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Biocomposites for sustainable construction: A review of material properties, applications, research gaps, and contribution to circular economy

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A R T I C L E I N F O

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A B S T R A C T

To promote circular economy practices in the construction sector, researchers are investigating potential alternatives to traditional building materials. Biocomposites might be an eco-friendly substitute for synthetic composites, which has increased demand across numerous applications. This study reviews and synthesises current knowledge in the field of biocomposites for building applications and identifies existing research gaps. The literature highlights several forms of biocomposites employed in the construction industry, which can be broadly categorised as polymer, mineral/cement, and alkali-activated or geopolymer biocomposites incorporating bio-fibres or fillers. The constituents, production methods, and mechanical and functional properties of these materials are examined. Potential applications of biocomposites are discussed based on their material characteristics, along with their contribution to the circular economy within the building sector. Finally, key research gaps that hinder the large-scale adoption of biocomposites in the construction industry are highlighted, and future research directions and commercial initiatives are proposed.

List of Abbreviations

AA	Alkali-activated
AA-GP	Alkali-activated and geopolymer
AAM	Alkali-activated material
CS	Compressive strength
FS	Flexural strength
GP	Geopolymer
OPC	Ordinary Portland cement
PHA	Polyhydroxyalkanoates
PLA	Polylactic acid
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PVA	Polyvinyl acetate
TS	Tensile strength
VMA	Viscosity modifying agent
WA	Water absorption

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1. Introduction

Due to growing concerns over the environment, significant progress has been made in the research of eco-friendly materials by introducing and promoting biocomposites [1–3]. The scientific and industrial communities widely acknowledge the need for eco-efficient products, recycling, and reusing in response to the increasing demand for resources [4]. Biocomposites comprise biodegradable reinforcements (like biofibres) and matrices, which may be more easily recycled or disposed of in landfills without causing harm to the environment. A recent analysis predicts that the global biocomposite market will have an annual growth rate of 11.8 % between 2016 and 2024 [5]. Biocomposite materials have been in use for centuries. Their use can be traced back to prehistoric periods, such as the construction of the Great Wall of China, which includes stone, clay bricks, red willow reeds, clay reeds, willow branches, and sand in 121 B.C [6,7].

Biocomposites have made significant progress due to the utilisation of diverse raw materials, manufacturing techniques, characterisation methods, and applications [8–10]. Biofibres, including hemp, basalt, wood, coir, rice husk, ramie, kenaf, sisal, jute, flax, and others, have garnered considerable attention as a potential substitute for synthetic fibres such as carbon and glass [11,12]. Fig. 1 displays the polymeric matrix and fillers used in the production of biocomposites. The extraction of biofibres is a critical step that impacts the performance of reinforcements. This process has the potential to create employment opportunities in rural areas through collection, transportation, and processing. Additionally, the use of biofibres as reinforcing agents in various matrices is well-established and has led to increased commercial applications of products made from these materials. Biocomposites have been extensively used across various industries, including packaging, aerospace, and construction [13].

Biocomposites can offer numerous advantages over traditional materials, including reduced CO_2 emissions and potential carbon neutrality, thermal insulation capabilities, effective damping performance, improved health benefits for occupants and workers, broad accessibility, reduced weight, and increased energy efficiency [15–19]. Moreover, the use of uncommon biomaterials has the potential to establish an entirely novel value chain for agricultural crops [20–22]. However, biocomposite materials can have some challenges, like inadequate resistance to moisture and fire, incompatibility between fibres and matrix, logistical difficulties in supply, complex processability, and highly variable characteristics due to fibre variability [23,24]. Furthermore, the characteristics and durability of biocomposites exhibit substantial variance due to the diverse origins of biofibres [25]. To achieve long-term durability and desired attributes, it is necessary to tackle many issues related to materials and production. Therefore, it is crucial to have a comprehensive understanding of the mechanical and functional properties of various biocomposites, especially for construction applications.

