Establishing the Indicators of Sustainable Building Materials

Alireza Moghayedi, Karen Le Jeune, Mark Massyn, and Paimaan Byron

Abstract Sustainable building materials are products with a relatively positive impact on economies, communities and the environment. Understanding the key indicators in developing sustainable building materials, which affect the economic, social and environmental aspects of buildings, is a critical perspective to aid their evolution. Research in sustainable building materials is relatively new, and therefore this study examined the existing literature on sustainable building materials in academic journals with the intent of identifying and clustering key indicators and proposing a conceptual framework for the development of sustainable building materials. This study employed a verifiable and reproducible systematic literature review of building materials, analyzing and scrutinizing 203 academic articles for the co-occurrence of keywords, using a mixed bibliographic and bibliometric method. It emerged from the study that the groups themed "Process", "Material", "Element" and "Technology" contained the greatest number of, and most statistically significant, indicators associated with sustainable building material. It was found that, in developing and evaluating sustainable building materials, sustainability, LCA (Life Cycle Assessment), embodied energy and recycling appear to be the predominant processes used; concrete, bricks, C&D (Construction and Demolition) waste, and fibre are the foremost materials; walls and roofs are the main building components; and composite, 3D printing, nanotechnology and prefabrication are the leading technology features. Also, the results of the analysis of interconnections between indicators revealed that a significant interconnection exists between embodied energy, LCA, concrete, composite and durability to the sustainability of building materials. Based on the taxonomy of indicators and the analysis of their interconnections, a conceptual framework for developing sustainable building materials was proposed in the paper.

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1 Introduction

Housing and building conditions reflect the living standards of society. One of the main approaches to significantly improving housing and building conditions is to employ sustainable building materials in the construction of such projects [1]. The sustainable building materials approach has a high potential to make a valuable contribution to sustainable development. Sustainable building materials are materials with a relatively positive impact on economies, communities and the environment [2]. Various characteristics of building materials, such as their composition of raw materials and natural resources used, life cycle energy consumed, safe disposal and recycling opportunities, impact on the environment, long-distance transportation required, and end-user satisfaction should be carefully considered before they are used in construction [3]. This implies that building materials must be sustainable in order to address the technical, environmental, social and economic issues associated with the use of conventional building materials [4]. The exclusive use of energy-efficient traditional materials present challenges to satisfying the ever-growing demand for housing and buildings. Optimal utilization of available resources and raw materials to produce simple, resource- and energy-efficient, healthier, comfortable and environmentally friendly sustainable building materials to overcome these challenges, therefore, has become a necessity. Sustainable building materials were developed to improve the sustainability performance of buildings through reduced water usage, higher energy efficiency, enhanced indoor quality and minimal construction waste [4]. Sustainable building materials contribute to the competitiveness of building contractors, optimize building performance, extend buildings' predictable lifespan and have been touted as the only way to meet the ever-increasing demand for buildings due to burgeoning population growth and over-urbanization [5]. However, studies on sustainable building materials have not explicitly investigated nor extensively analyzed or understood the challenges of developing sustainable building materials concerning their features and performance. Previous studies have focused either on the challenges of alternative and sustainable design and construction [5] or investigated the challenges of developing and adopting green building technologies [6, 7]. Hence, there is a need for a deeper and better understanding of the key indicators of sustainable building materials to develop a framework for developing sustainable building materials and evaluating their impact on the building sustainability index [4]. Furthermore, there is limited knowledge of the extent of the interconnections between the indicators of sustainable building materials. Therefore, this research attempts answering the following research questions: What are the indicators associated with sustainable building materials, in the context of the themes of material, technology, process and element? What are the interconnections between the indicators of sustainable building materials?

2 Research Methodology

The bibliometric research approach was used in developing the bibliographical analysis which assists in identifying the characteristics and size of the collection of publications and elaborating on growing research trends. With this potential result, the bibliometric research approach helps to fulfil the research aim of determining the key indicators associated with sustainable building materials and whether there are interconnections between these key indicators. The bibliometric research approach comprises of four phases: keyword definition; database definition; document search; and analysis of the defined literature sample. The methodological procedures for grasping the bibliometric examination described were developed between November and December 2020. The initial step for establishing this bibliometric examination was the definition of the pertinent keywords. It was determined that the keywords to be used should be: "construction", "sustainable", and "building materials" to reflect the theme of this research. Two major scientific databases, Scopus and Web of Science, were used to search for relevant and appropriate documents. The research results were limited to final peer review articles published in English with no restriction on the date of publications. Following the database search, the titles and keywords of 203 documents were deemed to be aligned to the research objectives.

