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Review

Biomaterials in Concrete for Engineering Applications: A Bibliometric Review

Haidee Yulady Jaramillo [1], Oscar Hernan Vasco-Echeverri [2], Luis Alfonso Moreno-Pacheco [3] and Ricardo Andrés García-León [4,*]

1 Facultad de Ingeniería, Ingeniería Civil, Universidad Francisco de Paula Santander Ocaña, Ocaña C.P. 546552, Colombia; hyjaramillo@ufpso.edu.co
2 Facultad de Ingeniería Química, Universidad Pontificia Bolivariana, Medellín C.P. 050031, Colombia
3 Sección de Estudios de Posgrado e Investigación, Escuela Superior de Ingeniería Mecánica y Eléctrica, Instituto Politécnico Nacional, Unidad Zacatenco, Ciudad de México C.P. 07738, Mexico
4 Facultad de Ingeniería, Ingeniería Mecánica, Grupo de Investigación INGAP, Universidad Francisco de Paula Santander Ocaña, Ocaña C.P. 546552, Colombia
* Correspondence: ragarcial@ufpso.edu.co

Abstract: The incorporation of biomaterials into concrete for engineering applications has gained significant attention in recent years due to its potential to enhance both the mechanical properties and sustainability of construction materials. This study conducts a comprehensive bibliometric analysis (BA) to examine the state of the research on utilizing biomaterials in concrete through the analysis of scientific production considering the information in the *Scopus* database. The BA provides insights into this interdisciplinary field's evolution, trends, and global research landscape. Key aspects explored include the types of biomaterials employed, their impacts on concrete properties, and the environmental benefits associated with their masonry use. R-Software was used to analyze the scientific growth and topics (BA) in the field of biomaterials in concrete for industrial applications. The results exposed that biomaterials in concrete related to scientific production represent a total amount of 1558 documents published by 489 journals and 4521 authors, which represents an annual rate of 20.81% higher than other related topics, with India, the United Kingdom, and China being the most representative countries. Finally, this work exposes the growing interest in sustainable construction practices and the promising future of biomaterial-infused concrete in the engineering sector, seeking to advance the knowledge and application of biomaterials in concrete technology.

Keywords: sustainability; recycling; biomaterials; bibliometric; masonry products; trends

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1. Introduction

1.1. Background

Demographic, economic, and industrial development has influenced the increase in environmental problems worldwide due to air, water, and soil pollution [1,2]. Anthropogenic activities, such as the burning of fossil fuels, forestry, agriculture, and waste disposal (landfilling and incineration), contribute to climate change and the increase in greenhouse gases (GHGs); these are compounds present in the atmosphere that significantly increase its temperature by absorbing and emitting infrared radiation. The main GHGs and their sources vary depending on their relative contributions and duration in the atmosphere. The most significant greenhouse gases include Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), and Fluorinated gases, such as hydrofluorocarbons (HFC), perfluorocarbons (PFC), and sulfur hexafluoride (SF_6). In this way, it is essential to highlight that the intensification of agriculture, deforestation, industry, and the burning of fossil fuels are the main human activities that contribute to the emission of these greenhouse gases, which increase the concentration of these gases in the atmosphere, which in turn contributes to global warming and climate change [3].

The biodegradable portion of products, waste, and residues of biological origin from agricultural, livestock, and forestry activities, as well as related industries, including fishing and aquaculture, is called biomass [4]. Worldwide, natural biomasses have been recognized as promising, attractive, and sustainable materials since they can be used in various environmental, agricultural, and construction applications through physical, chemical, and thermal techniques [5]. Biomass has been identified as an alternative source of materials for biocomposite production [6]. On the other hand, the development of biomass from agricultural waste, through the intensive use of non-conventional raw materials, has been established as an economically viable technique, especially when it comes to fibers [7]. Regulations aimed at reducing non-renewable natural resources and maximizing the waste value have promoted the use of discarded materials as high-quality raw materials [8].

Agricultural waste has been recognized as being suitable for paper production, composites, and engineering materials. Among the plant products used are palm oil, sugarcane bagasse, corn stalks, coconut fiber, bamboo, pineapple, banana, rice, and coffee husks [9,10]. These wastes represent the most abundant natural fibers, with cellulose fibers (CF) being their main fibrous components. FCs consist of a combination of lignin, hemicellulose, and pectin. In addition, they are considered to be alternative and competitive materials compared to glass and carbon composites due to their availability, low density, weight, mechanical properties, ecological nature (renewable and degradable), and economic viability. Therefore, they are presented as an alternative material option for producing value-added products, such as biomaterials [6,11].

In recent years, researchers have recognized the potential of plant fibers for cost-effective and efficient application in high-quality fiber-reinforced polymeric materials in construction project production [12]. Thus, research has been carried out to use agricultural waste in the construction industry due to its attractive properties compared to synthetic fibers. As a result, the use of cellulose-fiber materials as reinforcement for concrete and mortar has been investigated, using different natural fibers such as banana [13], bamboo [14], rice husk [15], wheat and barley straw [16], coconut, sisal, jute, palm, and linseed [17]. Note that the recovery of this plant waste in the construction sector has several objectives: economic, technical, and environmental [18].

On the other hand, coffee cultivation is highly economically and commercially important worldwide, being cultivated in approximately 80 countries [19]. However, this industry also generates byproducts and waste, such as pulp, peel, silver skin, and coffee residue. These by-products contain different compounds, such as carbohydrates, proteins, pectins, and bioactive polyphenols. Unfortunately, inadequate disposal of these wastes, including coffee pulp, husks, and effluents, has led to water and soil contamination problems [20,21]. Coffee husks are a renewable material source, since they contain components such as cellulose, hemicelluloses, and lignin. However, because the chemical composition of husk can vary between different plants and parts of the same plant, it is not easy to establish the exact percentages of its chemical composition [22]. Although there have been biotechnological applications of coffee husks, especially as fuel, their strength, stability, and modularity make them especially useful in various civil engineering applications due to their affordability and environmental advantages which are valued in the construction industry [23].

Due to the urban growth that cities are currently experiencing, and the climatic consequences associated with this phenomenon, research interest has been generated in incorporating environmentally sustainable construction materials that present mechanical properties similar to the blocks currently used in the masonry sector for construction. These materials seek to be a practical option for housing projects that promote environmental sustainability [24]. However, cement production entails high carbon dioxide (CO_2) emissions due to the high temperatures required to calculate the natural raw materials (cement minerals) used in manufacturing. These emissions mainly come from three main sources: around 525 kg per metric ton of cement produced ($kgCO_2/tm$) is generated during the decarburization of limestone in the kiln (i.e., reduction of carbon content), 335 $kgCO_2/tm$ is generated during fuel burning, and 50 $kgCO_2$/tm is generated during the use of electrical energy in cement production [25].

1.2. Literature Review

Considering the above, cement-based compounds are widely used in the construction industry due to their ease of acquisition, water resistance, thermal resistance, and ability to adapt to different sizes and shapes, which makes them suitable for the construction of various civil engineering structures [26]. For example, Santhyami et al. (2022) use dry garbage waste to produce sustainable eco-bricks in Indonesia. The results of their research demonstrated that it is possible to use materials discarded after a single use and convert them into products that promote sustainability and the use of resources through recycling [27]. In another study carried out by Saberian et al. (2021), a literature review was carried out on the use of coffee husks. The findings of this research indicated that this bio-material can be used as an aggregate in construction materials, offering various applications in civil engineering [28].

K. Li et al. (2022) processed cow manure to obtain a renewable and economical fiber for application in the construction sector. Different laboratory tests were carried out for the fiber characterization, such as thermogravimetry, spectroscopy, X-ray diffraction, and scanning electron microscopy (SEM). The results obtained in this study demonstrated that the tensile strength of the fiber could be improved by incorporating an alkali in the samples. This suggests that processing agro–industrial waste like cow dung may be a viable agro–industrial waste recycling alternative for sustainable construction [29]. Moussa et al. (2022) evaluated the mechanical, thermal, and acoustic properties of a composite based on coffee husks. The results showed that the material presented adequate mechanical behavior for unloaded structures, which made it useful for manufacturing construction bricks with good acoustic comfort [30]. Choi et al. (2022) evaluated the thermal and acoustic behavior of a coffee residue. Biomaterial samples from this waste were found to have a higher sound absorption coefficient and better acoustic performance than other material sources [1]. Pennarasi et al. (2019) added coconut fibers to concrete mixtures based on different ages and dosages. The results showed that adding coconut fibers significantly increases the mechanical properties of products derived from concrete mixtures such as pavers [31]. Similarly, other researchers have incorporated seashells and ground glass [32], rubber [33], and asphalt pavement aggregates (APA) into concrete mixtures [34].

In the context of degradable biomaterials, Yara-Amaya, (2019) has developed a bio-paver using coconut and fique fibers in a mixture with 20 or 30% of conventional hydraulic concrete. The objective was to evaluate the mechanical properties of the paver following the NTC and ASTM standards that regulate the behavior of this type of masonry product [35], reducing the cost of the paver by 15% compared to a concrete paver. Similar results have been reported for this approach [36]. On the other hand, Ojeda (2009) used African palm seed waste in the concrete mixture with a ratio of 1:4 to evaluate the compressive strength of 15 × 30 cm samples at 28 days, according to technical standards. The results showed that, for a 1:2:2 mixture (one cement, two sand, and two waste), there was a weight lightening in the samples of up to 35%, but also a decrease in resistance of up to 50% in comparison to samples without the addition of seed waste [37]. In addition, Acosta and Beltran (2017) investigated the addition of ash to concrete mixtures to evaluate the behavior of masonry materials for construction; the results showed that, with the use of recyclable materials with low granulometry, the mechanical properties of the concrete improve the masonry products [38].

Juan-Valdés et al. (2020) revealed that recycled concrete that incorporates ceramics as secondary materials shows a level of performance comparable to that of conventional concrete after 28 days; in part thanks to its pozzolanic characteristics (industrial byproducts) and a lower effective water–cement ratio. This behavior demonstrates the reuse potential of these materials and their possible contribution to the circular economy [39]. Finally, Ussa and Poveda (2015) developed a paver using construction waste in the concrete mix. However, it was observed that the wastes had low mechanical resistance and a lack of impermeability, which promote challenges that can be mitigated using thedesign of experiments prior to laboratory tests to optimize the research sources [40].

