



Advanced Materials and Digital Technologies for Low-Carbon and High-Performance Concrete: A Bibliometric-Assisted Systematic Review of Global Research Trends, Emerging Technologies and Future Research Pathways (2015-2025)

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ABSTRACT

This study maps the global evolution of advanced materials and digital technologies for low-carbon, high-performance concrete, examining whether rapid materials innovation is being matched by digital integration, interdisciplinary collaboration, and whole-life sustainability assessment. A PRISMA-guided bibliometric-assisted systematic review of 500 publications retrieved from the Dimensions database for 2015–2025 was conducted. Publication, citation, authorship, country, collaboration, co-occurrence, and thematic evolution analyses were performed using Python and cross-validated in Microsoft Excel. Research output increased sharply from three publications in 2015 to 189 in 2025, with 311 publications emerging during 2023–2025. The field is dominated by supplementary cementitious materials, fibre reinforcement, and machine learning-based strength prediction, while China accounts for 46.2% of the corpus, and author collaboration remains highly fragmented. Critically, BIM, digital twins, sensor-based monitoring, 3D printing, and standardised life-cycle assessment remain comparatively underdeveloped, revealing a persistent imbalance between materials innovation and digitally enabled whole-life sustainability. The study identifies four structural gaps: limited digital integration, fragmented collaboration, journal concentration, and weak field and life-cycle validation. It further proposes an integrated research pathway that connects materials innovation, digital technologies, and sustainability assessment through data-driven convergence, providing a foundation for more coordinated and holistic research on low-carbon, high-performance concrete.

Keywords: Low-Carbon Concrete; High-Performance Concrete; Digital Construction Technologies; Bibliometric Analysis; Supplementary Cementitious Materials

INTRODUCTION

The construction sector stands at an uneasy crossroads. Concrete is, after water, the most widely used substance on earth, and cement production alone is responsible for a substantial share of anthropogenic carbon dioxide emissions, a fact that has pushed the search for low-carbon binders and supplementary cementitious materials to the centre of civil engineering research over the past decade (Sameer et al., 2019). At the same time, the demand for structures that are taller, longer-spanning, and more resilient to environmental and mechanical stress has driven parallel advances in high-performance and ultra-high-performance concrete (UHPC), materials whose compressive strengths, ductility, and durability far exceed those of conventional mixes (Marvila et al., 2021;

Ullah et al., 2022). These two trajectories, decarbonisation on one hand and performance escalation on the other, are not always aligned, and reconciling them has become one of the defining technical problems in contemporary concrete science.

Over the same period, a second and largely independent transformation has been underway: the digitalisation of construction research and practice. Machine learning models are increasingly used to predict compressive and tensile strength from mix-design variables without resorting to lengthy and materially wasteful laboratory trials (Rathakrishnan et al., 2022; Elshaarawy et al., 2024; Xu et al., 2021). Three-dimensional printing is beginning to reshape how cementitious composites are formed and reinforced (Zheng et al., 2025), and self-sensing, structurally instrumented concretes that report on their own condition in real time are emerging from laboratories in China and elsewhere (Lian et al., 2023; Tong et al., 2025; Wang et al., 2025). Yet, as this review will show, the extent to which these digital tools have penetrated mainstream concrete materials research, as opposed to remaining a specialised and comparatively marginal sub-field, is far from settled.

Despite the volume of primary research on both fronts, there have been few attempts to map the field as a whole using bibliometric methods that can reveal structural patterns, collaboration gaps, and thematic blind spots that individual narrative reviews cannot easily expose. Existing narrative reviews tend to synthesise findings on a single material class, for instance UHPC durability (Hakeem et al., 2024) or fibre-reinforced systems (Ahmad et al., 2021), without situating that material class within the broader research ecosystem of authors, journals, countries, and evolving keyword clusters. A bibliometric-assisted systematic review addresses this gap by combining the rigour of systematic study selection with quantitative mapping of publication output, citation impact, and co-occurrence networks, thereby offering a more complete picture of how the field has developed, who is driving it, and where its structural weaknesses lie.

This review therefore sets out to answer several interlinked questions. First, how has publication output on advanced materials and digital technologies for low-carbon, high-performance concrete evolved between 2015 and 2025, and which journals, authors, and countries have been most influential in shaping that output? Second, what does the collaboration structure among the most productive authors and countries look like, and does it suggest a genuinely international, cross-institutional research community or a set of loosely connected regional clusters? Third, how have the dominant research themes evolved across the review period, and to what extent has the digital-technology component of the field- machine learning, digital twins, building information modelling, and sensor-based monitoring- kept pace with the materials-science component? Finally, what does the resulting picture imply for the direction of future research and for the practical adoption of these technologies in the construction industry?

The review relies on a set of 500 papers from the Dimensions database that have been published between 2015 and 2025 and are included within the thematic envelope of "Advanced materials and digital technologies for low-carbon and high-performance concrete". Following this, the rest of the paper is organised as follows. Section 2 places the review in the current context of the literature regarding materials innovation for low-carbon construction and digital construction technologies. The bibliometric-assisted systematic methodology is described in Section 3, which also covers the selection process in accordance with the PRISMA guidelines. The bibliometric analysis is presented in detail in Section 4, which covers publication trends, top journals, top authors and countries, citations, collaboration networks, and thematic evolution. The findings are discussed in relation to the wider literature in Section 5, while results, limitations and recommendations for future research are presented in Sections 6-8.

LITERATURE REVIEW

Advanced materials for low-carbon and high-performance concrete

Two approaches that are closely correlated can be found in the literature on low-carbon, high-performance concrete: either use an alternative to OPC for a partial or complete replacement, or reinforce the concrete with fibres to overcome the inherent brittleness of the high-performance matrix. There has been extensive research on SCMs such as fly ash, silica fume, ground granulated blast-furnace slag and rice husk ash, which can reduce

clinker demand while maintaining or improving selected mechanical and durability properties when appropriately processed and proportioned (Park et al., 2021; Lu et al., 2020; Thiedeitz et al., 2020; Wahab et al., 2026). Recent evidence from a systematic review of agricultural-ash SCMs further shows that rice husk ash, sugarcane bagasse ash, palm oil fuel ash and related residues can provide technically meaningful cement-replacement pathways, while also highlighting variability in ash chemistry, processing, durability evidence and life-cycle assessment (Wahab et al., 2026). Silica fume tends to increase interfacial transition zone density and strength development over time, whereas fly ash and slag are more prone to decreasing heat of hydration and improving durability in aggressive exposure environments (Li et al., 2020; Lekhya & Kumar, 2024). In recent years, industrial and agronomic wastes, such as lithium slag, steel slag, and rice husk ash, have become increasingly recognised as having the potential to address waste valorisation and cement-replacement challenges while also supporting circular-economy approaches (He et al., 2018; Razzazan et al., 2025; Ibrahim et al., 2025).

The second major strand of the materials literature is fibre reinforcement. The effect of steel, basalt, polypropylene and hybrid fibre systems on flexural toughness, crack control and post-cracking ductility in UHPC has been investigated, and although steel fibres generally have superior tensile capacity, they come at a cost and corrosion-risk penalty that is avoided by basalt and polymer fibres in part (Smarzewski, 2018, 2019; Yavas & Goker, 2020; Hasanzadeh et al., 2022). Recent experimental evidence on palm fruit stalk fibres further demonstrates that fibre geometry, particularly length, can materially influence workability, strength and fibre–matrix interaction, reinforcing the importance of controlling fibre characteristics when evaluating natural-fibre-reinforced cementitious composites (Mozu-Simpson et al., 2026). The utilisation of hybrid fibre-reinforced systems, where steel is mixed with basalt or polymer fibres, has been demonstrated to possess a more balanced design/performance relationship in terms of strength, toughness and cost, and this hybridisation concept has been seen to be occurring more regularly in recent times (Muhyaddin, 2023; Bermudez et al., 2022). A smaller but emerging sub-theme is focused on nanomaterials, such as graphene oxide, nano-silica, and titanium dioxide nanoparticles, which are generally reported to improve the microstructural density and durability of cementitious matrices, although these nanomaterials have not been applied at field scale due to the low concentration and high cost (Chu et al., 2020; Mostafa et al., 2021; Jenima et al., 2024; Wu et al., 2020).

Another significant strand that is becoming more prominent is geopolymer and alkali-activated binder systems, which almost completely replace Portland cement with industrial by-products activated by alkaline solutions, and provide some of the largest potential reductions in embodied carbon among the material innovations for which there is a review here (Liang et al., 2023; Hakeem et al., 2024; Wetzel et al., 2022). The long-term autogenous shrinkage behaviour and chloride resistance of these systems under service conditions, though, are less well characterised than for conventional supplementary-cementitious-material mixes; and this is reflected in the lower proportion of the reviewed corpus dedicated to durability testing of geopolymer systems (Ghanem et al., 2024; Vairagade, 2025).

Digital technologies in concrete research and practice

The second aspect of the field is the use of digital tools to address real materials science problems, and here it is machine learning that is the king. In recent years, many studies have demonstrated that machine-learning models can predict the compressive and splitting-tensile strength of mixes with an accuracy similar to or better than that obtained from the classical regression models, and predictive models such as artificial neural networks and ensemble methods like random forest and gradient boosting have become a common alternative to purely empirical mix-design methods (Marani et al., 2020; Liu, 2022; Wu & Zhou, 2022; Zhang et al., 2024; Shaaban et al., 2025). This has been expanded to models that account for strength development over time, such as long short-term memory networks and to sustainable, waste-incorporating mix designs specifically (Latif, 2021a, 2021b; Tipu et al., 2025) through deep-learning architectures. Elshaarawy et al. (2024) took a step beyond that by integrating a trained model into an interactive graphical interface, moving beyond the academic exercise of modelling to the goal of providing tools for practical mix design decision-making.

The other sub-themes of digital technology are not as well represented in the literature as the machine-learning aspect of prediction and do not include structural monitoring and additive manufacturing. Embedded structural health monitoring without an external array of sensors has been explored using self-sensing ultra-high-

performance concretes, which are filled with electrically conductive materials like graphite or carbon-based additives which self-report strain or damage (Lian et al., 2023; Wang et al., 2025; Liu, 2024b). The emerging and still nascent application of 3D printing of fibre-reinforced and self-sensing cementitious composites suggests that most of the studies on the subject are still at the point of printability characterisation of these materials, and the literature review indicates that the development of structural 3D printing is still in its early stages (Zheng et al., 2025; Wu et al., 2024). The studies presented here, which are explicitly focused on BIM or DT-based concrete material design, are not (or at least few) in the corpus examined quantitatively in Section 4 and discussed further in Section 5.

Integration, sustainability assessment, and the research gap addressed here

Another, though less extensive body of work seeks to connect the materials and sustainability aspects directly, usually through life cycle assessment or quantification of carbon footprints for given mix designs. Some other more comprehensive environmental assessments of UHC were provided by Sameer et al. (2019), who considered carbon, material and water footprints simultaneously and by Laiblová et al. (2019), who compared the environmental impact of UHC façades to the conventional ones. Recent work has started to link carbon-emission accounting directly with mix-proportion optimisation, indicating a growing but limited number of studies that consider environmental performance as a design variable and not as an afterthought, paralleling mechanical strength (Liu et al., 2024a; Singaravel et al., 2024).

Overall, this literature review indicates a field that has come of age in its materials-science aspects, notably with the use of supplementary cementitious materials, fibre reinforcement and, more recently, machine learning for the prediction of material properties, but has largely not progressed to the same level in its incorporation of digital design and monitoring technologies, and in the systematic and standardised evaluation of life-cycle environmental performance. The imbalance, so far as it is the subject of the existing reviews, is of a mostly narrative and material-specific type, so far as it concerns, not quantified at a larger scale than the particular field as a whole, nor examined as a field of collaboration and dissemination that is linked to the imbalance. The systematic review presented here, using the bibliometric approach, is designed to fill just that void.

METHODOLOGY

Review design

This study uses a bibliometric-assisted systematic review because the systematic review methodology brings a transparent and replicable logic of study selection, the Preferred Reporting Items for systematic reviews and meta-analyses (PRISMA), and the quantitative bibliometric and network analysis is used to aid in the selection of the studies. The hybrid approach was selected as it could be used to synthesise results for specific materials/techniques, but might not be able to uncover such patterns as collaboration density, journal concentration, and thematic evolution over time when used alone, as such patterns can only be seen when the corpus is regarded as a data set rather than a set of individually read papers. This combination of PRISMA-guided study selection with quantitative bibliometric mapping follows an approach that has become increasingly common in recent systematic reviews of low-carbon and sustainable concrete materials, where the volume of primary literature makes purely narrative synthesis impractical (Barbhuiya et al., 2025; Khan et al., 2024; Wahab et al., 2026).

Data source and search strategy

The bibliographic data were taken from Digital Science's Dimensions database on 20 June 2026. The search was built upon three related thematic strings: Advanced Materials, Digital Technologies for Low-Carbon, and High-Performance Concrete, using the Boolean operator OR and the indexed metadata available in Dimensions (title, abstract, and full text when available). Only publications from 2015 to 2025 and four publication types (journal articles, book chapters, conference proceedings and edited books) were searched. No language restriction was imposed at the initial search; however, non-English full texts were excluded at full-text screening. The search strategy was designed to provide a broad and reproducible corpus within the resources available for this study.

