Journal of Information Systems Engineering and Management
2025, 10(53s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Advancements in Energy-Storing Concrete: A Comprehensive Bibliometric Analysis of Evolving Trends and Innovations

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ARTICLE INFO

Received: 24 Dec 2024
Revised: 12 Feb 2025
Accepted: 26 Feb 2025

ABSTRACT

The paper explores a comprehensive bibliometric assessment of the works on energy-storing concrete technology, which attributes the major trends and development patterns in this regard. Within the scope of this analysis, 182 documents covering the period between 1965 and 2024 were retrieved from the Scopus database and included articles, conference proceedings, reviews, and book chapters. The study centres its focus on the key research clusters, which include digital storage, heat storage, compressive strength, and carbon dioxide emissions, and at the same time, other important areas like thermal performance and structural design are addressed. The analysis shows the Callon centrality and density of these themes, revealing established areas, new themes, and existing knowledge gaps. This strategic perspective creates a vision for the future in terms of extending such research scope on energy-storing concrete and in underdeveloped areas to expand the knowledge. The results are anticipated to be innovations in sustainable construction materials, and there are wider implications for improvements in energy efficiency and minimizing negative effects on the environment. Given the growing interest in energy-storing concrete concerning climate change applications, this type of study will assist many progressive researchers as well as practitioners in seeking ways of implementing energy-efficient building technologies.

Keywords: Energy-Storing Concrete, Bibliometric Analysis, Sustainable Construction, Technological

INTRODUCTION

The worldwide movement for changing the notions of development and the expanding need for energy sources of various types has resulted in thorough explorations and those of engineering, including material science. Among novel ideas Radiant energy-storing concrete is one of the most promising since this technology opens up new perspectives for the development of the construction business through energy storage directly inside the construction components (Z. Yang, Du, Jin, & Poelman, 2021) . Such development of urban structures is said to ameliorate energy efficiency and the sustainability challenges of the said infrastructures. With the application of construction material, energy-storing concrete can form an integral part of smart cities, as it will complement the conventional structural properties of concrete with energy storage capabilities (Donthu, Kumar, Pattnaik, & Pandey, 2021).

In energy-storing concrete, materials that store energy, such as phase change materials (PCMs) or conductive fillers, are embedded within the concrete. By doing this, the concrete is able to store and release thermal or electrical energy, contributing to building energy management systems and assisting in the integration of renewable energy sources (Y. Zhou et al., 2020). The advancement in this technology brings major benefits such as decreased energy use, reduced greenhouse gas emissions, and better building stability under energy fluctuations (hua Tian, lin Lv, en Huang, Liu, & Feng, 2017). However, the challenges for energy-efficient concrete structures will demand further technical developments and assessments of cost effectiveness, which are rather well established, but developing these technologies into reality remains challenging. A bibliometric review serves a useful function in this respect as it helps formulate the research organization structure, depict the scope and core trends of the research, and assess the outputs in the emerging area. Bibliometrics uses quantitative approaches to investigate literature and thus helps researchers understand the zealous activities for scientific production and cooperation (Donthu et al., 2021). It is through this lens that trends in research development and potential gaps can be understood, such as citation analysis, co-

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authorship, and theme critiquing. The goal of this research is to carry out a comprehensive and systematic bibliometric review of the research on energy-storing concrete in light of its development trajectories, specifics of the research issues, and renunciation in the available literature.

2. LITERATURE REVIEW

2.1 Evolution of Energy-Storing Concrete Research

The idea behind using energy-storing concrete, as it may be called, here or after its development, energy-saving technology in construction, has been greatly expanded. The first studies in this area were aimed at embedding PCMs inside concrete to use their thermal capacity. Such materials are known as PCM materials. PCM materials absorb heat or cold and then release it at lower temperatures, which is very useful in maintaining stable indoor temperatures and thereby cutting down the possible heating and cooling loads (Cabeza, de Gracia, Zsembinszki, & Borri, 2021). Integrating these materials into the concrete, the researchers aimed to create a new generation of building materials that would be durable and capable of managing Energy. The first studies showed that PCM-embedded concrete could effectively decrease energy consumption in buildings by limiting temperature variations. However, some problems were defined, including a mismatch between the PCM and concrete matrix, which caused PCM leakage from the reinforced concrete, and poor mechanical properties of the reinforced concrete (Cabeza et al., 2021). In light of these observations, most of the research focus subsequently turned to augmenting the compatibility and stability of the PCMs in the matrices using encapsulation and composite materials (C. Li et al., 2019). Encapsulation methods, including microencapsulation and shape-stabilized PCMs, were developed to avoid leakage and preserve the concrete composition.

As the industry advanced, scientists sought out other materials to help energy-storing concrete perform additional functions beside the management of temperature. Employing conducting fillers such as carbon fibers, graphene, and/or nanomaterials opened the way for an investigation of the electrical energy storage potential in concrete (C. Yang, Wang, & Chen, 2023). The high electrical conductivity of these materials made it possible to turn the concrete into an electrical energy-storing medium. This transformed concrete from being just a thermal energy-storing medium to a multifunctional material that could store both thermal and electrical energy. The development of such composites was a breakthrough because concrete was now made into a structural member and, at the same time, used as energy storage (C. Yang et al., 2023).

The most notable development in the evolution of energy-storing concrete research was the leap from thermal storage systems that used PCM as heat sinks to electrochemical energy storage systems. The rationale for this change was the growing need for energy storage systems that could enhance the integration of renewable energy sources and grid support. Supercapacitors, batteries, and other electrochemical devices were gradually embedded into concrete matrices to develop materials that were both structural and could harness, store, and release electrical energy whenever necessary (Z. Yang et al., 2021). Such advancements not only improved the energy content of concrete but also created opportunities for its use in smart grids and renewable energy systems.

Also, nanotechnology has contributed a lot to enhancing energy-storing concrete evolution. The use of nanomaterials such as carbon nanotubes and graphene oxide has enhanced the compressive and tensile strength of concrete as well as the durability and energy storage capacity (D. Wang, Liu, Chen, Wang, & Mao, 2024). Nanomaterials enhance the incorporation of conductive mediums that are consistent in energy storage and transmission through the structure of concrete (C. Zhou, Wang, & Zhang, 2022). Such changes have spurred the affirmative evolution of energy-storing concrete, thus enabling its practical use in high-strength buildings, pavements, and other infrastructure applications.

The scope of energy-storing concrete evolution reflects the relationship of materials and their attributes, structures and their performance, and effectively managing power. It has transformed from a pure thermal energy segment with PCM usage to a comprehensive inclusion of electrochemical storage systems and nanomaterials in the systems. The energy-storing concrete is already looking towards being a much more composite material ideally designed for sustainable and resilient infrastructure (Z. Yang et al., 2021). Further research is hoped to solve other issues related to scale-up of size, lifespan of components, and cost so that energy-storing concrete becomes commercially and economically viable in the construction industry.

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2.2 Material Innovations and Performance Enhancement

The advancements made in energy-storing concrete have been a result of the material innovations currently being carried out, concentrating on composite materials with enhanced mechanical and energy-storage features. However, normal concrete does not possess energy storage capacity; hence, the use of specialized materials with such properties as nano-enhanced phase change materials (PCMs), supercapacitors, and conductive polymers that achieve such functionalities (C. Li et al., 2019). Nano-enhanced PCMs, for instance, are very useful in increasing heat storage attenuation owing to their large surface area and even better thermal conductivity. Such properties facilitate quicker heat uptake and release, which enhances thermal control optimization in building applications (C. Zhou et al., 2022). Besides, conductive polymers and nanomaterials, including carbon nanotubes and graphene, have been used in the concrete's structural matrix to store electrical energy. These materials create a conductive mesh structure within the concrete, which allows the concrete components to act like a capacitor, which is capable of charging and discharging electrical energy (Z. Yang et al., 2021). The advantage of such dual capability is that the concrete is not only a load-bearing member but also an active member of the energy-managing systems. In this respect, supercapacitors have especially been placed in the mass of cement structures for efficient energy storage, acceptably due to their fast charge and discharge features, see; Ibrahim, Ilinca, and Perron (2008) and Jafarizadeh et al. (2024).The use of these innovative materials has helped to enhance the energy densities and the life spans of energy-storing concrete materials. For example, some studies have already confirmed that the addition of graphene oxide can help improve the mechanical performance of the concrete, which will increase the compressive strength and reduce the likelihood of cracks (D. Wang et al., 2024). These innovations enable the energy-storing components to be designed in such a way that they do not detract from the load-bearing capability of the concrete, making it suitable for various applications, including smart structures and green pavements (C. Li et al., 2019). Such developments propel energy-storing concrete into the pool of materials close to sustainable infrastructure development.