In the case of non-biodegradable materials, Di Marco Morales (2015) carried out research using polyethylene terephthalate (PET) plastic fibers to evaluate the mechanical behavior of biomaterials with the incorporation of this material in different lengths. The results indicated that adding PET to the concrete mix at 35% volume significantly improves the mechanical strength of the concrete [41,42]. Other authors like [43–46] have also used PET to produce recyclable biomaterials in pavements. These studies have shown that this type of material has good compressive behavior and is suitable for applications in civil engineering. On the other hand, Gustavo Gamba (2015) used recycled rubber particles in the concrete mixture to manufacture biomaterials. However, due to the low adhesion of the particles to the concrete, a low density was obtained in the biomaterials, with values similar to those of concrete without the addition of rubber particles [47].

Bravo-German et al. (2021) recently incorporated recyclable aggregates from pavement (RAP) waste into concrete mixtures, considering different experimental conditions. The results showed that up to 50% of the weight of the fine and coarse aggregate fractions in concrete can be replaced with recycled aggregate, which does not significantly affect its mechanical behavior [48]. Furthermore, García-León et al. (2023) developed an experimental study to improve the mechanical properties of a concrete cobble using recyclable additives (clay and ash). The results showed that adding additives to the concrete mix was possible, providing an increase in the paving cobble compressive strength [49].

These studies demonstrate the efforts of researchers in developing degradable biomaterials using different sources of waste and residues to manufacture construction products. Although promising results have been obtained regarding cost reduction and mechanical properties, it is important to continue researching and improving these biomaterials to ensure their viability and applicability in sustainable construction.

1.3. General Aspects

The use of biomaterials in concrete for engineering applications represents an emerging field that combines the principles of traditional concrete technology with the sustainability and functional benefits offered by biomaterials, therefore, is important to consider the following important points:

1. Biomaterials in Construction: Biomaterials are substances derived from organic sources, such as agricultural waste, byproducts, or even living organisms like fungi and bacteria. In recent years, researchers and engineers have explored their potential use in various construction applications to reduce the environmental impact of traditional building materials.
2. Sustainability: One of the driving factors behind the use of biomaterials in concrete is sustainability. Concrete production is associated with significant carbon emissions, energy consumption, and the depletion of natural resources. Biomaterials offer an eco-friendly alternative by utilizing renewable resources and reducing the carbon footprint of construction materials.
3. Types of Biomaterials: Biomaterials used in concrete can take various forms, including natural fibers (e.g., jute, hemp, bamboo), agricultural waste (e.g., rice husk ash, sugarcane bagasse ash), biopolymers (e.g., starch-based binders), and even microorganisms (e.g., bacteria for self-healing concrete). Each type of biomaterial offers unique properties and advantages.
4. Mechanical Properties: Incorporating biomaterials can affect concrete's mechanical properties. Researchers explore how these materials impact concrete's strength, durability, and other essential characteristics. This involves studying the bonding mechanisms between biomaterials and cementitious matrices.

5. Durability and Longevity: Understanding the long-term performance of biomaterial-enhanced concrete is crucial. This includes assessing its resistance to environmental factors such as moisture, temperature fluctuations, and chemical exposure.
6. Microstructure and Microbial Interactions: In cases where microorganisms are used in concrete (e.g., to induce self-healing properties), studying the microstructure and microbial interactions within the material is essential. This involves microbiological and materials science considerations.
7. Biodegradability and Decomposition: Some biomaterials may have a limited lifespan or be susceptible to biodegradation. Understanding their behavior over time is crucial for assessing the environmental impact of biomaterial-enriched concrete.
8. Standards and Regulations: Researchers and engineers must consider relevant standards and regulations that apply to construction materials, including those related to biomaterials. Compliance with industry standards is essential for ensuring the safety and reliability of construction projects.
9. Life Cycle Assessment (LCA): This is a methodology used to evaluate a product or material's environmental impact throughout its entire life cycle, from raw material extraction to disposal. Conducting LCAs for biomaterial-enhanced concrete helps quantify its environmental benefits.
10. Applications: Exploring the practical applications of biomaterial-enriched concrete is crucial. This includes assessing its suitability for various engineering applications, such as structural elements, pavements, and even sustainable building practices.

In this way, the incorporation of biomaterials in concrete for engineering applications holds promise for sustainable construction practices. In order for researchers and engineers to advance in this field, they must consider the theoretical aspects outlined above while conducting practical experiments and generating case studies to demonstrate the real-world feasibility and advantages of biomaterial-enriched concrete.

1.4. Sustainable Development Standards

The United Nations established the Sustainable Development Goals (SDGs); in particular, we focus on numbers 9 and 11, "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation" and "Make cities and human settlements inclusive, safe, resilient and sustainable", respectively [50]. These objectives have defined goals and indicators in place until 2030 and seek to promote research into new sources, materials, resources, and processes that are environmentally friendly and sustainable to balance demand and consumption at a global level. For this purpose, it is important to consider the parameters established by international organizations that promote sustainable construction. Some of these parameters are described below:

- Green construction and life cycle analysis—Green Building Callege—(GBC) [51].
- United Kingdon methods—Building Research Establishment Environmental Assessment Method—(BREEAM) [52].
- United States system—Leadership in Energy and Environmental Desing—(LEED) [53].
- Japanese system—Comprehensive Assessment System for Building—(CASBEE) [54].
- Colombian standard—Environmentally Sustainable Construction in Colombia—(CASA) [55].

1.5. Aim of This Work

Through the comprehensive analysis of the BA of using biomaterials in concrete for engineering applications, this work aims to: (1) Evaluate the current state of research related to incorporating biomaterials into concrete by conducting a thorough bibliometric analysis of scholarly publications in this field. (2) Identify and analyze the trends, patterns, research themes, methodologies, and evolution of the publication output over time. (3) Investigate the various types of biomaterials utilized in concrete, including, but not limited to, natural fibers, agricultural waste, biopolymers, and recycled materials. (4) Assess the effects of biomaterial incorporation on concrete's mechanical, durability, and thermal properties, providing insights into the potential enhancements and challenges associated with their use. (5) Explore the environmental advantages and sustainability aspects of integrating biomaterials in concrete, including reduced carbon footprint and resource conservation. (6) Shed light on the increasing interest and research activity in sustainable construction practices and the role of biomaterial-infused concrete in achieving these goals. And (7) offer a comprehensive bibliometric analysis as a valuable resource for researchers, engineers, and policymakers working in the field of construction materials and sustainable engineering.

2. Materials and Methods

2.1. Bibliometric Analysis (BA)

According to García-León et al., 2021, bibliometrics is the science that allows the quantitative analysis of scientific production using the literature to understand the evolution of a specific scientific discipline to observe thematic trends over the years, which allows us to obtain quantitative information about publication metrics, geographical points, author collaboration, top research institutions, and the most relevant journals [56]. Bibliometrics applies statistical and mathematical methods to written sources that contain elements such as language, keywords, descriptions, article title or journal in the publication, authors, type of document, language, and abstract. On the other hand, BA is also called a statistical bibliography due to its need to count or summarize existing publications; its main function is quantifying scientific production (articles and books). The BA was developed using *RStudio*® software with the BiblioShiny platform and Bibliometrix library [57], considering that this software is one of the most used free programs to perform bibliometric analysis on the study related to the research topic or subject [58].

In addition, the methodology proposed in Figure 1 was considered to develop the BA of the biomaterials used in concrete for engineering applications considering three steps, described as follows:

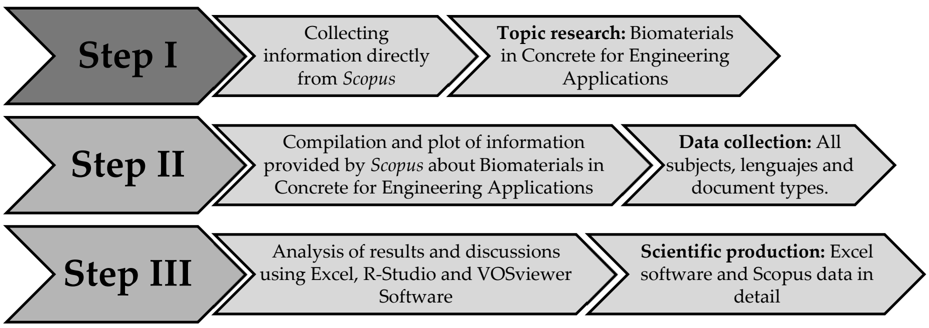


Figure 1. Methodology proposed for the BA.

Step I: Topic Research. In the initial phase, the research topic "Biomaterials in Concrete for Engineering Applications" is defined. This step includes a broad scope, encompassing all subject areas, languages, and document types. It serves as the foundation for the research journey, ensuring inclusivity and a comprehensive understanding of the subject matter.

Step II: Data Collection. The second step involves systematic data collection to support the research objectives. Researchers will employ Microsoft Excel software, utilizing the CSV (Comma-Separated Values) format for efficient data organization. Additionally, Scopus, a reputable data source, will be utilized to acquire a diverse range of research materials and publications relevant to biomaterials in concrete.

Step III: Scientific Production. The final step focuses on synthesizing the collected data and generating scientific output. Researchers use the wealth of information gathered in Step II to conduct in-depth analyses and create scientific content. This phase aims to contribute valuable knowledge to the field, potentially resulting in research papers, reports, presentations, or other forms of scientific communication [59]. In addition, the workflow proposed by García-León et al., 2021 [56] was used to develop the BA in this work using the data compiled from the *Scopus* database step by step.

2.2. Data Compilation/Collection

The information detailing scientific production (title, abstract, author, keywords, total citation per document, filiation, among others.) was collected on 20 September 2023 directly from *Scopus* database scientific publications on the use of biomaterials in concrete for engineering applications published from 2001 with the following search equation: ((biomaterial OR waste) AND (construction OR civil) AND (concrete) AND (sustainability)). A total of 1558 documents were found, but due to the detail errors and duplicates six documents were deleted (review type).

3. Results and Discussion

3.1. Main Results from the BA

Table 1 shows the general statistical analysis of the BA results on the biomaterials present in concrete for engineering applications. Note that a total of 1558 document types were analyzed, which were written in English because it is the language of scientific production worldwide [60].

Table 1. BA results.

