Conversion of waste into sustainable construction materials: a review of recent developments and prospects

Chen, L., Yang, M., Chen, Z., Xie, Z., Huang, L., Osman, A. I., Farghali, M., Sandanayake, M., Liu, E., Ahn, Y. H., Al-Muhtaseb, A. H., Rooney, D. W., & Yap, P.-S. (2024). Conversion of waste into sustainable construction materials: a review of recent developments and prospects. *Materials Today Sustainability*, *27*, Article 100930. https://doi.org/10.1016/j.mtsust.2024.100930

Published in:
Materials Today Sustainability

Document Version:
Publisher's PDF, also known as Version of record

Queen's University Belfast - Research Portal:
Link to publication record in Queen's University Belfast Research Portal

Publisher rights
Copyright 2024 The Authors.

This is an open access article published under a Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution and reproduction in any medium, provided the author and source are cited.

General rights
Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Open Access
This research has been made openly available by Queen's academics and its Open Research team. We would love to hear how access to this research benefits you. – Share your feedback with us: http://go.qub.ac.uk/oa-feedback

Download date:12. May. 2025

Materials Today Sustainability 27 (2024) 100930

Contents lists available at ScienceDirect

Materials Today Sustainability

journal homepage: www.journals.elsevier.com/materials-today-sustainability

Conversion of waste into sustainable construction materials: A review of recent developments and prospects

Lin Chen [a,b,c], Mingyu Yang [d], Zhonghao Chen [e,f], Zhuolin Xie [a,b], Lepeng Huang [a,b,*], Ahmed I. Osman [g,**], Mohamed Farghali [h,i], Malindu Sandanayake [j,***], Engui Liu [e], Yong Han Ahn [k], Ala'a H. Al-Muhtaseb [l,m], David W. Rooney [g], Pow-Seng Yap [e,****]

[a] *School of Civil Engineering, Chongqing University, Chongqing, 400045, China*
[b] *Key Laboratory of New Technology for Construction of Cities in Mountain Area, Ministry of Education, Chongqing University, Chongqing, 400045, China*
[c] *Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, UK*
[d] *School of Materials Science Engineering, Nanjing University of Science and Technology, Nanjing, 210094, China*
[e] *Department of Civil Engineering, Xi'an Jiaotong-Liverpool University, Suzhou, 215123, China*
[f] *School of Engineering, Westlake University, Hangzhou, Zhejiang 310030, China*
[g] *School of Chemistry and Chemical Engineering, David Keir Building, Queen's University Belfast, Stranmillis Road, Northern Ireland, Belfast, BT9 5AG, UK*
[h] *Department of Agricultural Engineering and Socio-Economics, Kobe University, Kobe, 657-8501, Japan*
[i] *Department of Animal and Poultry Hygiene & Environmental Sanitation, Faculty of Veterinary Medicine, Assiut University, Assiut, 71526, Egypt*
[j] *College of Sports, Health and Engineering, Victoria University, Melbourne, VIC, 3011, Australia*
[k] *Department of Architectural Engineering, Hanyang University ERICA, Ansan, 15588, South Korea*
[l] *Department of Petroleum and Chemical Engineering, College of Engineering, Sultan Qaboos University, Muscat, 123, Oman*
[m] *Sustainable Energy Research Centre, Sultan Qaboos University, Muscat, Oman*

ARTICLE INFO

Keywords:
Sustainable construction materials
Recycled wastes
Material characteristics
Engineering performances
Sustainability

ABSTRACT

The production and use of traditional building materials contribute to environmental pollution and natural resource depletion. Besides, disposal of agricultural, industrial, and construction waste and other solid wastes is a significant contemporary for both developing and developed countries. Consequently, this study comprehensively examines sustainable construction materials (SCMs) sourced from waste materials. It analyzes 190 peer-reviewed papers, evaluating their properties, engineering suitability, and their impacts on the environment, economy, and society. Findings reveal that most SCMs have good engineering performance, yet improvements are needed in demonstrating their environmental (33.3%), economic (40%), and social sustainability (73.3%). Also, most SCMs are in experimental stages, requiring further research on human toxicity, long-term savings, maintenance costs, and other vital indicators. This review highlights some of the current challenges facing SCMs to promote their further studies, reduce non-renewable energy consumption and solid waste recycling, and facilitate their application in green buildings.

1. Introduction

Demand for infrastructure construction in both developed and developing countries has increased significantly due to rapid growth in population size and economic development [1–3]. Globally, both the construction and operation phases of buildings contribute significantly to energy use and CO_2 emissions, constituting 36% and 39%, respectively [2,4]. Actions taken within the construction industry can swiftly impact global climate change, energy consumption, and economic and social realms. Construction and infrastructure are increasing all over the world, and consequently, the pressure on the environment is also increasing [5,6]. This surge in building construction has led to a

---

* Corresponding author.
** Corresponding author.
*** Corresponding author.
**** Corresponding author.

E-mail addresses: huang_lepeng@cqu.edu.cn (L. Huang), aosmanahmed01@qub.ac.uk (A.I. Osman), malindu.sandanayake@vu.edu.au (M. Sandanayake), PowSeng.Yap@xjtlu.edu.cn (P.-S. Yap).

https://doi.org/10.1016/j.mtsust.2024.100930
Received 9 May 2024; Received in revised form 22 July 2024; Accepted 24 July 2024

substantial depletion of natural resources [7–9], exacerbating concerns about sustainable development. The overuse and inefficient utilization of non-renewable resources pose significant challenges [10–13]. As a result, the construction industry is grappling with two pressing challenges: the depletion of natural resources and the limited uptake of sustainable construction materials (SCMs). With increasing demands for sustainability and the circular economy in construction, the widespread adoption of sustainable materials emerges as a pivotal factor in determining the industry's long-term viability [14].

SCMs have been identified as one of the main research topics in the area of sustainability in the construction industry. Nowadays, several studies on sustainable materials have been conducted and used to provide an overall overview of relevant academic work to inspire the future development of SCMs [15]. This body of research holds significance for various stakeholders, including engineers engaged in actual construction, policymakers, and academics [14,16]. Because SCMs can reduce the demand for natural non-renewable resources and reduce greenhouse gas emissions, thereby mitigating global warming [8,15]. The technical and environmental effects of SCMs adoption have been extensively studied in the existing literature, such as the impact of SCMs use on the quality of cement composite products and the impact of SCMs adoption on carbon emissions. Cost factors of SCMs adoption, such as labor and equipment inputs, have also been considered in the use of SCMs [17]. Thus, SCMs represent a cornerstone of sustainable development in construction, with far-reaching social, economic, and environmental implications [18].

The current array of sustainable materials utilized in construction, coupled with the absence of a robust evaluation framework for SCMs, has led to the inadvertent use of materials that do not meet SCMs criteria. Thus, there is a pressing need for a systematic classification and evaluation system to assess SCMs performance. This review systematically examines the various types of SCMs used within the construction industry, analyzing their material characteristics, engineering performance, and environmental impact. Additionally, it evaluates the specific environmental implications associated with different SCMs. Diverging from previous reviews, this paper offers a comprehensive analysis of the socio-economic ramifications of various SCMs, illustrating their economic benefits for the construction sector. Finally, the review delves into the challenges and future pathways for SCMs development, aiming to propel the construction industry towards greater sustainability.

2. Methodology

The review methodology to capture the SCMs-related studies was based on the text mining method, which is a popular method used in similar literature review studies [4]. Upon initial screening, it was observed that certain existing review-based studies were susceptible to subjectivity due to limited literature samples or pre-selection of journal sources within a specific research scope. To minimize subjectivity, the current studies used keywords to shortlist the influential articles with a focus on SCMs. Fig. 1 illustrates the methods flow of this literature review. Given the accessibility and widespread use of the Scopus and Web of Science databases, coupled with their clear and concise user interface, they were chosen as the primary sources for literature research to enhance efficiency. The text mining approach, supplemented by specific case studies, aligns well with the sustainability direction in the construction materials industry, offering predictive insights into development trends. The literature search targeted keywords related to SCMs, including types of SCMs, characteristics of SCMs, engineering performance of SCMs, environmental impacts of SCMs, and economic analysis of SCMs. Initially, the search spanned the last five years and yielded more than 1000 papers on SCMs. Relevant articles focusing on engineering performance, environmental impact, or economic implications were imported into the Endnote literature management database for further refinement. Subsequently, 190 articles underwent additional processing. These collected articles were then categorized into groups based on engineering performance, environmental impact, and economic implications. Notably, the challenges and future directions of SCMs were further explored and synthesized through a critical review of the 190 selected papers.

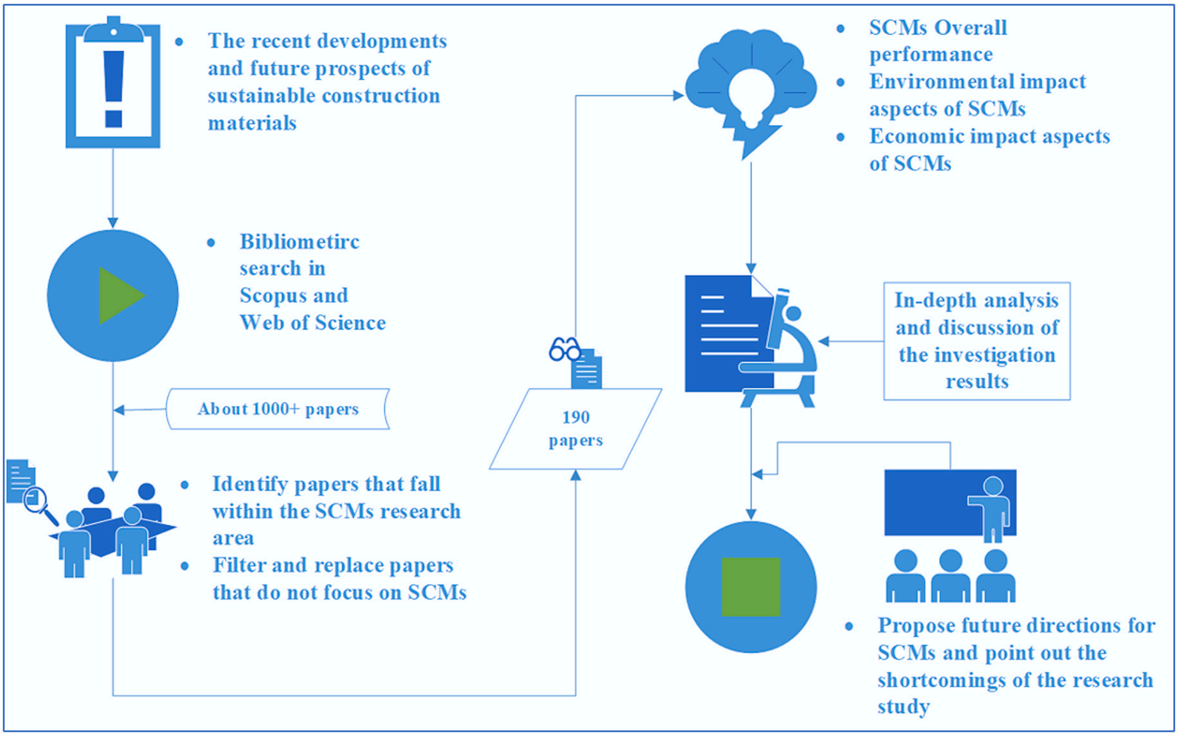

Fig. 1. The method of literature review of sustainable construction materials.

3. Classifications of sustainable construction materials

SCMs mainly include different types of waste materials as well as natural renewable materials. The classification of SCMs into waste materials and natural renewable materials is based primarily on the source of the raw material. Among them, waste materials mainly include industrial waste, agricultural waste, and construction and demolition (C&D) waste [7,17,19–21]. Natural renewable materials mainly focus on plants and plant derivatives, animal wool, and compacting earth. A specific systematic classification of SCMs is shown in Fig. 2.

3.1. Waste-based sustainable construction materials

Industrial waste poses a significant threat to soil and groundwater, leading to severe environmental hazards. To address these challenges, researchers globally are exploring innovative methods to recycle industrial waste and repurpose it as valuable raw materials in the construction sector [22]. For instance, fly ash from coal-fired power plants, silica fume from ferrosilicon alloy production, and blast furnace slag from steel manufacturing have been demonstrated to enhance the physical and mechanical properties of commercial concrete [23,24]. Additionally, replacing part of the fine aggregate with lathe iron waste dust (LIWD) increased the compressive strength, splitting tensile strength, and flexural strength of concrete by 38%, 13%, and 19%, respectively [25]. Another study showed that substituting 5% of cement with silica stone waste (SSW) powder improved the compressive and tensile strength of concrete by 18.8% and 10.46%, respectively [26]. Meanwhile, low-value solid waste materials, such as asphalt rock, can be effectively used as construction materials by enhancing their slagging characteristics with mineral additives like $CaCO_3$, MgO, and Kaolin. This approach significantly reduces the slagging ratio and pressure difference, demonstrating the potential of such waste materials in sustainable construction [27]. These materials not only improve the durability and strength of concrete but also contribute to sustainability by reducing the need for virgin raw materials.

Rice husk is widely used as a fuel in energy generation plants and rice milling processes across various countries. This combustion generates rice husk ash, a pozzolanic material rich in silica, comprising over 75% by weight. After combustion, 20% of the rice husk remains as ash, which is often discarded into water bodies, causing pollution. Rice husk ash produced below 500 °C has limited pozzolanic properties due to incomplete combustion and the presence of unburnt carbon [28]. However, ash produced at temperatures between 550 and 700 °C shows enhanced pozzolanic characteristics due to the formation of amorphous silica [29,30].

Research has explored utilizing rice husk ash as a partial substitute for cement and fine aggregates in cementitious composites [28,31]. Siddika et al. [32] conducted slump tests on fresh concrete with water-to-binder ratios of 0.40, 0.50, and 0.60, incorporating 10% and 15% rice husk ash as a cement replacement. They reported that at a water/binder ratio of 0.40, slump reductions were 22.5% and 37.5% for 10% and 15% rice husk ash, respectively. For a water/binder ratio of 0.50, the reductions were 16.1% and 35.5%, and for 0.60, the reductions were 10.5% and 24.2%. The study recommended using water-reducing admixtures to achieve workability comparable to control mixes. In terms of compressive strength, Siddika et al. [32] noted a decrease in flexural strength with the addition of 10% and 15% rice husk ash at all tested water/binder ratios. The reductions were 6.9% and 24% at a water/binder ratio of 0.40, 8.6% and 24.6% at 0.50, and 16.6% and 27.7% at 0.60. Similarly, Noaman et al. [33] studied composites with rice husk ash replacing 0%, 10%, 15%, 20%, and 25% of cement at water/binder ratios of 0.45, 0.50, and 0.55. They observed a slight improvement in compressive strength at a 10% replacement ratio, but higher ratios led to reduced strength. Flexural strength also decreased by 10.8%, 15.4%, 21.5%, and 27.7%, with rice husk ash replacement ratios of 10%, 15%, 20%, and 25%, respectively. The study recommended using lower proportions of rice husk ash to improve compressive strength.

