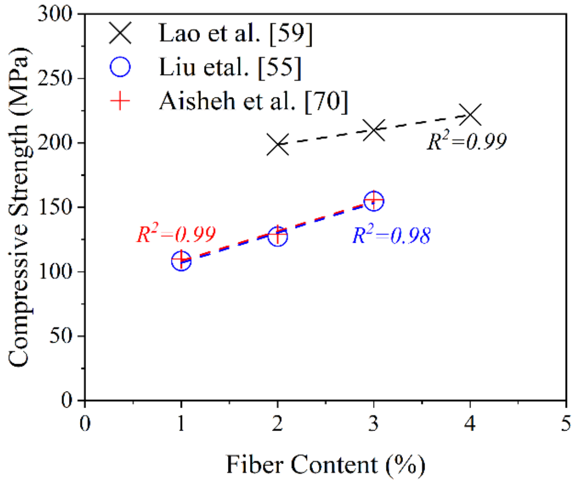

Figure 11. Impact of fiber quantity on compressive strength of cement-less UHPC reported

Although increasing fiber volume ratio generally enhances strength and ductility, the diminishing returns observed at higher fiber contents highlight the presence of saturation effects. Beyond an optimal threshold, fiber clustering and reduced workability can compromise matrix homogeneity, leading to localized weaknesses. These findings suggest that fiber optimization in cement-less UHPC should prioritize efficiency over quantity, particularly when considering practical mixing and casting constraints.

4.6. Effect of Fiber Length

Yang et al. [46] explored the bond performance between cement-less UHPC and steel fibers. Steel fiber lengths of 6 mm, 10 mm, 13 mm, and 15 mm were investigated. Increasing the length and ratios of steel fibers improved the tensile and shear characteristics of cement-less UHPC, leading to a rougher bond interface. This increased friction and mechanical interlocking, which enhanced bond stiffness and performance, and limited slip between the ribbed steel bar and cement-less UHPC. Xu et al. [45] used steel fiber lengths of 6 mm, 10 mm, 13 mm, and 15 mm. The influence of steel fiber shape on compressive strength was assessed using the $1/(L_f D_f)$ fraction, where L_f is the length of fibers, and D_f is their diameter. An increase in compressive strength is observed as the $1/(L_f D_f)$ fraction increases. Additionally, the impact on flexural capacity can be assessed by the length-to-diameter fraction, where an improvement in flexural capacity is noted as the length-to-diameter fraction increases. Liu et al. [56] reported that for the same steel fiber fraction, a higher aspect ratio reduced the flowability. Reducing fiber length did not always decrease compressive and flexural strength. For specimens cured for 28 days under standard conditions, both compressive and ultimate flexural strength improved with longer fibers. However, this strength showed variability with increased fiber length under steam curing. Generally, increasing the fiber aspect ratio improved the flexural capacity of samples under standard and steam curing environments. However, steam curing appeared to reduce the toughening effectiveness of the fibers. This effect might have resulted from increased porosity in the geopolymer matrix and diminished bond capacity among the fibers and the interface, which required future examination.

4.7. Effect of SF/GGBFS

It is noteworthy that binders other than SF and GGBFS have been used. However, many of the studies have utilized these two binders. Therefore, their fraction is discussed in this section only. Liu et al. [55] utilized these ratios of 0.05, 0.1, 0.2, and 0.3. SF had a complex impact on the workability and hardened characteristics of UHPGC, which was highly reliant on its quantity. Including 10% SF increased flowability but significantly degraded mechanical performance. However, specimens with 20% and 30% SF exhibited superior mechanical characteristics compared to those with 5% SF. The inclusion of SF in volumes of approximately 30% increased the fracture energy of cement-less UHPC by about 50%. Related to the improvement in steel fiber from 1% to 3% fraction, SF proved more effective in capacity development. Increasing SF content from 0% to 30% resulted in more than 25% improvement in the compressive strength of samples cured for a 28-day period at ambient temperature (27°C with relative humidity of approximately 72%). Wetzel & Middendorf [23] produced a cement-less UHPC using SF as ratio of the source materials, with volumes from 0% to 20%, to improve the workability of the concrete with low W/B ratios (ranging from 0.4 to 0.18). This resulted in improved fresh and mechanical characteristics. Sodium and potassium hydroxides were utilized as activators with a molarity of 5 M and 10 M, respectively. The study found that the cement-less UHPC achieved a notable compressive strength of 178.6 MPa with a 12.5% SF ratio. Abdellatief et al. [52] stated that the compressive strength was enhanced by 26.7%, 38.5%, 46.1%, and 38.1% at 28 days by the inclusion of 3% steel fiber ratio at various SF contents of 10%, 20%, 25%, and 30%, respectively. Tahwia et al. [71] reported that the least compressive strength of cement-less UHPC ranged from 94 MPa to 123 MPa, attained by a 10% addition of SF. The inclusion of 25% SF significantly enhanced the intensity of silica in the activator, ascribed to its fine grain size, which led to greater specific surface area, leading to increased activator activity. As a result, the compressive strength peaked, reaching values between 124 and 152 MPa.