2.3 Applications and Practical Implementations

Energy-storing concrete has been studied and used in various practical applications, such as building walls, pavements, bridge decks, and other structure parts. Such implementations are directed towards making use of the energy-storing characteristics of the material in improving energy efficiency and hence sustainable development in urban areas. One of the most desired areas of application is the construction of pavements since energy-storing concrete would be able to lower surface temperatures, hence combating the urban heat island effect. For example, C. Li et al. (2019) showed that phase change materials of embedded thin layer cement-based composites not only lowered the peak surface temperatures, which enhance pedestrian comfort level, but also reduced the energy costs towards cooling the cities that are usually scathing.Besides pavement, energy-storing concrete has been used in building envelopes in order to control temperature indoors. It has been observed that when walls are built with thermal energy storage materials, deflection of indoor temperature takes place, and this leads to enhanced thermal comfort while reducing the need for heating, ventilation, and air conditioning (HVAC) systems (Huo, Yan, Wu, Kuai, & Pan, 2024). Such applications are very much welcomed in net-zero energy buildings where there is no or very little energy use. This incorporation of energy storage materials into structural members makes it possible for the concrete or any other construction material in this case to carry two roles : as a construction material and an energy Storage. Another application of energy-storing concrete in construction that has garnered attention is in bridge decks. Researchers have shown that by harvesting thermal energy from energy-storing bridge decks, they can prevent all forms of freezing, which may lead to lower costs on repairs in the future (Cao & Ma, 2024). Nevertheless, the progress to commercialize energy-storing concrete has been largely stagnant, owing to the exorbitant cost of the sophisticated materials, difficulties involved in the evening out of energy storage, and some concerns regarding the long-term effects of a volatile environment on performance (Y. Zhou et al., 2020). Particularly, resolving these issues will be vital for wider adoption and actual use in infrastructures in the real world.

2.4 Sustainability and Environmental Impact

The energy-storing concrete's utilization is consistent with the approaches in construction that are environment-friendly, since it promotes energy efficiency and a reduction of carbon footprint. Other scholars have further stressed its role in the construction of net zero energy buildings and sustainable urban infrastructures (Zheng, Shafique, Luo, & Wang, 2024). This novel material helps to incorporate energy storage features into building components even

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without being the exterior walls of the buildings, allowing for energy management in the buildings towards environmental protection. By incorporating phase change materials (PCMs) or other advanced energy storage systems, energy-storing concrete is more energy efficient, maintaining optimal room temperatures without extra rather expensive heating and cooling devices .In addition, in order to assess the potential environmental impact of the various energy storage, materials incorporated into concrete, a life cycle analysis considering the use of such storage offers determined techniques that optimize the restraint (Zhao, Li, Tan, Zhu, & Chen, 2024). For example, the carbon dioxide profile of these composite materials has been reduced when virgin natural aggregates are replaced with recycled aggregates or when supplementary materials such as fly ash are included (Tahir, 2024). However, there remains a need to identify potential weaknesses of such materials, mainly in terms of durability and performance over time, in order to leverage the full extent of their environmental benefits (Srivastava, Singh, Garg, & Saran, 2024).The use of energy-storing concrete for construction appears to be a breakthrough in the advancement of green building practices as it lowers carbon emissions, reduces power demand, and helps to create low-carbon structures (D. Wang et al., 2024). Innovations of this kind are necessary in order to achieve sustainability targets and in order to move to a more energy-effectively constructed environment.

2.5 Challenges and Future Directions

Although there has been an increase in the amount of published work on energy-storing concrete, a few research gaps are evident. First of all, we do not fully understand how these materials are going to perform for a long period in the real world. Most of the studies are done at laboratory scales, with a few considerations given to the large-scale applications and their effects on building energy systems, including most of the studies concentrating on just the laboratory testing throughout the work. Second, the economic aspect of energy-storing concrete techniques is very limited, and even more so is the economic assessment of this technique versus conventional materials. Addressing these questions will be vital for the implementation of laboratory outcomes in practice. In addition to the advancements in material evolution and application techniques, there are still several issues that have not yet been resolved. These include the problems concerning co-existence with the concrete matrix, resistance to different environmental conditions over time, and the possibility of producing new materials in bulk (L. Wang, Zhang, Liu, & Wang, 2024).An interdisciplinary approach that interconnects materials science, structural engineering, and energy science would help address these issues. Also, to address these research gaps, the following bibliometric questions are posed:

Q1. What are the major research themes and trends in the field of energy-storing concrete?

Q2. Who are the leading researchers and institutions contributing to this area?

Q3. What are the most influential publications and citation networks in this field?

Q4. How has the focus of research evolved over time, and what are the emerging areas of interest?

Q5. What are the critical gaps and future directions identified through co-citation and thematic analysis?

3. MATERIALS AND METHODS

This bibliometric analysis utilizes various tools and methods to assess and interpret data from related publications energy-storing concrete. VOSviewer, Bibliometrics, and Biblioshiny in R represent the core technologies applied in this study. VOSviewer facilitates the construction and visualization of bibliometric networks. These networks can include journals, researchers, or individual publications, and they can be based on citations, bibliographic coupling, co-citations, or co-authorship relationships (Van Eck & Waltman, 2010). VOSviewer offers a means to analyse trends and patterns, providing visual insights into the structure and dynamics of scientific fields.Bibliometrics, with the aid of the 'bibliometrix' R package, is a comprehensive tool for performing quantitative research in scientific and bibliometrics. This tool can analyze data extracted from scientific publications to give various indicators, such as the most prolific authors or institutions, the most cited articles, and the most influential journals in a specific research domain (Aria & Cuccurullo, 2017). Biblioshiny, which is the web interface of the 'bibliometrix' R package, is a web-based platform to conduct bibliometric analysis without requiring advanced coding skills. It can produce extensive reports and graphs, facilitating the examination of complex bibliometric data.For this study, the sources of literature and data include scientific articles, conference papers, Book chapters, review, book, note, letters and conference

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review obtained from comprehensive databases such as Scopus. We selected these databases for their extensive coverage of quality peer-reviewed literature in energy-storing concrete. The search strategy will involve varying combinations of keywords pertinent to energy-storing concrete topics and contextually relevant to worlds landscape. We will establish inclusion criteria to ensure the data's relevance and quality, including publication between specific years, relevance to energy-storing concrete, and a clear connection to the world's context.We clean and filter the resulting dataset to eliminate duplicates and irrelevant entries. Data analysis involves bibliometric indicators such as citation analysis, co-authorship network analysis, keyword occurrence, and thematic mapping. The extracted data contains a wealth of information that, once processed, will reveal world's energy-storing concrete arena's evolution, interconnectedness, and current focal points.The methodology outlined is instrumental in achieving the study objectives, providing a systematic approach to dissecting and understanding the scholarly landscape of energy-storing concrete research. The visual and quantifiable outputs from VOSviewer and bibliometric/biblioshiny analyses contribute to forming a nuanced narrative of how the country's energy-storing concrete research aligns with global trends and its national vision for energy-storing concrete development.