Zareei et al. [34] observed improvements in compressive strength when rice husk ash was used to replace cement at varying levels: 2.1% for 5%, 4.2% for 10%, 11.0% for 15%, 11.9% for 20%, and 6.9% for

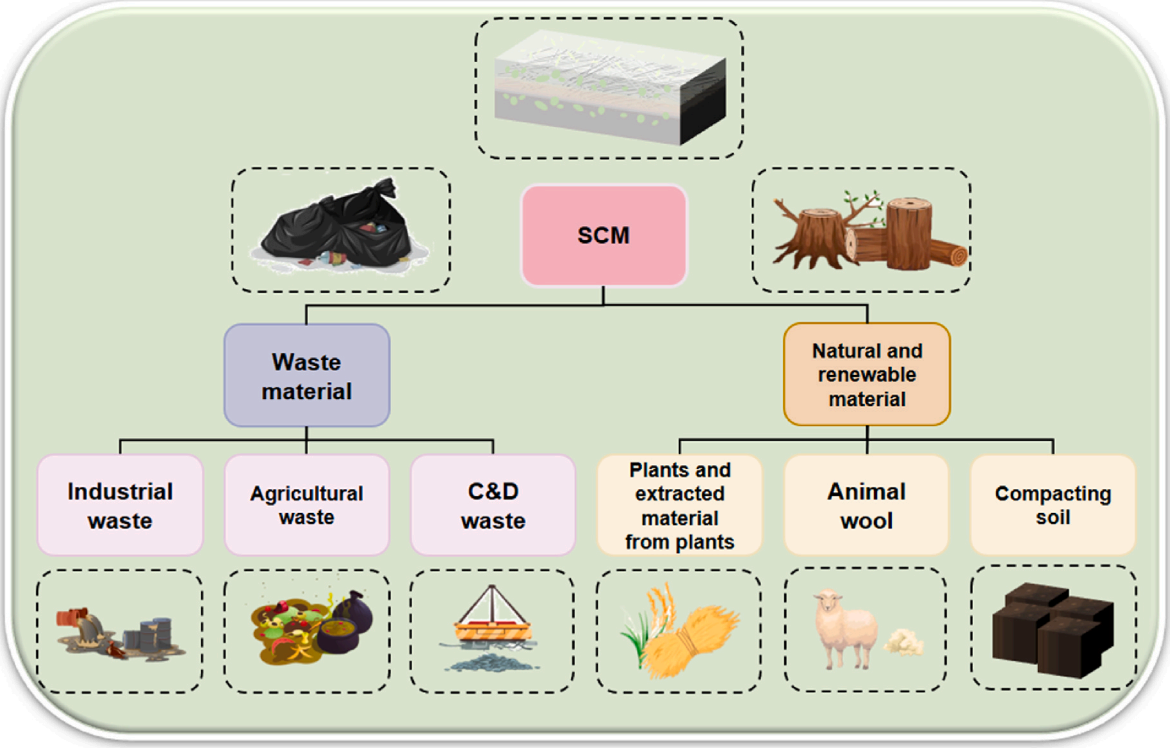

Fig. 2. The classification of SCMs.

25%. This enhancement is attributed to the pozzolanic reaction, high specific surface area, and reactive silica content of rice husk ash. Bie et al. [35] studied the effect of different burning conditions on rice husk ash's impact on compressive strength. They found that rice husk ash produced at 600 °C improved compressive strength, whereas ash produced at 700 °C decreased it compared to the reference sample without rice husk ash. It was concluded that burning at approximately 600 °C is optimal, yielding rice husk ash with a high specific surface area and amorphous SiO_2, while higher temperatures may leave more residual carbon. Rice husk ash also influences flexural strength in cementitious composites. Ash produced at 600 °C for 1 h increased flexural strength by 8.4%, 12.5%, and 6.5% for 5%, 10%, and 20% replacement ratios, respectively. When produced at 600 °C for 2 h, the flexural strength increased by 6.6%, 22.0%, and 18.4% for the same replacement ratios. Ash produced at 700 °C for 1 h led to a 5.2% decrease in flexural strength at a 5% replacement ratio, but at 10% and 20%, the flexural strength increased by 35.5% and 47.7%, respectively. These improvements are attributed to the small particle size and pozzolanic properties of rice husk ash. In conclusion, while higher replacement ratios of rice husk ash can detrimentally affect the mechanical properties of cementitious composites, lower replacement ratios are beneficial and improve these properties.

Incineration waste powder is particularly effective in reducing carbon emissions in cement-based composites. This approach leverages the pozzolanic properties of incineration waste powder to partially replace Portland cement, thus lowering the overall carbon footprint associated with cement production. Meanwhile, municipal solid waste incineration (MSWI) fly ash, a hazardous waste from incineration plants, can be effectively recycled into eco-friendly binders through flue gas-enhanced wet carbonation treatment. This process not only immobilizes potentially toxic elements and sequesters CO_2 but also produces binders with significantly higher compressive strength and reduced carbon emissions compared to traditional cement-based binders, highlighting its potential in sustainable construction and waste management [36].

Furthermore, industrial incineration waste rich in silicates and aluminates shows great potential in the preparation of alkali-activated cementitious materials. These materials undergo a chemical activation process using alkaline solutions, forming a stable three-dimensional aluminum silicate network. This network not only enhances the mechanical properties and durability of the composite but also provides a new pathway for the preparation of effective, sustainable building materials without the use of traditional cement [27]. Integrating these industrial by-products into cementitious composites addresses multiple environmental issues. It not only reduces the amount of waste sent to landfills but also lowers the risk of soil and water contamination and reduces greenhouse gas emissions associated with traditional cement production. The development and application of alkali-activated materials from incineration waste exemplify the circular economy concept, where waste materials are continuously repurposed, thus minimizing environmental impact and promoting sustainability in the construction industry. Meanwhile, research and development of SCMs from agricultural waste is also gaining significant popularity due to prevalent physical properties and the availability of waste materials in abundance. With the expansion of agricultural production, the generation of more agricultural waste could result in pressure on the management of agricultural waste and a potential risk of environmental problems. Partial or full reuse of agricultural waste and by-products in the development of construction materials is a viable interim solution to reduce agricultural waste and also minimize the extraction of virgin construction raw materials [7].

With urbanization and rapid urban renewal, a large amount of construction waste is generated due to the demolition of abandoned buildings. An investigation revealed that up to 80% of building and construction waste can be recycled for use in new construction projects. Materials like waste concrete, bricks, and glass can be repurposed as raw materials, offering a sustainable construction approach [37]. C&D waste is divided into two main categories: human-made resources and natural-made resources. Human-made resources include construction residues, construction sludge, construction waste, demolition waste, and decoration waste. Natural-made resources include disaster sites after earthquakes, floods, hurricanes, and tsunamis [38,39]. The construction waste originating from high-rise and infrastructure buildings may result in a considerable amount of construction materials being wasted at the construction site due to improper disposal [40–42]. Therefore, developing C&D waste recycling strategies to reduce the negative impacts of waste is an important way to achieve a sustainable construction industry.

Recently, nanoparticles derived from plant extracts and agro-wastes have attracted consideration as supplementary cementitious materials in cement-based construction materials owing to their environmental friendliness, cost-effectiveness, and low energy consumption [43]. Ainomugisha et al. [43] conducted a scientometric analysis and comprehensive review of 56 studies from 2005 to 2023, sourced from Web of Science, Scopus, PubMed databases, and gray literature. The review revealed that various agro-based nanoparticles, particularly nano-silica particles, show significant potential as supplementary cementitious materials. These nanoparticles notably enhance the microstructure of cementitious materials, making them denser, more microporous, and reducing cracks, while increasing the presence of C–S–H hydration products. This leads to improved quality of cement-based construction materials. The review concluded that agro-based nanoparticles enhance the performance properties of cementitious materials, including strength, microstructure, and durability, except for rheological properties. Optimal benefits are observed at low dosages (up to 5%), while higher proportions can be detrimental. Among the reviewed studies, the highest recorded improvements included a 92.5% increase in compressive strength at 28 days with 4% nano rice husk ash in high-strength control, a 211.1% rise in tensile strength using 10% nano palm oil fuel ash in mortar, and a 61% increase in flexural strength in ultra-high-performance composites.

Three types of agricultural waste— pineapple leaf, banana rachis, and sugarcane bagasse—have been utilized for isolating nanocelluloses. Among these, sugarcane bagasse has demonstrated superior performance in terms of crystalline index, thermal stability, substrate complexity, and crystal uniformity [44]. Nanocelluloses show promising potential as reinforcement materials in cement. The addition of 0.15%–0.2% cellulose nanofibers to cement paste enhances both its flexural and compressive strength [44,45]. In related research, incorporating 0.2% by weight of cellulose nanofibers was found to significantly increase the formation of calcium-silicate-hydrate gel within the cement matrix, resulting in a strength increase of 42–45% compared to traditional cement mortar [46]. Additionally, cellulose nanofibers improve mechanical properties by 15–25% and enhance flexural toughness by up to 74% [47].

Bacterial nanocellulose has also been used to improve fiber-cement composites' mechanical properties and maximum hydration temperature [48]. Nanocelluloses in cementitious materials improve hardening and bonding strength, reduce fiber pull-out, and decrease shrinkage. They aid in bridging microcracks, enhance fiber-matrix interaction, protect the fiber lumen from mineralization, accelerate hardening near the nanocelluloses surface, and reduce autogenous shrinkage [49]. The inherent characteristics of nanocelluloses, such as high surface area, high tensile strength, high aspect ratio, and elastic modulus, positively influence their interaction with cementitious materials [50]. The high crystallinity index of nanocelluloses increases the compressive strength of cementitious materials and helps eliminate pores formed during hydration. Their hydrophilic nature and highly reactive surface act as nucleation sites for early-stage cement hydration, leading to the formation of more homogeneous and compact microstructures [51]. Additionally, their superior water adsorption capacity allows them to function as water reservoirs, gradually releasing water in dry conditions to sustain hydration, which further refines pores and seals microcracks

[51]. Due to their high aspect ratio, nanocelluloses also help capture the spread of microcracks and enhance stress transfer at the cementitious material–nanocelluloses interface [51].

Nanocelluloses have garnered significant interest from the scientific community as materials for 3D printing. This technology allows for the production of items without the need for dies and casting forms, resulting in less waste material. It is highly energy-efficient and operates using air pressure rather than heat [52]. Various strategies for incorporating nanocellulose composites in 3D printing, highlight their environmental applications [53]. Another study noted that nanocelluloses hold great promise as renewable, biocompatible, and functional strengthening agents in 3D-printed components [54]. Additionally, 3D-printed nanocelluloses have been investigated for use in electrochemical devices and energy [55]. Films made from graphene- and nanocellulose-based pastes and inks, known for their high chemical stability, have been employed in creating liquid-phase electronic devices [56].

In conclusion, the incorporation of nanoparticles, especially nanocelluloses derived from agricultural wastes, significantly enhances construction materials. These nanoparticles improve cement's strength, durability, and microstructure, with notable benefits observed from sugarcane bagasse. Cellulose nanofibers boost flexural and compressive strength, aid in forming calcium-silicate-hydrate gel, and improve mechanical properties. Nanocelluloses also enhance bonding strength, reduce shrinkage, and act as nucleation sites for cement hydration, creating more compact microstructures and aiding in sustained hydration. Their application in 3D printing offers energy-efficient, waste-reducing solutions, making them valuable for sustainable construction and advanced electronic devices.

3.2. *Natural and renewable-based sustainable construction materials*

Natural plant materials or fibrous materials derived from plants are emerging as modern construction raw materials due to their sustainability and rapid growth. Bamboo, for example, matures for construction purposes within just 4–6 years, making it a highly sustainable option [57]. These plant-based materials are widely acknowledged for their environmentally friendly attributes and sustainability [17].

Additionally, animal hair, such as sheep's wool, is finding use as a sustainable construction material, particularly for thermal insulation in buildings or as a fiber material to enhance the mechanical properties of building components [58]. Natural wool materials offer an effective alternative to traditional acoustic materials, boasting reduced production costs and environmental benefits [20]. Utilizing sheep's wool and textile waste cotton as raw materials can improve the acoustic performance of construction materials, aligning with sustainability goals. Sheep's wool, in particular, offers notable advantages such as high strength, toughness, and elasticity, making it a sought-after material in the construction industry [59].

In terms of renewable resources, rammed earth is once again a viable and environmentally friendly construction option, as it is reusable [60]. Compared to other building materials, rammed earth consumes significantly less energy and produces lower greenhouse gas emissions. The raw materials for rammed earth can also be sourced locally with minimal preparation or handling, further reducing its environmental impact [21]. Ciancio and Beckett [61] found through their investigation of rammed earth construction projects that using locally sourced materials for rammed earth construction significantly reduces environmental impact compared to sourcing and transporting materials from distant locations. Compared to typical concrete houses, the energy consumed in transportation for rammed earth houses can be reduced by 85%. Additionally, the embodied energy of rammed earth structures is reduced by 62% compared to reinforced concrete framed structures and by 45% compared to fired clay brick masonry and reinforced concrete solid slab construction. All of these SCMs have the characteristics of sustainable materials mentioned in the previous section: low health impact, energy efficiency, and renewability. In this paper, different types of SCMs were selected for specific investigation and analysis, as shown in Table 1.

4. Characteristics of sustainable construction materials

Determining the sustainability of a material typically requires a multifaceted assessment. It's crucial to acknowledge that no material can have a net zero impact on the environment. However, it's feasible to evaluate a material based on its characteristics to ascertain its sustainability. An ideal SCMs should be environmentally friendly, cost-effective, and offer social benefits. This section delves into the characteristics of SCMs concerning health impacts, energy efficiency, and the use of renewable resources (Fig. 3).

4.1. *Low impact on health*

Conventional building materials are a major source of indoor air pollutants, and their impact is very broad, extending from indoors to outdoors, thus affecting human health and safety. Specific health impact indicators include indoor air quality (such as concentrations of volatile organic compounds, formaldehyde, and particulate matter PM2.5 and PM10), toxicity levels (such as the presence and concentration of heavy metals, asbestos, and lead), allergen levels (such as substances that can trigger asthma or other respiratory issues), microbial growth (such as the growth of mold and bacteria), and thermal comfort (such as the impact of materials on the indoor thermal environment). Thomas et al. [80] revealed the irreversible damage non-sustainable construction materials may cause to human health, emphasizing the urgent need for a shift towards more environmentally friendly materials. In response, Mardani et al. [81] proposed that sustainable construction materials incorporate non-toxic, natural, and organic components, significantly reducing overall impacts on human health. These materials demonstrate positive ecological and health effects throughout their life cycle, including stages of resource acquisition, production, use, processing, disposal, and recycling. Moreover, research by Bheel et al. [66] highlighted the particularly beneficial impact of plant-derived cellulose in sustainable building materials on human health. This finding not only emphasizes the health benefits of natural materials but also promotes the broader application of renewable resources. Simultaneously, Aneke and Shabangu [8] emphasized that recycling waste plastics and construction debris as building materials can mitigate health risks and push the construction industry towards more sustainable practices. Specifically, SCMs based on bamboo and wood have been proven to have a direct positive impact on human health and safety [58,82]. These studies underscore the potential of natural plant materials in improving indoor and outdoor air quality, enhancing the quality of living environments, and promoting healthy living.