Description	Result
Timespan	2001 to 2023
Source	489
Average years from publication	3.96
Average citations per document	18.67
Average citations per year per doc	3.75
References	64,082
Keywords Plus (ID)	6212
Author's Keywords (DE)	3286
Document Types	
Article	912
Conference-paper	385
Review-article	165
Book-chapter	85
Book	5
Others	6
Authors	
Authors	4521
Author Appearances	5886
Authors of single-authored documents	88
Authors of multi-authored documents	4433
Single-authored documents	95
Documents per Author	0.345
Authors per Document	2.9
Co-Authors per Documents	3.78
Collaboration Index	3.15

3.2. Document Summary

The analysis results, based on the 1558 documents, expose an increase in the number of publications from 2001 to 2023, indicating that the data and publications included in the analysis span over a period of 22 years, with an annual growth rate of 20.81% (higher than other topics in materials science [56,61–64]), as shown in Figure 2. Blue bars represent the number of articles by year, and the red line represents the accumulative number of articles for each year. It is evident that, from 2015, the topic of tribocorrosion studies had a significant increase in the number of publications, which was constant until 2018 and increased again until 2021, when more articles were published. According to the global analysis results (Table 1), published articles represent 58.54%, conference papers

33.33%, review articles 10.59%, and the other 9.50% of the total documents are conference reviews, books, and short surveys. We noticed that the use of biomaterials in concrete for engineering applications has been an important topic in civil engineering, with the aims to improve emissions and evaluate various material properties, including mechanical, physical, chemical, thermal, and bioclimatic aspects.

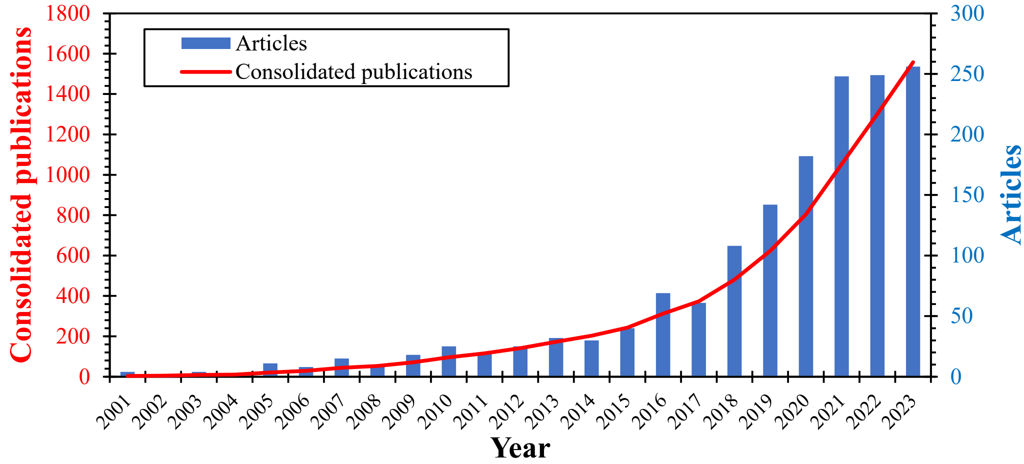


Figure 2. Consolidated publications and number of articles across the years.

3.3. Evolution of the Keywords across the Years

The keywords were extracted and analyzed according to their document frequency. Researchers use keywords to represent the main research topics, intending to achieve a better visualization, and allow others to search for specific topics by researchers in databases. Therefore, the BA used Author Keywords (AK) because they are extracted from the provided by the authors and are more complete than Keywords Plus (PK). Five different periods of time or years (2001–2016, 2017–2020, 2021–2021, 2022–2022, and 2023–2023) were analyzed as a function of the frequency of appearance based on the 1558 collected documents, as shown in Figure 3. Each line represents the relation between the word/synonym used for each period of time, differing by colors, and being widely used for keywords such as sustainability, concrete, recycling, and sustainable development. However, across the same period, the keywords are considered by month, showing the presence of sustainable development across the years. The increasing global focus on sustainable development has underscored the importance of adopting eco-friendly practices across all sectors, including civil engineering. Biomaterials, derived from renewable sources or biological organisms, hold immense promise as a sustainable alternative to traditional construction materials. However, the integration of biomaterials into civil applications, under the umbrella of sustainable development, represents a transformative paradigm shift in the construction industry. By embracing sustainability, civil engineers and stakeholders can unlock the full potential of biomaterials to create environmentally responsible, resource-efficient, and resilient infrastructure.

Figure 4 shows the twenty most popular/frequent keywords. Note that sustainability is the most common word used in the publications obtained from the BA (used in the search equation) after concrete and mechanical properties (compressive strength and durability), due to the importance of evaluating the mechanical behavior of materials developed with experimental design, adding biomaterials cannot be overstated. This approach facilitates the optimization of mechanical properties, cost-efficiency, and environmental sustainability while promoting innovation and market viability. As the demand for sustainable and high-performance materials grows, experimental design becomes a key tool for realizing the potential of biomaterial-enhanced composites across a wide spectrum of applications.

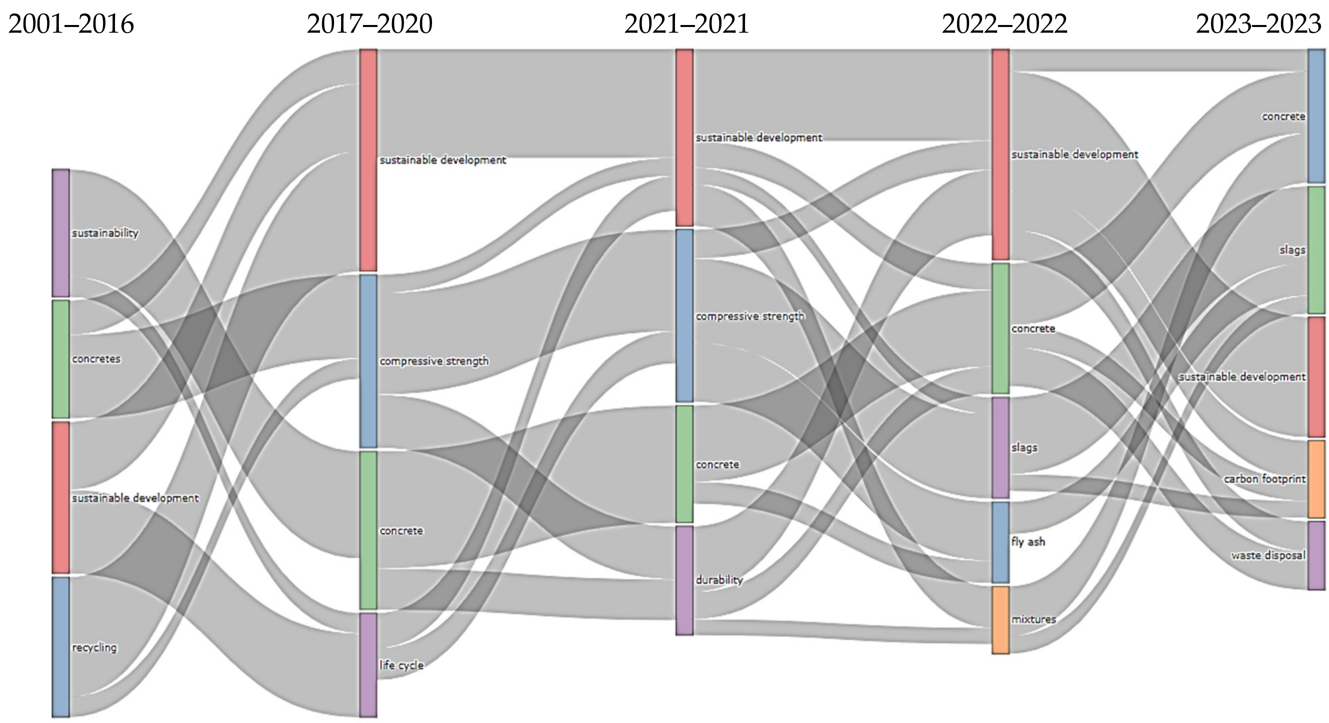


Figure 3. Evolution of the Author's keywords in four different periods of time.

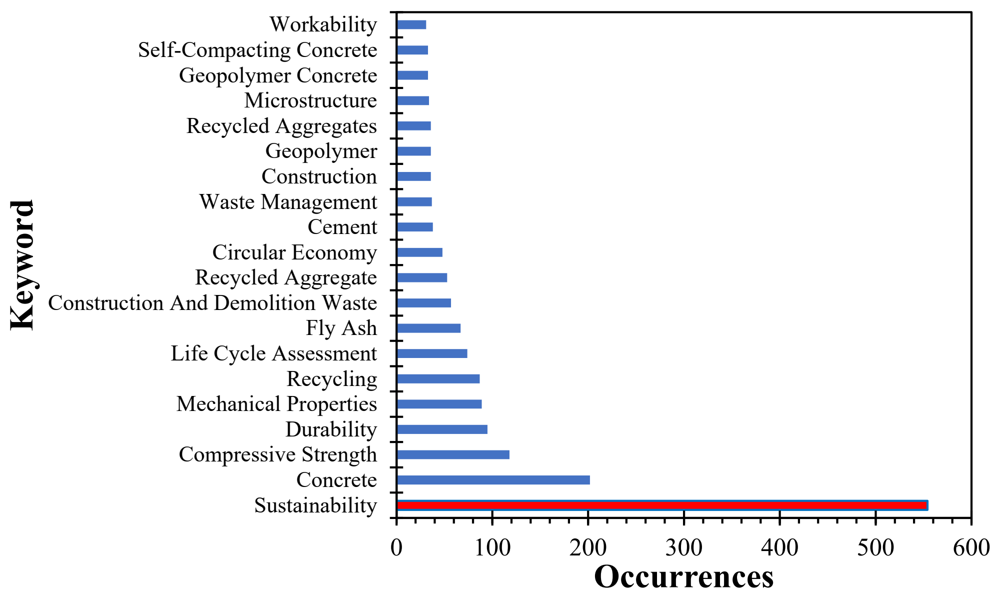


Figure 4. Twenty most popular/frequent keywords.

Figure 4 is supplemented with Figure 5, providing visual information about the co-incidence of the use of the principal keywords and their interaction with each other; a similar behavior is noted in networks of occurrence, appearance, and other areas. It is important to note that, from the 6212 keywords found, sustainability appears more than 500 times, taking its place as the most important subject within the topic of emissions to the environment. It is also important to mention that a number of studies have widely analyzed the use of biomaterials in cement for engineering applications, such as fly ash, recycled aggregate, geopolymer, and others, which are the most used in concrete.