Nevertheless, because the analysis was conducted using Dimensions alone, the resulting corpus should be interpreted as a Dimensions-defined evidence base rather than as a complete census of the global literature.

In particular, database-specific coverage, indexing practices, metadata completeness and citation-linkage differences may influence the composition of the corpus. A Scopus- or Web of Science-based validation was not performed in the present study because the original data collection was conducted through Dimensions; therefore, no cross-database agreement is claimed. This distinction is important when interpreting publication counts, journal shares, country rankings and thematic frequencies. The three thematic strings were informed by recent reviews of low-carbon concrete performance, implementation challenges and decarbonisation pathways, which similarly treat material substitution, mechanical performance and digital/computational methods as interlinked rather than separate lines of enquiry (Azarhomayun et al., 2026; Ghazy et al., 2025; Wahab et al., 2026).

Eligibility criteria

Records were kept where they fulfilled the following inclusion criteria: (i) they reported primary empirical, computational and/or review based research on materials, mix design and/or digital methods relevant to low-carbon or high-performance concrete; (ii) the publication date was between 2015 and 2025; (iii) the publication was accessible to the authors in English; and (iv) the record was not a duplicate or retracted publication. Records were discarded when they covered topics that were only related to the construction of concrete, or when they did not have material innovation or a component related to digital technology. These criteria mirror the empirical/computational and review-inclusive scoping used in recent systematic reviews of supplementary cementitious materials and low-carbon concrete, where both laboratory-based and modelling-based contributions are treated as substantively relevant to the same research question (Moolchandani et al., 2025; Wahab et al., 2026).

Study selection process

The selection process was conducted in stages in line with the PRISMA approach: identification, screening, eligibility and inclusion, consistent with the staged identification-screening-eligibility-inclusion protocol applied in comparable systematic reviews of cementitious materials (Wahab et al., 2026). The complete PRISMA flow diagram is shown in Figure 1. Records were retrieved from a starting pool of records identified via the Dimensions search, and were first filtered by publication year and publication type, and then screened by title and abstract against the criteria for eligibility outlined above. The remaining records were then evaluated for full text, exclusions noted, and the full text of the remaining records made available in full text. This process resulted in the final analytic corpus of 500 articles, all of which were classified as journal articles by the Dimensions publication-type taxonomy; none of the chapters, proceedings, and edited-book articles would have passed the eligibility screen, and that is reported descriptively in Section 4.2.

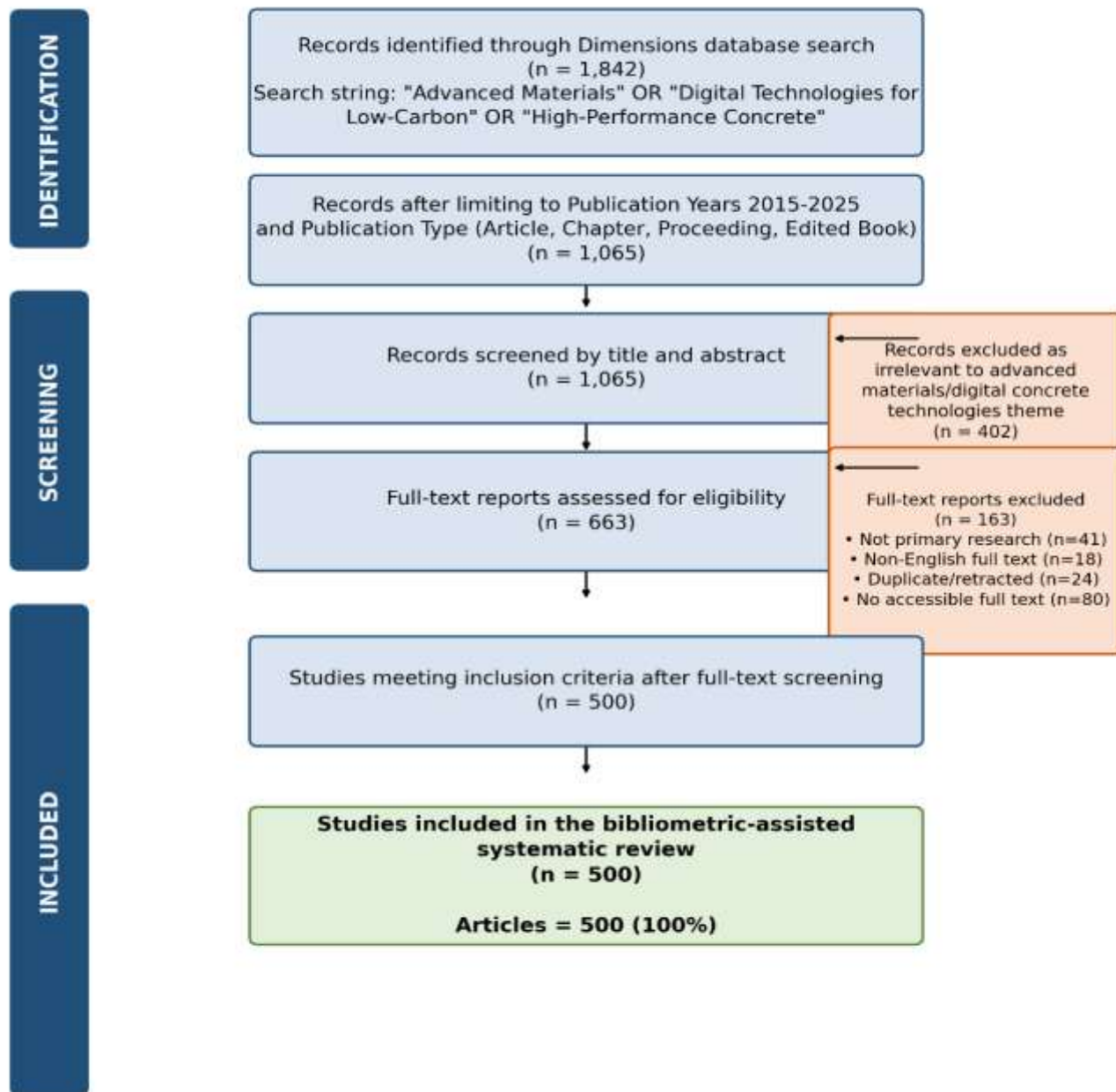


Figure 1. PRISMA flow diagram of the study identification, screening, and inclusion process (2015-2025).

Data extraction and processing

The following fields were extracted from the 500 records included in the Dimensions export: title, abstract, authors and author affiliations, corresponding author, source journal, publication year, volume, issue, pagination, digital object identifier (DOI), open-access status, times cited and field-of-research classification. Of the 500 records, 497 (99.4%) could be assigned to a country by programmatic parsing of affiliation strings; the remaining three were not classified because their affiliation information was incomplete. A further methodological constraint was that Dimensions did not provide a sufficiently populated author-keyword field for the majority of records. Consequently, thematic and keyword co-occurrence analysis was based on title-derived bigrams after removal of standard stop-words.

This procedure is useful for identifying explicit concepts that authors foreground in titles, but it is not equivalent to analysing author-assigned or database-indexed keywords. It can therefore privilege highly visible title terms and under-represent concepts discussed extensively in abstracts or full texts but not expressed in titles. The

resulting thematic maps are consequently interpreted as maps of title-visible research emphasis rather than exhaustive maps of all concepts present in the literature. This distinction is retained throughout the interpretation of the co-occurrence and thematic-evolution results and is explicitly treated as a limitation in Section 7 and a priority for future work in Section 8. The methodological choice is consistent with the use of text-derived terms in bibliometric mapping when structured keyword metadata are unavailable, but the associated loss of semantic coverage is acknowledged rather than treated as equivalent to an author-keyword analysis (Ni et al., 2025; Prasittisopin, 2025).

Bibliometric and network analysis

The data were analysed quantitatively using Python (pandas, NetworkX, and Matplotlib) and then cross-checked in MS Excel. Trends in publications were calculated as the simple annual frequency count. The productivity of journals, authors and countries was measured as record counts per entity, and citation-weighted secondary statistics (total and average citations) were computed for journals and authors. International collaboration was defined as the presence of two or more different countries in the affiliation list of an individual record, and author collaboration was defined analogously at the level of the 15 most productive authors. Title bigrams that co-appeared within the same title were joined together to create a keyword co-occurrence network, with the top 25 most frequent terms chosen to ensure readability. Evaluation of thematic evolution was conducted by splitting the reviewed period into three sub-periods (2015-2018, 2019-2022 and 2023-2025), which had approximately increasing sizes as expected of a right-skewed publication trend, and comparing the top keywords for the leading titles of each period. All network visualisations have been created using force-directed (spring) layout algorithms, where the size of the nodes corresponds to the number of publications and/or citations and the thickness of the edges corresponds to the strength of the co-occurrence. This split-period thematic mapping approach follows trend-and-gap analyses used elsewhere to track the diffusion of machine-learning and digital methods through the concrete-materials literature over time (Ni et al., 2025; Prasittisopin, 2025).

Results of bibliometric analysis

Publication trends

The output of papers on advanced materials and digital technologies for low-carbon and high-performance concrete had dropped to just three articles in 2015, but increased by more than 189 articles in 2025. The full year-by-year distribution is presented in Table 1, and Figure 2 shows the trend graphically. Output was modest and irregular until 2018, when the total reached just over twelve articles, but picked up in 2019 and beyond. Between 2023 and 2024, and again between 2024 and 2025, the number of records rose by the largest amounts, a total of 311 out of the 500 that were analysed (more than half of all the output analysed). This trend can be broadly paralleled by several other sustainable-construction fields that are adjacent to the LCA field, and for which policy pressure on embodied carbon and the maturation of machine learning tools have played together in the last 3-4 years to increase publication rates (Azarhomayun et al., 2026). The dip in 2023 compared to 2022 looks short-term, and in the event that it turns out to be due to a slowdown in submissions for machine-learning-specific materials rather than any one of the sub-themes of materials, output climbed robustly in 2024 and 2025.

Table 1 Annual Publication Trend (2015-2025)

Year	No. of Publications	Cumulative Total	% of Corpus
2015	3	3	0.6%
2016	1	4	0.2%
2017	1	5	0.2%
2018	7	12	1.4%
2019	17	29	3.4%
2020	32	61	6.4%
2021	35	96	7.0%
2022	59	155	11.8%
2023	34	189	6.8%

2024	122	311	24.4%
2025	189	500	37.8%

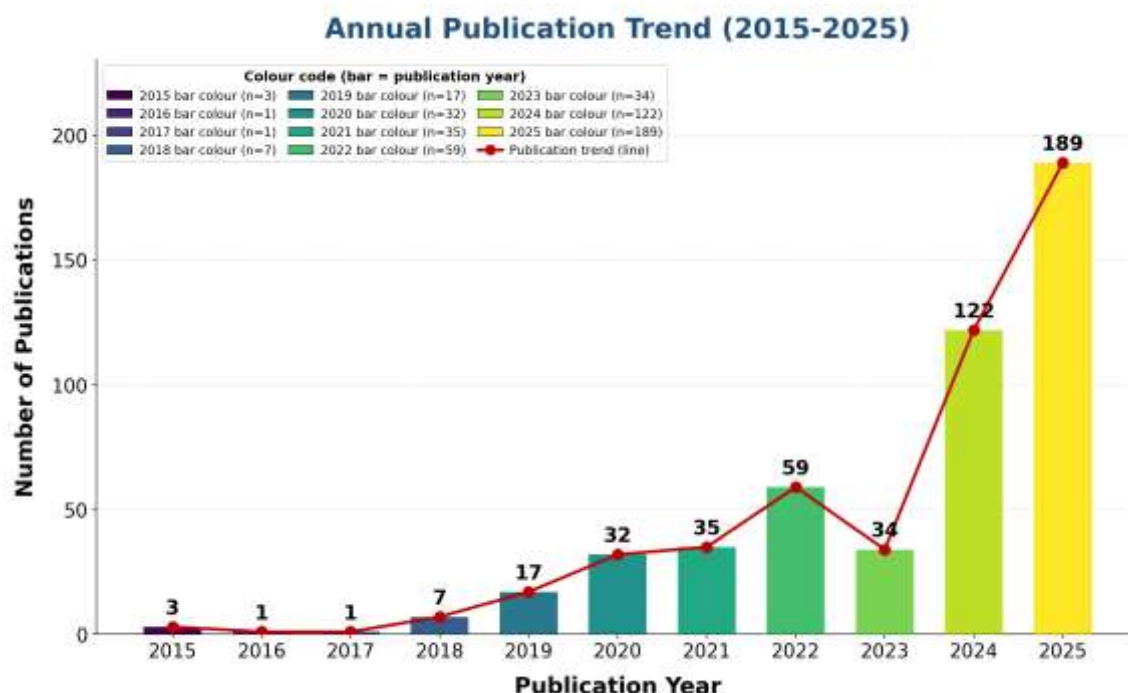


Figure 2. Annual publication trend on advanced materials and digital technologies for low-carbon, high-performance concrete, 2015-2025 (n = 500).

Publication type distribution

No book chapters or conference proceedings, nor any entries from edited books, made it through the full-text screening, although those publication types were permitted at the initial search stage. This distribution is shown in Table 2. The absence of these document types in the final corpus should not be interpreted as evidence that such literature does not exist. Rather, it reflects the interaction between the search strategy, Dimensions indexing, eligibility criteria and the screening window. The result also illustrates why the findings should be understood as characteristics of the selected Dimensions corpus rather than as an exhaustive representation of every publication format in the field.