This review aims to discuss the current knowledge and identify gaps in the research of biocomposites for construction applications. A data mining strategy is adopted to retrieve the relevant publications. Various types of biocomposites were identified from the literature, including polymer, mineral/cement, and alkali-activated or geopolymer biocomposites, focusing mainly on construction applications. Raw materials used and the manufacturing process of biocomposites are discussed, along with their mechanical and functional characteristics. In addition, the circular economy aspects are described using biocomposites in the construction sector.

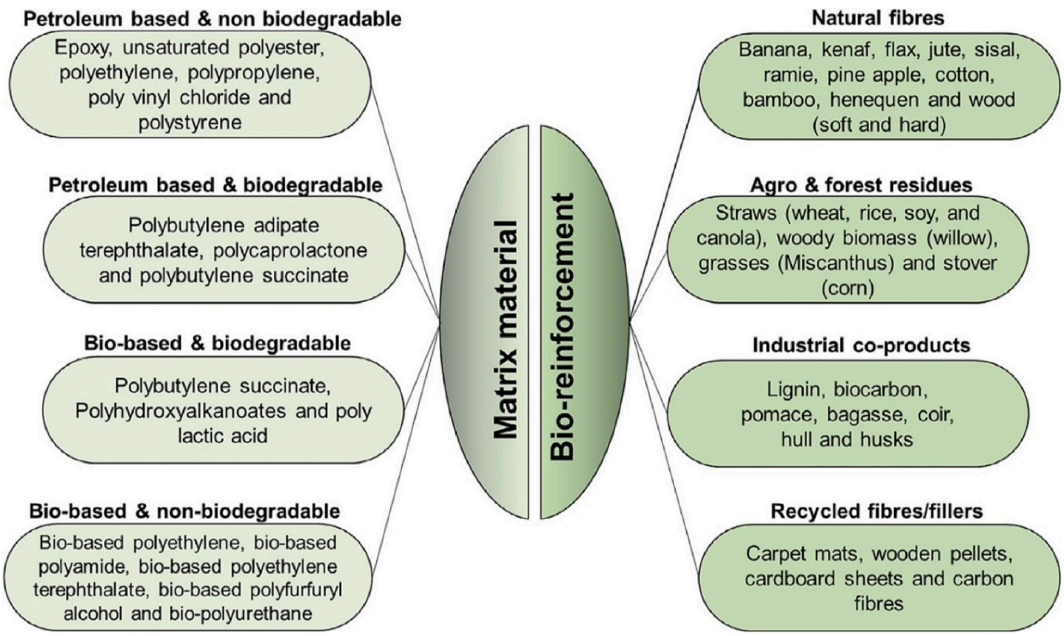

Fig. 1. Certain additives and matrices used in the production of biocomposites [14].

Finally, research gaps and limitations are identified that restrict the large-scale use of biocomposites, and future research directions and commercial strategies are proposed to benefit both industry and academia.

2. Review strategy

The 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) methodology was adopted to search and retrieve relevant literature. PRISMA methodology has four phases: identification, screening, eligibility, and inclusion. The flowchart of the PRISMA strategy used for the present study is displayed in Fig. 2. For the identification of reliable literature, it is crucial to select a pertinent database. Two trustworthy databases are used for searching literature, including Web of Science (WoS) and Scopus [26]. Based on searching different keywords and comparing the results of WoS and Scopus, it was determined that Scopus comprised a larger number of records than WoS. The selection of Scopus for the said purpose is also recommended by other researchers in several other sustainable construction studies [27–29]. Therefore, Scopus was selected to retrieve the related literature on biocomposites for construction applications. The search term selected was "*biocomposites OR bio-composites OR biobased OR bio-based AND material AND construction AND building*", which yielded 775 results in Scopus as of October 2024.