3.1 Bibliometric Data

A wide variety of scientific domains and fields of knowledge relate to the problem of energy-storing concrete. Because of the volume, multiplicity, and ramifications of these studies included in the Scopus database, the researcher must carefully choose the keywords for the study.

The Scopus database's search for "TITLE-ABS-KEY (energy AND storing AND concrete) AND

(LIMIT-TO (LANGUAGE , "English")) returned 182 documents, which were categorized as follows: Article 92; conference papers 66; Book Chapter 10; Review 8; Book 3, and others 3. The following Figure 2 shows over 60 years (1965–2024):

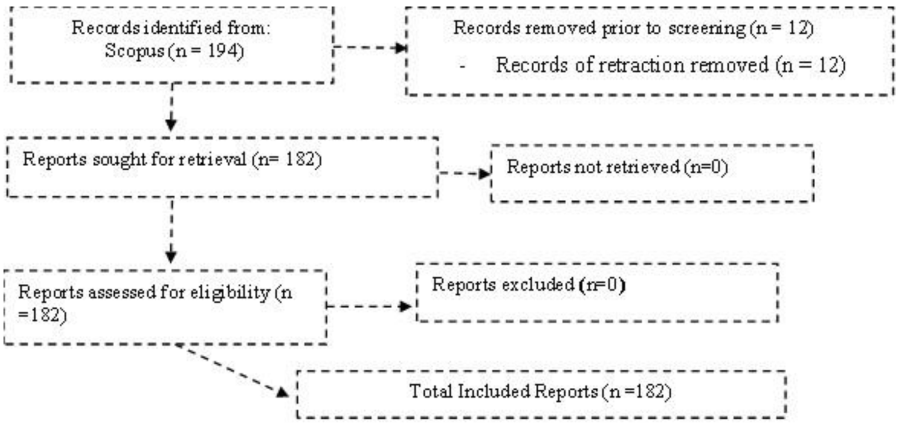

Figure 1. Flowchart of documents selection

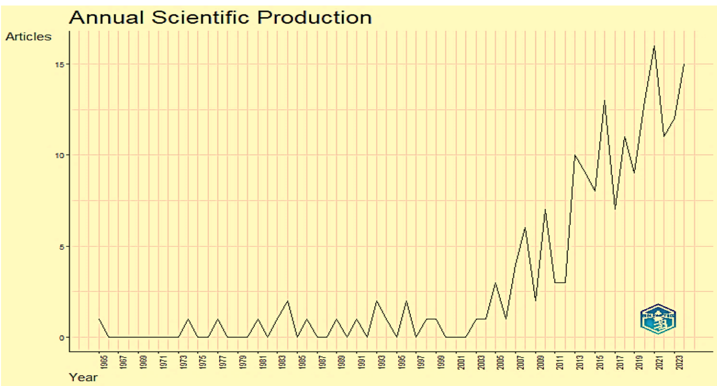

Figure 2. Annual Scientific Production

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e-ISSN: 2468-4376
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Figure 2 (Table 1 – Appendix) illustrates the annual scientific production in the sphere of energy-storing concrete has been overshadowed with respect to its growth pattern through time. Based on Part 1 of the history of this ever-evolving field of studies, there has been some published output; a mere single article appeared in the year 1965 and then no further articles until the early 1980s. A significant increase occurred in the middle of the last decade, especially in the amount of published works. This trend reflects the growing awareness of sustainable materials and energy-efficient construction technologies.

Active production of a specific topic is worth noting as it lasted only the years of 2005-2010. Despite constant publication activity within the timeline, it was very low until 2007, after which there was a sharp increase to a high of 7 articles in 2010. This upsurge perhaps can be associated with the rapid global awareness of sustainability and energy efficiency within the construction market. The years 2013 and 2020, among others, had a linear increase in article production of well over 10 articles per annum. In particular, the years of 2016, 2020, and 2021 recorded remarkable peaks in their supply where 13, 13, and 16 articles were produced, respectively, indicating heavy research and funding in this area. In 2024, the scientific production increased to about 15 articles, with interest and growth in this area continuing. Overall, the pattern of growth shows that energy-storing concrete has become a mature area of research, with the anticipation of the further growth of this area with increasing global attention towards sustainable construction.

3.2 Bibliometric Analysis Methods

There were five main ways that the study used bibliometric analysis (Zupic & Čater, 2015) to make networks, overlays, and densities that show the most important authors, references, research institutions, and countries in the field of energy-storing concrete for Scopus database publications. These were co-occurrence, citation, co-citation, co-authorship, and bibliographic coupling. We used the statistical tools VOSviewer, Bibliometrics, and Biblioshiny from R to analyze the publications.

4. RESULTS

4.1 Keywords Analysais Results

Figure 3 depicts the most commonly recurring words in various energy-storing concrete studies and investigations.

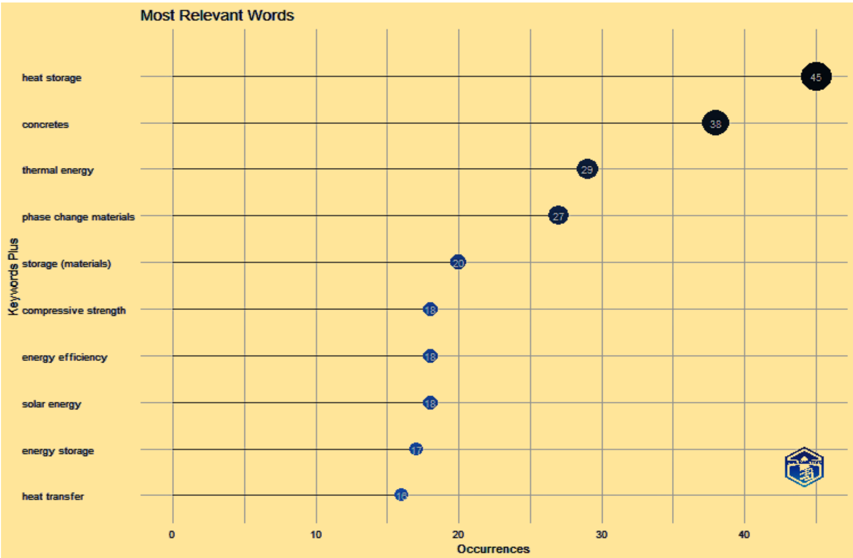

Figure 3. Most relevant words

The figure above shows that the most frequently mentioned keywords are associated with energy-storing concrete point towards the undercurrents and the technological trends in energy storage, material science, and sustainable architecture construction. The next major occurrences are heat storage (45), concretes (38), and thermal energy (29), thus encapsulating the emphasis on developing construction materials that can efficiently capture and store heat energy in concrete constructions. Materials that undergo phase change (27) play a crucial enabling role in thermal

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Journal of Information Systems Engineering and Management
2025, 10(53s)
e-ISSN: 2468-4376
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storage and are often emphasized along with storage (materials) (20) or compressive strength (18), which illustrate the combination of energy potentials with that of structure.

Words like energy efficiency (18), solar energy (18), or energy storage (17) reveal the interdisciplinary character of work on improving the energy efficiency of buildings. Further, heat transfer (16), carbon dioxide (11), and building materials (10) enhance focus on the environmental dimension of the research and the use of greener materials. The increased frequencies of thermal energy storage (8), thermal conductivity (8), and renewable energy resources (6) manifest the desire to seek functional advances in storage in a low-carbon economy. This vocabulary encompasses research work with a diverse focus on stronger materials with better energy efficiency.