Overall, the importance of integrating SCMs into modern building practices lies not only in the fight against growing environmental problems but also in their positive contribution to enhancing public health and safety. As the impact of environmental pollution on human health becomes more prominent, the negative effects of traditional building materials are increasingly recognized. In addition, a shift is urgently needed, and SCMs offer the possibility of such a shift. By introducing non-toxic, environmentally friendly and recyclable materials, not only can the construction industry reduce its reliance on and consumption of natural resources, but it can also minimize the negative impacts on the environment and human beings throughout a building's life cycle. In addition, the use of SCMs promotes the recycling of waste materials, which not only helps to reduce the pressure of construction waste on the environment but also provides a way to create a healthier living environment.

4.2. *Energy efficiency*

In an in-depth analysis of how SCMs contribute to energy efficiency

Table 1
Types of SCMs.

Classification of SCMs	Types of SCMs	Available of SCMs	Main application areas of SCMs	References
Waste materials	Cork	The waste from cork oak (*Quercus suber*) trees, which are grown in the Mediterranean	■ Insulation board ■ Acoustic panels ■ Green vertical systems ■ Electrical conductivity	[62–64]
	Straw bales	Agriculture waste	■ Insulation board ■ Partial replacement of cement	[65,66]
	Recycled plastic	The solid waste from urban, plant, and construction	■ Constituent materials in composite mortar and concrete ■ Green, efficient masonry bricks	[8,67]
	Precast concrete	Prefabricated component factory	■ Structural frame ■ Slab ■ Wall	[2,68]
	Ferrock	The waste from iron industries	■ Greener substitute for cement	[69]
	Timbercrete	Extracted sawdust from the agricultural waste	■ Architecture elements ■ Replacement of fine aggregate	[70,71]
	Terrazzo	Made with an epoxy resin, which	■ Flooring ■ As a cementing material to enhance the performance of concrete	[72,73]
Natural and renewable materials	Bamboo	Bamboo forest land	■ Trusses/roof ■ Walls ■ Flooring ■ Foundation ■ Scaffolding	[57]
	Sheep's wool	Obtained from sheep	■ Insulation board ■ Acoustic panels ■ Moisture absorption ■ Partial replacement of cement	[20,58,59]
	Rammed earth	Obtained from compacting soils	■ Structural elements	[60,74]
	Hempcrete	Extracted hemp fiber from plants	■ Insulation board ■ Acoustic panels	[8,75]
	Plant-based rigid polyurethane foam	Extracted from plants	■ Insulation board ■ Acoustic panels	[76,77]
	Mycelium	Obtained from natural biological process	■ Insulation board ■ Acoustic panels	[78,79]

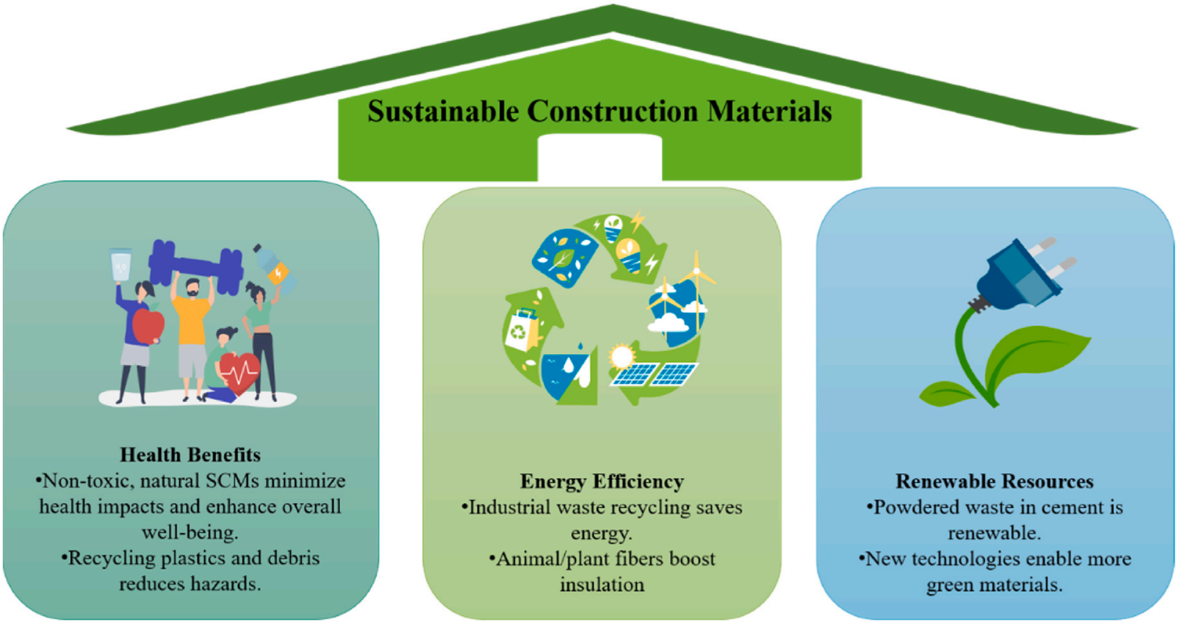

Fig. 3. The main factors that make SCMs enhance human health, energy efficiency, and renewable resources.

in buildings, we recognize that their benefits extend beyond only reducing energy consumption during construction. More importantly, SCMs optimize the overall energy management of a building through the innovative use and efficient recycling of waste resources, resulting in significant improvements in energy efficiency. This approach not only responds to the principles of the circular economy but also provides a practical path for the sustainable development of the construction industry. Firstly, through the reutilization of industrial, construction, and agricultural waste, SCMs diminish the dependency on virgin resources and simultaneously reduce the energy demand in the material production process. Studies have indicated that the employment of industrial waste as a supplementary cementitious material can achieve up to a 30%–70% reduction in energy consumption during production and approximately a 25%–40% decrease in CO_2 emission [10,15,83]. This data not only highlights the contribution of SCMs towards energy conservation and emission reduction but also underscores their potential to enhance the efficiency of building material production.

Moreover, the integration of animal and plant fibers into construction materials not only augments their thermal insulation capabilities but also enhances their structural stability. The use of animal fibers, such as sheep's wool, as natural thermal insulation materials has been shown to significantly improve the thermal efficiency of buildings. Research indicates that incorporating sheep's wool as insulation can substantially enhance the thermal performance of buildings [20,84]. The application of these natural insulating materials not only diminishes the reliance on fossil fuels but also contributes to a healthier and more sustainable living environment within buildings. Meanwhile, Xia et al. [85] conducted a study that recycled iron-rich industrial waste into radiation-shielding functional composites, significantly enhancing compressive strength and gamma-ray shielding capability while minimizing health impacts due to reduced toxic emissions. This sustainable approach lowers carbon emissions and energy consumption by over 60%, offering a low-cost, eco-friendly solution for industrial waste management and promoting zero-waste cities and a circular economy.

Therefore, the integrated application of SCMs plays a crucial role in promoting the construction industry towards a more energy-efficient, environmentally friendly and efficient development. By effectively utilizing renewable resources, enhancing the performance of building materials, and implementing energy-efficient building design strategies, SCMs provide effective solutions to current environmental issues and energy crises. These practices not only help to mitigate over-reliance on and consumption of natural resources and reduce energy demand during the building process and use phase but also directly combat the negative impacts of climate change by reducing greenhouse gas emissions. At the same time, the application of SCMs promotes technological innovation in the construction industry, laying a solid foundation for the long-term sustainable development of the construction industry by improving the recycling rate and life cycle efficiency of materials.

4.3. Renewable resources

The search for sustainable and renewable resources is increasingly becoming a focus of research within the current field of construction materials. In particular, resources such as agricultural residual ash, industrial and construction wastes as supplementary cement material have received much attention due to the remarkable reactivity, cost-effectiveness, and ease of accessibility they exhibit in concrete mixtures [80,86]. These properties not only mitigate the reliance on conventional cement but also promote the efficient utilization of waste, thereby reducing the overall environmental footprint of the construction industry. Further, Maraveas [1] stated that the use of renewable resources, such as agricultural residual ash in construction materials, effectively slows down the rate of depletion of non-renewable resources, which not only optimizes the recycling of resources but also contributes positively to ecosystem conservation. More importantly, these wastes also have renewable properties and have the potential to be a more renewable resource as long as these powdery wastes are subjected to appropriate treatment processes (crushing, grinding, activation, and others) [87–89].

Furthermore, the application of renewable technologies extends to the development of new sustainable building materials, such as mycelium-based materials [90–92]. Such materials not only exemplify the potential of renewable materials technologies for application in building practice but also open up a whole new category of materials science that combines biological principles with engineering design and pushes the boundaries of building materials innovation [93,94].

Thus, the application of renewable and sustainable resources to the research and development of building materials not only provides the construction industry with an effective way to minimize environmental impacts and conserve natural resources but also promotes technological innovation and collaboration within interdisciplinary fields. This progress indicates that through in-depth research and application of renewable technologies and resources, the development of sustainable building materials is expected to provide a solid scientific foundation and technological support for the realization of more environmentally, economically, and socially sustainable building practices.

5. Engineering performances of sustainable construction materials

The importance of a stable supply of materials should be considered a crucial factor in the evaluation of new building materials. Ensuring a stable and reliable supply of materials is essential for various reasons. It supports the long-term sustainability of construction practices by preventing resource depletion and ensuring continuous availability. This stability is vital for maintaining the balance between supply and demand, thereby avoiding potential shortages that could disrupt construction projects. The stability of material supply also plays a critical role in maintaining economic stability within the construction industry. Supply fluctuations can lead to price volatility, increasing construction costs and extending project timelines. Economic predictability is crucial for effective project planning and execution. Transporting materials over long distances can significantly impact the environment. By sourcing materials locally or regionally, a stable supply chain can reduce the carbon footprint associated with transportation, thus promoting more sustainable construction practices. Furthermore, consistent quality and performance of building materials are imperative for meeting construction standards and safety requirements. A reliable supply ensures that these standards are upheld throughout the construction process by providing consistent access to high-quality materials. Therefore, the stable supply of materials is a fundamental prerequisite for discussing their engineering performance, directly influencing the practical application and sustainability of building materials.

Concrete is the most widely used building material in construction projects; therefore, incorporating SCMs into concrete mixing and proportioning design is particularly crucial for achieving sustainable development within the construction industry. It is essential to reduce the environmental pollution and health hazards associated with conventional concrete materials while maintaining the practical performance of concrete. This includes ensuring that the strength design values and workability of the concrete meet industry requirements. When replacing traditional components such as cement, sand, and aggregates with various SCMs, it is vital to carefully consider their impact on the workability and strength performance of the concrete. This holistic approach not only addresses environmental and health concerns but also ensures that the resulting concrete remains functional and reliable for construction purposes [73,95,96]. Meanwhile, in the actual use of the building, the thermal insulation performance of the building and the sound insulation performance are also important considerations in engineering performance [63,65,75]. A building with good thermal insulation can reduce energy consumption during actual use and thus further improve sustainability [78]. At the same time, the performance of the building in terms of acoustic insulation will largely determine the quality of life of the people living in the building [20]. Hence, in the engineering performance section, four main benchmarks are proposed to assess the engineering performance of the popular SCMs, as shown in Table 2.

6. Sustainability performance of sustainable construction materials

Most traditional construction materials have been developed from the practical value of the material itself, for example, its mechanical properties such as high strength, high durability, and high suitability. However, material sustainability has been neglected, thus consuming large amounts of non-renewable energy and releasing toxic gases [106,

Table 2
Engineering performances of selected SCMs.

Type of SCMs	Workability	Strength	Thermal insulation	Acoustic insulation	References
Bamboo	● Bamboo fibers can reduce the workability of concrete	● The tensile strength is almost equal to steel. The ultimate tensile strength of bamboo varies between 140 MPa and 280 MPa. ● Bamboo fibers can effectively enhance the mechanical properties of concrete.	No contribution	No contribution	[57, 97–100]
Cork	● Workability and plastic viscosity are significantly reduced	● Under different curing methods, the cork-cement composite material was cured in water for 14 days and then air-cured to obtain the highest compressive strength due to water contained in the cork composite to continue hydration.	● Thermal conductivity is very low, and the thermal conductivity of samples in water and air are 0.46 and 0.38 W/(m-k), respectively.	● Excellent sound absorption performance	[62,63]
Straw bales	● The content of straw fiber increases, and the workability of concrete decreases.	● Under the condition of curing for 28 days, when the amount of straw fiber added is 0.50%, the compressive, splitting, tensile, and flexural strengths are increased by 32.88 MPa, 3.80 MPa, and 5.30 MPa, respectively	● Straw bales can be a good way to enhance the thermal insulation of building materials.	● Good performance in terms of acoustic properties.	[65,66, 101]
Recycled plastic	● The number of recycled waste plastic particles increases, its workability decreases.	● The test results show that as the number of recycled waste plastic particles increases, its compressive strength decreases.	● The thermal conductivity of conventional concrete is 1.7 W/mK, whereas that of recycled plastic aggregate concrete ranges from 1.1 to 0.5 W/mK, indicating better thermal insulation.	● Recycled plastic has improved acoustic insulation	[42,67, 102,103]
Recycled wood	● High construction convenience and strong workability.	● Recycled wood is characterized by high strength per weight and ease of use	● Particleboard based on recycled wood achieves a higher porosity and provides better insulation properties (11.7% reduction in thermal conductivity)	● The use of recycled wood in the building has a good sound insulation effect.	[82,104]
Recycled steel	● Recycled steel can reduce the workability of concrete	● The addition of recycled steel fibers increases the fatigue strength of concrete by 50%–65%.	No contribution	No contribution	[96]
Plant-based rigid polyurethane foam	● Polyurethane foam has a certain ease of construction	● The porosity (>90%) also shows that the chemical treatment increases the interfacial adhesion between the foam filler and the polyurethane matrix. The compressive strength has increased by about 20%. Similarly, the impact strength and flexural strength have also increased by 48% and 6%, respectively.	● The polyurethane foam cell size is small, the closed cell rate is higher, and it has good heat insulation performance.	● Polyurethane foam is widely used in architectural acoustics, and it can effectively reduce noise pollution.	[77,105]
Sheep's wool	● Concrete with a wool fiber content of less than 5% has a lower capillary absorption rate and good workability.	● Compared with ordinary Portland cement concrete, its compressive and flexural strength is higher.	● Better thermal conductivity of concrete with sheep wool fiber	● The wool-based material has good sound absorption performance, and the sound absorption coefficient value is greater than 0.7 in the frequency range of 800–3150 Hz.	[20,59]
Rammed earth	● In-situ material sourcing, convenient and fast construction.	● The compressive and tensile strength of concrete can be increased by up to 20%.	No contribution	No contribution	[21,74]
Hempcrete	● Needs to add more water to ensure workability	● Because of its poor compressive strength, it cannot be used as a load-bearing material for load-bearing wall structures.	● Good thermal insulation performance and can be used as the filling material and thermal insulation material of the structural frame.	Good sound insulation performance	[8]
Mycelium	No contribution	● The study found that the chitin-glucan extract extracted from the mycelium has quite a strong mycelial binder (tensile strength can reach 25 MPa, and the tensile strength of the fruit body extract can reach 200 MPa	● The plant fiber bundled with mycelial growth has low thermal conductivity (0.04–0.08 W/m-K), which makes it an excellent thermal insulation material.	● Mycelium itself is an excellent sound absorber, showing strong inherent low-frequency absorption (<1500 Hz)	[78,91]
Ferrock	● Ferrock decreases the workability of concrete with increasing dosage.	● 8% cement replacement has the best mechanical strength	No contribution	No contribution	[69]