The results were screened to retain only the most relevant documents, as displayed in Fig. 2. The Scopus results were retrieved in a comma-separated values (CSV) file containing bibliographic, citation, keywords, and abstract information. These results were further screened for eligibility and to narrow down the scope of the current study. Eligibility criteria were set to include documents related to biocomposite research for building materials, material properties, environmental aspects, etc. Whereas, research related to structural analysis and design, numerical modelling, structural members, timber structures/materials, sandwich panels, case studies, clay-based biocomposites, and research related to other applications like automobile, electronics, packaging, and solar panels were not included in this review study. Explicitly, biocomposites comprising fibres or fillers and binding matrix (which may or may not be bio-based) were considered for review. Finally, after screening using this eligibility criteria, 209 documents were retained. The full text of these documents was stored and reviewed for the current study. Using *construction* AND *building* keywords during the document search narrowed the selection, and some crucial documents on the topic might have been omitted. Therefore, several relevant documents were identified through the course of the literature review and are also presented here. The possible reason for the omission in the original database search might be the use of distinct keywords or a combination of keywords, which is a limitation of the search strategy. This identification criterion is mentioned in the PRISMA flowchart (Fig. 2) as identification by other methods, i.e., citation searches from the articles reviewed. However, this limitation does not impact the overall quality of the study conducted. After including the 31 documents identified via citation search, the total number of documents reviewed in this study was 240. The retrieved literature is reviewed, and a discussion on the topic is provided in the following sections.

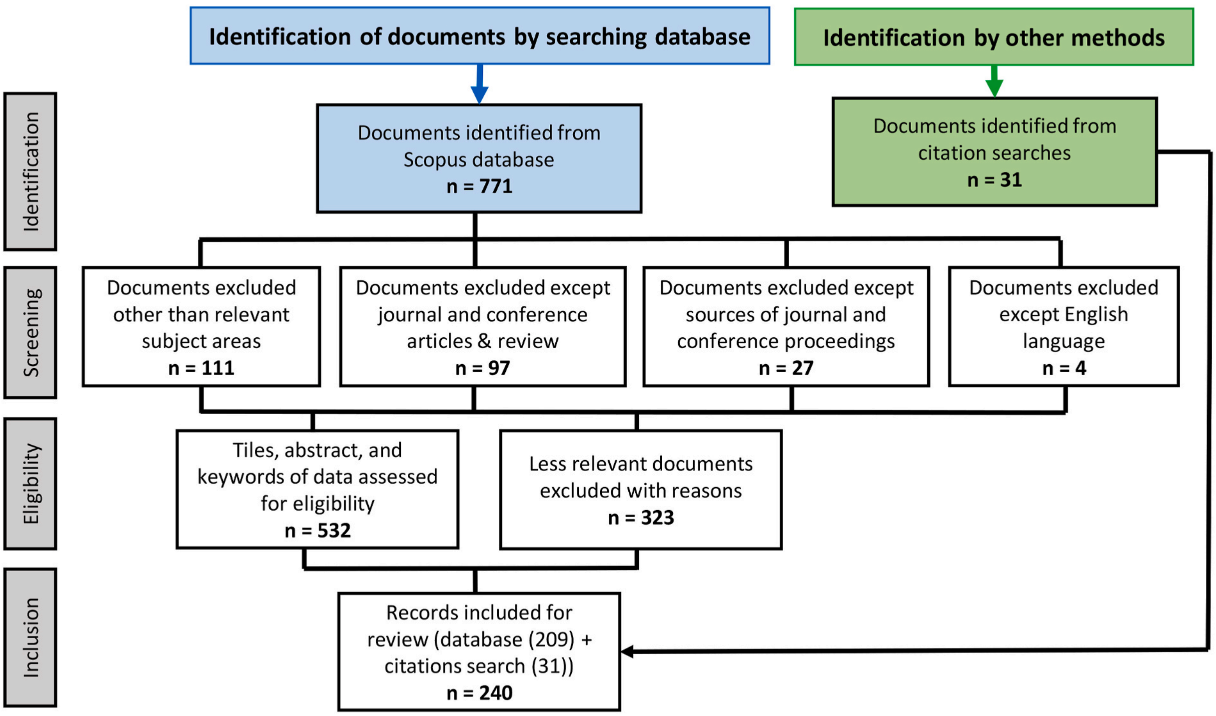

Fig. 2. PRISMA flow diagram of the data retrieval and selection criteria.