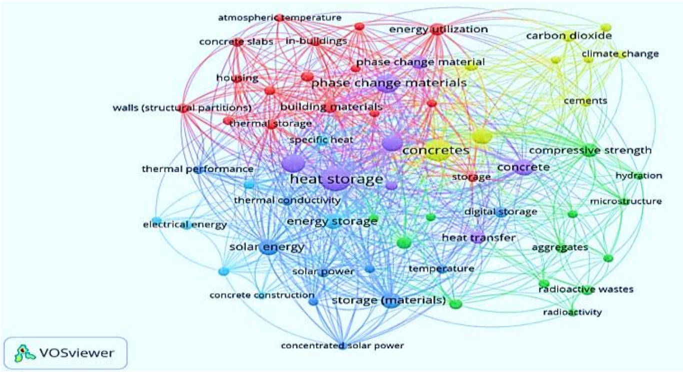

Figure 4. Network of keywords

Figure 4 shows the analysis of the keyword networks highlights two thematic clusters, which are recurrent areas in knowledge pertaining to energy-storing concrete. It comprises the aspects of sustainable and environmental values that are prevalent in Cluster 1 thanks to keywords like carbon dioxide, energy, cements, and carbon footprint. The values placed at energy (betweenness = 3.41) and carbon dioxide (betweenness = 1.01) show strong relationships with other themes, risking a number of issues on energy and its environmental-related problems. These terms also have a larger than 300 page rank, indicating that they have a stake in directing the course of the research.Cluster 2 contains lists related to construction and the material property sphere and includes the following keywords: reinforced concrete, Betweenness = 42.34; building materials, Betweenness = 50.26; and walls (structural partitions), Betweenness = 2.22. Building materials attract the highest PageRank (0.0215) and Betweenness, reflecting in which research activity, cement innovation, and energy storage integration appear to interact with the material. This twin cluster targets renewable energy resources, which also links with constructions for energy storage prospects.Summarizing, the network connects as many different disciplines as possible in research, where sustainability and modern building technologies determine the research problems. This increasing association of different themes probably indicates new directions in the way energy efficiency and environmental aspects are addressed in relation to building materials.

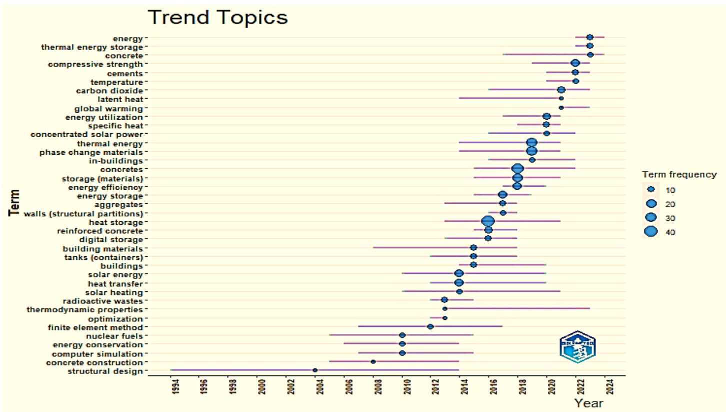

Figure 5. Trend topics

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According to the trend topics analysis of energy-storing concrete research in Figure 5, the development of primary topics forms a more dynamic evolution over the years. Knowledge concentrating around structural design and concrete construction spanned a few decades from 1994 to 2014, but who managed to grasp the essentials of focusing on the development of new materials with traditional construction practices. In the mid-2010s, circulation became wider and included also computer simulation, finite element method, and energy saving.Developing the use of building materials that incorporate solar energy occurred from 2010 to 2020, accompanied by a shift to building materials that include heat transfer functionality, in this case window insertion, occurring between 2012 and 2020. It has been noted in studies carried out from 2015 through to the present that there is a great deal of activity on container thermal energy, phase change materials, and energy efficiency, which means there is a great concentration on high temperature energy storage systems. There were high levels of reinforced concrete and digital storage seeking spans from 2015 to 2018, which were suggestive of fusion of different disciplines that incorporated the structural integrity and intelligence systems.The newer topics noticeable from 2020 to 2024 are compressive strength, concrete, and thermal energy storage, indicating that there was growing interest in enhancing the mechanical properties with practical construction applications. Of note in some modern research approaches are the dominance of carbon dioxide, global warming, topical heat, and latent heat seeking energy efficiency and optimization in any project on the way.

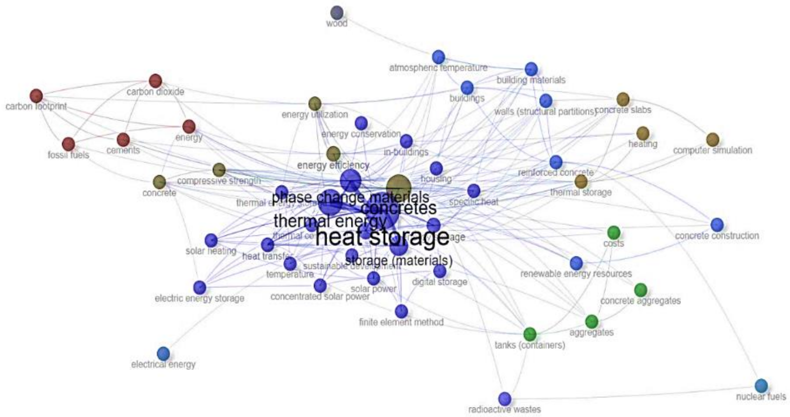

Figure 6. Co-occurrence Network

Co-occurrence networks highlight the associations made between different terms, especially in two dominant groups, or clusters. The main group of Cluster 1 contains nodes such as carbon dioxide, energy, cements, fossil fuels, and carbon footprint, with energy having the highest centrality measures (Energy: Betweenness: 3.41, Closeness: 0.0108, PageRank: 0.0150), survival of the fittest again. The second cluster is made up of reinforced concrete, building materials, buildings, walls (as internal partitions), and renewable energy resources. In this case, building materials have the most centrality in terms of betweenness (50.25), meaning they are quite effective in bridging many diverse aspects. The structure of the network presents that these two subjects, sustainability and construction materials, are two closely related fields of study.

4.2 Authors' Analysis Results

Several authors have multiple publications in well-known databases, such as the scopus, and among them are those who are more influential than others in terms of publications, citations, co-citation, co-authorship, and bibliographic coupling. This is shown in Figures 7 and 8.

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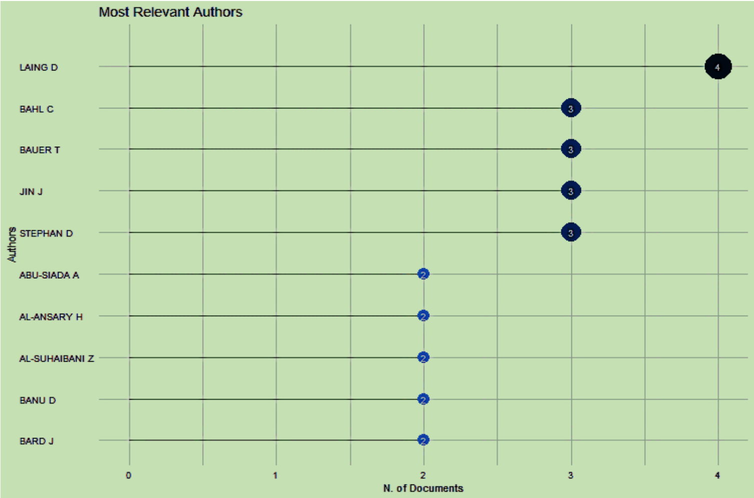

Figure 7. Most Relevant Authors

A thorough examination of the most published authors in the area of energy-storing concrete brings out key players who have been engaged in reshaping the scope of research in this domain. From the first five positions in the author ranking, LAING D produced the highest number of 4 articles, which is a clear indication of the researcher's well-focus and involvement in the advancement of the energy-storing concrete technology. Other authors of BAHL C, BAUER T, JIN J, and STEPHAN D produced 3 articles each suggesting their active research work having diverse implementation in the field of thermal energy storage in concrete and related fields.Above fill the authors except AL-ANSARY H, CABEZA LF, and BELLETTI B produced two articles indicating literature moderate attention with respective niches of research area. Also, the contributing authors "spectrum', which includes Khushnod RA and RASTEGAR J, displays

the characteristic of this research area, which is multidisciplinary: including material, civil, and sustainable construction engineers. At last, this group of authors has shown an interdisciplinary perspective in working towards common objectives that accelerate the introduction of energy-storing concrete technologies, such as incorporation of phase change materials into the matrix, modifying the properties of materials, or implementation of building envelopes as a way to reduce energy losses from buildings.