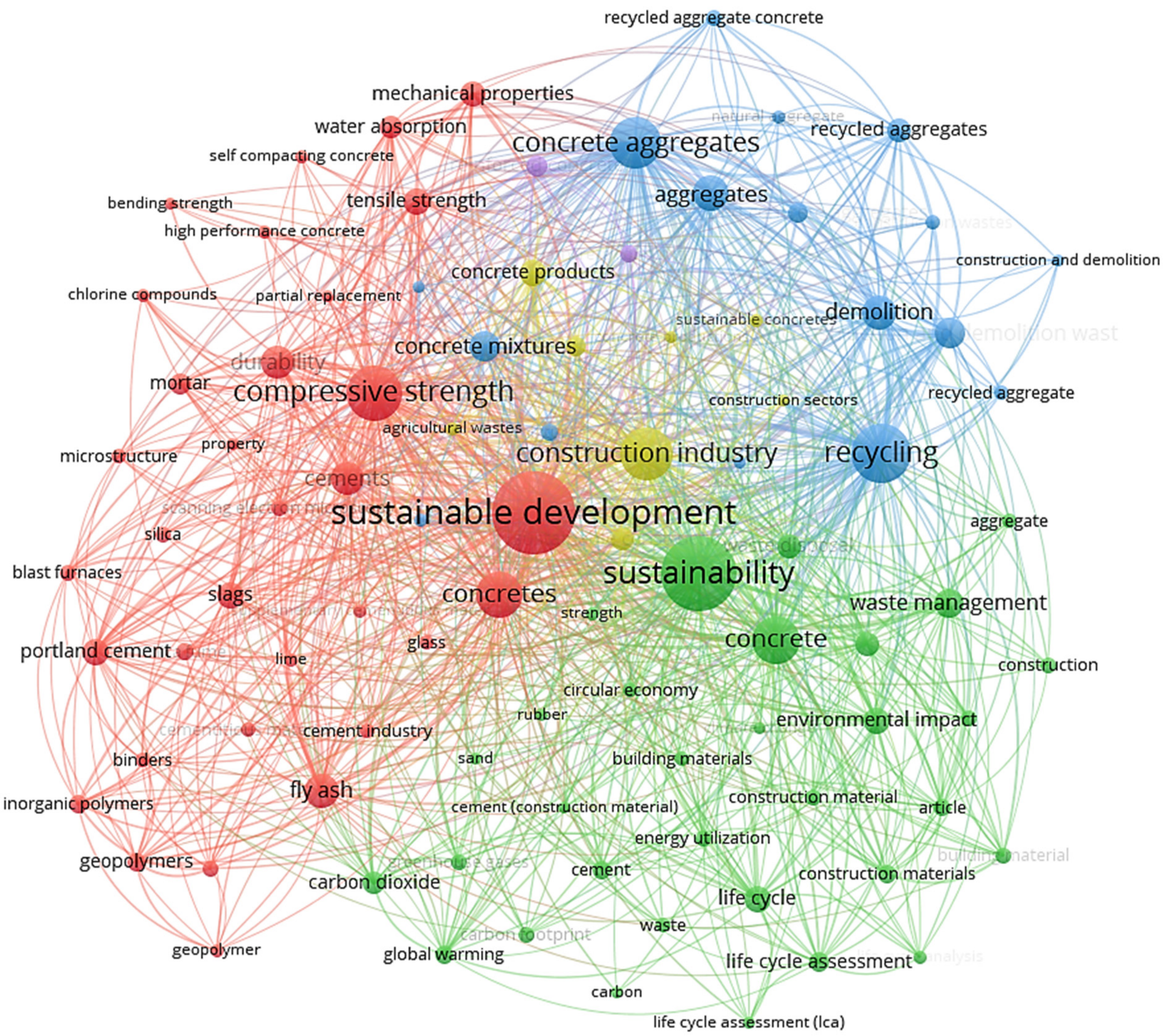


Figure 5. Co-occurrence between the keywords.

In this way, studies about the use of biomaterials in concrete for engineering applications have analyzed the behavior of the biomaterials under real conditions for civil engineering applications, as to compare the performance with the standards guidelines for each country. We noticed that some studies evaluate the addition of biomaterials to cement and conditions for the application. Still, due to the material's lifespan and costs, it is essential to increase its useful life using experimental designs in the laboratory. Additionally, environmental emissions have been studied because of climate change and conditions related to reducing the problem of industrial contamination.

The interaction between the keywords and the appearance times by area is shown in Figure 6; notice that, of the 6212 keywords counted in the BA, at least 20 keywords appear around 10 times in publications, with higher occurrences after 2015 when the increase in publications in the field of the use of biomaterials in concrete for engineering applications was evident (see Figure 5). As is observed, four circles related to associated areas of the keywords analyzed are used to expose information about areas of concrete sustainability and waste management (purple), compressive strength, concrete and cement (green), sustainable development, construction industry, and life cycle (red) and the last one about recycling, concrete, and aggregates. Notice that each one represents keywords from related studies to this important and emerging topic depending on the focus by country and authors.

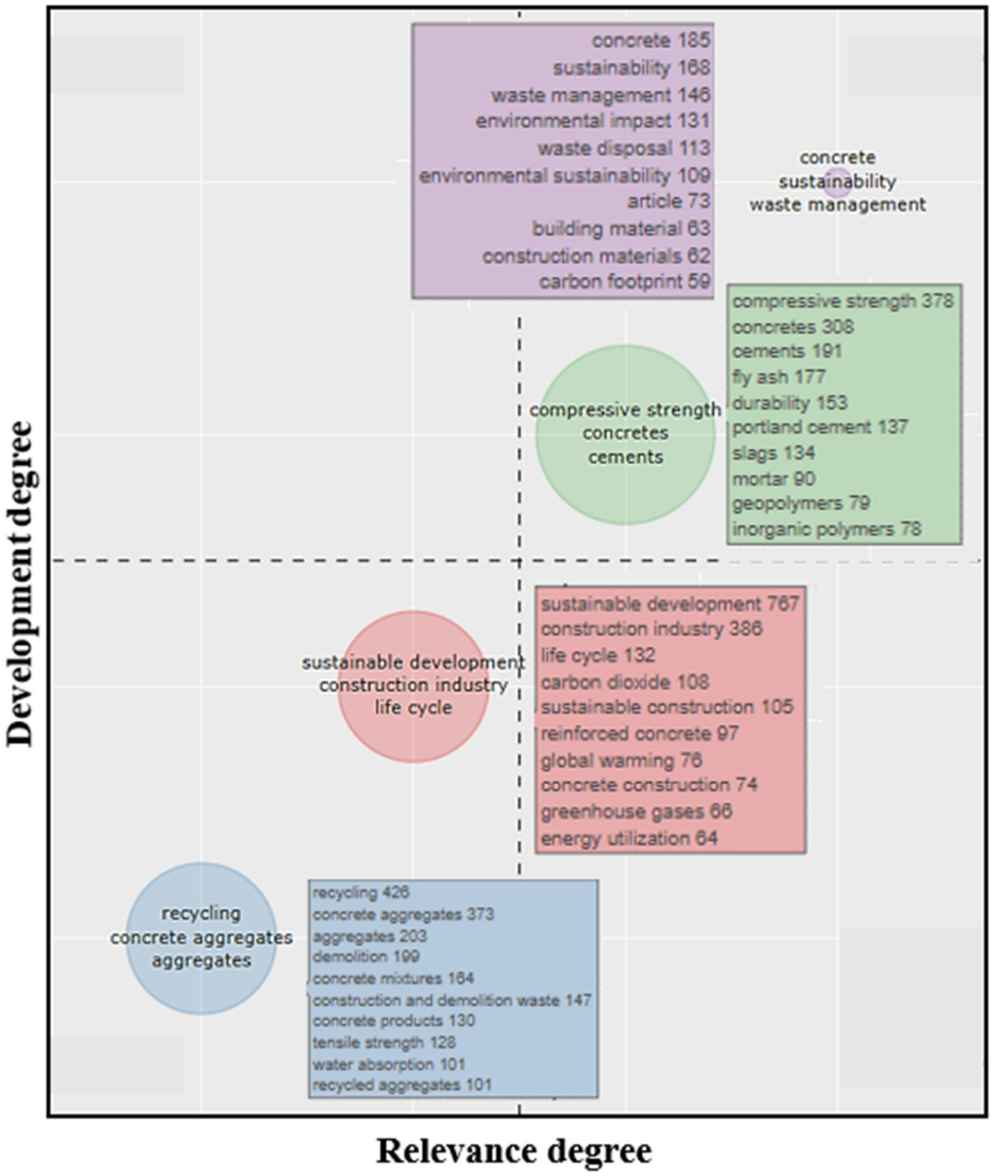


Figure 6. Keywords related to appearance times.

The continuous development and improvement of mechanical properties by different processes have been studied by adding aggregates to concrete mixtures, as observed in Figure 7. Notice that, from 2001 to 2015, there were not enough significant studies related to the use of biomaterials in concrete for engineering applications and the amount of occurrence; this is due to the international requirements and SDGs to improve human conditions in the future. However, since 2017, high growth of the main words' use, occurrences, and appearance have been important until this BA study.

Figure 8 shows two conceptual clusters (or themes) considering the Author Keywords (AK). Notice that the conceptual structure attempts to explain the most important subjects and trends in the scientific world in a particular area. In conclusion, what science talks about. Cluster 1, represented by red, concentrates on keywords related to recycled aggregates, sustainability, and mechanical properties that must be evaluated for civil engineering applications. In addition, in a small cluster (cluster 2—blue color), only three words appear: materials, construction, and building.

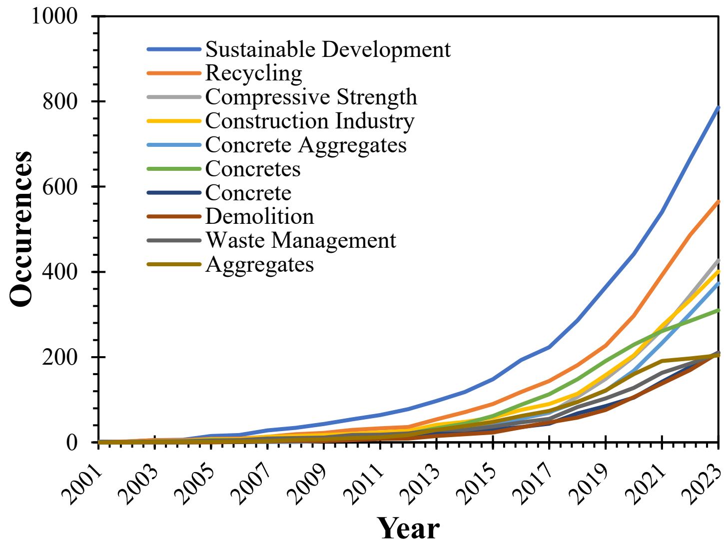


Figure 7. Behavior of the top 10 keywords across the years.