3 Data Analysis

The following criteria were used to analyze the portfolio of documents: Trend of publications over time; Research territory analysis; Keyword analysis; Keyword clustering analysis; and Interconnection analysis.

3.1 Publication Trend Over Time

Although the publication period was not restricted, only 2% of relevant documents were published before 2010, which denotes the novelty of the sustainable building materials research field. Figure 1 illustrates the consistent increase in publications,

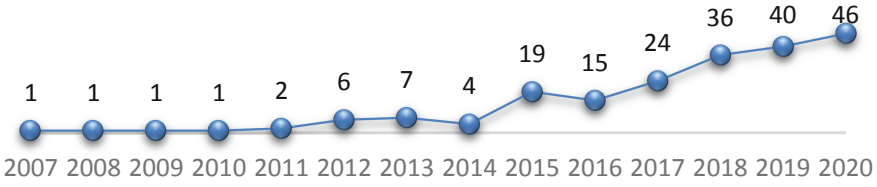

Fig. 1 Publication trend regarding sustainable building materials

noting that 72% of the selected documents were published in the last four years. This large number of recent publications appear to be driven by building material manufacturers, who under pressure because of the increased consideration around the integration of environmental and social sustainability, are being forced to develop new possibilities to reduce the environmental impact of building materials [8].

3.2 Territory of Research Publication

The top three contributors to sustainable building material research are Italy (24), Spain (18) and the United States of America (16) who account for more than 28% of all publications. India (15) and Brazil (13) are the only developing countries among the top ten countries with the most publications in this field of research and that 32% of the portfolio of documents are affiliated with developing countries. This could be interpreted to mean that research on sustainable building materials is a topic of less interest in developing countries when compared to developed countries.

3.3 Analysis of Keywords

The keywords were analyzed to verify the findings of the key research topics, which established indicators of sustainable building materials. The analysis was done manually to identify and eliminate keywords which conveyed possible similarities in concepts. The resultant list comprised 339 keywords extracted from the 203 documents selected from the database for the study. The frequency of a selected keyword was calculated, and then ranked according to frequency. In this way, 1,767 co-keywords were identified. The node table and edge matrix were imported to the Gephi software to establish and visualize a keyword network as illustrated in Fig. 2.

As shown in Fig. 2, each node represents a keyword, and its size reflects the number of recurrences of the keyword in the sample of documents. The largest nodes highlight the most important indicators and their distinct importance in building materials research studies. The high-frequency core keywords used by most researchers and identified in the first analytical iteration include sustainability, LCA, embodied energy, concrete and C&D waste. The links between the nodes in Fig. 2 denote the interconnections among keywords, and the thickness of each link denotes the interconnection strength between two keywords. Embodied energy and LCA; Sustainability and Concrete; Sustainability and Composites, Sustainability and Embodied energy; Sustainability and Durability; and Sustainability and Thermal effects are the pairs of keywords with the strongest interconnections. This finding suggests that significant research is being undertaken to determine the sustainability of concrete as a building material and the role of embodied energy in Life-cycle Cost Assessment.