3. Overview of biocomposites

Composites comprise multiple constituents mixed to produce a material with improved characteristics compared to its individual raw materials. Biocomposites often have different phases, including reinforcement and matrix. The former gives load-bearing strength, while the latter phase bonds the reinforcement. A biocomposite is manufactured by incorporating a biological/natural substance as the reinforcing material (biofibres or fillers), while the matrix can either be a biopolymer or synthetic polymer that functions as a binder [30,31]. The matrix and reinforcement function in a synergic way, delivering superior qualities compared to the separate constituents [32,33]. In the construction industry, based on the type of constituents used, biocomposites are mainly classified as polymer-based [34], mineral/cement-based [35], alkali-activated, and geopolymer biocomposites [36], as shown in Fig. 3. The subsequent sub-sections include a detailed description of the biocomposite types, their raw materials, fabrications methods, properties, and applications.

3.1. Polymer-based biocomposites

A polymer is a material composed of several molecules with high molecular masses. A polymer is formed by the repeated unit of a monomer chain, which can occur naturally (natural or biopolymer) or be produced artificially (synthetic polymer) [37].

3.1.1. Biopolymers

A biopolymer is a class of polymer that is formed from natural sources, typically from biomass, and it has the potential to be either partially or completely renewable [37,38]. Three categories of biopolymers can be distinguished according to their origin and method of synthesis, as listed in Table 1. Natural materials like proteins and carbohydrates or monomers like lactic acid may be used as raw materials for biopolymers. Moreover, other biopolymers, including polyhydroxyalkanoates (PHA), are potentially derived from microorganisms [39]. Some of the categories into which commercially available biopolymers fall include Polyhydroxyalkanoates (PHAs/PHBs), polyamides, polylactic acid (PLA), bio-polyethylene terephthalate (PET), polyols, cellulose acetate, and butyl rubber [40].

3.1.2. Fabrication of polymer-based biocomposites

Fabrication refers to the process by which composites of specific size, shape, and properties are produced from raw materials, including resin/binder and fillers [50]. Fig. 4(a)–(d) shows various types of fillers used to produce biocomposites, and Fig. 5 exhibits an example of a biocomposite sample made from bamboo fibres. The characteristics of biocomposites are significantly impacted by fabrication techniques and processing conditions. In order to determine a suitable method for producing biocomposites, the designer must consider a range of factors, including desired properties, fabrication rate, product dimensions, fabrication expense, and handling techniques [7]. Table 2 provides an overview of the benefits and limitations associated with various widely used manufacturing methods for biocomposites. Fig. 6 shows the hemp-polymer composite fabrication steps using the hand lay-up technique.

3.1.3. Properties of polymer-based biocomposites

The most studied characteristics of biocomposites include their thermal behaviour, morphology, rheological properties, mechanical properties, water absorption capacity, and acoustic properties [55–61]. Table A1 lists the properties of polymer-based biocomposites reviewed. It was noted that most of the studies conducted focused on mechanical strength, density, water absorption,

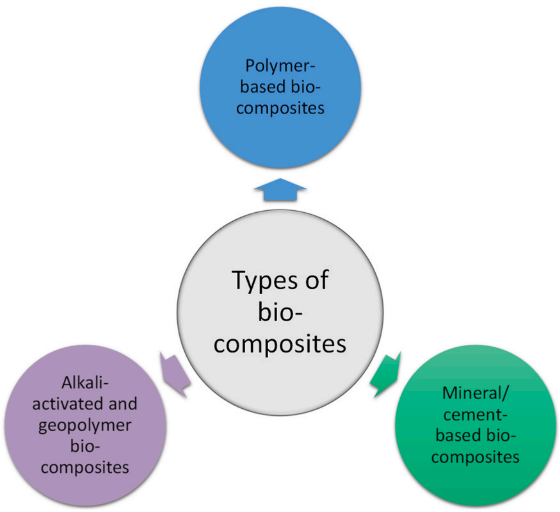

Fig. 3. Types of biocomposites for construction applications considered in the present study.

Table 1
Categories of biopolymers based on origin and method of synthesis.