(*continued on next page*)

Table 2 (*continued*)

Type of SCMs	Workability	Strength	Thermal insulation	Acoustic insulation	References
Timbercrete	● Timber sawdust reduces the workability of concrete	(compression, split tensile, and bending tests) and sustainability. ● 5% timber sawdust can partially replace the fine aggregate to meet the strength requirements and can be used for structural purposes.	● Timbercrete board has good thermal insulation performance.	● Good sound insulation performance of timbercrete board	[70,71]

107]. As the world continues to advance towards sustainable development goals, sustainable building materials are surfacing in the construction industry, which can effectively reduce resource consumption, waste emissions, and environmental loads and promote waste recycling. In addition, sustainable building materials are also environmentally, economically, and socially sustainable and are an effective measure to achieve carbon neutrality in the construction industry [9,12].

Climate change, human toxicity, and solid waste are the leading indicators for assessing the environmental benefits of materials for sustainable construction [9,27]. The construction industry is also paying more attention to controlling these three categories of indicators to save energy, reduce climate change and human impact, and reduce solid waste generation as development objectives to promote sustainable construction continuously [108]. Climate change refers to the change in global temperature caused by the greenhouse effect resulting from the release of 'greenhouse gases' such as carbon dioxide from human activities [109,110]. Previously, the scientific consensus was that these increased emissions were having a clear impact on the climate. Increased global temperatures are expected to lead to climate disruption, desertification, sea-level rise, and spreading. Human toxicity aims to quantify the extent to which a particular substance causes damage to living organisms [111]. Toxicity is assessed based on acceptable concentrations in air and water, daily intake, and guidelines for acceptable human toxicity intake. Solid waste represents the environmental problems associated with the loss of resources implied by the final disposal of waste and any waste disposed of in landfills or incinerated without energy recovery [112,113]. The solid waste generated by construction materials, the application of materials, the disposal of demolished structures, and the solid waste generated by construction materials is enormous.

Hence, certain authors have undertaken studies to evaluate the environmental impact of various SCMs, aiming to assess their environmental performance and promote their reuse or recycling. However, despite these efforts, the widespread adoption of these materials for sustainable construction remains limited, often confined to experimental and laboratory stages in specific cases [114]. This section provides a summary of the environmental impacts associated with these SCMs, examining whether each SCMs aligns with the three categories of environmental benefit impact indicators outlined in Table 3.

The ten types of SCMs listed in Table 3 present a dual role, as they have both negative and positive contributions to achieving environmental benefits. Some SCMs possess the capacity to mitigate the consequences of the global climate, human well-being, and the management of solid waste. Distinct material categories yield diverse ramifications upon the environment, yet they collectively culminate in the pursuit of sustainability. While it remains true that a trifecta of pivotal benchmarks fails to encapsulate the entirety of each SCMs' essence, the scrutiny delineated within Table 3 presents a compendium of the majority of SCMs, chronicling their ecological merits. This exposition underscores the evolution of SCMs as a conduit toward the realization of urban centers characterized by enduring ecological equilibrium, concurrently assuaging the adversities posed by the escalating specter of global temperature elevation [131]. Therefore, future research is needed to optimize the study of SCMs by showing how each type of SCMs achieves sustainable development goals and rationalizes the selection and use of SCMs according to environmentally beneficial goals and material targets.

Additionally, it is important to consider not only the environmental sustainability of SCMs but also their cost-effective [132]. Economic factors relate to the cost and benefit aspects of SCMs, such as the initial investment in the material, the benefits, and the payback time. When new construction materials or technologies are introduced into the construction industry, the economic factor is usually one of the primary considerations of the owner [133]. The use of SCMs can improve the environment's performance, enhance the image of the construction industry, and create more jobs for society [133]. However, if the initial investment cost of SCMs is substantial and the payback period is prolonged, it can greatly influence the adoption of SCMs by owners and financial institutions. Hence, the consideration of SCMs extends beyond their environmental suitability to ensure cost-effectiveness as well [134]. Table 4 presents a summary of the economic benefits analysis of various SCMs, serving as a valuable reference for investors, owners, and users.

The economic and cost-effectiveness of SCMs across various project types in India, Egypt, the USA, Australia, and Pakistan are outlined in Table 4. The analysis shows that, except for terrazzo, timber, and steel fiber, most sustainable materials provide economic efficiency benefits. Financial assessments vary, some calculating costs for an entire building and others per building unit, encompassing materials derived from experimental studies and computer simulations throughout a building's life cycle. It can be concluded that bamboo-reinforced prefabricated walls are more cost-effective and stronger than traditional walls in India [57]. Constructing walls with straw bale directly reduces costs [157]. The application of recycled PET bottles in housing results in considerable savings per unit [158]. In Egypt, using rammed earth for walls significantly reduces costs compared to conventional methods [137]. However, in the USA, wood construction is slightly more expensive than concrete [139]. Life-cycle cost analysis indicates that terrazzo flooring is the most expensive among commercial options [159]. Ferrock, as an alternative to traditional cement, proves cost-effective in experiments [160]. In Australia, sourcing mycelium composites for raw materials is relatively inexpensive [140]. Conversely, in Pakistan, steel fiber-reinforced pavements do not offer economic benefits in enhancing the mechanical efficiency of concrete compared to glass and polypropylene fibers [141].

The costs associated with SCMs are influenced by building design, site selection, local labor costs, material additives, repairs, maintenance, and other factors, making it challenging to derive clear economic benefits from a single material [161]. The use of sustainable materials not only contributes to societal benefits [162], but also supports the advancement of green building theories and the application of life cycle theories in construction, significantly altering attitudes and practices [163]. Furthermore, sustainable materials play a crucial role in the interdisciplinary development of sciences, contributing to the exploration of natural laws and the construction of resource-efficient societies globally [164]. A resource-saving society optimizes resource use in production, distribution, and consumption to maximize economic and social benefits and achieve sustainable development [165]. The construction industry's shift towards innovative materials and SCMs aligns with global sustainable development goals [166]. However, the social sustainability of sustainable materials like bamboo [167], straw bales [168], recycled plastic [169], and recycled wood [170] needs more

Table 3
Environmental performance of SCMs.

Type of SCMs	Climate change	Human toxicity	Solid waste	Key findings	References
Bamboo	▲	▲	▲	Reduces the climate's carbon dioxide by about 35% and releases a large amount of oxygen as it grows. The surface of bamboo has a natural waxy layer that reduces paint use and reduces the danger of paint to human health. Bamboo recycling can be made into bamboo fiber composite concrete, reducing the disposal of solid waste.	[115]
Straw bales	▲	△	▲	Usually burned directly, releasing toxic gases that pollute the environment. It can be used in bricks and walls, reducing the release of carbon dioxide. The use of straw in construction reduces the need for solid waste disposal.	[116]
Rammed earth	▲	N/A	▲	Rammed earth materials have a relatively low environmental impact and energy content compared to industrially produced materials. Earthen materials are elementary to recycle and can be re-used in new buildings at a low environmental cost, which reduces the need for climate change and waste disposal.	[117–119]
Hempcrete	▲	△	N/A	The total amount of carbon dioxide absorbed by Hemp during its growth is greater than the total amount released when used, but the fertilizers and pesticides that need to be applied affect human toxicity and reduce climate change as a sustainable material.	[120,121]
Recycled plastic	▲	▲	▲	Waste plastics can reinforce concrete, improve waste disposal, and reduce the resource consumption and carbon emissions of recycled plastic fibers produced through the mechanical recycling of plastic waste.	[122]
Wood	▲	▲	▲	Trees sequester carbon dioxide and release oxygen through photosynthesis. Sawdust and waste wood can be bioenergy recycled to promote the energy balance of wood products and reduce solid waste.	[123]
Mycelium	▲	N/A	▲	It can be used in particleboard and insulation. Packaging mycelium foam is a natural and renewable resource that reduces carbon dioxide emissions and solid waste disposal, making it an ideal natural alternative to wood, lightweight concrete, cork, and plastic.	[79,124,125]
Ferrock	▲	N/A	▲	With specific treatment, it is an excellent condensing material, ideal for use in saline environments. When dry ferrock absorbs and binds large amounts of carbon dioxide, helping to trap greenhouse gases and reduce the impact of climate change.	[126–128]
Terrazzo	▲	N/A	▲	A product made of crushed stone, glass, quartzite, or other aggregates mixed into cement bonding material and then ground and polished on the surface, it can effectively reduce the disposal of solid waste, and its reuse can reduce the release of carbon dioxide.	[129]
Recycled steel	▲	N/A	▲	Can be used as a whole or partial replacement for commercial bulk steel fibers in cementitious repair applications,	[130]

(*continued on next page*)

Table 3 (*continued*)

Type of SCMs	Climate change	Human toxicity	Solid waste	Key findings	References
				effectively improving the high carbon footprint of the construction industry and reducing the impact on climate change and the disposal of steel waste.	

Note: ▲ indicates positive impact. △ indicates a negative impact. N/A indicates no mention.

Table 4
Economics performance of SCMs.

Project description	Application type	Country	Economics performance	References
Bamboo-enhanced prefabricated wall panels	Wall	India	Offers cost-effectiveness and maintains strong durability compared to partition brick walls	[135]
Straw bale for rural residences	Wall	India	Achieves notable direct cost savings for wall construction	[136]
Rammed earth in modern construction	Wall	Egypt	Costs a fraction of traditional construction methods, providing significant savings	[137]
PET bottles as alternative bricks assessment	Brick	India	Using PET bottle cells leads to considerable savings per house	[138]
Cost dynamics analysis of timber and concrete	Building	USA	Timber construction costs slightly more than modeled concrete buildings	[139]
Economic analysis of engineered mycelium composites	Composite	Australia	Competitively priced against synthetic foams and wood, mycelium composites provide a low raw material cost	[140]
Economic analysis of concrete and pavement	Pavement	Pakistan	Steel fiber is less economical compared to glass and polypropylene fiber	[141]
Life-cycle cost analysis of commercial flooring	Flooring	USA	Terrazzo, rubber, and ceramic tile are among the most expensive flooring alternatives	[142]
Life cycle assessment of Ferrock and Portland cement	Materials	USA	Ferrock reduces building time and costs, enhancing its desirability	[143]

focus to guide the global construction industry towards building a resource-efficient society. Future assessments should strengthen the evaluation of the social sustainability of mainstream sustainable building materials, providing crucial data for global sustainability efforts.

7. Environmental, social, and governance (ESG) impacts of sustainable construction materials

Environmental, social, and governance (ESG) are the three key pillars for evaluating an investment or project's sustainability and ethical implications. This section offers a concise overview of the SCMs covered in this review, focusing on those derived roughly from natural sources and industrial waste through ESG criteria (Table 5).

7.1. Natural materials

Natural materials such as bamboo, cork, straw bales, sheep's wool, rammed earth, and mycelium offer significant environmental benefits by reducing carbon emissions, conserving energy, and minimizing waste. These materials are considered renewable and biodegradable, which helps reduce landfill waste and pollution. For instance, bamboo grows rapidly and absorbs CO_2 at a similar or even higher rate than trees. Studies show that bamboo forests have a relatively high carbon density, ranging between 169 and 260 tons of carbon per hectare of land [171,172]. Similarly, cork harvesting supports carbon sequestration from the atmosphere and green building development in the built environment. Research has shown that the cork captures, on average, 5 tons of CO_2 per hectare annually. Additionally, a cork tree with an average diameter of 38 cm yields about 11 kg of cork over 10 years, meaning that cork production can reach approximately 6590 kg per hectare in 10 years [173]. These findings suggest a promising future for CO_2 storage in biomass and offer a new resource for green building materials.

In the context of construction, these materials often deliver outstanding benefits, including structural strength and safety [174] and insulation [175], among others, resulting in significant energy savings and enhanced durability of buildings [176]. Socially, natural materials support rural economies by creating jobs and improving livelihoods [177]. As indicated earlier, they enhance indoor air quality and overall building safety, with studies indicating positive health impacts from using natural materials in construction. Governance practices for natural materials focus on sustainability, transparency, and adherence to standards [178,179] to enhance supply security and resource efficiency. Industries using these materials should commit to environmentally and socially responsible practices. This can be achieved by adhering to specific regulations set by government authorities and industry standards [180].

7.2. Industrial and waste materials

Industrial and waste materials such as precast concrete, recycled plastic, plant-based rigid polyurethane foam, recycled wood, recycled steel, hempcrete, ferrock, timbercrete, and terrazzo play a crucial role in construction sustainability. This is primarily achieved by applying innovative and diverse material technologies and combining industrial solid wastes to develop value-added engineering materials for construction. For example, precast concrete [181] minimizes waste through precise manufacturing in a factory setting, unlike onsite casting. It frequently uses recycled materials, reducing the need for new resources. Factory curing processes are more efficient in energy and time, enhancing material quality and reducing carbon emissions. Precast concrete enhances safety at construction sites by manufacturing off-site and benefits communities by shortening construction periods and decreasing disturbances. Building and environmental regulations, such as ACI (American Concrete Institute) and LEED (Leadership in Energy and Environmental Design) standards, govern precast concrete manufacturing and construction to promote best practices. Using recycled steel can cut energy consumption by about 70% and carbon emissions by 60% compared to new steel production [182], significantly lowering the carbon footprint. These materials help divert waste from landfills and promote recycling industrial by-products, such as recycled

Table 5
listing the ESG impacts of each of the sustainable construction materials in review.