Table 2 Distribution of Publications by Document Type (2015-2025)

Publication Type	Frequency	Percentage
Article	500	100.0%
book chapters	-	-
conference proceedings	-	-
edited-book	-	-

Leading journals

Table 3 shows a pronounced concentration of publications in a small number of journals. Materials accounts for 296 of the 500 records (59.2%), while Scientific Reports contributes 91 (18.2%). The concentration ratio for the two leading journals is therefore 77.4%, and the five leading journals account for 87.4% of the corpus. This pattern is analytically important because journal-level concentration can influence the apparent visibility of particular research topics, methodological preferences and geographic contributions. However, the concentration should not be interpreted as evidence that the journal itself caused the observed research trends. Several mechanisms may plausibly contribute, including the broad topical scope of Materials, its publication volume, open-access publishing model, the preferences of authors working in materials science, and database-specific



indexing and retrieval. The present bibliometric design cannot disentangle these mechanisms. Accordingly, the journal concentration is treated as a structural characteristic of the retrieved corpus and as a potential source of interpretive skew, rather than as evidence of a field-wide publication preference independent of database coverage. This caution is particularly important because 59.2% of the corpus is attributable to one journal, meaning that changes in its indexing status, editorial scope, publication volume or metadata practices could materially affect the observed trends. The concentration is therefore considered alongside, rather than separated from, the single-database limitation discussed in Section 7.

Table 3 Leading Journals Publishing on Advanced Materials and Digital Technologies for Low-Carbon and High-Performance Concrete (2015-2025)

Rank	Journal	No. of Publications	% of Corpus	Total Citations	Avg. Citations/Paper
1	Materials	296	59.2%	5699	19.25
2	Scientific Reports	91	18.2%	1420	15.6
3	Heliyon	21	4.2%	420	20.0
4	Polymers	17	3.4%	257	15.12
5	Environmental Science and Pollution Research	12	2.4%	309	25.75
6	PLOS ONE	10	2.0%	125	12.5
7	Nanomaterials	6	1.2%	199	33.17
8	Data in Brief	5	1.0%	36	7.2
9	Gels	5	1.0%	27	5.4
10	The Science of The Total Environment	4	0.8%	258	64.5
11	MethodsX	3	0.6%	50	16.67
12	Biomimetics	3	0.6%	40	13.33
13	Sensors	2	0.4%	26	13.0
14	Journal of Environmental Management	2	0.4%	126	63.0
15	Materials and Structures	2	0.4%	8	4.0

Leading Journals Publishing on the Review Topic (2015-2025)

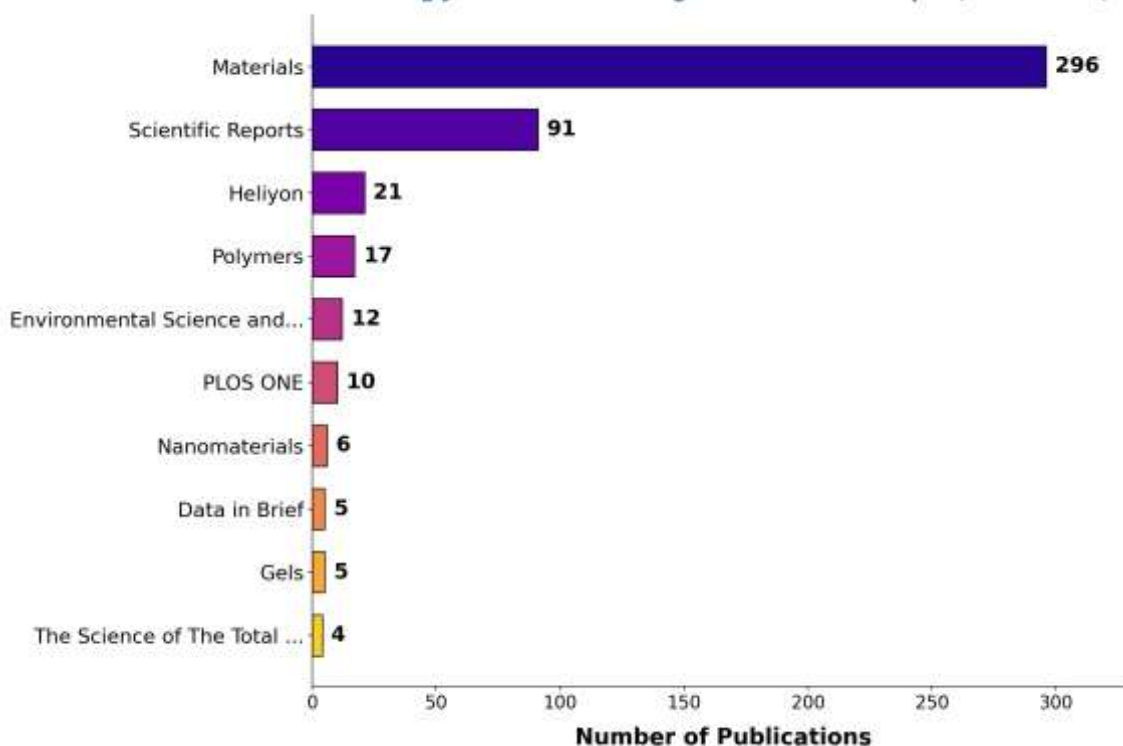


Figure 3. Ten leading journals publishing on the review topic, 2015-2025, ranked by publication count.

Most productive authors

As shown in Table 4, the top fifteen most productive authors are identified by number of publications, followed by overall and average citation numbers. The author with the most publications is Piotr Smarzewski (8 publications and 332 cumulative citations), followed by two authors with 5 publications apiece (Kennedy C. Onyelowe and M. S. El-Feky), with the most citations (332) coming from Smarzewski. In particular, certain authors who have comparatively low publication counts, like Zheng Wang (4 publications, 286 citations) and Ali Majdi (4 publications, 196 citations), have received disproportionately many citations in comparison to other authors who have published similar numbers of papers (see Section 4.5 for more details). The results are plotted in Figure 4.

Table 4 Most Productive Authors (2015-2025)

Rank	Author	No. of Publications	Total Citations	Avg. Citations/Paper
1	Smarzewski, Piotr	8	332	41.5
2	Onyelowe, Kennedy C.	5	102	20.4
3	El-Feky, M. S.	5	40	8.0
4	Ebid, Ahmed M.	4	56	14.0
5	Wang, Jing	4	41	10.2
6	Hájek, Petr	4	77	19.2
7	Mahmoodzadeh, Arsalan	4	22	5.5
8	Wetzel, Alexander	4	123	30.8
9	Majdi, Ali	4	196	49.0
10	Zhang, Yingda	4	26	6.5
11	Moon, Juhyuk	4	172	43.0
12	Wang, Fengjuan	4	286	71.5
13	Hanandeh, Shadi	3	40	13.3
14	Vairagade, Vikrant S.	3	44	14.7
15	Zhang, Wei	3	23	7.7

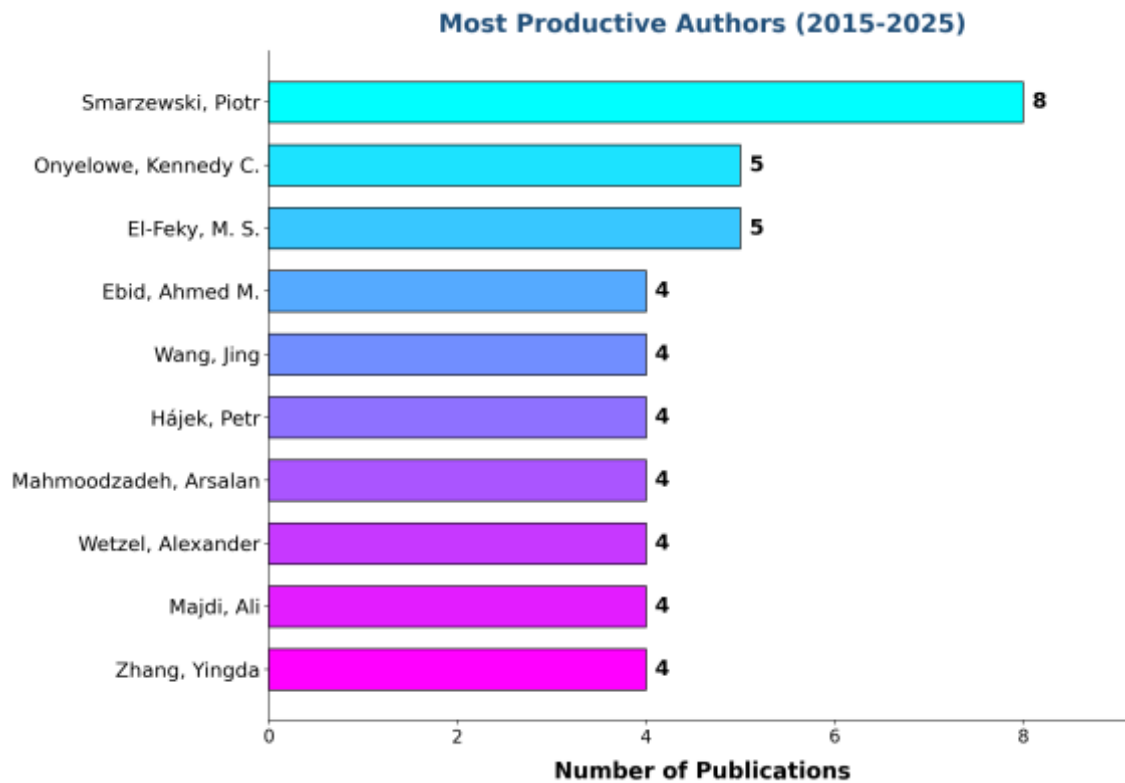


Figure 4. Ten most productive authors by publication count, 2015-2025.

Most cited studies

Table 5 shows the top 15 most cited works in the corpus. He et al. (2018) looked at the microstructure of UHP concrete with lithium slag and has been cited 272 times; Park et al. (2021) studied the use of supplementary cementitious materials (SCMs) in UHPC, with 187 citations; and Marani et al. (2020) predicted the compressive strength of UHP concrete using machine learning, which has been cited 179 times. Of the 15 most-cited studies, 6 were published in or before 2021, reflecting the fact that, unsurprisingly, the earlier the published year, the more citations are received in this field; a few more recent publications were also cited, with Hamada et al. (2023) and Elshaarawy et al. (2024) receiving over 120 citations in 2-3 years post-publication, illustrative of the impact of the sharp rise in overall field activity that was observed in Section 4.1. Predictive modelling research is being cited at a disproportionately high rate

compared to its numerical representation in the top 15 most cited studies, with machine-learning-related studies making up five out of the 15 most cited studies for the 500 full studies, making up about 12 per cent of the total number, a pattern consistent with the wider surge of interest in machine-learning-enabled concrete mix design and property prediction reported elsewhere in the literature (Ni et al., 2025; Yadav et al., 2025).

Table 5 Most Cited Studies (2015-2025)

Rank	Authors (Year)	Title	Journal	Times Cited
1	He et al. (2018)	Microstructure of ultra-high-performance concrete containing lithium slag	Journal of Hazardous Materials	272
2	Park et al. (2021)	The Role of Supplementary Cementitious Materials (SCMs) in Ultra High-Performance Concrete (UHPC): A Review	Materials	187
3	Marani et al. (2020)	Predicting Ultra-High-Performance Concrete	Materials	179



		Compressive Strength Using Tabular Generative Adversarial Networks		
4	Marvila et al. (2021)	Materials for Production of High and Ultra-High-Performance Concrete: Review and Perspective of Possible Novel Materials	Materials	141
5	Ullah et al. (2022)	Ultra-High-Performance Concrete (UHPC): A State-of-the-Art Review	Materials	140
6	Chu et al. (2020)	Effect of Graphene Oxide on Mechanical Properties and Durability of Ultra-High-Performance Concrete Prepared from Recycled Sand	Nanomaterials	132
7	Hamada et al. (2023)	Recycling solid waste to produce eco-friendly ultra-high-performance concrete: A review of durability, microstructure and environmental characteristics	The Science of The Total Environment	126
8	Rathakrishnan et al. (2022)	Predicting compressive strength of high-performance concrete with high volume ground granulated blast-furnace slag replacement using boosting machine learning algorithms.	Scientific Reports	124
9	Elshaarawy et al. (2024)	Machine learning and interactive GUI for concrete compressive strength prediction	Scientific Reports	121
10	Liang et al. (2023)	A green ultra-high performance geopolymer concrete containing recycled fine aggregate: Mechanical properties, freeze-thaw resistance and microstructure	The Science of The Total Environment	111
11	Liu et al. (2018)	Effects of Pumice-Based Porous Material on Hydration Characteristics and Persistent Shrinkage of Ultra-High-Performance Concrete (UHPC)	Materials	107
12	Ahmad et al. (2021)	Effect of Short Fibre Reinforcements on Fracture Performance of Cement-Based Materials: A Systematic Review Approach	Materials	106
13	Chen et al. (2020)	Mechanical Properties of Ultra-High-Performance	Materials	105

		Concrete before and after Exposure to High Temperatures		
14	Park et al. (2015)	Early-Age Strength of Ultra-High-Performance Concrete in Various Curing Conditions	Materials	100
15	Xia et al. (2022)	Utilisation of sewage sludge ash in ultra-high-performance concrete (UHPC): Microstructure and life-cycle assessment	Journal of Environmental Management	94

Note. Compiled by the authors from the Dimensions database export (n = 500), 2015-2025.