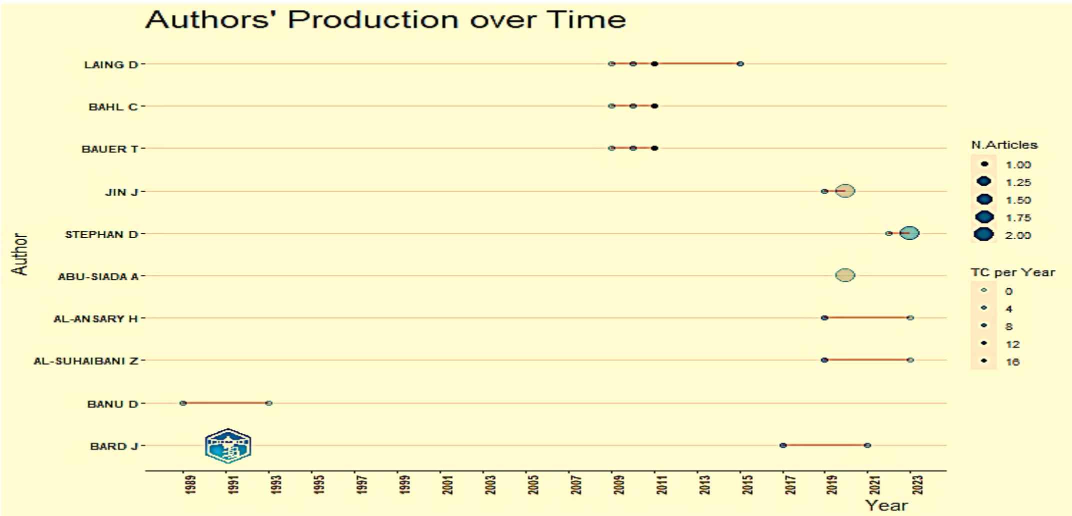

Figure 8. Authors' Production over Time

The assessment of authors' productivity dynamics paints the picture of several leading researchers who have made further steps in the direction of energy-storing concrete and thermal energy storage systems. LAING D was consistently active as an author from 2009 to 2015, with publications mostly concerning thermal energy storage

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(TES) systems for parabolic trough power plants with direct steam generation. His work that has been more cited appeared in Solar Energy Journal SAGE in 2011 and has received 226 citations, showing its great impact.Meanwhile, Stephen D has also started to actively publish in this area recently, with the last papers dated 2022 and the latest from 2023, although still lacking enough citations, explaining the properties of ultra-high-performance concrete. JIN J has concentrated on smart energy storage systems in a green building since 2019, which would indicate that he is trying to move into such advanced integration.

In particular, BAHL C and BAUER T formed a co-authorship that appears to be the most expanded of all papers during 2009–2011 and helped create TES systems. Bahel C, Domestic changes in planning and development are around 226 including Yuan L. Energy Storage Technology in Parabolic Trough Concentrated Solar Power Plants, Solar Energy doi: 10.1016/j.solener.2011.10.012. Their Solar Energy 2011 paper has been highly cited, with 226 citations.

New authors like AL-ANSARY H and AL-SUHAIBANI Z have recently released optimization work on TES systems for concentrated solar power plants, which is also a fertile area of research on energy storage. By and large, the chronology exhibits the influence of precipitating as well as modern factors.

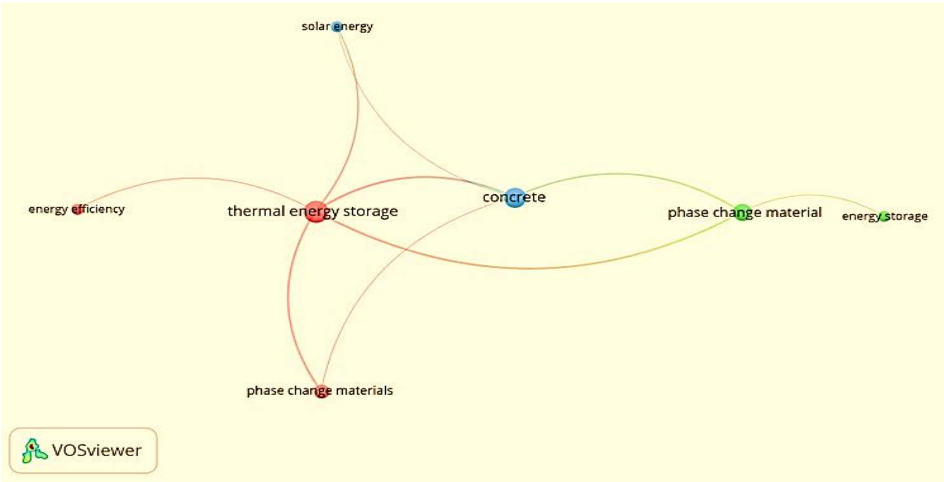

Figure 9. Authors' Network

Figure 9 shows that among the authors' networks indicates the existence of a core group of researchers, with a noticeable degree of interrelations with Bentz D.P. (Betweenness = 17) and Zhang Z. (Betweenness = 27) being the most active members. High betweenness measures confirm the strong attachment and control by selected members of this community. The author Zhang Z. holds the highest value for closeness (0.0167) and page rank (0.0726), and mainly, he acts as a popular node, implying that this author contributes considerably to the research network. Other authors such as Hawes D.W. (1990, 1992), Kosny J., and Lee T. exhibit lower betweenness that positions the authors on the margins, but still, productive research is being done in the cluster. It has created a network structure that demonstrates the extent of collaboration in research studies related to energy-storing concrete.

4.3 Sources and Documents Analysis Results

There are several references and sources on energy-storing concrete, but the following are the most relevant ones.

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2025, 10(53s)
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Figure 10. wordcloud

There are several other major sources of concrete research in energy storage, which include prominent journals and conference papers in the subject matter relating to energy, construction, and material science. Energy Procedia takes the lead, being the most cited source with six articles, while Construction and Building Materials, Energy and Buildings, and Solar Energy provide five articles each in that order. These sources clearly emphasize the areas of construction materials and energy utilization for efficiency.Energies and the Journal of Energy Storage have also been important sources, contributing four articles each, especially on energy-saving materials technology in buildings. Other articles of interest may be sourced from Applied Energy, Advanced Materials Research, and Materials Today: Proceedings, where the articles focus on new concrete and thermal Energy Storage. The source distribution as shown particularly addresses the concerns about dome-foot core materials from multidisciplinary perspectives including engineering, sustainability, and materials science., as shown in Figure 10 (Figure 17 – Appendix) .