Material	Environmental	Social	Governance	References
Bamboo	● Renewable, fast-growing ● Absorbs CO_2 ● Improves soil	◆ Supports rural economies ◆ Safer, easier construction ◆ Improves indoor air quality	■ Regulated to ensure sustainability ■ Adheres to building codes and environmental regulations	[57]
Precast concrete	● Reduces waste through manufacturing ● Incorporates recycled materials ● Energy-efficient production	◆ Improved construction safety ◆ Enhances building safety ◆ Reduced construction time	■ Adheres to building codes and environmental regulations	[144]
Cork	● Renewable and biodegradable ● Carbon sequestration	◆ Improves indoor air quality and acoustic insulation ◆ Supports rural economies	■ Regulated to ensure sustainability ■ Adheres to building codes and environmental regulations	[145]
Straw bales	● By-product of agriculture, reducing waste ● Carbon sequestration	◆ Reduces building costs ◆ Reduced environmental footprint	■ Regulated to ensure sustainability ■ Adheres to building codes and environmental regulations	[146]
Recycled plastic	● Reduces plastic waste ● Conserves energy compared to new plastic	◆ Supports local economies ◆ Reduced environmental pollution	■ Regulations ensure product quality and safety ■ Compliance with standards	[147]
Recycled wood	● Reduces deforestation, waste, and emission ● Conserves energy	◆ Supports sustainable forestry and local economies ◆ Reduced waste and resource conservation	■ Adherence to building codes and environmental regulations	[148]
Recycled steel	● Cuts energy use and carbon emission ● Minimizes waste	◆ Provides jobs and economic benefits ◆ Reduced environmental impact	■ Follows recycling and production regulations ■ Compliance with industry standards	[149]
Plant-based rigidp olyurethane foam	● Renewable materials, ● Biodegradable, less toxic	◆ Safer handling and installation ◆ Improves indoor air quality ◆ Energy-efficient buildings	■ Adheres to environmental regulations and standards	[150]
Sheep's wool	● Renewable and biodegradable ● Excellent insulation ● Low environmental impact	◆ Supports rural communities	■ Compliance with environmental and industrial standards	[151]
Rammed earth	● Uses natural materials ● Low carbon footprint ● Locally sourced materials	◆ Supports local economies	■ Building codes ensure safety and sustainability	[152]
Hempcrete	● Made from renewable hemp fibers ● Sequesters carbon	◆ Supports rural economies ◆ Improved indoor air quality and comfort	■ Compliance with environmental and industrial standards	[153]
Mycelium	● Biodegradable ● Low environmental impact	◆ Supports innovative agricultural and engineering practices ◆ Reduced waste and sustainable materials	■ Compliance with environmental and industrial standards	[78]
Ferrock	● Made from waste ● Sustainable alternative to concrete	◆ Supports recycling industries ◆ Innovative materials with reduced environmental impact	■ Compliance with environmental and industrial standards	[154]
Timbercrete	● Incorporates waste, reducing waste ● Lower carbon footprint	◆ Supports sustainable forestry and local economies ◆ Reduced waste and sustainable construction materials	■ Adheres to building codes and environmental regulations	[155]
Terrazzo	● Incorporate recycled materials ● Durable and long-lasting ● Energy-efficient production	◆ Provides job opportunities in recycling and production ◆ Improves aesthetic appeal and safety	■ Adheres to building codes and environmental regulations	[156]

wood and timbercrete. Socially, they create jobs in recycling industries and contribute to community well-being by reducing environmental pollution [183]. Recycled products used in construction meet the same quality standards as new materials, ensuring they comply with all codes and standards, such as industrial by-products used in concrete. Using recycled and waste materials can also boost a project's market appeal because of its higher sustainability profile, as shown by the life cycle analysis.

8. Challenges and future outlooks

Currently, the construction sector consumes about 40% of the total energy produced by human activity in industry, agriculture, and transport [184]. As a result, many countries promote and implement sustainable development, continuously improving all three aspects: environmental, social, and economical. However, in analyzing and aggregating SCMs, we found that the 15 most common materials were progressively not analyzed in the three processes of engineering performance, environmental, economic, and social analysis, as too few or no researchers were currently working on this aspect. In addition, in the individual analysis of each material, we found that only some of the indicators for SCMs were analyzed through the researchers identifying the most significant indicators for the material. These indicators were carried out in terms of environmental, economic, and social aspects. On the environmental aspect, the three key indicators for sustainable materials are human toxicity, climate change, and solid waste. On the social aspect, adaptability, thermal comfort, local resources, and housing are the four key social indicators for SCMs. On the economic aspect, the five key economic indicators for SCMs are maintenance costs, operating costs, initial costs, long-term savings, and longevity [185].

Furthermore, the majority of extant sustainable materials continue to reside within the confines of laboratory experimentation, thereby omitting comprehensive evaluation encompassing the trifecta of environmental, societal, and economic dimensions. Consequently, a substantial proportion of SCMs remains entrenched in the nascent sphere of laboratory investigation. Certain materials necessitate more exhaustive scrutiny of human toxicity, enduring cost benefits, maintenance expenditures, habitation considerations, and other pivotal benchmarks, as illustrated in Fig. 4. It is worth noting that the methodology for analyzing the sustainability indicators of SCMs draws directly from the cited references, using an established integrated assessment methodology, and these indicators include environmental, economic, and social aspects [9,27,185]. In addition, in order to clearly demonstrate the current research status of the mainstream 15 SCMs, Table 6 systematically marked the performance of these materials in terms of engineering, environmental, economic, and social perspectives with a check mark (✓)

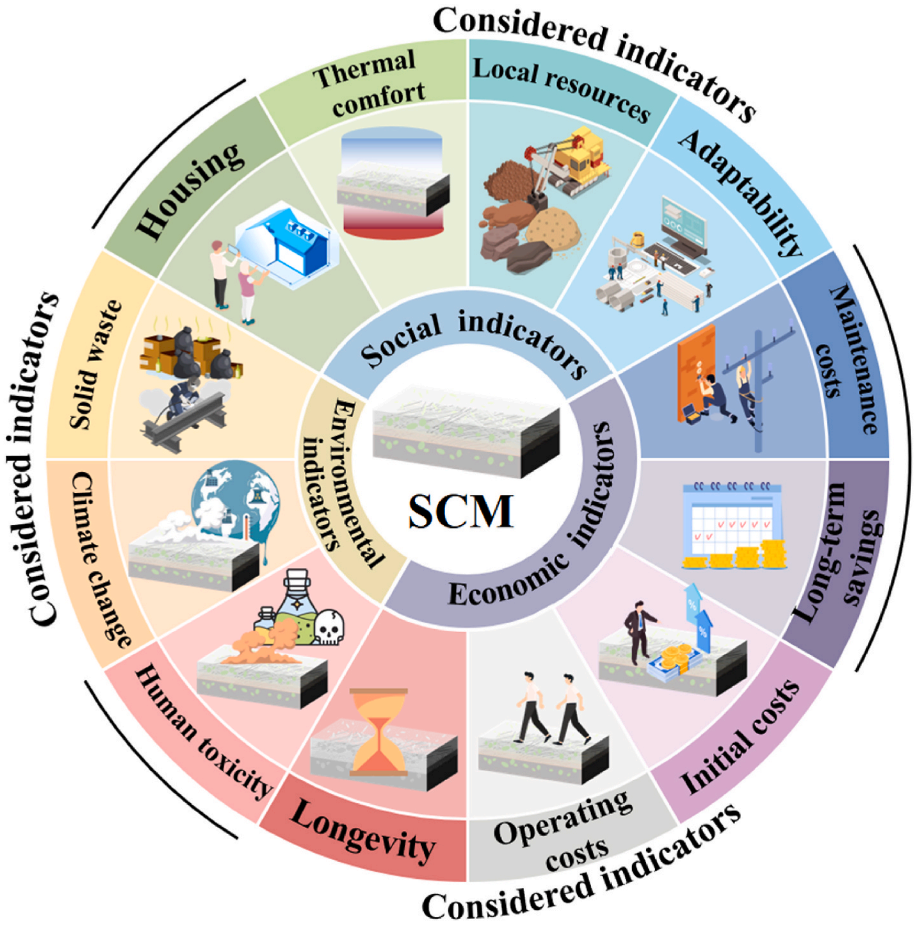

Fig. 4. Summary of sustainability for SCMs.

Table 6
Comprehensive performance of SCMs.

No.	Type of SCMs	Engineering performance	Environmental performance	Economics performance	Social performance
1	Bamboo	✓	✓	✓	✓
2	Precast concrete	✓	×	×	×
3	Cork	✓	×	×	×
4	Straw bales	✓	✓	✓	✓
5	Recycled plastic	✓	✓	✓	✓
6	Recycled wood	✓	✓	✓	✓
7	Recycled steel	✓	✓	✓	×
8	Plant-based rigid polyurethane foam	✓	×	×	×
9	Sheep’s wool	✓	×	×	×
10	Rammed earth	✓	✓	✓	×
11	Hempcrete	✓	✓	×	×
12	Mycelium	✓	✓	✓	×
13	Ferrock	✓	✓	✓	×
14	Timbercrete	✓	×	×	×
15	Terrazzo	✓	✓	✓	×

Note: √ indicates that it has been studied. × indicates that it has not been studied.

if there is a study related to these four aspects in the previously analyzed references and a cross (×) if there is not, and percentage calculations were made based on the statistical results, which identified the need to strengthen the research in the future on these specific aspects of the material.

Overall, Table 6 outlines the aggregate metrics of the SCMs’ efficacy based on the preceding analysis. The results illustrate that a significant portion of the studies validate the commendable engineering prowess of SCMs. However, one-third underscore the need to elucidate their ecological sustainability, 40% the economic sustainability, and a staggering 73.3% the societal sustainability. Markedly, certain materials are deficient in workability, thermal shielding, and sonic insulation. Of the 15 SCMs assessed, only quintessential materials like cork, straw bales, sheep’s wool, hempcrete, and timbercrete boast exhaustive engineering performance evaluations. Hence, the remaining ten exhibit lapses in diverse performance realms. It would be judicious for scholars to prioritize these gaps, particularly focusing on workability, thermal barrier properties, and sound insulation in subsequent investigations.

In the environmental analysis of SCMs, the number of materials considered decreased from 15 to 10, as shown in Table 6. While reviewing papers and summarizing the environmental benefits of various materials, it was found that few researchers have analyzed the environmental benefits of precast concrete, cork, plant-based rigid polyurethane foam, sheep's wool, and timbercrete. Furthermore, the environmental performance of SCMs shows that most of the materials are not analyzed for human toxicity indicators or directly impact people's health. Therefore, researchers could conduct environmental benefit analyses and indicator analyses for the five SCMs in future studies.

Besides, the number of SCMs analyzed in terms of economic performance has been reduced from 10 in the previous environmental analysis to 9, as shown in Table 6. Almost no researcher analyzed the economic performance of the six materials: precast concrete, cork, plant-based rigid polyurethane foam, sheep's wool, timbercrete, and hempcrete. Furthermore, in the economic performance, some sustainable materials are economically beneficial, but most of the materials are not analyzed for their maintenance costs and long-term savings, and some even cost more than existing materials. Therefore, researchers should delve into the economic performance of SCMs across various indicators, recognizing their pivotal role for investment decision-makers.

Moreover, regarding social aspects, the housing indicator describes housing affordability for everyone in society, but most of the materials are only analyzed in terms of adaptability, thermal comfort, and local resources, as these indicators are more relevant to the positive impact of sustainable development on society [186]. SCMs are evaluated in terms of environmental, economic, and social aspects, and their performance in terms of economic, environmental, and social sustainability is essential in the investment decision process [187]. In addition, in terms of social sustainability, there are uncontrolled factors in applying and promoting SCMs, such as government policies, legal support, and consensus [188]. Therefore, in each new study of sustainable materials in the future, the impact and analysis of the material on each indicator should be considered. This is the current challenge and opportunity for SCMs, which need to find a balance between the material's environmental, economic, and social aspects so that it becomes a truly SCMs rather than showing sustainability is only one aspect [189]. Finally, to achieve sustainability in construction, changes are also needed in four areas: technology, management, economics, and policy [190].

9. Conclusion

This study provides a systematic review of recent developments of SCMs in the building construction industry. It offers an overview of the current research status of various SCMs and evaluates their characteristics, engineering performance, environmental impact, economic viability, and social sustainability. The findings demonstrate that SCMs typically exhibit properties marked by minimal impact on health and the environment, along with high energy efficiency and reliance on renewable resources. However, while SCMs generally possess good strength and workability, some materials may lack adequate thermal and sound insulation properties. Moreover, while many SCMs contribute to reducing carbon dioxide emissions, mitigating climate change, and minimizing solid waste, certain materials may not address or directly impact human toxicity concerns. Furthermore, the economic performance of SCMs remains relatively understudied, with most materials costing relatively little in terms of building components, but a subset may incur higher total costs, particularly concerning regional economic factors. Moreover, a considerable number of SCMs are still in the laboratory stage or have limited applicability. In summary, this study not only elucidates the current landscape of SCMs but also serves as a compelling call for increased scholarly engagement with the economic resilience, social sustainability, and technical viability of these materials. It brings to the forefront the critical importance of SCMs within the architectural and construction sectors, showcasing their pivotal role in steering the industry toward carbon neutrality.

In the future, the landscape of SCMs is marked by an urgent need to extend research beyond the laboratory and into comprehensive, real-world applications that thoroughly evaluate their environmental, economic, and social impacts. Besides, future studies should predominantly aim to address significant research gaps, particularly focusing on human toxicity, long-term economic viability, and social adaptability. This requires broadening the scope of environmental impact studies to include lesser-studied materials such as precast concrete, cork, and plant-based foams. Additionally, there is a need to enhance economic analyses to encompass the full lifecycle costs, including maintenance and longevity, of all SCMs. Socially, research should also move beyond mere adaptability and thermal comfort to encompass broader societal impacts, such as housing affordability and contributions to community well-being. Collectively, these efforts require a multi-disciplinary approach and collaboration between academia, industry, and government to ensure SCMs contribute holistically to sustainability goals. Future studies should also incorporate adaptive frameworks that consider evolving government policies, market dynamics, and community needs to ensure that SCMs meet the triple bottom line of sustainability—environmentally sound, economically viable, and socially acceptable—thus paving the way for their broader adoption and implementation in global construction practices.