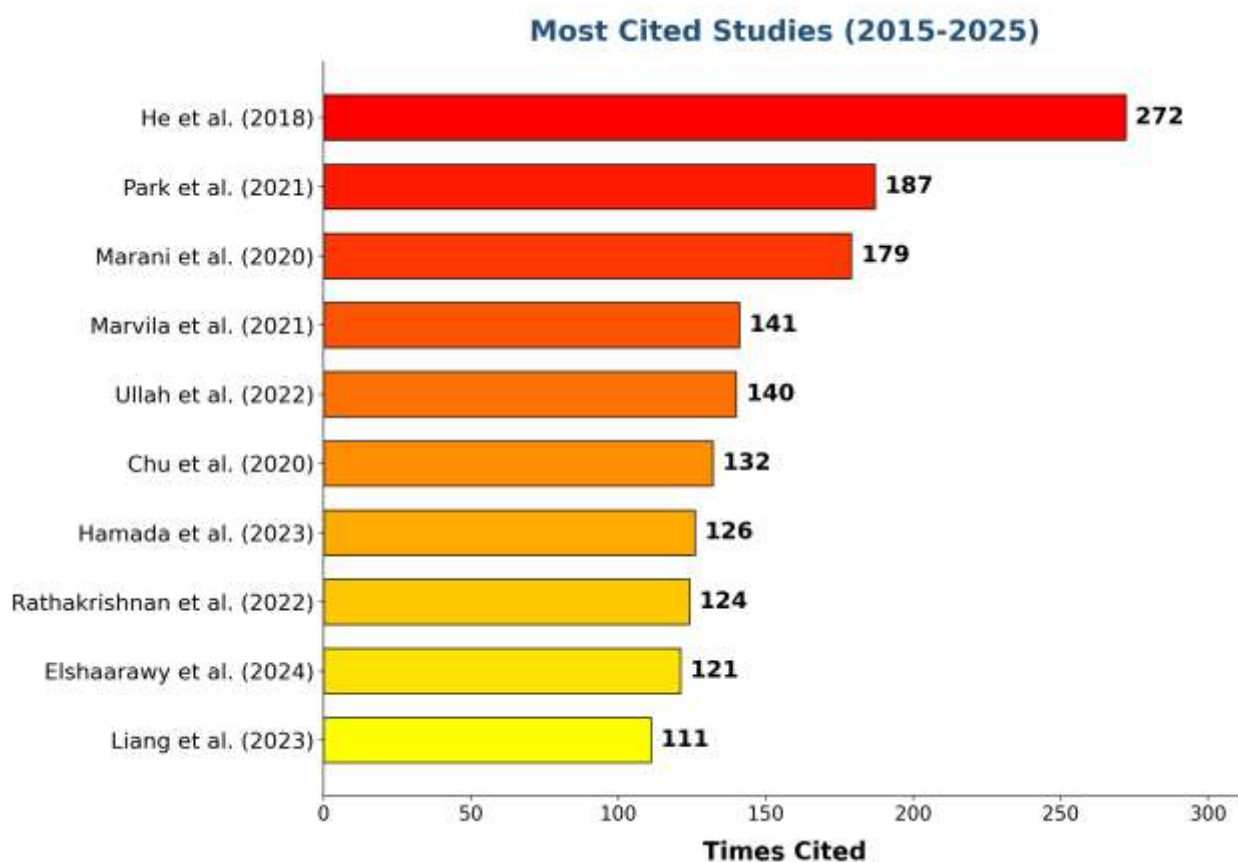


Figure 5. Ten most cited studies in the reviewed corpus, ranked by total citations received.

Most productive countries

The 15 countries with the most author affiliations are presented in Table 6 and Figure 6. China leads the way with 231 records (46.2 per cent after normalisation, against 43 records for the second-ranked country, Saudi Arabia). The United States (33), Egypt (32), Poland (31) and South Korea (31) are compressed in the second tier, followed by India (28), Iran (22), Australia (19) and Germany (17). This distribution is a result of the scale of the Chinese construction-research infrastructure and is representative of a more general trend seen in many sustainable-materials research areas, where a small number of countries several in the Middle East and North Africa or South and East Asia are becoming above-average contributors in relation to their proportion of global research output, perhaps due to a mix of national infrastructure investment priorities as well as the clustering of open-access mega-journal submissions from these regions, a concentration pattern also noted in recent reviews of low-carbon concrete research output (Barbhuiya et al., 2025).

Table 6 Most Productive Countries (2015-2025)

Rank	Country	No. of Publications	% of Corpus
1	China	231	46.2%
2	Saudi Arabia	43	8.6%
3	United States	33	6.6%
4	Egypt	32	6.4%
5	Poland	31	6.2%
6	South Korea	31	6.2%
7	India	28	5.6%
8	Iran	22	4.4%
9	Australia	19	3.8%
10	Germany	17	3.4%
11	Pakistan	16	3.2%
12	Canada	16	3.2%
13	Iraq	15	3.0%
14	Malaysia	12	2.4%
15	Czech Republic	12	2.4%

Most Productive Countries (2015-2025)

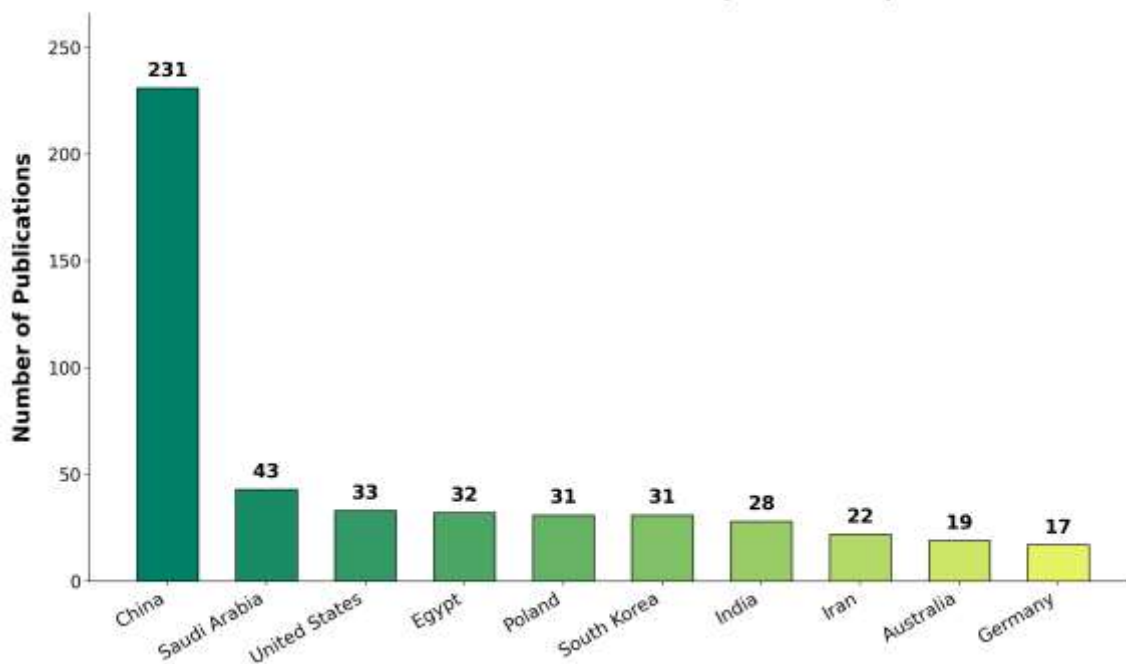


Figure 6. Ten most productive countries by author-affiliation count, 2015-2025.

Collaboration networks

International collaboration among countries

The international co-authorship network between the fifteen most productive countries is visualised in Figure 7, where the size of the nodes is proportional to the number of publications, and the width of the edges is proportional to the number of times the two countries were involved in the same publications. The most popular links between two countries are shown in full in Table 7. The most frequent co-authorship occurred between Egypt and Saudi Arabia with 13 co-authored papers, followed by Pakistan and Saudi Arabia (12), and China and Saudi Arabia (8). Saudi Arabia is a clear collaboration hub in the network, as it shows up in six of the top 10 country pairs, even though it is only second in raw productivity, meaning that Saudi-affiliated institutions

collaborate more than their rank in publications would suggest. Some of the top output-producing nations by themselves, such as South Korea, Malaysia and the United States, are only marginally related or even absent from the most intensive collaboration links, suggesting that the high self-sufficiency of the countries by production does not automatically lead to a high level of collaboration among others within the selected field.

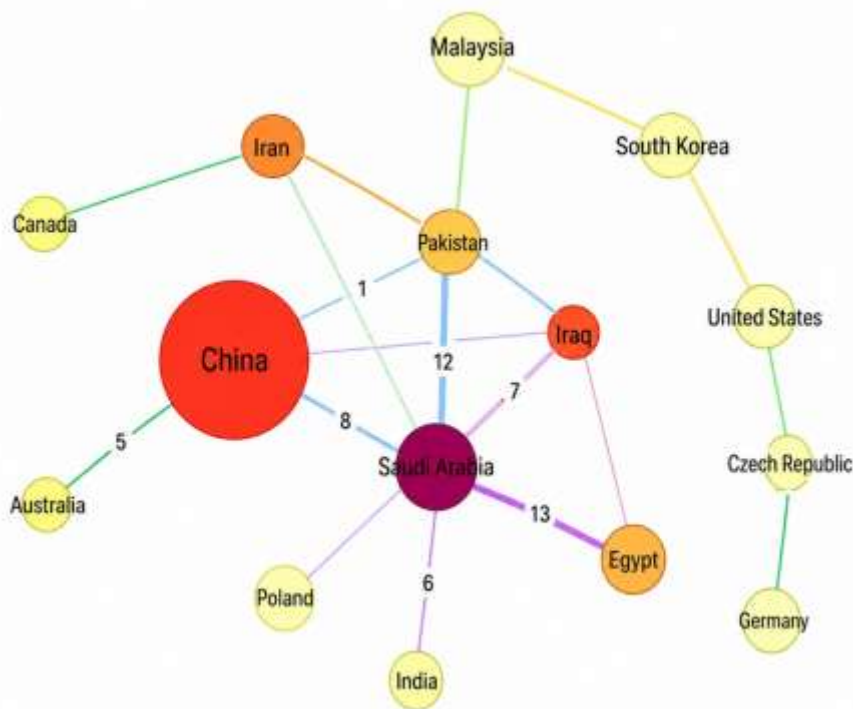


Figure 7. International co-authorship network among the fifteen most productive countries. Node size reflects publication count; edge width reflects the number of co-authored papers; node colour reflects network degree.

Table 7 International Co-authorship Pairs Among the Most Productive Countries (2015-2025)

Rank	Country A	Country B	No. of Co-auth
1	Egypt	Saudi Arabia	13
2	Pakistan	Saudi Arabia	12
3	China	Saudi Arabia	8
4	Iraq	Saudi Arabia	7
5	China	Pakistan	7
6	India	Saudi Arabia	6
7	Nigeria	Uganda	6
8	Australia	China	5
9	Egypt	Uganda	5
10	Nigeria	Saudi Arabia	5
11	Iran	Saudi Arabia	5
12	Egypt	Iraq	5
13	China	Japan	4
14	Egypt	Nigeria	4
15	Saudi Arabia	Uganda	4
16	Canada	Iran	4
17	China	Iraq	4
18	Iran	Iraq	4
19	Chile	Egypt	3
20	Chile	Jordan	3

Collaboration network among authors

The co-authorship network of the 15 most prolific authors, shown in Figure 8, reveals that these authors are closely connected. There is very little network structure, with just three collaboration edges connecting the fifteen nodes – forming a small triangular cluster of three authors: Kennedy C Onyelowe, Shadi Hanandeh, and Ahmed M Ebid – and the remaining twelve of the fifteen most productive authors having no direct co-authorship relationships among themselves within this set of documents. This sparsity suggests that high individual productivity in this field is realised largely through independent research groups or through small clusters, on the level of the individual authors, of the journals involved, in line with the finding reported in Section 4.3, and of the countries involved, reported in Section 4.7.1.