Kathirvel & Sreekumaran [58] also reported an increase in the compressive strength by increasing the substitution rate of GGBFS with SF.

4.8. Production of Cement-Less UHPC with Non-Alkaline Activators

Non-alkaline activators have recently been deployed to address several disadvantages associated with alkaline activation, such as their high pH values, potential to burn, and cause respiratory issues [24, 25]. Moreover, the high costs and availability issues of alkaline activators are also concerning [25]. Dahal et al. [16] utilized calcium oxide as an activator for GGBFS. To accelerate the activation process, CF was used, ranging from 0% to 6%. Up till 5% CF level, the compressive strength of cement-less UHPC was reported over 150 MPa. A life cycle assessment demonstrated 70% lower CO_2 releases related to conventional cement-based UHPC. Oinam et al. [27] investigated the effect of NCFs on enhancing the hydration properties of cement-less UHPC utilizing CaO-activated GGBFS. The study focused on the addition of saturated NCFs as an internal-curing substance to provide extra water to the UHPC matrix, aiming to boost the reaction potential of unhydrated phases. NCFs were incorporated at levels ranging from 0% to 1.5% by weight of the GGBFS and CaO. Analysis through TGA and FTIR revealed that increasing the NCF content improved the formation of hydration products, as indicated by a rise in heat of hydration and more active reactions of unhydrated phases. Morphological observations showed hydration products forming on and around the NCFs due to the internal curing effect. Notably, the inclusion of NCFs remained neutral towards the compressive and tensile capacity of the UHPC; instead, it led to a slight improvement at certain NCF contents. Kang et al. [72] produced cement-less UHPC by enhancing the reactivity of low-calcium FA. The composite demonstrated excellent workability and capacity, achieving about 110 MPa after 3 days of steam curing at 60 °C. SF played a crucial role by providing nucleation sites, accelerating the reaction, and improving the composite's performance.

4.9. Integrated Interpretation and Research Implications

Collectively, the findings discussed in this section indicate that cement-less UHPC has demonstrated strong potential at the material level, particularly in achieving ultra-high compressive strength and enhanced tensile behavior. However, the performance is highly dependent on tightly controlled mix design, curing regimes, and fiber optimization. The lack of comprehensive studies addressing durability, reinforcement interaction, and large-scale structural behavior suggests that the field remains in a developmental stage. Future research should prioritize performance-based design approaches, durability assessment, and structural validation to facilitate the transition from laboratory-scale studies to practical engineering applications.

5. Conclusions

This work conducted a scientometric review on the production of cement-less UHPC for the first time. The current state of research on cementless UHPC was extensively reviewed. The following important conclusions were drawn from the review.

- The number of publications on cement-less UHPC has surged recently, with 21 publications each in 2022 and 2023, and 20 already in 2024. This increase reflects growing interest in its environmental benefits and the search for alternative geopolymer binders. Over 80% of the research is focused on Engineering and Materials Science.
- In this study, the most frequently used keywords in cement-less UHPC research were identified using VOSviewer, highlighting terms such as geopolymers, compressive strength, steel fibers, and mechanical properties. The emphasis has been on the mechanical properties of cement-less UHPC, with steel fibers being a common focus. The analysis also revealed a lack of attention to durability, fire endurance, and corrosion resistance, indicating potential areas for further research.
- Construction and Building Materials published 15 articles on cement-less UHPC, reflecting a link strength of 302, but ranks third in total citations. Cement and Concrete Composites has the highest citation count with 621 from four articles, followed by Case Studies in Construction Materials with five articles and 342 citations.
- The leading authors are Xu Shenchun, Liu Jian, and Wu Chengqing, with 10, 8, and 8 publications, respectively. Xu Shenchun's research includes mix design with alkaline activators, bond behavior with steel reinforcement, resistance to sodium sulfate, performance of multi-layer protective slabs, and behavior under projectile impacts and explosions. Liu Jian's work includes studies on the effects of temperature on mechanical properties and meso-scale modeling of cement-less UHPC subjected to high-velocity impacts. Abdellatief Mohamed also contributed significantly to research on mechanical performance, microstructural analysis, ecological assessment, and the use of industrial wastes in cement-less UHPC production.
- The mix design of cement-less UHPC features a low W/B fraction (0.20 to 0.35) for high capacity and durability. Previous works show that high-energy mixing and controlled curing conditions are essential. Research shows that GGBFS, SF, and FA are frequently used binders, with steel fibers commonly included. GGBFS requires an alkaline activator due to its latent hydraulic reactivity, and some studies use a binary binder system for optimal performance.