CRediT authorship contribution statement

Lin Chen: Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Mingyu Yang:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Zhonghao Chen:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Zhuolin Xie:** Writing – original draft, Validation, Methodology. **Lepeng Huang:** Writing – review & editing, Validation, Project administration, Methodology, Formal analysis, Conceptualization. **Ahmed I. Osman:** Writing – review & editing, Validation, Project administration, Funding acquisition. **Mohamed Farghali:** Writing – original draft, Validation. **Malindu Sandanayake:** Writing – review & editing, Validation, Resources, Project administration. **Engui Liu:** Writing – review & editing, Validation, Supervision. **Yong Han Ahn:** Writing – review & editing, Validation, Resources. **Ala'a H. Al-Muhtaseb:** Writing – review & editing, Validation. **David W. Rooney:** Writing – review & editing, Validation, Resources. **Pow-Seng Yap:** Writing – review & editing, Supervision, Validation, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] C. Maraveas, Production of sustainable construction materials using agro-wastes, Materials 13 (2) (2020).

[2] S. Son, K. Park, H. Fitriani, S. Kim, Embodied CO_2 reduction effects of composite precast concrete frame for heavily loaded long-span logistics buildings, Sustainability 13 (3) (2021).

[3] L. Chen, Z. Chen, Z. Xie, L. Wei, J. Hua, L. Huang, P.-S. Yap, Recent developments on natural fiber concrete: a review of properties, sustainability, applications, barriers, and opportunities, Developments in the Built Environment 16 (2023) 100255.

[4] S. Kc, D. Gautam, Progress in sustainable structural engineering: a review, Innovative Infrastructure Solutions 6 (2) (2021) 68.

[5] T. Liu, L. Chen, M. Yang, M. Sandanayake, P. Miao, Y. Shi, P.-S. Yap, Sustainability considerations of green buildings: a detailed overview on current advancements and future considerations 14 (21) (2022) 14393.

[6] A.I. Osman, L. Chen, M. Yang, G. Msigwa, M. Farghali, S. Fawzy, D.W. Rooney, P.-S. Yap, Cost, environmental impact, and resilience of renewable energy under a changing climate: a review, Environmental Chemistry Letters, 21(2) (2023) 741-764.

[7] P. Ricciardi, E. Belloni, F. Merli, C. Buratti, Sustainable panels made with industrial and agricultural waste: thermal and environmental critical analysis of the experimental results, Appl. Sci. 11 (2) (2021).

[8] F.I. Aneke, C. Shabangu, Green-efficient masonry bricks produced from scrap plastic waste and foundry sand, Case Stud. Constr. Mater. 14 (2021) e00515.

[9] L. Chen, L. Huang, J. Hua, Z. Chen, L. Wei, A.I. Osman, S. Fawzy, D.W. Rooney, L. Dong, P.-S. Yap, Green construction for low-carbon cities: a review, Environ. Chem. Lett. 21 (3) (2023) 1627–1657.

[10] S.A. Zamora-Castro, R. Salgado-Estrada, L.C. Sandoval-Herazo, R.A. Melendez-Armenta, E. Manzano-Huerta, E. Yelmi-Carrillo, A.L. Herrera-May, Sustainable development of concrete through aggregates and innovative materials: a review, Appl. Sci. 11 (2) (2021).

[11] L. Chen, Z. Chen, Y. Zhang, Y. Liu, A.I. Osman, M. Farghali, J. Hua, A. Al-Fatesh, I. Ihara, D.W. Rooney, P.-S. Yap, Artificial intelligence-based solutions for climate change: a review, Environ. Chem. Lett. 21 (5) (2023) 2525–2557.

[12] L. Chen, G. Msigwa, M. Yang, A.I. Osman, S. Fawzy, D.W. Rooney, P.-S. Yap, Strategies to achieve a carbon neutral society: a review, Environ. Chem. Lett. 20 (4) (2022) 2277–2310.

[13] M. Farghali, A.I. Osman, I.M.A. Mohamed, Z. Chen, L. Chen, I. Ihara, P.-S. Yap, D. W. Rooney, Strategies to save energy in the context of the energy crisis: a review, Environ. Chem. Lett. 21 (4) (2023) 2003–2039.

[14] M. Yang, L. Chen, J. Wang, G. Msigwa, A.I. Osman, S. Fawzy, D.W. Rooney, P.-S. Yap, Circular economy strategies for combating climate change and other environmental issues, Environ. Chem. Lett. 21 (1) (2023) 55–80.

[15] H.M. Hamada, B.S. Thomas, F.M. Yahaya, K. Muthusamy, J. Yang, J.A. Abdalla, R.A. Hawileh, Sustainable use of palm oil fuel ash as a supplementary cementitious material: a comprehensive review, J. Build. Eng. 40 (2021) 102286.

[16] M. Yang, L. Chen, G. Msigwa, K.H.D. Tang, P.-S. Yap, Implications of COVID-19 on global environmental pollution and carbon emissions with strategies for sustainability in the COVID-19 era, Sci. Total Environ. 809 (2022) 151657.

[17] F. Tahmasebinia, Y. Ma, K. Joshua, S.M. Sepasgozar, Y. Yu, J. Li, S. Sepasgozar, F. A. Marroquin, Sustainable architecture creating arches using a bamboo grid shell structure: numerical analysis and design, Sustainability 13 (5) (2021).

[18] M. Manjunatha, S. Preethi, Malingaraya, H.G. Mounika, K.N. Niveditha, Ravi, Life cycle assessment (LCA) of concrete prepared with sustainable cement-based materials, Mater. Today: Proc. 47 (2021) 3637–3644.

[19] Z. He, A. Shen, H. Wu, W. Wang, L. Wang, C. Yao, J. Wu, Research progress on recycled clay brick waste as an alternative to cement for sustainable construction materials, Constr Build Mater 274 (2021) 122113.

[20] S.I. Borlea, A.-E. Tiuc, O. Nemeş, H. Vermeşan, O. Vasile, Innovative use of sheep wool for obtaining materials with improved sound-absorbing properties, Materials 13 (3) (2020).

[21] A. Karrech, V. Strazzeri, M. Elchalakani, Improved thermal insulance of cement stabilised rammed earth embedding lightweight aggregates, Construct. Build. Mater. 268 (2021) 121075.

[22] F. Althoey, M.A. Hosen, Physical and mechanical characteristics of sustainable concrete comprising industrial waste materials as a replacement of conventional aggregate, Sustainability 13 (8) (2021) 4306.

[23] H. El-Chabib, 11 - properties of SCC with supplementary cementing materials, in: R. Siddique (Ed.), Self-Compacting Concrete: Materials, Properties and Applications, Woodhead Publishing, 2020, pp. 283–308.

[24] D. Dey, D. Srinivas, B. Panda, P. Suraneni, T.G. Sitharam, Use of industrial waste materials for 3D printing of sustainable concrete: a review, J. Clean. Prod. 340 (2022) 130749.

[25] F. Althoey, M.A. Hosen, Physical and mechanical characteristics of sustainable concrete comprising industrial waste materials as a replacement of conventional aggregate 13 (8) (2021) 4306.

[26] S. Abbasi, M.H. Jannaty, R.H. Faraj, S. Shahbazpanahi, A. Mosavi, The effect of incorporating silica stone waste on the mechanical properties of sustainable concretes 13 (17) (2020) 3832.

[27] J. Xiang, X. Zhang, F. Yi, S. Zhang, H. Yang, J.a. Shao, X. Wang, H. Chen, Improved Slagging Characteristics of Low-Value Solid Waste Fuel Asphalt Rock by Mineral Additives of $CaCO_3$, MgO, and Kaolin under Fluidized Bed Condition, Waste Disposal & Sustainable Energy, 2024.

[28] X. Li, D. Qin, Y. Hu, W. Ahmad, A. Ahmad, F. Aslam, P. Joyklad, A systematic review of waste materials in cement-based composites for construction applications, J. Build. Eng. 45 (2022) 103447.

[29] G.R. De Sensale, Effect of rice-husk ash on durability of cementitious materials, Cement Concr. Compos. 32 (9) (2010) 718–725.

[30] R. Zerbino, G. Giaccio, G.C. Isaia, Concrete incorporating rice-husk ash without processing, Construct. Build. Mater. 25 (1) (2011) 371–378.

[31] J. Alex, J. Dhanalakshmi, B. Ambedkar, Experimental investigation on rice husk ash as cement replacement on concrete production, Construct. Build. Mater. 127 (2016) 353–362.

[32] A. Siddika, M.A.A. Mamun, M.H. Ali, Study on concrete with rice husk ash, Innovative Infrastructure Solutions 3 (2018) 1–9.

[33] M.A. Noaman, M.N. Islam, M.R. Islam, M.R. Karim, Mechanical properties of brick aggregate concrete containing rice husk ash as a partial replacement of cement, J. Mater. Civ. Eng. 30 (6) (2018) 04018086.

[34] S.A. Zareei, F. Ameri, F. Dorostkar, M. Ahmadi, Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: evaluating durability and mechanical properties, Case Stud. Constr. Mater. 7 (2017) 73–81.

[35] R.-S. Bie, X.-F. Song, Q.-Q. Liu, X.-Y. Ji, P. Chen, Studies on effects of burning conditions and rice husk ash (RHA) blending amount on the mechanical behavior of cement, Cement and Concrete Composites 55 (2015) 162–168.

[36] M. Lu, W. Ge, Y. Xia, C. Sun, X. Lin, D.C.W. Tsang, T.-C. Ling, Y. Hu, L. Wang, J. Yan, Upcycling MSWI fly ash into green binders via flue gas-enhanced wet carbonation, J. Clean. Prod. 440 (2024) 141013.

[37] M. Sandanayake, Y. Bouras, R. Haigh, Z. Vrcelj, Current sustainable trends of using waste materials in concrete—a decade review 12 (22) (2020) 9622.

[38] A. Nawaz, J. Chen, X. Su, Exploring the trends in construction and demolition waste (C&DW) research: a scientometric analysis approach, Sustain. Energy Technol. Assessments 55 (2023) 102953.

[39] K. Chen, J. Wang, B. Yu, H. Wu, J. Zhang, Critical evaluation of construction and demolition waste and associated environmental impacts: a scientometric analysis, J. Clean. Prod. 287 (2021) 125071.

[40] U.A. Umar, N. Shafiq, F.A. Ahmad, A case study on the effective implementation of the reuse and recycling of construction & demolition waste management practices in Malaysia, Ain Shams Eng. J. 12 (1) (2021) 283–291.

[41] Z.-h. He, X.-d. Han, M.-y. Zhang, Q. Yuan, J.-y. Shi, P.-m. Zhan, A novel development of green UHPC containing waste concrete powder derived from construction and demolition waste, Powder Technol. 398 (2022) 117075.

[42] V.S.N.S. Goli, A. Mohammad, D.N. Singh, Application of municipal plastic waste as a manmade neo-construction material: issues & wayforward, Resour. Conserv. Recycl. 161 (2020) 105008.

[43] S. Ainomugisha, M. Matovu, M. Manga, Application of green agro-based nanoparticles in cement-based construction materials: a systematic review, J. Build. Eng. 87 (2024) 108955.

[44] A. Kumari, S. Kumar Yadav, Moving towards sustainable nanoengineered building materials with less energy consumption, Energy Build. 318 (2024) 114475.

[45] T. Fu, F. Montes, P. Suraneni, J. Youngblood, J. Weiss, The influence of cellulose nanocrystals on the hydration and flexural strength of Portland cement pastes, Polymers 9 (9) (2017) 424.

[46] O.A. Hisseine, W. Wilson, L. Sorelli, B. Tolnai, A. Tagnit-Hamou, Nanocellulose for improved concrete performance: a macro-to-micro investigation for disclosing the effects of cellulose filaments on strength of cement systems, Construct. Build. Mater. 206 (2019) 84–96.

[47] F. Mohammadkazemi, K. Doosthoseini, E. Ganjian, M. Azin, Manufacturing of bacterial nano-cellulose reinforced fiber−cement composites, Construct. Build. Mater. 101 (2015) 958–964.

[48] A. Balea, E. Fuente, A. Blanco, C. Negro, Nanocelluloses: natural-based materials for fiber-reinforced cement composites. A critical review, Polymers 11 (3) (2019) 518.

[49] L.O. de Souza, M. Liebscher, L.M.S. de Souza, F. de Andrade Silva, V. Mechtcherine, Effect of microcrystalline and nano-fibrillated cellulose on the mechanical behavior and microstructure of cement pastes, Construct. Build. Mater. 408 (2023) 133812.

[50] F.A.S. Hansted, A.L.S. Hansted, E.R.D. Padilla, J.C. Caraschi, D. Goveia, C. Inácio de Campos, The use of nanocellulose in the production of medium density particleboard panels and the modification of its physical properties, Bioresources 14 (3) (2019).

[51] E.G. Deze, E. Cuenca, A.M.L. Násner, M. Iakovlev, S. Sideri, A. Sapalidis, R. P. Borg, L. Ferrara, Nanocellulose enriched mortars: evaluation of nanocellulose properties affecting microstructure, strength and development of mixing protocols, Mater. Today: Proc. 54 (2022) 50–56.

[52] L.Y. Ee, S.F.Y. Li, Recent advances in 3D printing of nanocellulose: structure, preparation, and application prospects, Nanoscale Adv. 3 (5) (2021) 1167–1208.

[53] H. Françon, Z. Wang, A. Marais, K. Mystek, A. Piper, H. Granberg, A. Malti, P. Gatenholm, P.A. Larsson, L. Wågberg, Ambient-dried, 3D-printable and electrically conducting cellulose nanofiber aerogels by inclusion of functional polymers, Adv. Funct. Mater. 30 (12) (2020) 1909383.

[54] A.S. Finny, O. Popoola, S. Andreescu, 3D-Printable nanocellulose-based functional materials: fundamentals and applications, Nanomaterials 11 (9) (2021) 2358.

[55] J.M. González-Domínguez, A. Baigorri, M.Á. Álvarez-Sánchez, E. Colom, B. Villacampa, A. Ansón-Casaos, E. García-Bordejé, A.M. Benito, W.K. Maser, Waterborne graphene-and nanocellulose-based inks for functional conductive films and 3D structures, Nanomaterials 11 (6) (2021) 1435.

[56] B. Kumar, D.H. Pham, J. Kim, Strong, highly porous and sustainable nanocellulose foam made using bioderived hyperbranched crosslinker for thermal insulation and sound absorption, Carbohydrate Polymers 334 (2024) 122016.

[57] M. Yadav, A. Mathur, Bamboo as a sustainable material in the construction industry: an overview, Mater. Today: Proc. 43 (2021) 2872–2876.

[58] T.M. Tiza, S.K. Singh, L. Kumar, M.P. Shettar, S.P. Singh, Assessing the potentials of Bamboo and sheep wool fiber as sustainable construction materials: A review, Materials Today, Proceedings 47 (2021) 4484–4489.

[59] I. Ahmad Wani, R. ul Rehman Kumar, Experimental investigation on using sheep wool as fiber reinforcement in concrete giving increment in overall strength, Mater. Today: Proc. 45 (2021) 4405–4409.