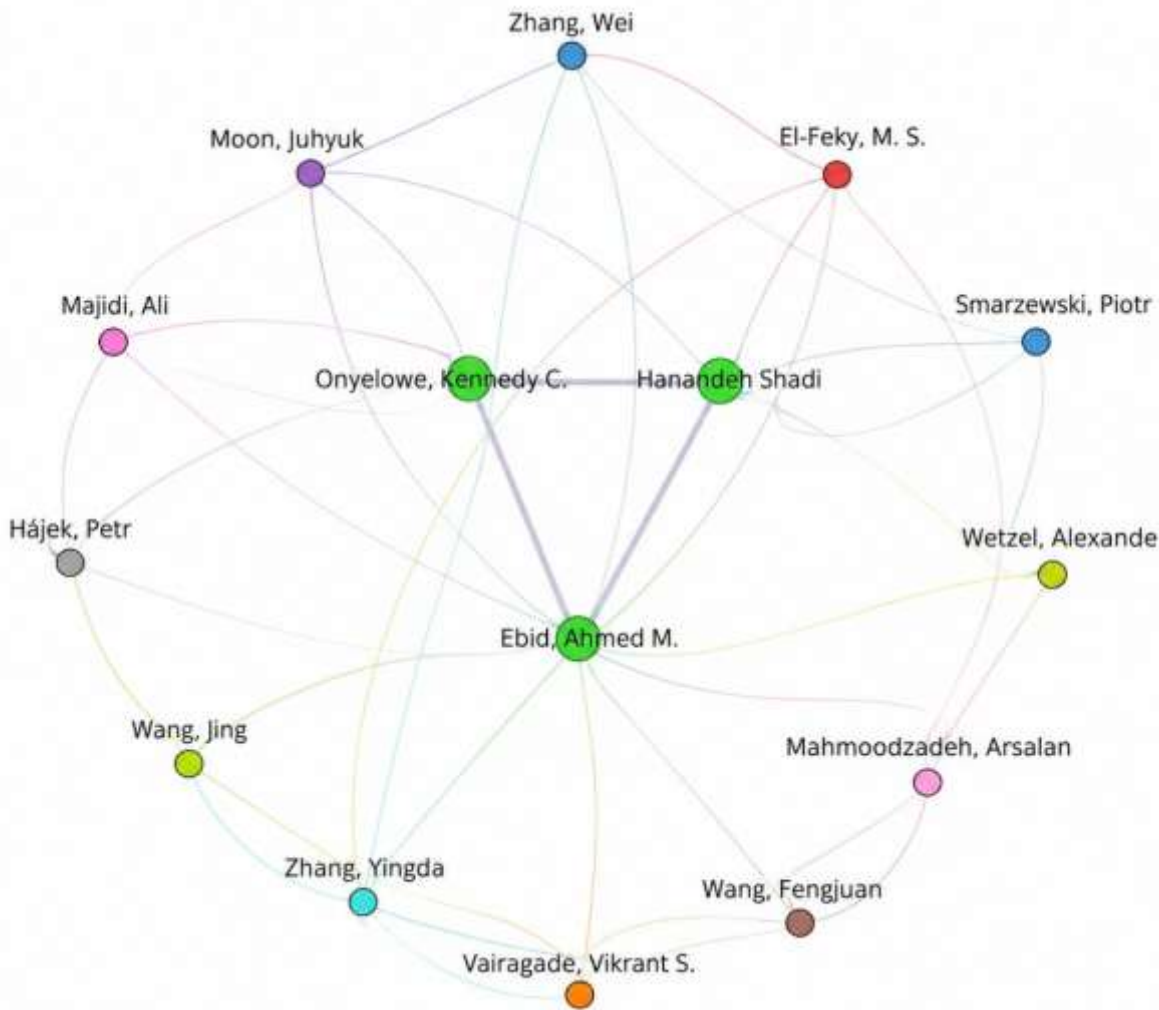


Figure 8. Co-authorship network among the fifteen most productive authors. Node size reflects publication count; edge width reflects the number of co-authored papers between two authors.

Author keyword co-occurrence and thematic analysis

Keyword co-occurrence network

The majority of records did not have a sufficiently populated author-keyword field, and therefore thematic terms were extracted from title-text bigrams, as outlined in Section 3.5. The 20 most common title-derived terms are listed in Table 8, and the co-occurrence network for the 25 most common terms is shown in Figure 9. The leading nodes are “machine learning” (38 occurrences) and “compressive strength” (30 occurrences), which indicates that predictive modelling is highly visible in article titles within the retrieved corpus. A second cluster contains

fibre-reinforcement terms such as “fibre reinforced”, “steel fibre” and “basalt fibre”, while another contains supplementary-cementitious-material terms such as “fly ash”, “silica fume” and “rice husk ash”. These patterns are consistent with recent focused reviews of agricultural-ash SCMs and natural-fibre reinforcement (Mozu-Simpson et al., 2026; Wahab et al., 2026). However, the analysis should not be interpreted as a complete measure of thematic prevalence. A concept may be important within an article, but absent from its title, and closely related concepts may be expressed using different terminology. Thus, the apparent low visibility of BIM, digital twins, structural health monitoring and life-cycle assessment partly reflects their limited occurrence in titles and cannot, on its own, demonstrate that these topics are absent from the broader literature. The title-derived network is consequently used as an indicator of explicit thematic emphasis, while the need for abstract/full-text text mining is recognised as a methodological priority for future bibliometric studies.

Table 8 Top Author Keywords (Title-Derived Bigrams), 2015-2025

Rank	Keyword	Frequency
1	machine learning	38
2	compressive strength	30
3	fiber reinforced	16
4	fly ash	15
5	silica fume	12
6	cementitious materials	11
7	rice husk	10
8	husk ash	10
9	supplementary cementitious	10
10	cementitious composites	10
11	steel fiber	9
12	steel fibers	8
13	flexural behavior	8
14	autogenous shrinkage	8
15	basalt fiber	7
16	strength prediction	6
17	curing conditions	6
18	learning techniques	6
19	bond strength	6
20	cement-based materials	6

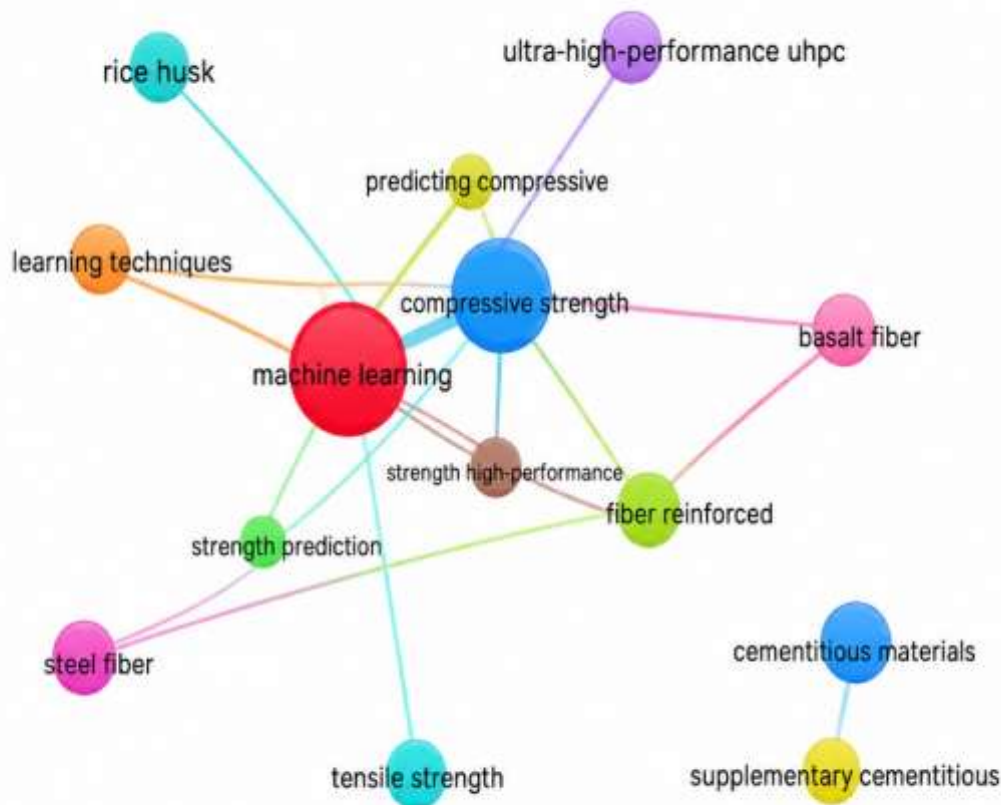


Figure 9. Keyword co-occurrence network of the twenty-five most frequent title-derived author keywords, 2015-2025. Node size reflects term frequency; edge width reflects co-occurrence strength within the same title.

Thematic evolution across three periods

The corpus was further split into three sub-periods: 2015-2018 (12 records), 2019-2022 (143 records), and 2023-2025 (345 records) and leading title-derived keywords were compared in each sub-period. This evolution is shown graphically in Figure 10, and the keyword-frequency data used for this purpose are detailed in Table 9. During the earliest period, the output of the field was small and consisted almost exclusively of narrowly descriptive, single-study terms, such as "early-age strength," "lithium slag," and "heat-treated ultra-high," because there were only twelve articles in this time frame and no clear thematic cluster had yet developed. Predictive modelling, in the form of "machine learning" and "compressive strength", appeared in eight titles, and was already part of the thematic mainstream of the field, well before the reader might expect to see the two concepts in recent literature. The terms "machine learning" and "compressive strength" reinforce further, reaching 30 and 22 occurrences, respectively, in the third and latest period, and supplementary-cementitious-material and fibre-reinforcement terms, such as "fly ash" (14), "fiber reinforced" (12), "silica fume" (9), "steel fiber" (8) and "rice husk" (8), also become stabilized and form a second tier of resources. This trajectory suggests a maturation from the earlier phases, where case studies were more spread out across disciplines of materials, to a more thematic, or focused, organization of the field, around themes of property prediction (with the help of machine learning) and a recurring set of themes related to supplementary materials and fibre reinforcements, with comparatively little thematic diversification into digital monitoring or life-cycle assessment territory even in the most recent period, a lag that is also flagged in recent reviews of AI-assisted and machine-learning-based concrete design as a persistent gap between predictive-modelling capability and its integration into monitoring or whole-life assessment workflows (Mahjoubi et al., 2025; Prasittisopin, 2025).

Table 9 Thematic Evolution of Author Keywords Across Three Periods (2015-2025)

Rank	Period 1 (2015-2018) n=12	Freq	Period 2 (2019-2022) n=143	Freq	Period 3 (2023-2025) n=345	Freq
1	early-age strength	1	machine learning	8	machine learning	30
2	curing conditions	1	compressive strength	8	compressive strength	22
3	conditions microstructure	1	autogenous shrinkage	5	fly ash	14
4	containing lithium	1	cementitious materials	5	fiber reinforced	12
5	lithium slag	1	fiber reinforced	4	silica fume	9
6	slag microstructural	1	supplementary cementitious	4	steel fiber	8
7	heat-treated ultra-high	1	silica fume	3	rice husk	8
8	optimum production	1	steel fibers	3	cementitious composites	8
9	production test	1	bond strength	3	flexural behavior	7
10	test method	1	strength prediction	3	husk ash	7



Figure 10. Thematic evolution of the leading title-derived author keywords across three publication periods: 2015-2018, 2019-2022, and 2023-2025.

Thematic strategic map

Figure 11 places the most important themes of the field on a strategic (density-centrality) map, a typical bibliometric tool used for the classification of research themes as motor themes (well-developed and central to the field), basic or transversal themes (important but less internally cohesive), niche themes (well-developed but peripheral), and emerging and declining themes. Machine learning is well-developed and has strong links to other thematic clusters, while compressive-strength prediction is developed but linked to the other thematic clusters. The supplementary cementitious material and fibre reinforcement quadrant sits in the middle of the basic quadrant and the motor quadrant, as they are considered the basic, cross-cutting themes that are tied to other research areas of interest, but not necessarily the most tightly internally cohesive, consistent with their characterisation elsewhere as foundational but hybridised research strands that cut across multiple low-carbon and high-performance concrete applications (Moolchandani et al., 2025). Well-developed but comparatively self-contained sub-literatures are found in the autogenous shrinkage and methodological work quadrant, which represents the neural network. The emerging-or-declining quadrant, where both density and centrality are low, contains some small themes, such as waste-glass utilisation, curing-condition studies, and bond-strength testing, that should be investigated further in a future bibliometric update to see if these are truly new directions for research or contracting areas of past interest.