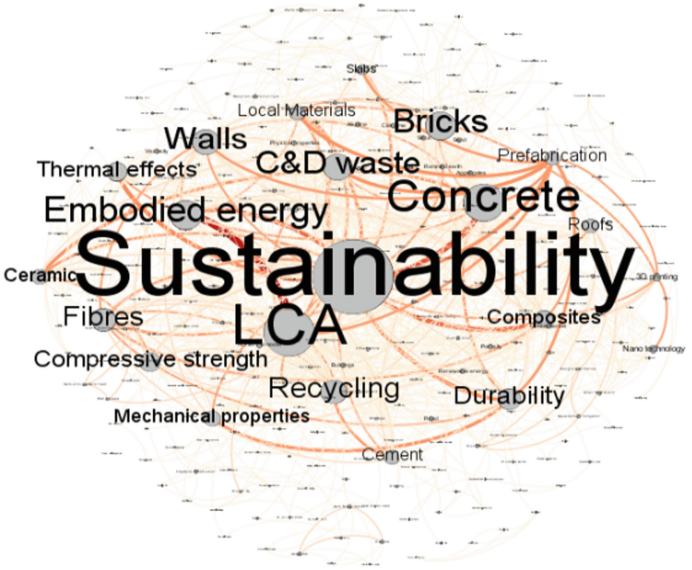

Fig. 2 Keyword network

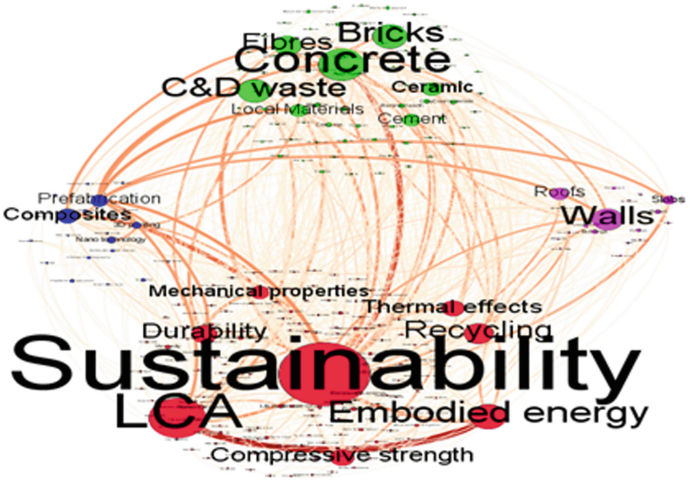

Fig. 3 Clustering of four major groups

3.4 Keyword Clustering Analysis

Sustainability of building material is associated with characteristics of raw materials, the manufacturing technology used, the building component for which the material is

produced and process of evaluating the material [1]. Figure 3 illustrates the concentration of clustering of keywords into four groups: Material—31% (green nodes), Technology—6.5% (blue nodes), Process—56% (red nodes) and Element—6.5% (pink nodes).

Furthermore, the network diagram clarifies the interconnections and relationships of each keyword within-group and with other groups. For instance, the strongest interconnection is between the keywords "LCA" and "Embodied energy", while the most significant relationship is found to be between the Material and Process groups. Connected components and average clustering coefficient were applied to four groups of keywords to evaluate and validate the clustering. The connected components of all four groups are 1, which confirms that all the keywords in each group are interconnected. Moreover, the average clustering coefficients for all four groups are greater than 0.5, which substantiates that the finding that the nodes in each group are clustered tightly with strong interconnections [9].

Material cluster. In this cluster, concrete emerges as the main building material indicator being researched, and has strong links to other materials and additives, such as ceramic, bricks, C&D waste, fibre, cement and local materials. This suggests that the potential exists for developing sustainable building materials by combining some of these materials and additives. For instance, utilising local materials or recycling bricks, adding fibre or ceramics or C&D waste to the mixture of concrete can reduce the cost and negative environmental impact of concrete [10].

Technology cluster. The Technology cluster congregates the technologies employed in manufacturing the building materials, such as composites, prefabrication, nanotechnology and 3D printing. Among these keywords, composites and prefabrication are dominant, which outlines the importance of these two technological indicators. To optimise the sustainability and functionality of building materials, it is necessary to employ the combination of several new technologies in the procedure of manufacturing building materials [2]. To this end, the complex relationships among the new technologies, such as composites, prefabrication, 3D printing and nanotechnology suggests these technologies are generating much interest among researchers in the field of sustainable materials.

Process cluster. The high-frequency indicators in this cluster are LCA, embodied energy, durability, recycling and thermal effects most likely because of the economic and environmental issues associated with building materials, such as high cost of materials, high impact on the environment, and excessive resource (water, energy) consumption [8]. The processing cluster appears to attract the majority of interest from researchers and is connected with keywords within all three of the other clusters, suggesting a close association between technical processes and the sustainability of building materials.