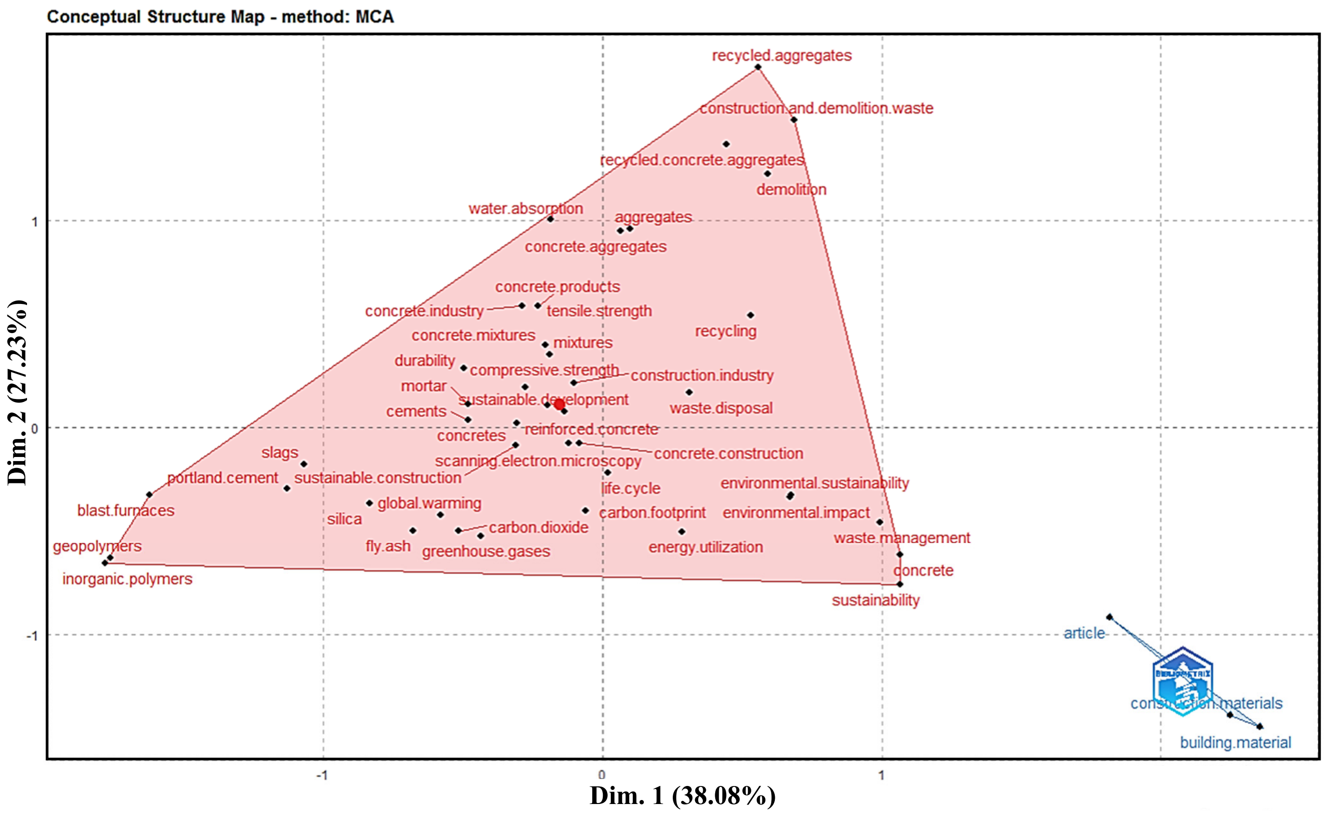


Figure 8. Conceptual structure map for all keyword analyzed by clusters.

Materials play a fundamental role in industrial applications, where their choice directly impacts performance, efficiency, and sustainability. This abstract explores the diverse range of materials utilized in industrial settings, focusing on their adaptability and appropriateness for specific engineering needs. The materials can be categorized into recyclables, suitable for resource-conscious practices, and engineering-use materials tailored for different applications.

Recyclable materials (RM) include metals, plastics, glasses, paper, and paperboard. Steel and aluminum find their place in structural elements and pipelines, while plastics, such as PET, HDPE, PVC, and LDPE, offer versatility in non-structural applications. Tempered glass, distinguished for its safety features, graces windows in industrial constructions. In addition, RM, including blueprints and packaging, promotes sustainable practices, reducing waste and resource consumption. Engineering-use materials extend the spectrum of possibilities, and cobblestone lends its durability and charm to pathways and driveways. However, electrical components find utility in ducts, facilitating seamless electrical installations. In fixing elements, electronic components cater to control systems, and decorative elements enhance aesthetics, shaping the ambiance of industrial spaces in almost all cases. Understanding the properties, advantages, and limitations of biomaterials is important for engineers, architects, and industrial professionals to make informed decisions across diverse industrial applications, as shown in Table 2.

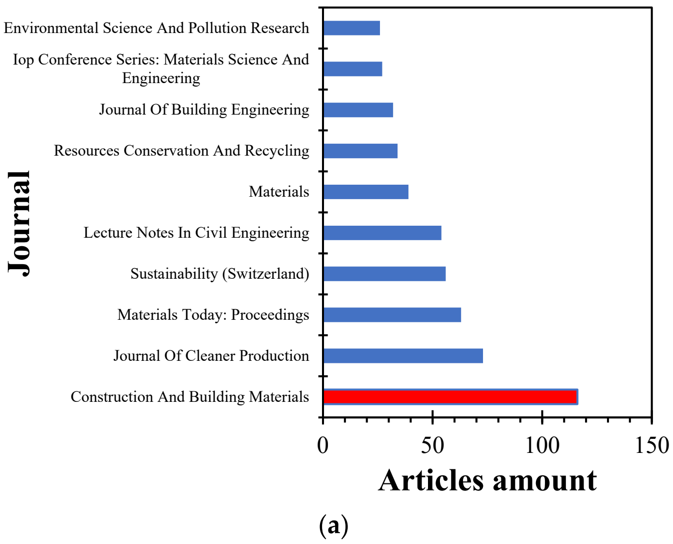
Table 2. Kind of materials for industrial applications.

Recyclables				**Engineering Use**				**Biomaterials**
Metals		**Plastics**		**Glasses**		**Paper and Paperboard**		**Industrial Residues**
R	**C**	**R**	**C**	**R**	**C**	**R**	**C**	**R**
Estructures	Steel	Pipelines	PET	Windows	Tempered	Blueprints	Magazines	Coffee husk
Pipelines	Aluminium	Coatings	HDPE	Doors	Recycled	Packaging	Newspapers	Rice husk
Ductes	Cobble	Electrical components	PVC	Isolations	---	Panelrs	Boxes	Cacao
Fixing elements	---	Electronic components	LDPE	Decorative elements	---	---	Packaging	Farm wastes
Benefits of recycling								
1.	Carbon emissions reduction.							
2.	Environmental pollution reduction.							
3.	Consumption reduction of natural resources.							
4.	Waste volume reduction in landfills.							
5.	Circular economy and sustainability promotion.							
6.	Energy saving.							

Note: Where R is recyclable and C is commercial.

3.4. Most Important Journals

A total of 489 journals contain the 1558 documents which were used in the BA. The documents were published in quartiles Q1 and Q2 mainly by 4521 authors. The most relevant 10 journals represent 33.38% of the total documents, as shown in Figure 9a. The most relevant journal is Construction and Building Materials, which is dedicated to the investigation and innovative use of materials in construction and repair for subject areas such as material science, civil, and structural engineering. This journal has a cite score of 12.4, h_{index} 230, and 7.4 for impact factor. The journal's age is important as is the impact factor that provides the good quality of the journals on civil engineering, sustainability, material science, and others. Figure 9b shows the evolution of the five more relevant journals across the years. Note that the *Construction and Building Materials* journal, being the most relevant journal on this subject, published their first article on the Use of Biomaterials in Concrete for Engineering Applications in 2009 the most relevant in this field. However, the other journals have been growing since 2015 in this important area for the sustainability of civil engineering construction, as is evident in the documents published in the *Journal of Cleaner Production* in second place on the list.



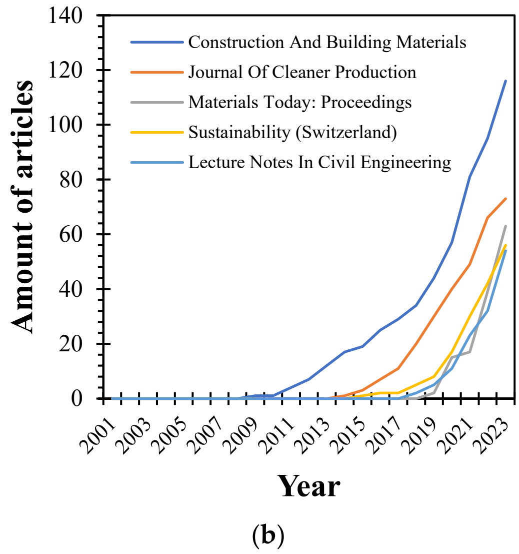


Figure 9. The most influential journals: (**a**) number of articles, and (**b**) evolution of the five more relevant journals across the years.

3.5. Most Relevant Authors

The top 20 most important authors on the use of biomaterials in concrete for engineering applications are shown in Table 3. From the BA of local documents, De Brito J and Tam VWY are the most important authors by document citations. These authors had ten and eight publications related to biomaterials in concrete, respectively. Notice that the most relevant documents by a citation from the *Scopus* profile are the Mechanical behavior of concrete made with fine recycled concrete aggregates (792 citations) and the Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach (673 citations). In addition, the documents present a significant amount of TCs by the amount of document by the author.

Table 3. First 20 most relevant authors from BA.