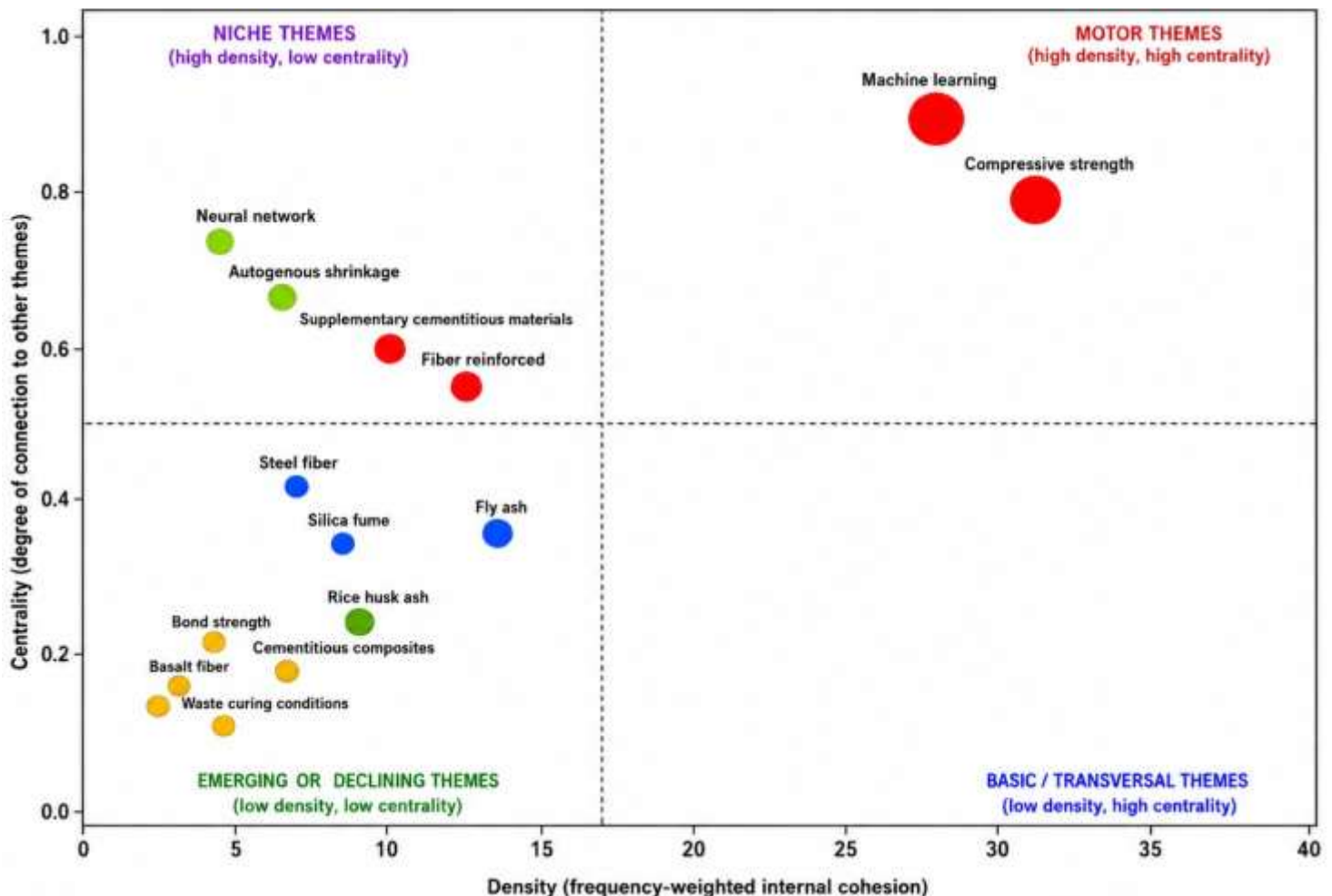


Figure 11. Thematic strategic map of research trends, 2015-2025, classifying leading themes by density (internal cohesion) and centrality (connection to other themes). Bubble size reflects theme frequency.

Innovative construction and research-gap frameworks

Based on the bibliometric evidence outlined above, Figure 12 shows a proposed framework for linking the three major research layers of the field (material innovation, digital and process technologies, sustainability assessment) with a 'convergence point' situated at the centre where data is used to drive convergence and link to

performance and sustainability outcomes. This framework is designed as a synthesising tool, not as a novel finding. It is an interpretation of the relative success found in this corpus for materials-level innovation and the relative failure for digital and life-cycle integration, into a framework that can inform design for future research. This is complemented by Figure 13, which presents a clear research-gap framework: the four structural gaps identified in the bibliometric analysis (under-representation of digital technology, disconnect in collaboration, concentration on specific journals, and lack of validation on the research life cycle and field), and the interaction of these gaps which suggest that the current literature focuses on materials-level mechanical optimisation over digitalisation and integration with whole-life sustainability, echoing calls in the broader low-carbon concrete literature for decarbonisation pathways that treat material, digital and life-cycle performance as jointly optimised rather than separately pursued objectives (Azarhomayun et al., 2026; Ghazy et al., 2025). The frameworks are discussed in subsequent sections, along with their implications for future research, in Sections 5 and 8.

Integrated Framework for Digitally-Enabled Low-Carbon, High-Performance Concrete

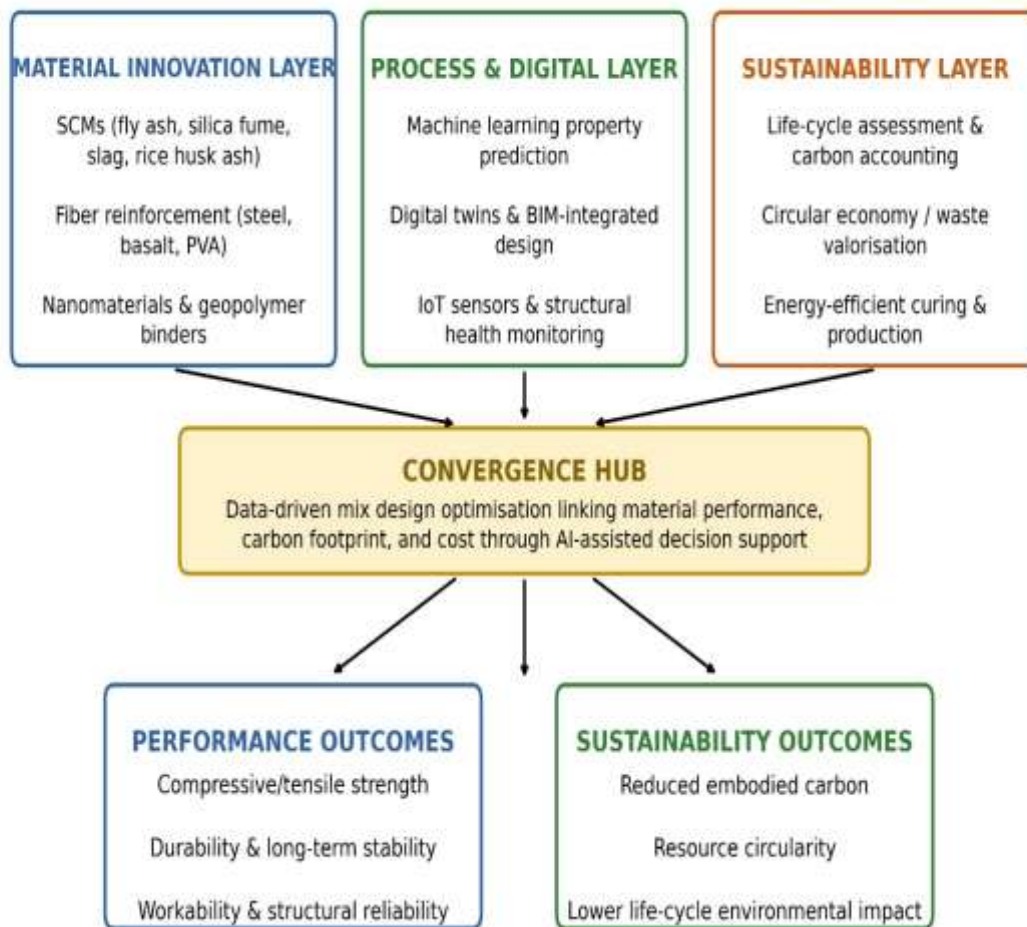


Figure 12. Integrated framework for digitally enabled, low-carbon, high-performance concrete, linking material innovation, digital and process technologies, and sustainability assessment through a data-driven convergence hub.

Research Gap Framework: Advanced Materials and Digital Technologies for Low-Carbon, High-Performance Concrete

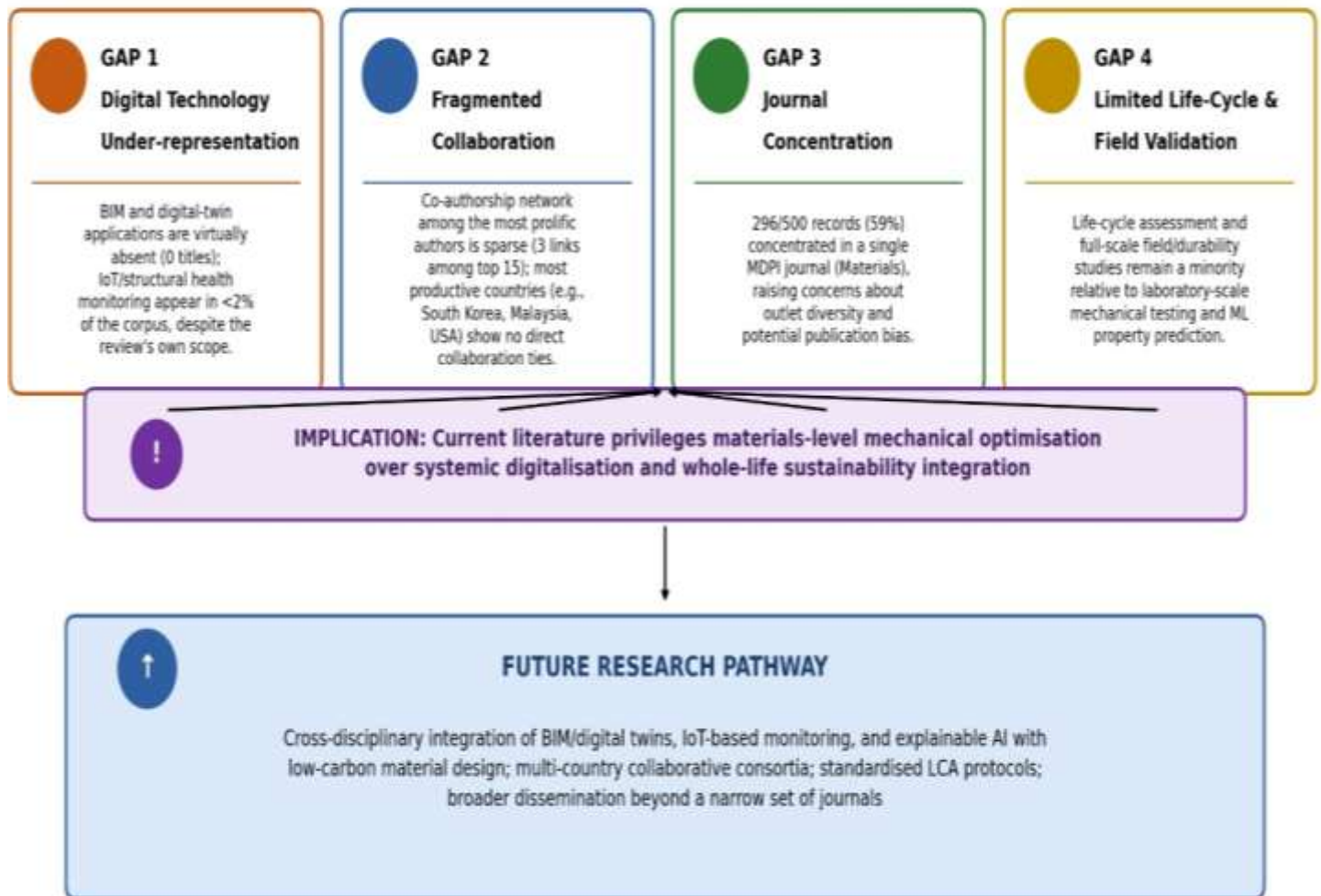


Figure 13. Research gap framework summarising four structural gaps identified in the reviewed literature and their implication for future research pathways.

DISCUSSION

The bibliometric evidence gathered in Section 4 leads to several interrelated conclusions regarding the state of research on advanced materials and digital technologies for low-carbon and high-performance concrete. When these numbers are taken together, they suggest a field that is growing quickly in size and has a very narrow scope of places it is disseminated and the themes it addresses, but is structurally divided in its modes of collaboration and lacks a balance in its handling and promotion of materials innovation, digital integration and sustainability validations.

The rapid increase in publications is broadly consistent with growth reported in adjacent materials-informatics and sustainable-construction research, where regulatory pressure to reduce embodied carbon and the maturation of machine-learning methods have increased research activity (Rathakrishnan et al., 2022; Zhang et al., 2024; Azarhomayun et al., 2026). However, the journal distribution requires a more cautious interpretation of this apparent expansion. Materials alone accounts for 59.2% of the corpus (296/500), Scientific Reports accounts for a further 18.2%, and the top five journals together account for 87.4%. Such concentration may reflect genuine topical alignment with materials-focused publishing, but it may also reflect the publication volume, broad scope and accessibility of high-throughput journals, author submission behaviour, and the coverage characteristics of Dimensions.

It is therefore not possible to determine from the present data whether the concentration reflects the intrinsic structure of the research field or a publication and indexing pattern specific to the database and period examined. The concentration nevertheless matters because a corpus dominated by one outlet can amplify the thematic, geographic and methodological profile of that outlet and can make field-level conclusions more sensitive to its editorial scope and indexing status. For this reason, the present findings should be read as describing the retrieved research ecosystem rather than as an unbiased estimate of the entire global field. A useful validation in future work would be to repeat the same search in Scopus and/or Web of Science, harmonise records using DOI-level deduplication, and compare the journal, country and thematic distributions across databases. Such a sensitivity analysis would show which patterns remain stable and which are database-dependent.

The country-level results are also less clear-cut than they may initially appear. The dominance of China is not surprising, representing nearly half of the country-attributable output, especially when compared to the extent of construction-research investment and infrastructure activity in the country, and is generally consistent with the existing overwhelming dominance of China across most subfields of civil-engineering materials research reported in other pieces of bibliometric literature (Barbhuiya et al., 2025; Khan et al., 2024). The most interesting aspect of the network of international collaboration reported in Section 4.7.1 is the extent to which Saudi Arabia has strong bilateral relationships with Egypt, Pakistan, China, Iraq, and India, which have led to its disproportionately central role in the network, with far from an evenly distributed international network of collaboration, but one organised around a small number of institutional partnerships from the Gulf region. A couple of countries with high absolute productivity, such as South Korea and the United States, are only somewhat linked to this collaboration structure, with geographies of productivity and geographies of collaboration following partly independent dynamics, which could well be shaped by varying requirements of funding agencies for international co-investigation, institutional partnership agreements, or simply by different publication cultures between more domestically self-sufficient research systems and those which are more dependent on cross-border collaboration for their output.