Element cluster. The Element cluster highlights that research on sustainable materials focusses mainly on components of buildings/construction, such as walls, roofs and slabs. The keywords in this group have relatively fewer linkages with the keywords in other clusters, which suggests that the research on sustainable building

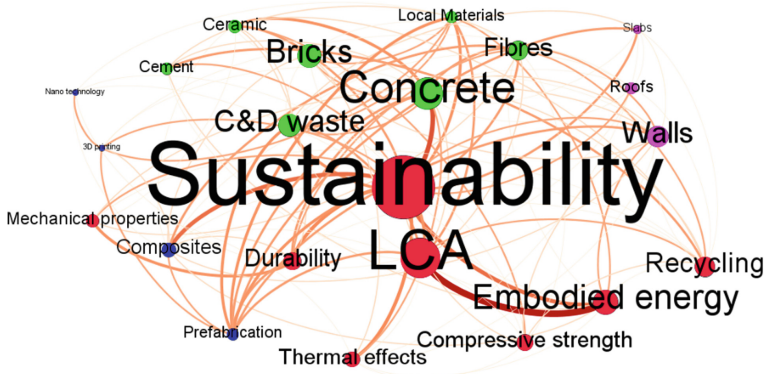

Fig. 4 Interconnection network between the key indicators

materials has less association at the scale of building elements (macro level) as opposed to building components (micro level).

Interconnection analysis. The range of edge degrees was adjusted at 50% recurring to illustrate the interconnections of key indicators of sustainable building materials and the results are presented in Fig. 4.

Figure 4 shows the significant interest among several scholars in the life cycle assessment and embodied energy of building materials. This is due to the high embodied energy of common building materials because of the immoderate use of virgin resources and the inefficient (and wasteful) consumption of energy and water during the manufacturing process of conventional building materials [8]. Sustainability, as the core indicator with the highest number of occurrences and largest number of interconnections, linked (in order of importance) to Concrete, Embodied energy, Composites, Thermal effects, Durability, C&D waste, LCA, Local materials, Fibre, Ceramic, Slabs, Cement, Walls, Roofs, 3D printing, Prefabrication and Mechanical properties. Indirect interconnections are found between Sustainability and Recycling, Nanotechnology, Compressive strength and Bricks.

The sustainable building materials framework showcased in Fig. 5 elucidates the cycle of developing sustainable building materials based on selecting suitable materials and additives, harnessing applicable technologies, targeting the most relevant building elements, and applying the appropriate processes to evaluate the sustainability of the building materials.

4 Conclusion

This study provides a holistic assessment of the key indicators found in the research field of sustainable building materials, clustered into four major groups, namely, material, technology, process and element. The research employs a verifiable and

Fig. 5 Sustainable building materials framework

systematic review of relevant publications, summarizes the status of research in the field of sustainable building materials, develops a sustainable building materials conceptual framework and offers future research topic prospects. The major findings of this study are that: research into sustainable building materials is a relatively young field of research yielding a steady increase in publications. The results reveal that developed countries, such as Italy, Spain and the United States, are the main contributors to sustainable building material research, with developing countries, such as India and Brazil, contributing significantly to this field of research due to construction being one of the key economic activities in these countries. Other developing countries could strengthen their research efforts concerning sustainable building materials as a possible solution to solving housing shortages. This study reveals the key indicators in sustainable building materials, and the interconnections of co-indicators, and benefits studies that straddle the theoretical sciences and real-time construction projects. Furthermore, the analysis of keyword networks revealed that in developing and evaluating sustainable building materials, LCA, embodied energy and recycling are the predominant processes being investigated; concrete, bricks, C&D waste and fibre are the foremost materials under consideration; walls and roofs are the main building elements chosen to incorporate sustainable building materials; and composite, 3D printing, nanotechnology and prefabrication are the leading technologies being researched. Also, the results of the interconnectedness of indicators revealed strong relations between sustainability [of building materials] and embodied energy, LCA, concrete, composite and durability. The proposed sustainable building materials conceptual framework highlights the clustering of topics which should be examined to facilitate the development of sustainable building materials. Although the study of sustainable building materials has been increasing over the past years, this study provides offers insight into the gaps in literature and research opportunities. Future research may consider using the sustainable building materials conceptual framework to develop sustainable building materials and evaluate

the impact of these materials on the social, environmental, and economic aspects of construction and housing projects. It would also be pertinent to identify the challenges and barriers to developing and adopting sustainable building materials.

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