[60] S.S. Narani, P. Zare, M. Abbaspour, A. Fahimifar, S. Siddiqua, S.M. Mir Mohammad Hosseini, Evaluation of fiber-reinforced and cement-stabilized rammed-earth composite under cyclic loading, Construct. Build. Mater. 296 (2021) 123746.

[61] D. Ciancio, C. Beckett, Rammed earth: an overview of a sustainable construction material, in: Proceedings of the Third International Conference on Sustainable Construction Materials and Technologies, 2013, pp. 18–21. Kyoto, Japan.

[62] S. Merabti, S. Kenai, R. Belarbi, J. Khatib, Thermo-mechanical and physical properties of waste granular cork composite with slag cement, Construct. Build. Mater. 272 (2021) 121923.

[63] A. Cortês, A. Tadeu, M.I. Santos, J. de Brito, J. Almeida, Innovative module of expanded cork agglomerate for green vertical systems, Build. Environ. 188 (2021) 107461.

[64] R.M. Novais, L. Senff, J. Carvalheiras, A.M. Lacasta, I.R. Cantalapiedra, J. A. Labrincha, Simple and effective route to tailor the thermal, acoustic and hygrothermal properties of cork-containing waste derived inorganic polymer composites, J. Build. Eng. 42 (2021) 102501.

[65] B. Dorsey, Refocusing on sustainability: promoting straw bale building for government-assisted, self-help housing programs in Utah and abroad, Sustainability 13 (5) (2021).

[66] N. Bheel, S. Sohu, P. Awoyera, A. Kumar, S.A. Abbasi, O.B. Olalusi, Effect of wheat straw ash on fresh and hardened concrete reinforced with jute fiber, Adv. Civ. Eng. 2021 (2021) 6659125.

[67] O. Olofinnade, S. Chandra, P. Chakraborty, Recycling of high impact polystyrene and low-density polyethylene plastic wastes in lightweight based concrete for sustainable construction, Mater. Today: Proc. 38 (2021) 2151–2156.

[68] R. Chippagiri, H.R. Gavali, R.V. Ralegaonkar, M. Riley, A. Shaw, A. Bras, Application of sustainable prefabricated wall technology for energy efficient social housing, Sustainability 13 (3) (2021).

[69] D.S. Vijayan, S. Dineshkumar, T. Arvindan, Shreelakshmi Janarthanan, Evaluation of ferrock: a greener substitute to cement, Mater. Today: Proc. 22 (2020) 781–787.

[70] S.N.C. Deraman, M.A.D.A. Rashid, S.A. Saad, N.M. Husain, S.A. Masjuki, Effects of durian sawdust as a partial replacement of fine aggregate in concrete, IOP Conf. Ser. Mater. Sci. Eng. 1144 (1) (2021) 012027.

[71] C. Setter, R.R. de Melo, J.F. do Carmo, D.M. Stangerlin, A.S. Pimenta, Cement boards reinforced with wood sawdust: an option for sustainable construction, SN Appl. Sci. 2 (10) (2020) 1631.

[72] R. Fürst, T. Vlach, M. Pokorný, V. Mózer, Study of Behavior of Textile-Reinforced Concrete with Epoxy Resin Matrix in Fire, Fire Technology, 2021.

[73] G.F. Huseien, A.R. Sam, I. Faridmehr, M.H. Baghban, Performance of epoxy resin polymer as self-healing cementitious materials agent in mortar, Materials 14 (5) (2021).

[74] S.S.D. Raavi, D.D. Tripura, Ultrasonic pulse velocity and statistical analysis for predicting and evaluating the properties of rammed earth with natural and brick aggregates, Construct. Build. Mater. 298 (2021) 123840.

[75] P. Saravanakumar, E. John Bisher, R.A. Aravinndh, K. Sanjay Kumar, Usage of fibre content in hemp as a material in building construction, IOP Conf. Ser. Mater. Sci. Eng. 1145 (1) (2021) 012057.

[76] Y. Cheng, Z. Xu, S. Chen, Y. Ji, D. Zhang, J. Liang, The influence of closed pore ratio on sound absorption of plant-based polyurethane foam using control unit model, Appl. Acoust. 180 (2021) 108083.

[77] I. Singh, S.K. Samal, S. Mohanty, S.K. Nayak, Recent advancement in plant oil derived polyol-based polyurethane foam for future perspective: a review, Eur. J. Lipid Sci. Technol. 122 (3) (2020) 1900225.

[78] M. Jones, A. Mautner, S. Luenco, A. Bismarck, S. John, Engineered mycelium composite construction materials from fungal biorefineries: a critical review, Mater. Des. 187 (2020) 108397.

[79] S. Manan, M.W. Ullah, M. Ul-Islam, O.M. Atta, G. Yang, Synthesis and applications of fungal mycelium-based advanced functional materials, Journal of Bioresources and Bioproducts 6 (1) (2021) 1–10.

[80] B.S. Thomas, J. Yang, K.H. Mo, J.A. Abdalla, R.A. Hawileh, E. Ariyachandra, Biomass ashes from agricultural wastes as supplementary cementitious materials or aggregate replacement in cement/geopolymer concrete: a comprehensive review, J. Build. Eng. 40 (2021) 102332.

[81] A. Mardani, D. Streimikiene, R. Rostami, M. Ismail, R. Mohamad zin, M. Khoshnava, The role of green building materials in reducing environmental and human health impacts, Int. J. Environ. Res. Publ. Health 17 (2020).

[82] P. Pelli, Service innovation and sustainable construction: analyses of wood vis-à-vis other construction projects, Cleaner Engineering and Technology 2 (2021) 100061.

[83] H. Wang, T. Qi, G. Feng, X. Wen, Z. Wang, X. Shi, X. Du, Effect of partial substitution of corn straw fly ash for fly ash as supplementary cementitious material on the mechanical properties of cemented coal gangue backfill, Constr Build Mater 280 (2021) 122553.

[84] Y. Abdellatef, M. Kavgic, Thermal, microstructural and numerical analysis of hempcrete-microencapsulated phase change material composites, Appl. Therm. Eng. 178 (2020) 115520.

[85] Y. Xia, D. Shi, R. Zhao, K. Yu, M. Liu, H. Mei, L. Xu, Y. Zhao, L. Wang, J. Yan, Iron-rich industrial waste enhanced low-carbon radiation shielding functional composites, J. Clean. Prod. 449 (2024) 141649.

[86] Z. Tang, W. Li, V.W.Y. Tam, C. Xue, Advanced progress in recycling municipal and construction solid wastes for manufacturing sustainable construction materials, Resour. Conserv. Recycl. X 6 (2020) 100036.

[87] P. Jędrzejczak, M.N. Collins, T. Jesionowski, Ł. Klapiszewski, The role of lignin and lignin-based materials in sustainable construction – a comprehensive review, Int. J. Biol. Macromol. 187 (2021) 624–650.

[88] A. Det Udomsap, P. Hallinger, A bibliometric review of research on sustainable construction, 1994–2018, J. Clean. Prod. 254 (2020) 120073.

[89] M.U. Hossain, S.T. Ng, P. Antwi-Afari, B. Amor, Circular economy and the construction industry: existing trends, challenges and prospective framework for sustainable construction, Renew. Sustain. Energy Rev. 130 (2020) 109948.

[90] K. Joshi, M.K. Meher, K.M. Poluri, Fabrication and characterization of bioblocks from agricultural waste using fungal mycelium for renewable and sustainable applications, ACS Appl. Bio Mater. 3 (4) (2020) 1884–1892.

[91] E. Elsacker, S. Vandelook, A. Van Wylick, J. Ruytinx, L. De Laet, E. Peeters, A comprehensive framework for the production of mycelium-based lignocellulosic composites, Sci. Total Environ. 725 (2020) 138431.

[92] Y. Lu, Z.A. Khan, M.S. Alvarez-Alvarado, Y. Zhang, Z. Huang, M. Imran, A critical review of sustainable energy policies for the promotion of renewable energy sources 12 (12) (2020) 5078.

[93] P.A. Østergaard, N. Duic, Y. Noorollahi, H. Mikulcic, S. Kalogirou, Sustainable development using renewable energy technology, Renew. Energy 146 (2020) 2430–2437.

[94] M.R. Munaro, S.F. Tavares, L. Bragança, Towards circular and more sustainable buildings: a systematic literature review on the circular economy in the built environment, J. Clean. Prod. 260 (2020) 121134.

[95] D.N. Tawasil, E. Aminudin, N.H. Abdul Shukor Lim, N.M. Nik Soh, P.C. Leng, G. H. Ling, M.H. Ahmad, Coconut fibre and sawdust as green building materials: a laboratory assessment on physical and mechanical properties of particleboards, Buildings 11 (6) (2021).

[96] Y. Paluri, V. Noolu, H. Mudavath, R. Kumar Pancharathi, Flexural fatigue behavior of steel fiber-reinforced reclaimed asphalt pavement–based concrete: an experimental study, practice periodical on structural design and construction 26 (1) (2021) 04020053.

[97] L. Molari, J.J. García, On the radial variation of the transverse mechanical properties of bamboo, J. Build. Eng. 33 (2021) 101557.

[98] P. Yogesh, K. Ravi, R. Karthik, M. Bhavana, S. Muthukumar, D. Sathyan, Strength and workability characteristics of hybrid bamboo and steel fiber reinforced concrete, Mater. Today: Proc. 80 (2023) 1135–1141.

[99] Q. Lv, W. Wang, Y. Liu, Study on thermal insulation performance of cross-laminated bamboo wall, J. Renew. Mater. 7 (11) (2019) 1231–1250.

[100] S. Singh, A. Chourasia, R.S. Bisht, S. Yadav, Thermal and Acoustic Performance of Cement Fibreboard and Bamboo Buildings, 2021.

[101] S. Cascone, R. Rapisarda, D. Cascone, Physical properties of straw bales as a construction material, A Review 11 (12) (2019) 3388.

[102] S.I. Basha, M.R. Ali, S.U. Al-Dulaijan, M. Maslehuddin, Mechanical and thermal properties of lightweight recycled plastic aggregate concrete, J. Build. Eng. 32 (2020) 101710.

[103] D.V. Marques, R.L. Barcelos, H.R.T. Silva, P. Egert, G.O.C. Parma, E. Girotto, D. Consoni, R. Benavides, L. Silva, R.F. Magnago, Recycled polyethylene terephthalate-based boards for thermal-acoustic insulation, J. Clean. Prod. 189 (2018) 251–262.

[104] V. Uemura Silva, M.F. Nascimento, P. Resende Oliveira, T.H. Panzera, M. O. Rezende, D.A.L. Silva, V. Borges de Moura Aquino, F.A. Rocco Lahr, A. L. Christoforo, Circular vs. linear economy of building materials: a case study for particleboards made of recycled wood and biopolymer vs. conventional particleboards, Construct. Build. Mater. 285 (2021) 122906.

[105] C. Kuranchie, A. Yaya, Y.D. Bensah, The effect of natural fibre reinforcement on polyurethane composite foams – a review, Scientific African 11 (2021) e00722.

[106] M. Norouzi, M. Chàfer, L.F. Cabeza, L. Jiménez, D. Boer, Circular economy in the building and construction sector: a scientific evolution analysis, J. Build. Eng. 44 (2021).

[107] G.L.F. Benachio, M.D.C.D. Freitas, S.F. Tavares, Interactions between lean construction principles and circular economy practices for the construction industry, J Constr Eng Manage 147 (7) (2021).

[108] H. Huang, T. Wang, B. Kolosz, J. Andresen, S. Garcia, M. Fang, M.M. Maroto-Valer, Life-cycle assessment of emerging CO_2 mineral carbonation-cured concrete blocks: comparative analysis of CO_2 reduction potential and optimization of environmental impacts, J. Clean. Prod. 241 (2019).

[109] S.M. Musavi, F. Barahuie, M. Irani, A. Safamanesh, A. Malekpour, Enhanced properties of phase change material -SiO2-graphene nanocomposite for developing structural–functional integrated cement for solar energy absorption and storage, Renew. Energy 174 (2021) 918–927.

[110] J. Brozovsky, S. Corio, N. Gaitani, A. Gustavsen, Evaluation of sustainable strategies and design solutions at high-latitude urban settlements to enhance outdoor thermal comfort, Energy Build. 244 (2021).

[111] G. Sánchez-Barroso, M. Botejara-Antúnez, J. García-Sanz-Calcedo, F. Zamora-Polo, A life cycle analysis of ionizing radiation shielding construction systems in healthcare buildings, J. Build. Eng. 41 (2021).

[112] S.E. Hale, A.J. Roque, G. Okkenhaug, E. Sørmo, T. Lenoir, C. Carlsson, D. Kupryianchyk, P. Flyhammar, B. Žlender, The reuse of excavated soils from construction and demolition projects: limitations and possibilities, Sustainability 13 (11) (2021).

[113] F. Colangelo, I. Farina, M. Travaglioni, C. Salzano, R. Cioffi, A. Petrillo, Innovative materials in Italy for eco-friendly and sustainable buildings, Mater 14 (8) (2021).

[114] L. Chen, Y. Zhang, Z. Chen, Y. Dong, Y. Jiang, J. Hua, Y. Liu, A.I. Osman, M. Farghali, L. Huang, D.W. Rooney, P.-S. Yap, Biomaterials technology and policies in the building sector: a review, Environ. Chem. Lett. 22 (2) (2024) 715–750.

[115] R. Manandhar, J.H. Kim, J.T. Kim, Environmental, social and economic sustainability of bamboo and bamboo-based construction materials in buildings, J. Asian Architect. Build Eng. 18 (2) (2019) 52–62.

[116] C. Cornaro, V. Zanella, P. Robazza, E. Belloni, C. Buratti, An innovative straw bale wall package for sustainable buildings: experimental characterization, energy and environmental performance assessment, Energy Build. 208 (2020).

[117] J. Fernandes, M. Peixoto, R. Mateus, H. Gervásio, Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: Rammed earth and compressed earth blocks, J. Clean. Prod. 241 (2019) 118286.

[118] J. Fernandes, M. Peixoto, R. Mateus, H. Gervásio, Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: rammed earth and compressed earth blocks, J. Clean. Prod. 241 (2019).

[119] V. Toufigh, E. Kianfar, The effects of stabilizers on the thermal and the mechanical properties of rammed earth at various humidities and their environmental impacts, Constr Build Mater 200 (2019) 616–629.

[120] F. Scrucca, C. Ingrao, C. Maalouf, T. Moussa, G. Polidori, A. Messineo, C. Arcidiacono, F. Asdrubali, Energy and carbon footprint assessment of production of hemp hurds for application in buildings, Environ. Impact Assess. Rev. 84 (2020).

[121] R. Haik, G. Bar-Nes, A. Peled, I.A. Meir, Alternative unfired binders as lime replacement in hemp concrete, Constr Build Mater 241 (2020).

[122] P.O. Awoyera, A. Adesina, Plastic wastes to construction products: status, limitations and future perspective, Case Stud. Constr. Mater. 12 (2020).