Author	Local			Year Start	Most Relevant Document from *Scopus* Profile	Document Citations
	h_index	TC	NP			
De Brito J	9	391	10	2016	Mechanical behaviour of concrete made with fine recycled concrete aggregates	792
Tam VWY	8	1135	8	2008	Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach	673
Adesina A	7	369	8	2019	Plastic wastes to construction products: Status, limitations and future perspective	203
Alyousef R	7	473	8	2019	Clean production and properties of geopolymer concrete: A review	391
Colangelo F	7	347	8	2017	Coal fly ash as raw material for the manufacture of geopolymer-based products	267
Mo KH	7	362	8	2018	Evaluation of thermal conductivity, mechanical and transport properties of lightweight aggregate foamed geopolymer concrete	311
Alabduljabbar H	6	335	7	2019	Properties and utilizations of waste tire rubber in concrete: A review	206

Table 3. *Cont.*

Author	Local			Year Start	Most Relevant Document from *Scopus* Profile	Document Citations
	h_index	TC	NP			
Bheel N	6	117	8	2021	Influence of coconut shell ash on workability, mechanical properties, and embodied carbon of concrete	42
Faleschini F	6	231	6	2016	Properties of concretes with black/oxidizing electric arc furnace slag aggregate	169
Farina I	6	278	7	2018	Recycled nylon fibers as cement mortar reinforcement	164
Ling T-C	6	452	7	2013	Durability of recycled aggregate concrete—A review	455
Matos AM	6	509	7	2012	One-step synthesis of dipyrromethanes in water	101
Poon CS	6	502	7	2014	Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates	753
Yang J	6	365	6	2020	Concrete with recycled concrete aggregate and crushed clay bricks	293
Arulrajah A	5	375	5	2018	Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications	338
Cioffi R	5	242	6	2017	Recycling of MSWI fly ash by means of cementitious double step cold bonding pelletization: Technological assessment for the production of lightweight artificial aggregates	184
He Z-H	5	167	5	2021	Utilization of CO_2 curing to enhance the properties of recycled aggregate and prepared concrete: A review	216
Horpibulsuk S	5	375	5	2018	Analysis of strength development in cement-stabilized silty clay from microstructural considerations	425
Jhatial AA	5	69	5	2020	Investigating embodied carbon, mechanical properties, and durability of high-performance concrete using ternary and quaternary blends of metakaolin, nano-silica, and fly ash	32
Li J	5	170	7	2013	A model for estimating construction waste generation index for building project in China	26

Note: TC means total citations and NP is the number of publications.

3.6. Most Local Cited Documents (From the BA)

Table 4 provides a list of the 10 most relevant documents widely cited by the locally cited references (LC—analyzed in this study) published in different journals, focusing on topics related to sustainable construction and the use of recycled and alternative materials in the construction industry for a time span from 2008 to 2018 (when an increase in the publications in this field as was observed, as shown in Figure 9a), indicating a relatively recent and ongoing interest in these topics within the academic community. The articles primarily center on sustainable construction practices, recycling of materials, and the development of eco-friendly construction solutions. Most of the articles are published in construction-related journals, emphasizing the importance of these subjects within the construction and building materials domain. Each article's total citations (TCs) demonstrates its impact and influence within the research community. In particular, several articles have received many citations, highlighting their importance in the field. Some of the articles are reviews or overviews, which synthesize existing research and provide comprehensive insights into specific topics, such as recycled aggregates, waste tire rubber in concrete, and supplementary cementitious materials. The topics covered range from materials science to energy analysis and life cycle assessments, demonstrating the interdisciplinary nature of sustainable construction research, as was observed.

Table 4. Most local 10 cited references.

First Author	Journal	Year	Title	TC from *Scopus*	Ref.
Behera M	Constr Build Mater	2014	Recycled aggregate from C&D waste & its use in concrete—A breakthrough towards sustainability in construction sector: A review	766	[65]
Tam VWY	Constr Build Mater	2018	A review of recycled aggregate in concrete applications (2000–2017)	610	[66]
Shu X	Constr Build Mater	2014	Recycling of waste tire rubber in asphalt and portland cement concrete: An overview	459	[67]
Corinaldesi V	Constr Build Mater	2009	Influence of mineral additions on the performance of 100% recycled aggregate concrete	402	[68]
Kisku N	Constr Build Mater	2017	A critical review and assessment for usage of recycled aggregate as sustainable construction material	385	[69]
Part WK	Constr Build Mater	2015	An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products	364	[70]
Aye L	Energy Build	2012	Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules	312	[71]
Aprianti E	Constr Build Mater	2015	Supplementary cementitious materials origin from agricultural wastes—A review	311	[72]
Naik TR	Pract Period Struct Des Constr	2008	Sustainability of Concrete Construction	276	[73]
Aprianti S E	J Clean Prod	2017	A huge number of artificial waste material can be supplementary cementitious material (SCM) for concrete production—a review part II	271	[74]

Figure 10 shows the most general documents that globally can be considered to be the documents with more citations and appearances in the references of the collected documents analyzed in the BA from the *Scopus* database. In this way, the most relevant documents appearing with the bigger red circle, were published by Akhtar A and Sarmah A.K., published in *Construction and Building Materials journal*; this is because of the bond between documents that have similar keywords and citations between them, as was observed in the correlative plot obtained from the BA.

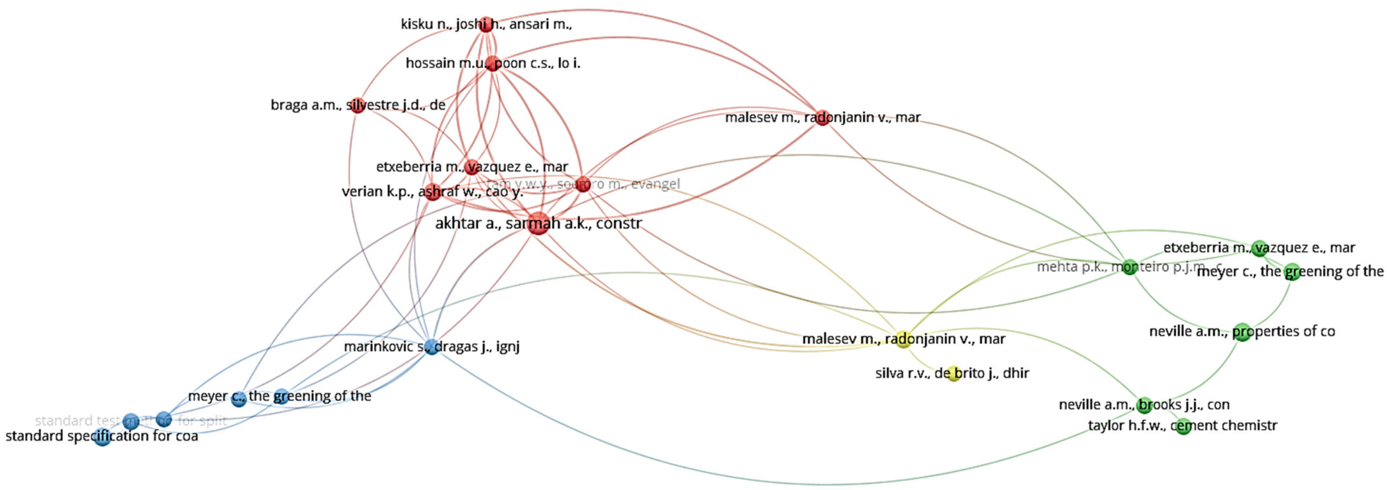


Figure 10. Relationship between local documents from BA.

3.7. Most Relevant 20 Institutions/Universities

The most relevant institutions are presented in Figure 11. This plot was obtained considering the number of publications and frequency of appearance since 2001, based on the affiliations of the authors of the publications analyzed. The Rmit University is the most important institution, with 71 articles in appearance, followed by the University Teknologi Malaysia with 61 documents, and in third place the National Institute of Technology with 54 published papers. These institutions account for 39.67% of the published documents and the resting percentage (60.33%) of institutions with less than 40 documents.

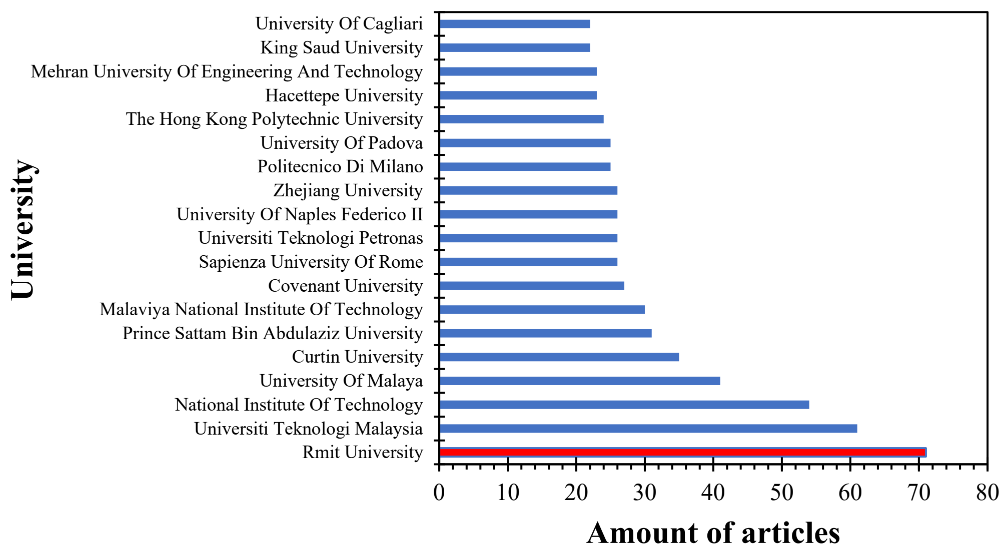


Figure 11. More relevant universities.

Figure 12 summarizes research citations in different countries, along with the article's frequency and the average number of citations per article. The total number of citations reflects the overall impact and influence of research from each country. Australia, India, and China stand out as the top three countries regarding total citations, indicating their significant contributions to the global research landscape. Frequency represents the number of articles from each country that have received citations. India has the highest frequency, with 1023 articles, followed by China, with 432 articles. This suggests a substantial volume of research output from these countries. The average number of citations per article provides insights into each country's research quality and impact. Greece has the highest average article citations (54 from BA), indicating that its research tends to be highly cited on average.

Hong Kong also stands out with a notably high average. However, the table includes diverse countries, highlighting the global nature of research contributions. Particularly, countries from Asia (India, China, Malaysia, Hong Kong, Bangladesh) and Europe (Italy, Portugal, Spain, Greece) feature prominently in terms of citations and frequency. In addition, regarding research output, dome countries with high frequencies, such as India and China, have a substantial research output, covering a wide range of topics and disciplines.