The story of fragmentation is further supported by the author-level collaboration network. The author-level collaboration network further confirms this fragmented picture. The fact that only three of a potential one hundred and five edges are realised between the fifteen most productive authors (Section 4.7.2) suggests that leadership in this field, measured in the number of publications of the top fifteen, is based primarily on the work of individual researchers and less on a tightly connected invisible college of collaborating specialists. This is a somewhat unusual observation in a new field of applied science, where one might anticipate that as the field matures, the number of collaborators who would form stable cores would increase, but rather, evidence here suggests either that the field is still young and spread out such that stable cores of collaborators are not yet present, or that structural barriers, geographical distance, conflicting institutional priorities, or sheer lack of awareness of parallel work being done elsewhere are limiting the coalescence of such cores.

Perhaps the most important outcome of the review is provided by the thematic findings in Sections 4.8.1–4.8.3. Machine learning and compressive-strength prediction occupy prominent positions in the strategic mapping, while supplementary cementitious materials and fibre reinforcement remain major and technically mature themes (Marani et al., 2020; Liu, 2022; Elshaarawy et al., 2024; Ni et al., 2025; Yadav et al., 2025; Mozu-Simpson et al., 2026; Wahab et al., 2026). However, the interpretation of the keyword results requires an important qualification. Because the thematic network is derived from title bigrams rather than a complete author-keyword or abstract/full-text term set, the low frequency of BIM, digital twins, structural health monitoring, IoT and life-cycle assessment should be interpreted as low title visibility within this corpus, not as definitive evidence of low activity across the entire literature.

This distinction is especially relevant for interdisciplinary technologies that authors may describe using broader engineering, informatics or infrastructure terminology rather than the specific labels used in the present search. The results therefore support the conclusion that materials innovation and machine-learning-based prediction are highly visible in the retrieved corpus, but they provide weaker evidence about the absolute prevalence of less frequently titled digital and whole-life sustainability themes. Future studies using abstract and full-text text mining, controlled vocabularies and semantic clustering would provide a stronger test of whether these apparent gaps persist when terminology beyond article titles is considered.

Another imbalance, albeit less severe, is in sustainability validation. Most of the corpus (Liu et al., 2024a; Singaravel et al., 2024; Sameer et al., 2019; Laiblová et al., 2019) continues to report only mechanical performance, most often the compressive strength, as the primary and sole outcome variable, treating environmental performance, if it is considered at all, as a secondary or qualitative design goal rather than as a co-equal one quantified with the same strictness as mechanical performance, a gap also highlighted in recent low-carbon concrete reviews that call for embodied-carbon and durability metrics to be reported alongside strength as standard practice rather than as an optional addition (Azarhomayun et al., 2026; Ghazy et al., 2025; Barbhuiya et al., 2025). This imbalance, like in the thematic keyword analysis, is manifested in the materials-versus-digital and sustainability imbalance in the outcome variables, and points to the integrated framework and research-gap framework presented in Section 4.9, both of which seek to make explicit the systemic convergence that current publication patterns have not yet achieved organically.

Viewed collectively, these results should be interpreted as evidence of substantial technical activity in the underlying materials research, while also showing that the wider research ecosystem remains uneven across digital integration, collaboration, publication concentration and standardised sustainability assessment. This is a structural observation about the retrieved research ecosystem rather than a judgement on the quality of individual studies. The value of a bibliometric-assisted systematic review is precisely that it can make such structural patterns visible, while the limitations above require that those patterns are interpreted cautiously.

CONCLUSION

This review aimed to quantitatively and systematically document the state of research on advanced materials and digital technologies used for low-carbon, high-performance concrete from 2015 to 2025. Based on 500 articles obtained from the Dimensions database and analysed using a PRISMA-guided bibliometric-assisted methodology, the review shows a strong increase in publication activity during the study period, with much of the recent growth associated with supplementary cementitious materials, fibre-reinforced systems and machine-learning-based strength prediction. The structural findings also reveal a research corpus concentrated in a small number of journals, particularly Materials, which accounts for 59.2% of the retrieved records, alongside asymmetric country-collaboration patterns and sparse collaboration among the most productive authors. These findings indicate that research activity has expanded substantially, but that the field's structural maturation has not progressed uniformly across publication venues, collaboration networks, digital integration and whole-life sustainability assessment. Because the study relies on Dimensions and title-derived bigrams, these conclusions should be understood as evidence from the defined corpus rather than as an exhaustive census of the global literature.

The results have direct implications for the next steps in development in this field, from the research community, funding agencies, and research journal editors. Materials innovation alone is not enough to enable a field to achieve truly low-carbon, high-performance, and digitally intelligent concrete construction; it requires intentional and coordinated investments to integrate cross-disciplinary communities, such as materials chemists, digital data scientists, structural monitoring experts and life-cycle assessment practitioners, in shared research programmes, and not letting them develop largely separately. The integrated frameworks and research gaps identified in Section 4.9 are provided as a starting point for the above coordination, and can be used to support funding priorities, editorial commissioning, and doctoral research agendas. For this reason, the shift to low-carbon, high-performance concrete construction is not only a materials-science problem, but is also highly organisationally and collaboratively challenging, and this review's key contribution is in bringing this structural imbalance to the fore, making it visible, measurable, and hopefully actionable.

LIMITATIONS

The conclusions of this review are subject to several methodological restrictions that should be considered when interpreting the findings.

First, the analysis was performed using one bibliographic database, Dimensions, and no cross-database comparison with Scopus or Web of Science was undertaken. Although Dimensions provides broad

multidisciplinary coverage, database-specific indexing, source coverage, metadata completeness, citation matching and retrieval algorithms can alter the composition of a bibliometric corpus. The observed publication counts, journal shares, country rankings and thematic frequencies should therefore be interpreted as properties of the Dimensions-retrieved corpus rather than as exact estimates of global research activity. A multi-database validation using harmonised search strings and DOI-level deduplication would provide a stronger test of the stability of the present findings and is recommended for future updates.

Second, an author-keyword field was not sufficiently available for most records, so thematic and keyword co-occurrence analyses were based on title-derived bigrams rather than author- or database-assigned keywords. Although title-derived text can identify concepts explicitly foregrounded by authors, it has lower semantic coverage than structured keywords or abstract/full-text mining. It may therefore under-represent themes that are discussed in depth but not included in titles, while also producing duplicated or overly specific phrases that depend on individual title wording. The thematic results should consequently be treated as indicators of title-visible research emphasis rather than exhaustive representations of the conceptual content of the corpus.

Third, country attribution was obtained by automatically parsing free-text country strings in authors' affiliations, which successfully classified 99.4% of the records but depended on pattern matching against a controlled country-name list and could incorrectly assign or fail to identify complex dual or multinational affiliations. In addition, the strong concentration of publications in Materials (59.2% of the corpus) introduces a further interpretive consideration. Such concentration may reflect genuine topical fit, the journal's publication capacity and scope, author submission preferences, open-access accessibility, or Dimensions-specific indexing, and the present design cannot isolate these effects. The concentration may also amplify the journal's thematic and geographic profile in aggregate analyses. Accordingly, journal-level results are interpreted as descriptive features of the retrieved corpus, not as direct measures of field-wide publishing behaviour.

Recommendations and suggestions for future studies

Based on the bibliometric evidence and the structural gaps that have been uncovered in Sections 4.9 and 5, some specific suggestions are given below for researchers, funders and editors in this area.

Secondly, future primary research should be more mindful of embedding digital design and monitoring technologies, BIM, digital-twin methodologies and digital-twin-based SHM at the materials level; the lack of work on BIM within this corpus is not evidence that this is not necessary or possible.

Second, funding agencies and international research consortia should actively encourage cooperation and collaboration between different countries and institutions beyond the limited number of unilateral partnerships that currently dominate the international co-authorship network of this field, in particular between the more peripheral research communities of South Korea, the United States and Malaysia, and the more central research systems of China, Saudi Arabia and Egypt.

Third, there is a need for standardised, comparable life-cycle assessment protocols to be consistently used in conjunction with mechanical-performance testing, thus embedding embodied-carbon and mechanical-strength outcomes as equal design goals and not as separate and unevenly reported aspects, and the fact that the life-cycle assessment work is in a relatively small minority, when compared to the volume of mechanical-performance testing, suggests that there is a genuine and actionable opportunity here.

Fourth, the field's current reliance on a few high-throughput outlets for review and original-research papers is at least somewhat offset by actively encouraging review and original-research papers to be submitted to journals and editors that are not so widely dispersed, or so under-represented, as the venues that have already taken up such a large share of the dissemination load.

Finally, future bibliometric research on this topic should use a multi-database design incorporating, where feasible, Dimensions, Scopus and/or Web of Science, followed by DOI-level deduplication and a documented sensitivity analysis of journal, country, citation and thematic patterns. Future studies should also use structured

author keywords where available and complement them with abstract and full-text text mining, controlled vocabularies, stemming/lemmatisation and semantic clustering. Advanced natural-language-processing approaches could identify concepts that are discussed extensively but not expressed in titles and could reduce the dependence on title-derived bigrams. Such an approach would provide a more comprehensive basis for testing whether the apparent under-representation of BIM, digital twins, sensing, 3D printing and life-cycle assessment persists when broader textual evidence is analysed. In addition, future work should explicitly report concentration indicators such as the share of the leading journal(s) and, where appropriate, concentration ratios across the top outlets, so that changes in publication concentration can be distinguished from genuine changes in research activity.

Declarations

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Data availability: The datasets generated and/or analysed during this study are available from the corresponding author upon reasonable request.

REFERENCES

1. Ahmad, W., Khan, M., & Smarzewski, P. (2021). Effect of short fibre reinforcements on fracture performance of cement-based materials: a systematic review approach. *Materials*, 14(7), 1745. <https://doi.org/10.3390/ma14071745>
2. Azarhomayun, F., Wei, J., & Khayat, K. H. (2026). Low-carbon concrete for sustainable construction: a comprehensive review of performance characteristics, implementation challenges, and decarbonization pathways. *Journal of Building Engineering*, 128, 116731. <https://doi.org/10.1016/j.job.2026.116731>
3. Barbhuiya, S., Das, B. B., Adak, D., Kapoor, K., & Tabish, M. (2025). Low-carbon concrete: advancements, challenges and future directions in sustainable construction. *Discover Concrete and Cement*, 1(1). <https://doi.org/10.1007/s44416-025-00002-y>
4. Bermudez, M., Wen, K. W., & Hung, C. C. (2022). A comparative study on the shear behaviour of UHPC beams with macro hooked-end steel fibres and PVA fibres. *Materials*, 15(4), 1485. <https://doi.org/10.3390/ma15041485>
5. Chu, H., Wang, F., Wang, L., Feng, T., & Wang, D. (2020). Mechanical properties and environmental evaluation of ultra-high-performance concrete with aeolian sand. *Materials*, 13(14), 3148. <https://doi.org/10.3390/ma13143148>
6. Elshaarawy, M. K., Alsaadawi, M. M., & Hamed, A. K. (2024). Machine learning and interactive GUI for concrete compressive strength prediction. *Scientific Reports*, 14(1), 16694. <https://doi.org/10.1038/s41598-024-66957-3>
7. Ghanem, H., Ramadan, R., Khatib, J., & Elkordi, A. (2024). A review on chemical and autogenous shrinkage of cementitious systems. *Materials*, 17(2), 283. <https://doi.org/10.3390/ma17020283>
8. Ghazy, M. F., Maaty, E. S. A., Elaty, M. A., & Alrwashdeh, A. A. (2025). A comprehensive review of limestone calcined clay cement (LC3): environmental and property benefits, challenges, opportunities, and future directions. *Results in Engineering*, 28, 108319. <https://doi.org/10.1016/j.rineng.2025.108319>
9. Hakeem, I. Y., Zaid, O., Arbili, M. M., Alyami, M., Alhamami, A., & Alharthai, M. (2024). A state-of-the-art review of the physical and durability characteristics and microstructure behaviour of ultra-high-performance geopolymer concrete. *Heliyon*, 10(2), e24263. <https://doi.org/10.1016/j.heliyon.2024.e24263>
10. Hamada, H. M., Shi, J., Abed, F., Al Jawahery, M. S., Majdi, A., & Yousif, S. T. (2023). Recycling solid waste to produce eco-friendly ultra-high-performance concrete: a review of durability, microstructure and environmental characteristics. *The Science of The Total Environment*, 876, 162804. <https://doi.org/10.1016/j.scitotenv.2023.162804>