[123] B. D'Amico, F. Pomponi, J. Hart, Global potential for material substitution in building construction: the case of cross laminated timber, J. Clean. Prod. 279 (2021).

[124] C. Bruscato, E. Malvessi, R.N. Brandalise, M. Camassola, High performance of macrofungi in the production of mycelium-based biofoams using sawdust — sustainable technology for waste reduction, J. Clean. Prod. 234 (2019) 225–232.

[125] P.P. Dias, L.B. Jayasinghe, D. Waldmann, Investigation of Mycelium-Miscanthus composites as building insulation material, Results in Materials 10 (2021) 100189.

[126] D.S. Vijayan, Dineshkumar, S. Arvindan, T.S. Janarthanan, Evaluation of ferrock: a greener substitute to cement, Mater. Today: Proc. (2020) 781–787.

[127] B.B. Mitikie, B.D. Gari, W.A. Elsaigh, Ferrock cement and oxalic acid for enhanced concrete strength and durability against sulphate attack, Eng. Res. Express 6 (2) (2024) 025122.

[128] M.S. Ali, S. Shukri, M. Patel, A. Ahad, Alternative Building Materials for Sustainable Development in Ethiopian Construction, 2020.

[129] T. Sravani, R. Prasanna Venkatesan, A. Madhumathi, A comparative LCA study of passive cooling roof materials for a residential building: an Indian Case study, Mater. Today: Proc. 64 (2022) 1014–1022.

[130] K.M. Liew, A. Akbar, The recent progress of recycled steel fiber reinforced concrete, Construct. Build. Mater. 232 (2020) 117232.

[131] M.A. Omer, T.J.S.C. Noguchi, Society, A Conceptual Framework for Understanding the Contribution of Building Materials in the Achievement of Sustainable Development Goals (SDGs), vol. 52, 2020 101869.

[132] N. Sathiparan, A. Anburuvel, V.V. Selvam, Utilization of agro-waste groundnut shell and its derivatives in sustainable construction and building materials – a review, J. Build. Eng. 66 (2023) 105866.

[133] S. Meshram, S.P. Raut, K. Ansari, M. Madurwar, M. Daniyal, M.A. Khan, V. Katare, A.H. Khan, N.A. Khan, M.A. Hasan, Waste slags as sustainable construction materials: a compressive review on physico mechanical properties, J. Mater. Res. Technol. 23 (2023) 5821–5845.

[134] A. Bala, S. Gupta, Engineered bamboo and bamboo-reinforced concrete elements as sustainable building materials: a review, Construct. Build. Mater. 394 (2023) 132116.

[135] P. Varun Raj, P. Surya Teja, K. Sai Siddhartha, J.S. Kalyana Rama, Housing with low-cost materials and techniques for a sustainable construction in India-A review, Mater. Today: Proc. 43 (2021) 1850–1855.

[136] M. Verma, P. Singh, M. Dhanorkar, Sustainability in residue management: a review with special reference to Indian agriculture, Paddy Water Environ. 22 (1) (2024) 1–15.

[137] E. Hany, N. Fouad, M. Abdel-Wahab, E. Sadek, Investigating the mechanical and thermal properties of compressed earth bricks made by eco-friendly stabilization materials as partial or full replacement of cement, Construct. Build. Mater. 281 (2021) 122535.

[138] L. Pradeep, S. Pragyan Dash, D. Jivan Pati, N. Mary Boby, Determining the feasibility of using PET bottles as construction material in urban context, Mater. Today: Proc. 60 (2022) 384–393.

[139] S. Ahmed, I. Arocho, Analysis of cost comparison and effects of change orders during construction: study of a mass timber and a concrete building project, J. Build. Eng. 33 (2021) 101856.

[140] M. Jones, A. Mautner, S. Luenco, A. Bismarck, S.J.M. John, Design, Engineered Mycelium Composite Construction Materials from Fungal Biorefineries: A Critical Review, 187, 2020 108397.

[141] I. Hussain, B. Ali, T. Akhtar, M.S. Jameel, S.S. Raza, Comparison of mechanical properties of concrete and design thickness of pavement with different types of fiber-reinforcements (steel, glass, and polypropylene), Case Stud. Construct. Mater. 13 (2020) e00429.

[142] T.-P. Huynh, H.-P. Phan, V.-H. Pham, V.-A. Ngo, H.-T. Luu, Utilization of waste incineration bottom ash as fine aggregate in the production of terrazzo tiles for pavement, in: J.N. Reddy, C.M. Wang, V.H. Luong, A.T. Le (Eds.), ICSCEA 2021, Springer Nature Singapore, Singapore, 2023, pp. 555–565.

[143] M. Al Shdifat, M.L. Jalón, E. Puertas, J. Chiachío, A quantitative group decision-making methodology for structural eco-materials selection based on qualitative sustainability attributes 13 (22) (2023) 12310.

[144] R.W.M. Wong, B.P.Y. Loo, Sustainability implications of using precast concrete in construction: an in-depth project-level analysis spanning two decades, J. Clean. Prod. 378 (2022) 134486.

[145] R.M. Novais, L. Senff, J. Carvalheiras, M.P. Seabra, R.C. Pullar, J.A. Labrincha, Sustainable and efficient cork - inorganic polymer composites: an innovative and eco-friendly approach to produce ultra-lightweight and low thermal conductivity materials, Cem. Concr. Compos. 97 (2019) 107–117.

[146] C. Cornaro, V. Zanella, P. Robazza, E. Belloni, C. Buratti, An innovative straw bale wall package for sustainable buildings: experimental characterization, energy and environmental performance assessment, Energy Build. 208 (2020) 109636.

[147] P.O. Awoyera, A. Adesina, Plastic wastes to construction products: status, limitations and future perspective, Case Stud. Constr. Mater. 12 (2020) e00330.

[148] B. Yu, A. Fingrut, Sustainable building design (SBD) with reclaimed wood library constructed in collaboration with 3D scanning technology in the UK, Resour. Conserv. Recycl. 186 (2022) 106566.

[149] A. Kanyilmaz, M. Birhane, R. Fishwick, C. del Castillo, Reuse of steel in the construction industry: challenges and opportunities, International Journal of Steel Structures 23 (5) (2023) 1399–1416.

[150] A.M. Alsuhaibani, M.S. Refat, S.A. Qaisrani, F. Jamil, Z. Abbas, A. Zehra, K. Baluch, J.-G. Kim, M. Mubeen, Green buildings model: impact of rigid polyurethane foam on indoor environment and sustainable development in energy sector, Heliyon 9 (3) (2023) e14451.

[151] S. Hetimy, N. Megahed, O.A. Eleinen, D. Elgheznawy, Exploring the potential of sheep wool as an eco-friendly insulation material: a comprehensive review and analytical ranking, Sustain. Mater. Technol. 39 (2024) e00812.

[152] M. Gomaa, S. Schade, D.W. Bao, Y.M. Xie, Automation in rammed earth construction for industry 4.0: precedent work, current progress and future prospect, J. Clean. Prod. 398 (2023) 136569.

[153] L. Essaghouri, R. Mao, X. Li, Environmental benefits of using hempcrete walls in residential construction: an LCA-based comparative case study in Morocco, Environ. Impact Assess. Rev. 100 (2023) 107085.

[154] N. Shinde, R. Gobinath, S. Chidambaram, M. Shewale, An experimental investigation on concrete blocks using Ferrock as a green binding material, Materials Today, Proceedings (2023).

[155] I.J. Mogaji, S.A. Makanjuola, O. Alake, Study on density and water absorption properties of timbercrete block, Mater. Today: Proc. (2023).

[156] H. Liang, W. Xie, P. Wei, Y. Zhou, Z. Zhang, The effect of the decorative surface layer on the dynamic properties of a symmetric concrete slab 13 (7) (2021) 1174.

[157] H. Peng, P. Walker, D. Maskell, B. Jones, Structural characteristics of load bearing straw bale walls, Construct. Build. Mater. 287 (2021) 122911.

[158] M.S. Haque, Sustainable use of plastic brick from waste PET plastic bottle as building block in Rohingya refugee camp: a review, Environ. Sci. Pollut. Control Ser. 26 (36) (2019) 36163–36183.

[159] Y. Zhou, V.W.Y. Tam, K.N. Le, Sensitivity analysis of design variables in life-cycle environmental impacts of buildings, J. Build. Eng. 65 (2023) 105749.

[160] A.V. Orhon, M. Altin, Utilization of alternative building materials for sustainable construction, in: I. Dincer, C.O. Colpan, M.A. Ezan (Eds.), Environmentally-Benign Energy Solutions, Springer International Publishing, Cham, 2020, pp. 727–750.

[161] S. Gounder, A. Hasan, A. Shrestha, A. Elmualim, Barriers to the use of sustainable materials in Australian building projects, Eng. Construct. Architect. Manag. 30 (1) (2023) 189–209.

[162] S. Barbhuiya, B.B. Das, Life Cycle Assessment of construction materials: methodologies, applications and future directions for sustainable decision-making, Case Stud. Constr. Mater. 19 (2023) e02326.

[163] A. Luca, G. Antonio, L. Scalia Giada, L. Fata Concetta Manuela, M. Rosa, Life cycle assessment of a new industrial process for sustainable construction materials, Ecol. Indicat. 148 (2023) 110042.

[164] E. Allen, J. Iano, Fundamentals of Building Construction: Materials and Methods, John Wiley & Sons, 2019.

[165] K. Schanes, J. Jäger, P. Drummond, Three scenario narratives for a resource-efficient and low-carbon europe in 2050, Ecol. Econ. 155 (2019) 70–79.

[166] H. Fitriani, S. Ajayi, Investigation of requisite measures for enhancing sustainable construction practices in Indonesia, Eng. Construct. Architect. Manag. 30 (6) (2023) 2602–2620.

[167] S. Madhushan, S. Buddika, S. Bandara, S. Navaratnam, N. Abeysuriya, Uses of bamboo for sustainable construction—a structural and durability perspective—a review 15 (14) (2023) 11137.

[168] C. Sun, J. Gu, Q. Dong, D. Qu, W. Chang, X. Yin, Are straw bales better insulation materials for constructions? A review, Developments in the Built Environment 15 (2023) 100209.

[169] M. Jawaid, B. Singh, L.K. Kian, S.A. Zaki, A.M. Radzi, Processing techniques on plastic waste materials for construction and building applications, Curr. Opin. Green Sustainable Chem. 40 (2023) 100761.

[170] J. Iždinský, Z. Vidholdová, L. Reinprecht, Particleboards from recycled wood 11 (11) (2020) 1166.

[171] L. Yiping, L. Yanxia, K. Buckingham, G. Henley, Z. Guomo, Bamboo and Climate Change Mitigation: a Comparative Analysis of Carbon Sequestration, vol. 30, International Network for Bamboo and Rattan, 2010.

[172] A.S. Devi, K.S. Singh, Carbon storage and sequestration potential in aboveground biomass of bamboos in North East India, Sci. Rep. 11 (1) (2021) 837.

[173] G. Spampinato, D.E. Massimo, C.M. Musarella, P. De Paola, A. Malerba, M. Musolino, Carbon Sequestration by Cork Oak Forests and Raw Material to Built up Post Carbon City, International Symposium on New Metropolitan Perspectives, Springer, 2018, pp. 663–671.

[174] J. Vengala, B. Mohanthy, S. Raghunath, Seismic performance of Bamboo housing–an overview, Proc. World Bamboo Congr 1 (2015) 389–407.

[175] J. Wang, C. Demartino, Y. Xiao, Y. Li, Thermal insulation performance of bamboo- and wood-based shear walls in light-frame buildings, Energy Build. 168 (2018) 167–179.

[176] S. Madhushan, S. Buddika, S. Bandara, S. Navaratnam, N. Abeysuriya, Uses of bamboo for sustainable construction—a structural and durability perspective—a review, Sustainability 15 (14) (2023) 11137.

[177] D. Akwada, E.T. Akinlabi, Economic, social and environmental assessment of bamboo for infrastructure development, in: International Conference on Infrastructure Development in Africa, 2016, pp. 1–15.

[178] S. Bringezu, J. Potočnik, H. Schandl, Y. Lu, A. Ramaswami, M. Swilling, S. Suh, Multi-scale governance of sustainable natural resource use—challenges and opportunities for monitoring and institutional development at the national and global level, Sustainability 8 (8) (2016) 778.

[179] Y. Krozer, F. Coenen, J. Hanganu, M. Lordkipanidze, M. Sbarcea, Towards innovative governance of nature areas, Sustainability 12 (24) (2020) 10624.

[180] L. Shen, J. Yang, R. Zhang, C. Shao, X. Song, The benefits and barriers for promoting bamboo as a green building material in China—an integrative analysis, Sustainability 11 (9) (2019) 2493.

[181] R.W. Wong, B.P. Loo, Sustainability implications of using precast concrete in construction: an in-depth project-level analysis spanning two decades, J. Clean. Prod. 378 (2022) 134486.

[182] M.R. Factsheet, EuRIC AISBL–Recycling: Bridging Circular Economy & Climate Policy, URL: https://www.euric-aisbl.eu/[in English].

[183] F. Di Maio, P.C. Rem, A robust indicator for promoting circular economy through recycling, J. Environ. Protect. 6 (10) (2015) 1095–1104.

[184] A.M. Maglad, M. Houda, R. Alrowais, A.M. Khan, M. Jameel, S.K.U. Rehman, H. Khan, M.F. Javed, M.F. Rehman, Bim-based energy analysis and optimization using insight 360 (case study), Case Stud. Constr. Mater. 18 (2023) e01755.

[185] S. Dalirazar, Z. Sabzi, Strategic analysis of barriers and solutions to development of sustainable buildings using PESTLE technique, International Journal of Construction Management 23 (1) (2023) 167–181.

[186] M.-L. Tseng, S.-X. Li, C.-W.R. Lin, A.S.F. Chiu, Validating green building social sustainability indicators in China using the fuzzy delphi method, Journal of Industrial and Production Engineering 40 (1) (2023) 35–53.

[187] M.A. Abdelaal, S.M. Seif, M.M. El-Tafesh, N. Bahnas, M.M. Elserafy, E. S. Bakhoum, Sustainable assessment of concrete structures using BIM–LCA–AHP integrated approach, Environ. Dev. Sustain. (2023).

[188] G. Kaur, R. Kander, The sustainability of industrial hemp: a literature review of its economic, Environmental, and Social Sustainability 15 (8) (2023) 6457.

[189] Q. Chang, L. Liu, M.U. Farooqi, B. Thomas, Y.O. Özkılıç, Data-driven based estimation of waste-derived ceramic concrete from experimental results with its environmental assessment, J. Mater. Res. Technol. 24 (2023) 6348–6368.

[190] N. Murtagh, L. Scott, J. Fan, Sustainable and resilient construction: current status and future challenges, J. Clean. Prod. 268 (2020) 122264.