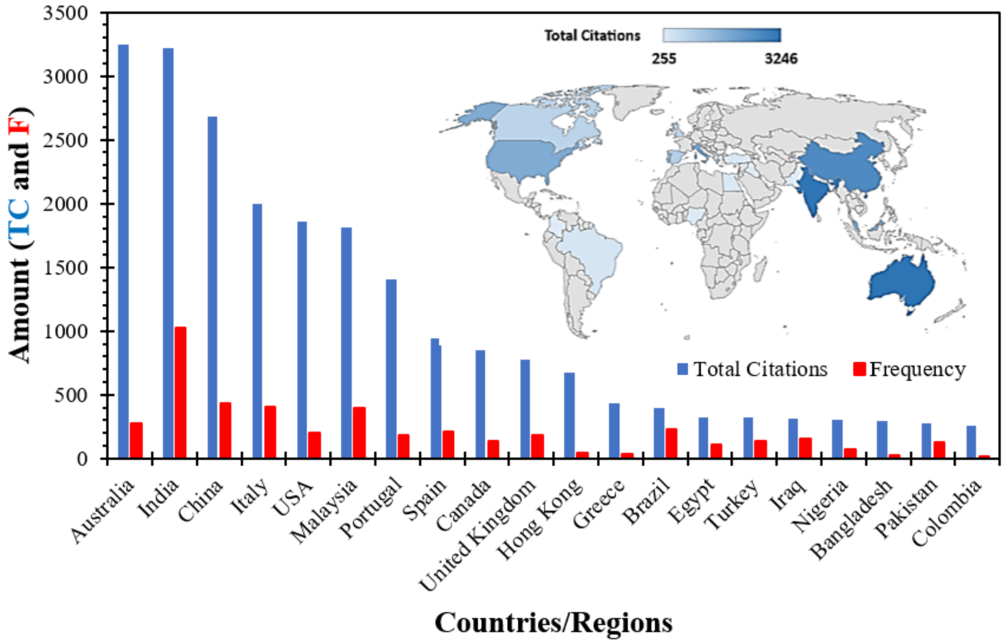


Figure 12. Top 20 countries by scientific production.

Conversely, countries like Iraq and Nigeria have lower research output but still contribute to the global research landscape. Finally, countries like Bangladesh and Colombia may have fewer articles but exhibit relatively high average article citations, suggesting emerging areas of research excellence. In this way, insights into potential research collaborations and knowledge exchange opportunities among countries with complementary strengths in different research areas.

3.8. Collaboration between Authors

Figure 13 shows the most relevant country and authors by the institution from the BA, which illustrates the connections between the author, their affiliated university, and the associated keywords. This visually represents the interplay between scholarly research, academic institutions, and the thematic focus of the work. This graphical representation serves as a concise summary of the key elements that define the academic context and the research interests of the author. Notice that Farina I and Colangelo F mainly developed studies in collaboration with other countries, with a common keyword (Sustainability related to concrete).

In Figure 14a, it is possible to identify the networks of co-citations between authors in three main networks (red, blue, and green), with predominate authors like De Brito J, Poon C.S., Wang J, Sddiquer R, Jumaat M.Z, and Chinfaprasirt P. The main networks (green and red) of collaborations by principal authors worldwide are shown in Figure 14b. Notice that the number one authors (Colangelo F and Farina I) have a collaborative network with China and India—notice also that some collaborative networks work with three people or less.

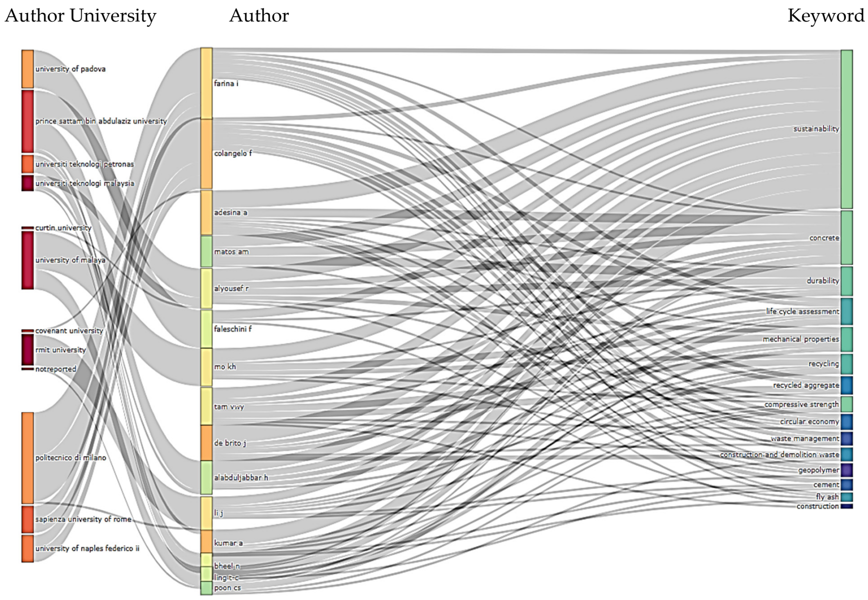
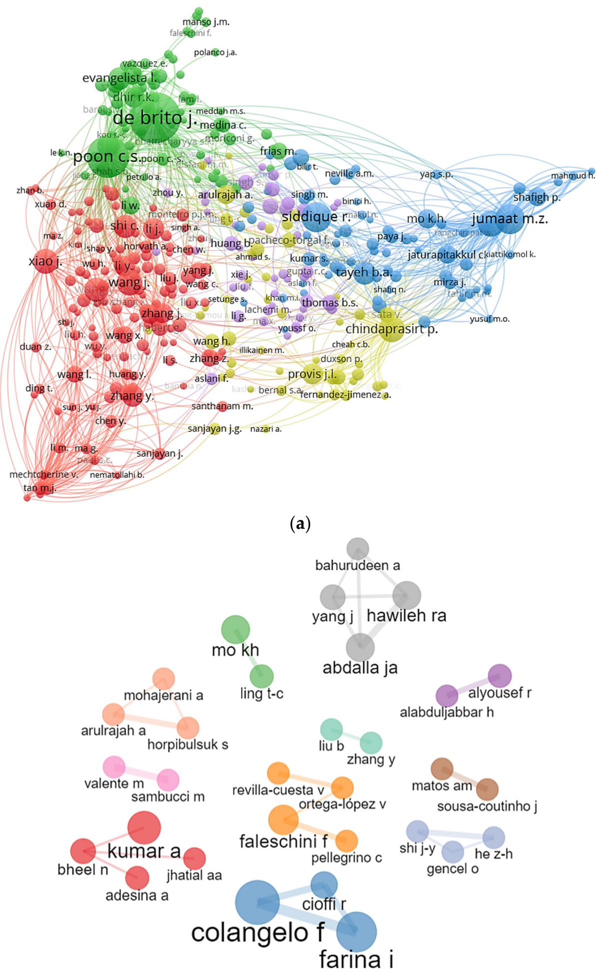


Figure 13. Relation between most relevant university and Author-Keyword.



(**a**)

(**b**)

Figure 14. The top 20 most productive authors around the world. (**a**) Networks of co-citations between authors, and (**b**) collaborative networks between authors.

The collaborative networks between authors, shown in Figure 15, show the collaborative networks between countries related to the publications and authors' frequency. The influence of collaborative networks around the world is led by India (purple circles) with the USA, China, and Hong Kong (pink circles), and Malaysia with the UK (green and yellow circles). Notice that collaborations also have been made in smaller proportions according to the circle sizes. As was observed, there are countries with collaborative relationships with smaller cities in the same region, which have developed important work related to the subject.

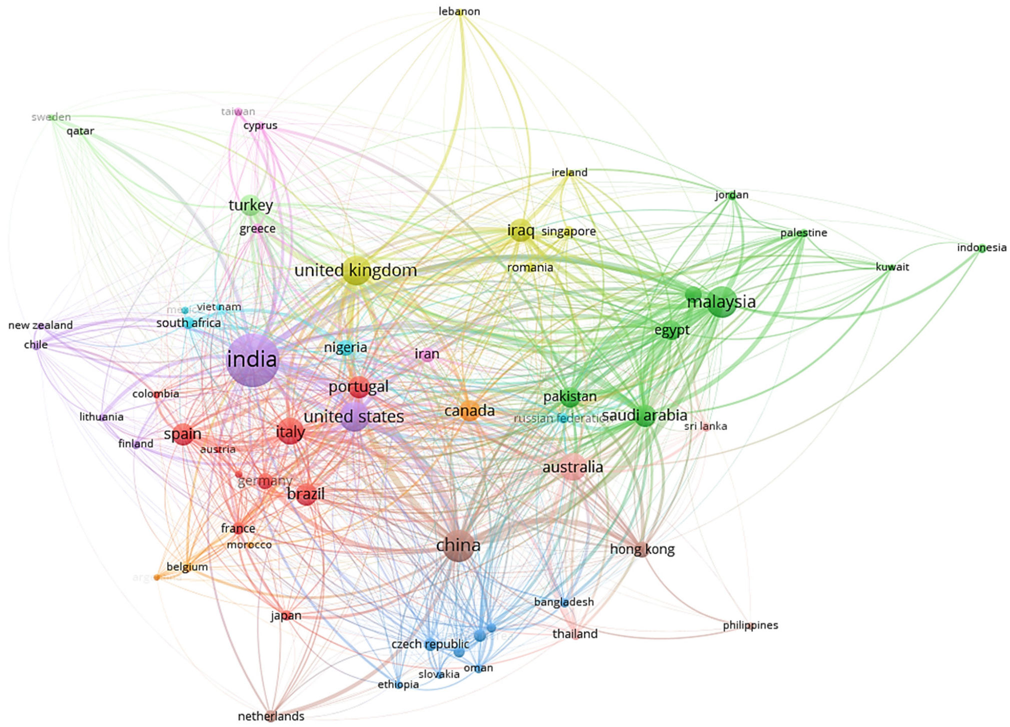


Figure 15. Relationship between countries from BA.

4. The Use of Biomaterials for Engineering Applications

4.1. Trends and Future Research

The use of biomaterials in concrete for engineering applications is an evolving field with several emerging trends and future research directions. These trends reflect the growing interest in sustainable construction practices and the desire to enhance concrete's mechanical properties and environmental performance. Some trends and areas of future research are described in Figure 16.

The use of biomaterials in concrete for engineering applications is a dynamic and multidisciplinary field with numerous opportunities for research and innovation. Future studies will aim to optimize biomaterial integration, assess environmental impact, and develop practical solutions that contribute to more sustainable and resilient construction practices.