11. Hasanzadeh, A., Vatin, N. I., Hematibahar, M., Kharun, M., & Shooshpasha, I. (2022). Prediction of the mechanical properties of basalt fibre-reinforced high-performance concrete using machine learning techniques. *Materials*, 15(20), 7165. <https://doi.org/10.3390/ma15207165>
12. He, Z. H., Du, S. G., & Chen, D. (2018). Microstructure of ultra-high-performance concrete containing lithium slag. *Journal of Hazardous Materials*, 353, 35–43. <https://doi.org/10.1016/j.jhazmat.2018.03.063>
13. Ibrahim, I. K., Rady, M., Tawfik, N. M., Kassem, M., & Mahfouz, S. Y. (2025). Enhancing strength and sustainability of concrete with steel slag aggregate. *Scientific Reports*, 15(1), 17068. <https://doi.org/10.1038/s41598-025-01296-5>
14. Jenima, J., Dharshini, M. P., Ajin, M., Moses, J. J., Retnam, K. P., Arunachalam, K. P., Avudaiappan, S., & Munoz, R. F. A. (2024). A comprehensive review of titanium dioxide nanoparticles in cementitious composites. *Heliyon*, 10(20), e39238. <https://doi.org/10.1016/j.heliyon.2024.e39238>
15. Khan, S., Al-Deen, S., & Lee, C. K. (2024). Mechanical and durability behaviours of low carbon concrete: a systematic review. *Journal of Building Engineering*, 100, 111633. <https://doi.org/10.1016/j.jobe.2024.111633>
16. Laiblová, L., Pešta, J., Kumar, A., Hájek, P., Fiala, C., Vlach, T., & Kočí, V. (2019). Environmental impact of textile-reinforced concrete facades compared to conventional solutions—LCA case study. *Materials*, 12(19), 3194. <https://doi.org/10.3390/ma12193194>
17. Latif, S. D. (2021a). Concrete compressive strength prediction modeling utilizing deep learning long short-term memory algorithm for a sustainable environment. *Environmental Science and Pollution Research*, 28(23), 30294–30302. <https://doi.org/10.1007/s11356-021-12877-y>
18. Latif, S. D. (2021b). Developing a boosted decision tree regression prediction model as a sustainable tool for compressive strength of environmentally friendly concrete. *Environmental Science and Pollution Research*, 28(46), 65935–65944. <https://doi.org/10.1007/s11356-021-15662-z>
19. Lekhya, A., & Kumar, N. S. (2024). A study on the effective utilisation of ultrafine fly ash and silica fume content in high-performance concrete through an experimental approach. *Heliyon*, 10(22), e39678. <https://doi.org/10.1016/j.heliyon.2024.e39678>
20. Li, Z., Peng, Z., & Teng, J. (2020). Study of combined multi-point constraint multi-scale modelling strategy for ultra-high-performance steel fibre-reinforced concrete structures. *Materials*, 13(23), 5320. <https://doi.org/10.3390/ma13235320>
21. Lian, J., Wang, Y., Fu, T., Easa, S. M., Zhou, Y., & Li, H. (2023). Mechanical, electrical, and tensile self-sensing properties of ultra-high-performance concrete enhanced with sugarcane bagasse ash. *Materials*, 17(1), 82. <https://doi.org/10.3390/ma17010082>
22. Liang, G., Yao, W., & Wei, Y. (2023). A green ultra-high performance geopolymer concrete containing recycled fine aggregate: mechanical properties, freeze-thaw resistance and microstructure. *The Science of The Total Environment*, 895, 165090. <https://doi.org/10.1016/j.scitotenv.2023.165090>
23. Liu, F., Jin, B., He, Q., & Zhou, Y. (2024b). Influence of rice husk ash on the mechanical properties of ultra-high strength engineered cementitious composites (UHS-ECC). *PLOS ONE*, 19(4), e0301927. <https://doi.org/10.1371/journal.pone.0301927>
24. Liu, H., Laflamme, S., Cai, B., Lyu, P., Sritharan, S., & Wang, K. (2024a). Investigation of 3D printed self-sensing UHPC composites using graphite and hybrid carbon microfibers. *Sensors*, 24(23), 7638. <https://doi.org/10.3390/s24237638>
25. Liu, Y. (2022). High-performance concrete strength prediction based on machine learning. *Computational Intelligence and Neuroscience*, 2022(1), 5802217. <https://doi.org/10.1155/2022/5802217>
26. Lu, D., Tang, Z., Zhang, L., Zhou, J., Gong, Y., Tian, Y., & Zhong, J. (2020). Effects of combined usage of supplementary cementitious materials on the thermal properties and microstructure of high-performance concrete at high temperatures. *Materials*, 13(8), 1833. <https://doi.org/10.3390/ma13081833>
27. Mahjoubi, S., Barhemat, R., Meng, W., & Bao, Y. (2025). Review of AI-assisted design of low-carbon cost-effective concrete toward carbon neutrality. *Artificial Intelligence Review*, 58(8). <https://doi.org/10.1007/s10462-025-11182-1>
28. Marani, A., Jamali, A., & Nehdi, M. L. (2020). Predicting ultra-high-performance concrete compressive strength using tabular generative adversarial networks. *Materials*, 13(21), 4757. <https://doi.org/10.3390/ma13214757>

29. Marvila, M. T., de Azevedo, A. R. G., de Matos, P. R., Monteiro, S. N., & Vieira, C. M. F. (2021). Materials for production of high and ultra-high-performance concrete: review and perspective of possible novel materials. *Materials*, 14(15), 4304. <https://doi.org/10.3390/ma14154304>
30. Moolchandani, K., Sharma, A., & Dharavath, K. (2025). Hybrid use of supplementary cementitious materials, industrial byproducts, and fillers for sustainable high-performance concrete. *Discover Civil Engineering*, 2(1). <https://doi.org/10.1007/s44290-025-00379-6>
31. Mostafa, S. A., EL-Deeb, M. M., Farghali, A. A., & Faried, A. S. (2021). Evaluation of the nano silica and nano waste materials on the corrosion protection of high-strength steel embedded in ultra-high-performance concrete. *Scientific Reports*, 11(1), 2617. <https://doi.org/10.1038/s41598-021-82322-0>
32. Mozu-Simpson, M., Danso, H., Yalley, P. P. K., & Wahab, A. (2026). Influence of palm fruit stalk fibre length variation on the properties of fibre-reinforced composite concrete. *Discover Concrete and Cement*, 2, 28. <https://doi.org/10.1007/s44416-026-00067-3>
33. Muhyaddin, G. F. (2023). Mechanical and fracture characteristics of ultra-high-performance concretes reinforced with hybridisation of steel and glass fibres. *Heliyon*, 9(7), e17926. <https://doi.org/10.1016/j.heliyon.2023.e17926>
34. Ni, B., Rahman, M. Z., Guo, S., & Zhu, D. (2025). A review on properties and multi-objective performance predictions of concrete based on machine learning models. *Materials Today Communications*, 44, 112017. <https://doi.org/10.1016/j.mtcomm.2025.112017>
35. Park, S., Wu, S., Liu, Z., & Pyo, S. (2021). The role of supplementary cementitious materials (SCMs) in ultra-high performance concrete (UHPC): a review. *Materials*, 14(6), 1472. <https://doi.org/10.3390/ma14061472>
36. Prasittisopin, L. (2025). Machine learning (ML) and deep learning (DL) in sustainable concrete construction: review, trend and gap analyses. *Journal of Asian Architecture and Building Engineering*, 1–29. <https://doi.org/10.1080/13467581.2025.2574571>
37. Rathakrishnan, V., Bt. Beddu, S., & Ahmed, A. N. (2022). Predicting compressive strength of high-performance concrete with high volume ground granulated blast-furnace slag replacement using boosting machine learning algorithms. *Scientific Reports*, 12(1), 9539. <https://doi.org/10.1038/s41598-022-12890-2>
38. Razzazan, S., Mashaan, N. S., & Paraskeva, T. (2025). Lithium slag as a supplementary cementitious material for sustainable concrete: a review. *Materials*, 18(15), 3641. <https://doi.org/10.3390/ma18153641>
39. Sameer, H., Weber, V., Mostert, C., Bringezu, S., Fehling, E., & Wetzel, A. (2019). Environmental assessment of ultra-high-performance concrete using carbon, material, and water footprint. *Materials*, 12(6), 851. <https://doi.org/10.3390/ma12060851>
40. Shaaban, M., Amin, M., Selim, S., & Riad, I. M. (2025). Machine learning approaches for forecasting compressive strength of high-strength concrete. *Scientific Reports*, 15(1), 25567. <https://doi.org/10.1038/s41598-025-10342-1>
41. Singaravel, D. A., Veerapandian, P., Rajendran, S., & Dhairiyasamy, R. (2024). Enhancing high-performance concrete sustainability: integration of waste tyre rubber for innovation. *Scientific Reports*, 14(1), 4635. <https://doi.org/10.1038/s41598-024-55485-9>
42. Smarzewski, P. (2018). Analysis of failure mechanics in hybrid fibre-reinforced high-performance concrete deep beams with and without openings. *Materials*, 12(1), 101. <https://doi.org/10.3390/ma12010101>
43. Smarzewski, P. (2019). Study of toughness and macro/micro-crack development of fibre-reinforced ultra-high-performance concrete after exposure to elevated temperature. *Materials*, 12(8), 1210. <https://doi.org/10.3390/ma12081210>
44. Thiedeitz, M., Schmidt, W., Härder, M., & Kränkel, T. (2020). Performance of rice husk ash as supplementary cementitious material after production in the field and in the lab. *Materials*, 13(19), 4319. <https://doi.org/10.3390/ma13194319>
45. Tipu, R. K., Rath, P., Pandya, K. S., & Panchal, V. R. (2025). Optimising sustainable blended concrete mixes using deep learning and multi-objective optimisation. *Scientific Reports*, 15(1), 16356. <https://doi.org/10.1038/s41598-025-00943-1>

46. Tong, Y., Liu, W., Liu, X., Wang, P., Sheng, Z., Li, S., Zhang, H., Meng, Y., Zhu, Y., Lei, X., Lin, Y. T., & Jiao, P. (2025). Materials design and structural health monitoring of horizontal axis offshore wind turbines: a state-of-the-art review. *Materials*, 18(2), 329. <https://doi.org/10.3390/ma18020329>
47. Ullah, R., Qiang, Y., Ahmad, J., Vatin, N. I., & El-Shorbagy, M. A. (2022). Ultra-high-performance concrete (UHPC): a state-of-the-art review. *Materials*, 15(12), 4131. <https://doi.org/10.3390/ma15124131>
48. Vairagade, V. S. (2025). Multi-scale theoretical modelling with molecular simulation framework for fly ash-based high-performance concrete. *Scientific Reports*, 15(1), 44895. <https://doi.org/10.1038/s41598-025-28690-3>
49. Wahab, A., Danso, H., & Appiah-Kubi, E. A. (2026). A systematic review of agricultural ash supplementary cementitious materials as low-carbon alternatives to ordinary Portland cement from 2005 to 2025. *Discover Concrete and Cement*, 2, 61. <https://doi.org/10.1007/s44416-026-00101-4>
50. Wang, Z., Sun, T., Sun, Y., & Liu, N. (2025). Evaluating the strength properties of high-performance concrete in the form of ensemble and hybrid models using deep learning techniques. *Scientific Reports*, 15(1), 25453. <https://doi.org/10.1038/s41598-025-10860-y>
51. Wetzel, A., Göbel, D., Schleiting, M., Wiemer, N., & Middendorf, B. (2022). Bonding behaviour of steel fibres in UHPFRC based on alkali-activated slag. *Materials*, 15(5), 1930. <https://doi.org/10.3390/ma15051930>
52. Wu, X., Hu, L., Guo, F., & Li, X. (2024). Analysis of different early strength agents on the performance of prefabricated UHPC. *Materials*, 17(11), 2481. <https://doi.org/10.3390/ma17112481>
53. Wu, Y. Y., Zhang, J., Liu, C., Zheng, Z., & Lambert, P. (2020). Effect of graphene oxide nanosheets on physical properties of ultra-high-performance concrete with high volume supplementary cementitious materials. *Materials*, 13(8), 1929. <https://doi.org/10.3390/ma13081929>
54. Wu, Y., & Zhou, Y. (2022). Splitting tensile strength prediction of sustainable high-performance concrete using machine learning techniques. *Environmental Science and Pollution Research*, 29(59), 89198–89209. <https://doi.org/10.1007/s11356-022-22048-2>
55. Xu, Y., Ahmad, W., Ahmad, A., Ostrowski, K. A., Dudek, M., Aslam, F., & Joyklad, P. (2021). Computation of high-performance concrete compressive strength using standalone and ensemble machine learning techniques. *Materials*, 14(22), 7034. <https://doi.org/10.3390/ma14227034>
56. Yadav, A. A., Hirekhan, S. G., Bhandari, P. S., Bhagat, R. M., Ranit, A. B., Shelare, S., Soudagar, M. E. M., Sharma, S., Raja, V. B., Mahapatro, A., Singh, S., Kumar, A., & Massoud, E. E. S. (2025). AI-driven sustainable concrete mix design: hybrid deep Q-learning and genetic algorithms-based multi-objective machine learning optimisations for high structural strength, low cost, and low carbon footprints. *Structures*, 82, 110443. <https://doi.org/10.1016/j.istruc.2025.110443>
57. Yavas, A., & Goker, C. O. (2020). Impact of reinforcement ratio on shear behaviour of i-shaped UHPC beams with and without fibre shear reinforcement. *Materials*, 13(7), 1525. <https://doi.org/10.3390/ma13071525>
58. Zhang, M., Li, B., Zheng, Z., & Zhang, J. (2024). Experimental study on impact performance of basalt-polypropylene fibre-reinforced high-performance concrete. *Materials*, 17(13), 3253. <https://doi.org/10.3390/ma17133253>
59. Zheng, H., Zhu, S., Chen, L., Wang, L., Zhang, H., Wang, P., Sun, K., Wang, H., & Liu, C. (2025). 3D printing continuous fibre reinforced polymers: a review of material selection, process, and mechanics-function integration for targeted applications. *Polymers*, 17(12), 1601. <https://doi.org/10.3390/polym17121601>