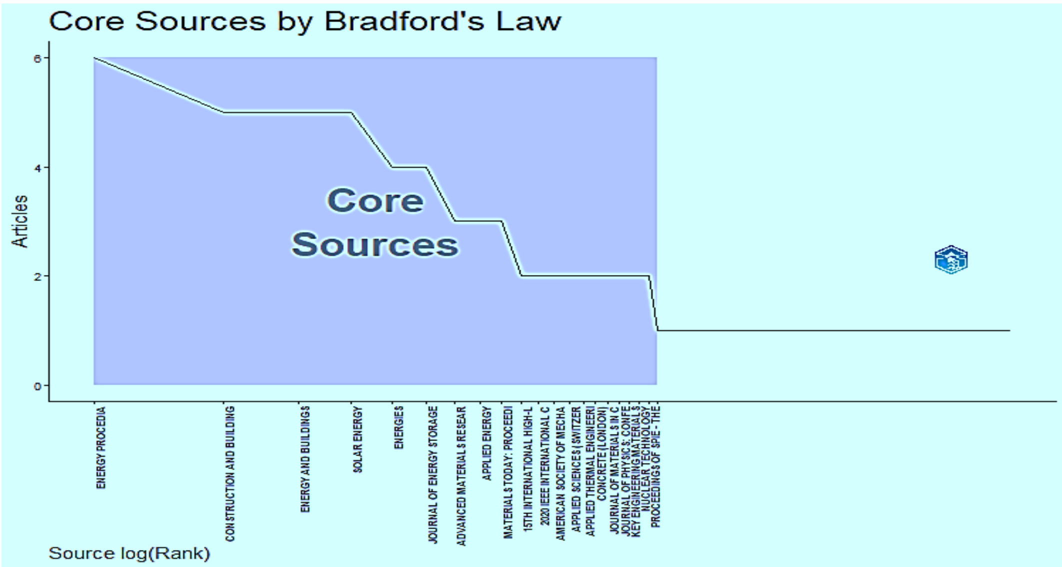

Figure 11. Core Sources by Bradford's Law

According to Bradford's Law of Scattering (Figure 11), it seems that the centre of gravity of the energy-storing concrete research literature is located in Zone 1. This zone consists of high-profile periodicals and conference proceedings such as Energy Procedia (6 articles), Construction and Building Materials (5 articles), Energy and Buildings (5 articles), and Solar Energy (5 articles), etc. These sources constitute the base literature of the resources and are important in sharing the critical findings of the research.

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Other prominent journals in Zone 1 include Energies, Journal of Energy Storage, and Applied Energy, which are known for active contributions to the development of energy storage systems and materials. These core sources point out a clear understanding of the interdisciplinary nature of the systems, which includes energy efficiency, sustainable materials, and new thermal storage technologies, and therefore factors that should be taken into consideration by researchers in this area.

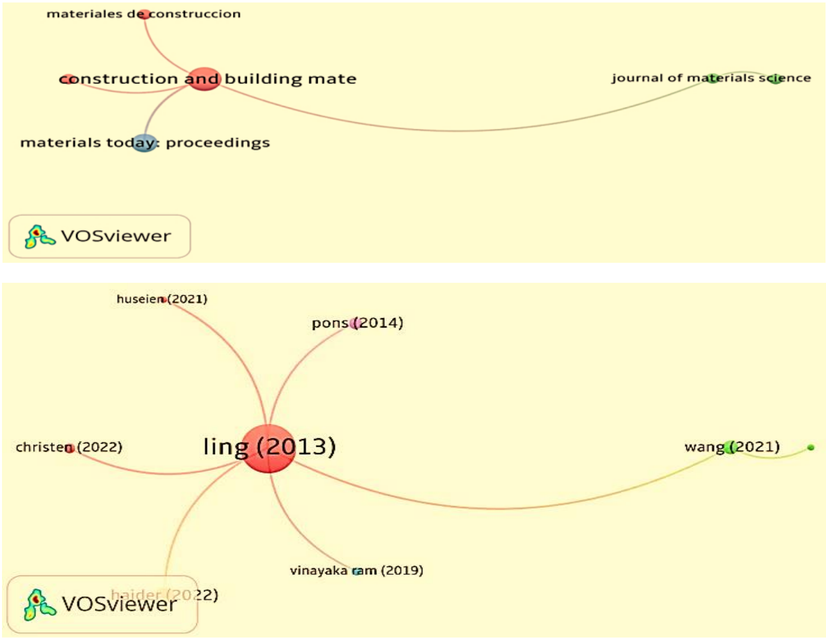

Figure 12. Sources and documents Networks

The bibliometric analysis of Energy-Storing Concrete Dynamics depicts the relationships between the essential sources and key documents that have advanced the growth of the research in this field. The network map shows sources, including journals, conference papers, and other literature, that have significantly contributed to energy-storing concrete research development. It appears that Construction and Building Materials as well as Energy Storage Materials Journals played a crucial role in the network, as these two journals serve as the umbrella for virtually all high-quality

journals.Another dimension of the analysis involves strong document co-citation relationships. For instance, (Pelay, Luo, Fan, Stitou, & Rood, 2017) and Cui et al. (2022) are related to high-compression strength, thermal, and CO2 sequestration, whereas Liu, Chen, Yang, and Li (2020). describe spacer-embedded isalized particles to enhance structural performance. These clusters demonstrate that key themes that existed within broader fields developed separately while the fields developed, and these themes were later fused to form integrated clusters. The linked nodes between the clusters propose interdisciplinary extensions, especially in energy storage, structural architecture, and

green building. It follows that the energy-storing concept pushes for the input of multiple scientific disciplines, thus broadening its frontiers. The figure brings out the role of specific works and journals in influencing both the current position in the field and the future direction in research. Advances in the development of such solutions are made possible through interdisciplinary approaches, especially between energy storage and environmental sustainability sectors.

4.4 Institutions and Countries' Results

The following figure shows the network of research institutions and countries most cited on the topic of energy-storing concrete.

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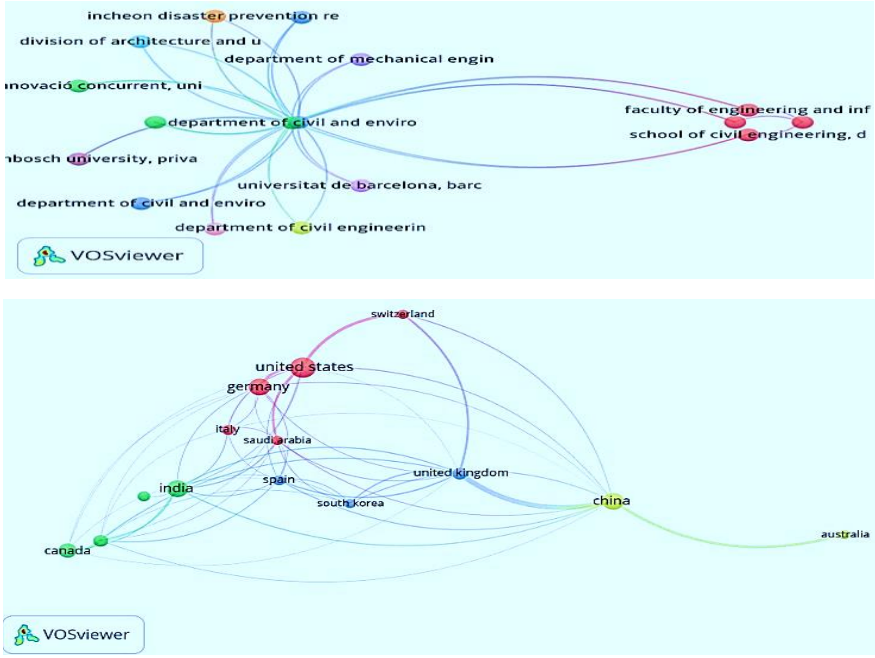

Figure 13. Institutions and countries Networks

The bibliometric analysis of Energy-Storing Concrete Dynamics helps to illustrate the geographical and institutional frameworks that have begun shaping the research within this relatively new field. The network visualization articulates the countries and institutions that are at the forefront of the contributors' knowledge, as certain institutions and nations are central to the nodes expected for output and research influence.The study clearly explains that the network is dominated by renowned institutions such as universities and research centers originating from China, the United States, and Europe. Chinese institutions are especially sociable, as they indicate the extensive Chinese public expenditures on sustainable construction and energy efficiency technologies. The United States also presents this profile, indicating that there is worldwide interest oriented towards industries to develop materials that would enhance energy storage and lower carbon emissions. On a country basis, the most important contributors include China, America, and European nations, notably Germany and the UK. The network suggests that these kinds of countries and their cooperation in the network are interlinked for effective exchange of knowledge across international boundaries. It is very likely that these collaborations are the ones promoting creativity and enhancing the speed for technologies' advancement in energy storage for the construction sector.The importance of international collaborations and institutional cooperations, which make strides to enhance sustainability and to foster energy efficiency in the invested place, is hereby again very much borne out.