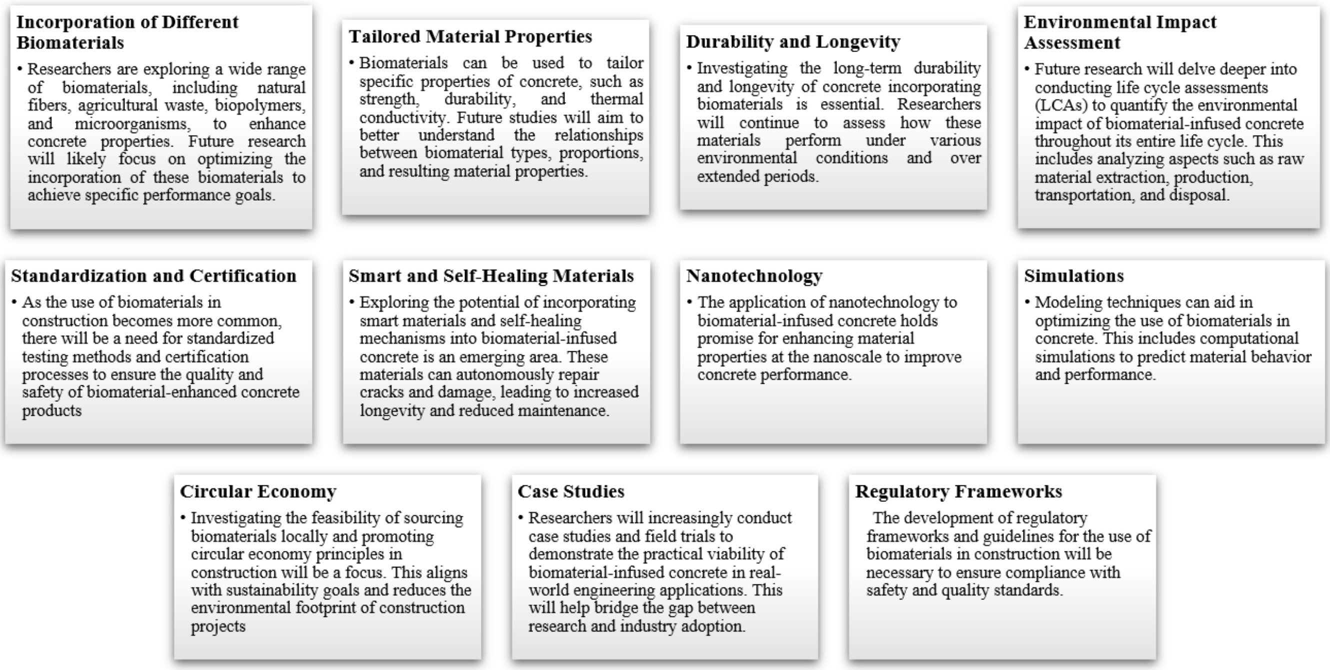


Figure 16. Key trends and areas of future research.

4.2. Challenges and Barriers

The acceptability of recycled aggregate in construction is hindered by several factors, including a negative public perception of recycling activities and a lack of consumer confidence in the quality of the finished product made from recycled materials. Despite the substantial utilization of recycled aggregate in civil engineering construction, barriers persist that impede its broader adoption. One of the primary obstacles is the influence of economic factors. While concrete made with recycled aggregate can match the concrete quality with virgin aggregate, skepticism surrounds the use of recycled materials from this selection. Therefore, recycled concrete will only be preferred when the cost of recycled aggregate significantly undercuts that of natural materials, even when meeting specified standards. Another challenge lies in the variability of recycled aggregate quality, which can be readily addressed by improvements in construction and demolition (C&D) processing plants. A lack of well-developed collection and processing facilities and infrastructure further impedes the broader use of recycled aggregate in construction [66].

Availability is crucial, as a shortage of potentially usable recycled material can significantly impact construction decisions. Additionally, the appropriate use of recycled aggregate based on its quality is essential, with higher-quality concrete debris earmarked for recycled aggregate and lower-quality material utilized as road base aggregate. The proximity between recycled aggregate factories and ready-mixed concrete factories is vital to minimize transportation costs, which can deter manufacturers and contractors from using recycled aggregate. Distrust concerning the technical feasibility of recycled aggregate is another issue voiced by clients, concrete producers, and contractors—acceptance as a realistic alternative to virgin aggregate hinges on demonstrating compliance with high-quality standards. Lastly, a general lack of trust exists among purchasers and users of recycled products, leading to a reluctance to embrace these eco-friendly alternatives. Addressing these barriers requires a multi-faceted approach involving improved processing facilities, greater accessibility to recycled materials, enhanced quality control, and increased awareness and trust-building efforts among consumers and industry stakeholders. Overcoming these challenges is essential to realizing the economic and environmental benefits of using recycled aggregate in construction [75].

The use of biomaterials in engineering applications presents numerous opportunities for innovation and sustainability. However, it also comes with several challenges and barriers that must be addressed for successful integration. Some key challenges and barriers associated with the use of biomaterials in engineering applications are detailed in Figure 17. Notice that biomaterials need to be compatible with the specific application and environment they are intended for. It is crucial to ensure that biomaterials can withstand mechanical stresses, temperature variations, and chemical exposures for their successful use in engineering applications. Many biomaterials can be expensive, especially those derived from natural sources or produced using specialized processes. Cost considerations are essential for widespread adoption in engineering applications where cost-effectiveness is a primary concern [76], and other costs related to establishing standardized testing methods and quality control measures for biomaterials are critical to ensure consistent performance and reliability across different applications. In this way, biomaterials used in engineering applications need to have sufficient durability and longevity to justify their use, especially in situations where replacements or maintenance are costly or impractical, they need to have enough durability and longevity to justify their use.

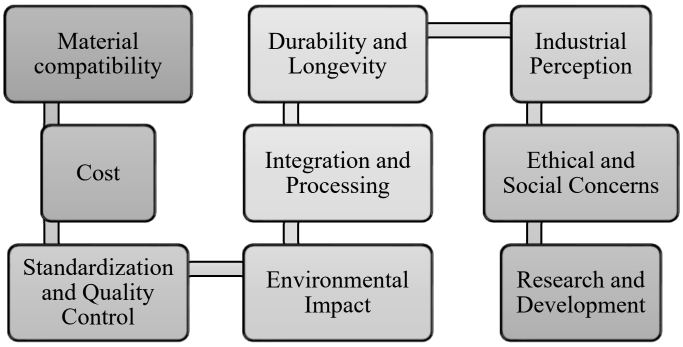


Figure 17. Key challenges and barriers associated with the use of biomaterials in engineering applications.

On the other hand, biomaterials often require specialized processing techniques to convert them into usable forms. Developing suitable processing methods and ensuring compatibility with existing manufacturing processes can be challenging. It is important to manage and calculate costs related to CAPEX and OPEX [77]. While biomaterials are often considered more environmentally friendly than traditional materials (biodegradability), the environmental impact of their production, use, and disposal must be carefully evaluated. This point includes considerations of resource consumption, energy use, and biodegradability; in addition, it may face resistance or skepticism from the public and stakeholders unfamiliar with their benefits and safety. It is important to take this into account through effective communication and education to gain acceptance in the industrial sector.

Finally, the use of specific biomaterials, such as those derived from animal sources or genetically modified organisms, can raise ethical and social concerns, so ethical considerations must be carefully addressed. However, continuous research and development efforts are required to discover new biomaterials, improve existing ones, and find novel engineering applications; this demands significant investments in research and collaboration among interdisciplinary teams in universities and research groups. Addressing these challenges and barriers requires collaboration among scientists, engineers, regulators, and industry stakeholders. Advances in biomaterials science and technology, along with careful consideration of ethical and environmental implications, can help overcome these obstacles and promote the widespread use of biomaterials in engineering applications.

5. Conclusions

The success of the BA study hinges significantly on the appropriate categorization, quality assurance, and proper organization of the data sourced from databases. Furthermore, challenges arise due to the constraints posed by logical operators, such as accented characters in authors' names, which may not be reliably recognized by R-Studio software. Consequently, to minimize the margin of error, meticulous attention was devoted to rectifying inaccuracies encountered during the data import process using Excel software. In this way, the following conclusions are listed:

1. This BA study offers comprehensive insights into the realm of biomaterials' use in concrete for engineering applications, encompassing a wide array of scientific production in this field.
2. Data collection was conducted directly from the Scopus database, and meticulous checks and corrections were made using Excel to address accentuation issues in the dataset. In total, the dataset comprised 1558 documents spanning four primary areas of study.
3. Notably, Australia, India, and China emerge as the leading contributors to this field, boasting the highest total citations, underscoring their substantial impact on the global research landscape.
4. The investigation of scientific publications relating to the use of biomaterials in concrete for engineering applications involved sophisticated data analysis and temporal trends visualized through bibliometric analysis (BA).
5. The findings reveal a remarkable surge in research activity in this domain, particularly since 2015, with a notable growth rate of 20.81%. Australia excels in terms of total citations, while India leads in the frequency of document appearances. Several European countries also make noteworthy contributions, as evidenced by the statistical results of analyzed data sources.
6. Keyword analysis, involving a collection of 6212 keywords, highlights the prominence of "sustainability," which occurs over 500 times, signifying its paramount importance, particularly concerning environmental emissions. The temporal evolution of keywords underscores the enduring significance of sustainability in this field.
7. Keywords examination reveals that studies on the use of biomaterials in cement for engineering applications extensively investigate materials such as fly ash, recycled aggregate, and geopolymer, which are prevalent components in concrete formulations.
8. The economic factors stand out as a major driver in determining the adoption of recycled aggregate in construction. Cost-competitiveness plays a crucial role, and recycled concrete is more likely to be preferred when it significantly undercuts the cost of natural materials, even while meeting quality standards.
9. Quality control, trust-building efforts, and better processing facilities are essential to address the issue of recycled aggregate quality variability. Increasing trust among consumers and industry stakeholders is vital for the broader acceptance of recycled products. The multi-faceted approach that combines improved processing, enhanced quality control, and increased awareness is key to unlock the economic and environmental benefits of recycled aggregate in construction.
10. Cost considerations are paramount in the adoption of biomaterials for engineering applications, especially when compared to traditional materials. It is essential that biomaterials are cost-effective for them to gain widespread use. Additionally, biomaterials must be compatible with specific applications and environments, demonstrating the ability to withstand mechanical stresses, temperature variations, and chemical exposures.
11. Standardized testing methods and quality control measures are critical to ensure consistent performance and the reliability of biomaterials across various applications. Environmental impact assessment, including resource consumption, energy use, and biodegradability, is essential, considering that biomaterials are often perceived as more environmentally friendly. Effective communication and education are necessary to gain acceptance in the industrial sector.

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