- Various curing regimes were evaluated for their effects on cement-less UHPC properties, including ambient, standard, and hybrid curing. Hybrid curing, which combines steam curing at 90°C for 48 hours with subsequent ambient curing, resulted in the highest compressive strength and densest microstructure, achieving a capacity comparable to 28 days of standard curing within just 3 days. Alternative curing methods, such as heat and autoclave curing, also significantly enhanced compressive strength, with autoclave curing showing the most improvement. Additionally, steam curing at 80°C generally improved both compressive and flexural capacity compared to standard curing, though the impact varied depending on the type and size of steel fibers used.
- The effect of SB fractions on cement-less UHPC was examined, revealing that higher S/B fractions, up to 0.8, enhanced packing density, compressive strength, and tensile performance. The highest packing density of 0.78 and compressive strength of 160.7 MPa were achieved at an S/B fraction of 0.8. The tensile properties, including tensile capacity, strain capacity, and strain energy density, also improved with higher S/B fractions. For cement-less UHPC with steel fibers, increasing the S/B fraction led to better performance due to improved bond capacity between the fibers and the matrix. However, for cement-less UHPC reinforced with polypropylene fibers, lower S/B fractions were more beneficial for tensile performance. These findings indicate that the optimal S/B fraction for cement-less UHPC depends on the type of reinforcing fibers used.
- Most studies have incorporated steel fiber fractions up to 3%. Higher fractions tend to enhance the compressive, flexural, and tensile capacity of the mix. However, the flowability of the matrix is adversely affected. Moreover, elastic modulus in excess of 30 GPa has been frequently reported.
- Increasing the length and fraction of steel fibers in cement-less UHPC improves tensile and shear properties by creating a rougher bond interface, which enhances bond stiffness and performance. The compressive and flexural capacity are positively influenced by the length-to-diameter fraction (L_fD_f) of the fibers. However, longer fibers can reduce flowability, and their effectiveness may decrease under steam curing due to increased porosity and weakened fiber-matrix bonds.
- The use of SF in cement-less UHPC significantly affects its properties, with its impact varying based on the amount used. While 10% SF improves flowability but degrades mechanical performance, 20% and 30% SF enhance mechanical characteristics and increase fracture energy by about 49.7%. Compressive strength is notably improved by up to 25% with 30% SF compared to lower amounts, and SF proves more effective in capacity development than increasing steel fiber content. However, these results must be studied in combination with other factors such as the type of activator, binder, and range of HRWR used.

5.1. Future Research Recommendations

Based on the comprehensive review conducted in this study, the authors highlight the following research areas that need further exploration in order to ascertain the performance of cement-less UHPC. Addressing these aspects will provide a more holistic understanding of cement-less UHPC's potential and limitations, paving the way for more widespread and effective utilization in the construction industry.

- While many studies on cement-less UHPC have predominantly focused on its mechanical properties, a comprehensive exploration of its structural performance is needed. Research should expand to examine how cement-less UHPC performs under various loading conditions, such as shear and flexural stresses, especially in reinforced concrete members.
- Investigating the bond behavior of steel bars in cement-less UHPC is also crucial for understanding its application in practical construction scenarios. Due to the high compressive strength, it is expected from the existing expressions to overestimate the development length in cement-less UHPC. Therefore, future studies need to propose expressions for the development length of steel bars/lap splices in cement-less UHPC.
- Additionally, the performance of cement-less UHPC in corrosive environments needs thorough evaluation to ensure its longevity and reliability in adverse conditions.
- The potential for fire spalling behavior, which can significantly impact structural integrity during high-temperature exposures, requires detailed study.
- Moreover, assessing the durability properties of cement-less UHPC, including its resistance to weathering, chemical attacks, and physical wear, is essential for establishing its suitability and safety for long-term use in various construction applications.

While durability, corrosion resistance, and fire performance are all critical research gaps for cement-less UHPC, their relative importance varies with respect to real-world structural applications. Among these, durability and reinforcement corrosion behavior represent the most immediate and critical challenges, as they directly govern service life, maintenance requirements, and design reliability under normal operating conditions. Structures are continuously exposed to environmental actions such as moisture ingress, chloride penetration, and chemical attack, making long-term durability assessment essential before widespread adoption. Fire resistance, although crucial for safety-critical structures, typically represents an accidental or extreme loading condition and is addressed through prescriptive design measures in many codes. Consequently, fire performance studies are important but secondary to durability and corrosion when considering routine structural implementation. Addressing these prioritized gaps will enable a clearer transition of cement-less UHPC from laboratory-scale material development to practical structural design and code acceptance.

6. Declarations

6.1. Author Contributions

Conceptualization, A.E. and A.R.; methodology, A.E.; software, A.E.; validation, A.R., M.J.I., and M.I.; formal analysis, A.E.; investigation, A.E. and A.R; resources, A.R.; data curation, A.E.; writing—original draft preparation, A.E. and A.R.; writing—review and editing, M.J.I. and M.I.; visualization, A.R. and M.I.; supervision, A.R. and M.I.; project administration, A.R. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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