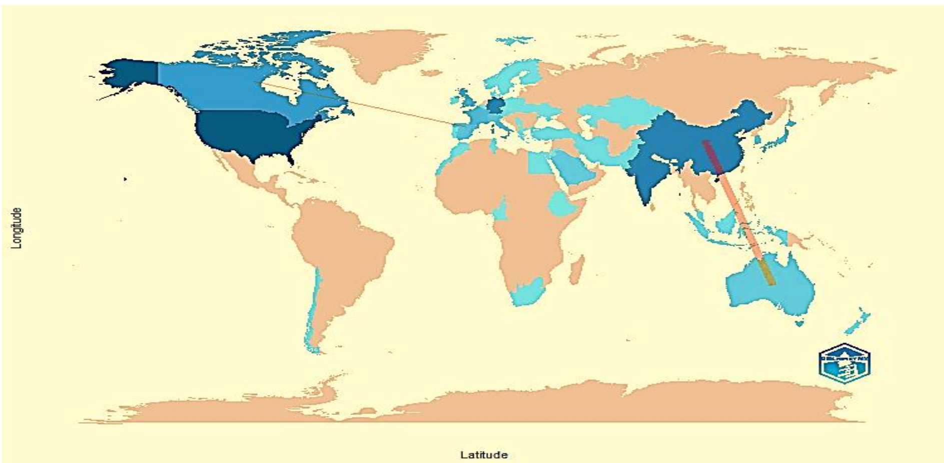

Figure 14. Countries' Collaboration World Map

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Figure 14 (Figure 16 – Appendix) shows a map is useful when visualizing how countries do research together, as it covers the intensity and frequency of those partnerships. The United States, together with China, leads as countries with the highest number of such global connectivity's where partners such as Germany, Saudi Arabia, and Australia are involved. China has three Australian connections, and the USA has global collaborations from Europe, through North America, and down to Asia. As with research, viewing such groupings as Canada-France and Saudi Arabia-Egypt illustrates these research regions within a particular geographical area.Figure 14 depicts the five leading countries, viz., USA, UK, China, Germany, and India, publication trends over the years from 1965 to 2024. The USA has long kept a substantial number of publications, and between the years of 2005 and 2024, this increased the volume of publications to 82 articles in 2024. At the same time, the UK and China showed a clear ramp-up, especially since the early 2010s. China, on the other hand, showed the steepest rise after a significant rise post-2010 with its output of 55 articles by 2024. Germany and India, despite starting late in the race, have been on a gradual and consistent rise over the years, reaching 54 and 57 articles in 2024, respectively. Thus the map and publication patterns speak volumes about the changing trend of research across the biosciences fields, embracing interdependence, sophistication, and rapid proliferation of scientific products.

4.5 Thematic Map

Thematic maps are built on two basic principles of organizing themes: centrality and density. Centrality indicates how one specific theme is associated with its other themes, while density shows how developed this particular theme is in terms of the research. These two relationships assist in the sequencing of research themes around the four quadrants of the thematic map. Themes that are thought out and well settled are referred to as motor themes (M-SQM), which have high centrality and high density; motor themes that have CQM as basic themes; motor themes with low centrality yet quite a number of settled ideas as niche themes; and low centrality and density are themes that are still developing or declining.

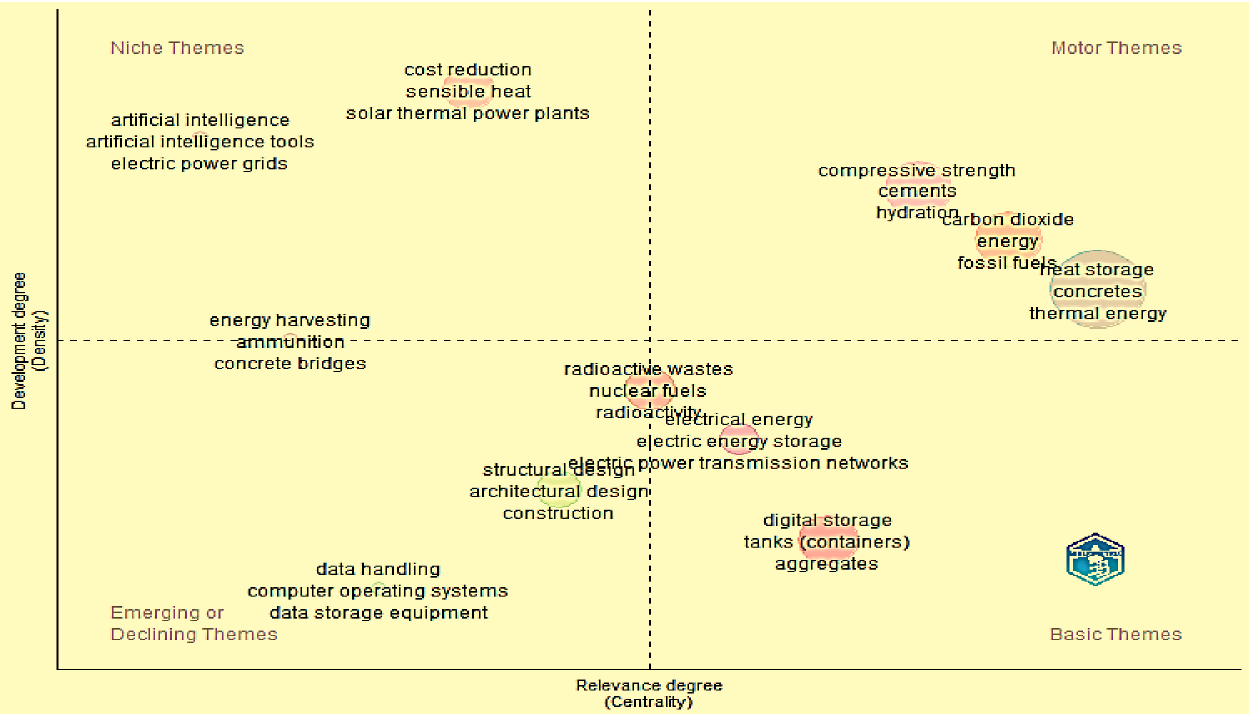

Figure 15. Thematic Map

With respect to energy-storing concrete, a thematic map assists in determining the principal areas of thermal performance, structural design, compressive strength, etc. through their relevance to other themes and developmental stages of the theme. For example, it can be deduced that the research area addressed by George et al.

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(2021) is motivated by high centrality features; therefore, nominated themes like "heat storage" and "carbon dioxide emissions" become the developed themes of the niche theme. However, there are themes like "artificial intelligence," which have low centrality at the moment as an emerging theme but have potential to grow. This categorization allows the researchers to fill in the blanks, comprehend the progress of the domain, and position themselves accordingly to carry out further research in the area (Shen et al., 2021). On the other hand, niche and window of opportunity themes such as 'data handling', 'digital storage', and 'energy harvesting' are narrowly developed and rapidly draw attention to their possible development as they could be found to interact with much consumed data. These themes, while relatively less developed, point out interesting paths for future investigations and possible novel usages. Their appearance within the thematic map indicates their future potential importance, particularly with future technology or having more cross-cutting influences within energy research. In this respect, researchers are motivated to further investigate these themes, which are emerging, to know their potential in the development of energy-storing concrete technologies and sustainability concerns.

5. DISCUSSION

The investigation of the changing trends in the field of energy-storing concrete reveals several important results, including keywords, authors, documents, sources, organizations, and associated countries. Among the most commonly used keywords are heat storage, thermal energy, phase change materials, energy storage, and compressive strength, which demonstrate the links between thermal energy management and concrete technology. These words indicate a rise in the usage of energy-efficient building materials in construction (Shen et al., 2021). In contrast to previous studies in which the comprehension of energy storage strategies was limited only to solar technologies, especially through the study of its integration into concrete, this is a new direction of research that meets C. Li et al. (2019) goals of sustainability.Major accomplishments have been achieved in the research areas by Tamme, Laing, Steinmann, and Bauer (2022), the most renowned and innovative authors in the sphere of thermal energy storage technology development. However, they continue to impact industry through several high-impact publications as well. Their studies on solar power plants with direct steam generation and thermal storage systems for parabolic trough power plants Tamme et al. (2022) have contributed well towards the proposition of concrete as a good source for energy storage. Among more recent contributors, Tian, Stephan, and Lehmann (2023) and H. Li, Jin, and Abu-Siada (2020), for example, target energy-storing concrete systems with ultra-high-performance-strenuous concrete, suggesting that energy-storing concrete may find more building system applications.The most significant works in this field are published in such editions as Energy Procedia, Solar Energy, and Construction and Building Materials. These journals focus on the publication of findings relating to sustainable construction and energy efficiency. This study also classifies more journals under the category of thermal energy management, including thermal mass, and thus further expands its limitations than previous bibliometric studies. Recently published works by

Tay, Lee, Lee, and Kueh (2022) separately examine whether electrical energy and advanced materials research are focus areas, including civil engineering constructions or ports.Key players within this research domain are universities and research institutions located in the USA, China, and Germany, among other countries. For example, institutions like the Fraunhofer Institute for Solar Energy Systems and Lawrence Berkeley National Lab are spearheading the integration of thermal energy storage into the fabric of buildings such as concrete (Stritih et al., 2018). The geographical representation of research is well developed in Asia and Europe, which implies that countries with good infrastructure development are adopting energy-storing concrete technologies faster. This is supported by H. Li et al. (2020), who found that regional policies facilitate promotion of suitable practices of sustainable construction.Thematic evolution analysis indicates that there have been considerable changes in research domains, and there are three key phases: the first phase is centered on the material with thermal energy properties, followed by the development of the later stage, which aims at the mechanical energy clothing, which contains in-built energy-storing concrete for the buildings. Analysis of recent publications reveals themes such as conserving energy and reducing carbon footprints or using renewable energy, which present a drift towards sustainable development trends (Elbony & Sydhom, 2022). These themes denote moving beyond the typical experimental stage of energy-storing concrete towards its commercial use, thereby solving issues of scalability and performance.With respect to prior bibliometric works on sustainable building materials, this study marks an important change in focus from concept and laboratory studies toward applied research and implementation. Previous studies, including Cabeza et al. (2021)

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focused on the thermal performance of phase change materials but did not pursue any considerable details of inserting them into concrete systems. Such inter-disciplinary amalgamation will lead to more innovative solutions, which the current research demonstrates. It is believed that the results of this study will also assist in future research and policy formation directed towards wider acceptance of energy-storing concrete for green buildings.

6. CONCLUSION & RECOMMENDATIONS

The bibliometric assessment performed for the energy-storing concrete reveals an emerging trend of intermingling energy storage systems and the construction towards sustainability. Key researchers, including Laing D., Stephan D., and Jin J., have made considerable efforts to incorporate thermal energy storage systems inside the concrete envelope, and their contributions are identified in the study. Thermal energy storage, phase change materials, and compressive strength are some of the core concepts that support the energy performance and structural aspects as well. It is also worth mentioning that analysis of the trends from this database demonstrates a rather rapid development scene of the field as more attention is given to material science, energy saving, and environmental fields.

On the other hand, in spite of the achievements made, it has to be stated that there are still a few areas that require further investigation, one of which is the ability to apply the energy-storing concrete into the field. Existing studies often are oriented towards laboratory experiments, which leads to leaving the possibility of a practical implementation and cost for the implementation poorly examined. Besides, the application of IT, such as sensor networks and smart monitoring systems, in concrete works is still a new area, which further shows the possibility for more studies in the future. Given the strengthening of energy-storing concrete, the collaboration between the academic institutions and the industrial partners will be essential in dealing with these issues.

To progress in this field, it is advised that further research undertake extensive implementations and develop uniform testing procedures for assessment of endurance in future work. There is a great need to establish links between engineering materials science and energy management by adopting a multidisciplinary approach. Furthermore, the national governments would also encourage incentives for the use of green building materials that are in line with global sustainability trends. If these recommendations are followed, the commercial potential of energy-storing concrete to be integrated with energy-efficient buildings and utilized for climate change mitigation could be real-time achieved.

Acknowledgments

I extend my sincere gratitude to the University of Bisha for its continuous support and dedication to advancing scientific research. The resources and guidance provided by the university have been invaluable in the completion of this research. This study would not have been possible without the encouragement and commitment of the institution to fostering innovation and academic excellence.

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APPENDIX:

Table 1 : Words frequency over time

DESCRIPTION	RESULTS
MAIN INFORMATION ABOUT DATA	
Timespan	1965:2024
Sources (Journals, Books, etc)	142
Documents	182
Annual Growth Rate %	4.7
Document Average Age	9.77
Average citations per doc	18.36
References	5020
DOCUMENT CONTENTS	
Keywords Plus (ID)	1861
Author's Keywords (DE)	499
AUTHORS	
Authors	634
Authors of single-authored docs	18
AUTHORS COLLABORATION	
Single-authored docs	18
Co-Authors per Doc	3.75
International co-authorships %	15.93
DOCUMENT TYPES	
article	92
book	3
book chapter	10
conference paper	66
conference review	1
letter	1
note	1
review	8

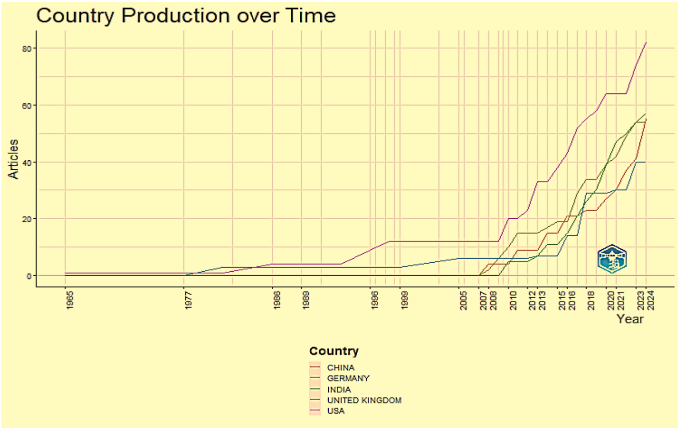

Figure 16. Country Production over Time

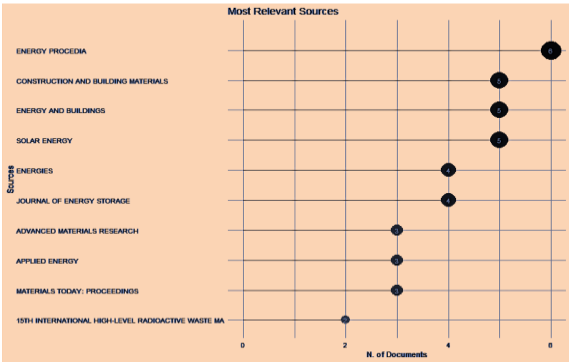

Figure 17. Most Relevant Sources

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