Reference	Biopolymer type	Chemical group	Examples
[41–43]	Polymers derived via microbial fermentation	PHA	• Polyhydroxybutyrate-cohydroxyvalerate (PHBV) • Polyhydroxybutyrate (PHB)
[44–46]	Biomass-based polymers	Proteins and lipids Polysaccharides	• Cellulosic and lignocellulosic materials (wood, straws, etc.) • Carbohydrates (potatoes, wheat, maize, etc.) • Whey, casein, collagen/gelatin from animals • Pectins (chitosan/chitin, gums, etc.) • Plants (zein, gluten, soya)
[47–49]	Agro-source monomers are employed to manufacture polymers	Polyhydroxy acids	• Polyglycolic acid (PGA) • Polylactic acid (PLA)

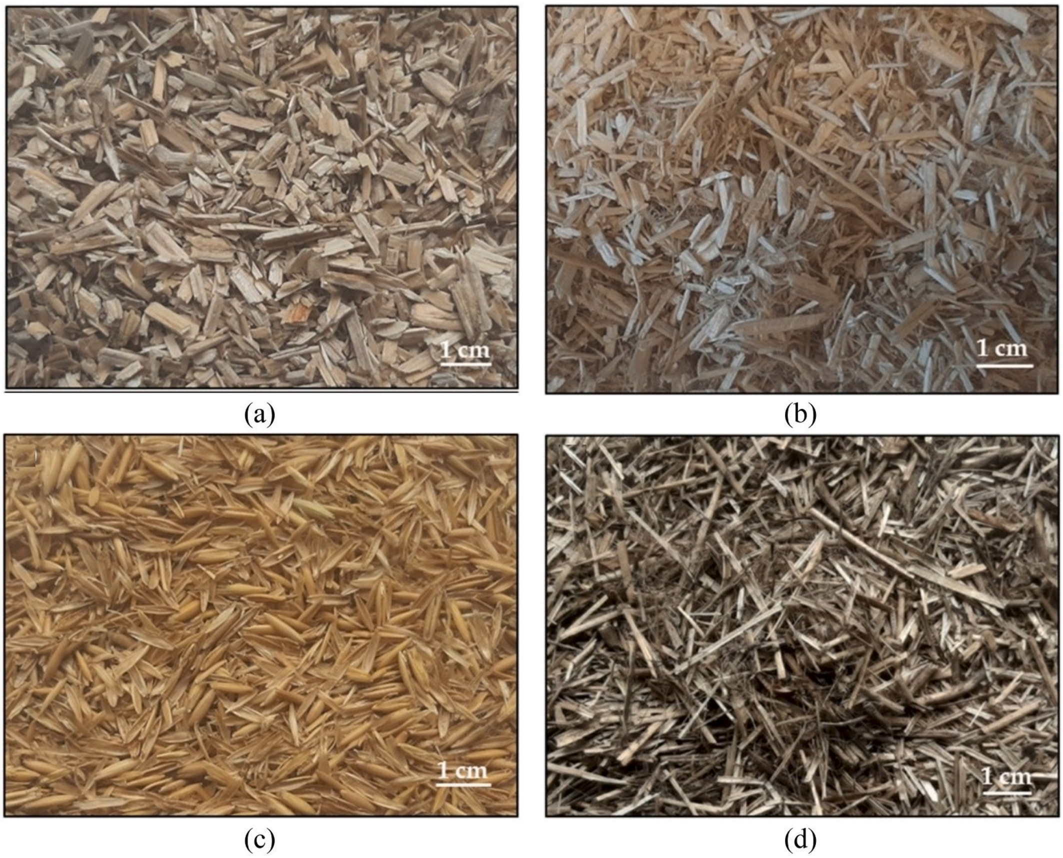

Fig. 4. Bio-based filler materials used for fabricating biocomposites: (a,b) hemp shives; (c) oat husk; (d) flax shives [52].

thermal conductivity, and acoustic properties of biocomposites.

3.1.3.1. Density. The density or unit weight of composites holds significant importance in several aspects of construction projects, including structural design, material selection, load estimate, and comprehension of material behaviour. This aids in determining mass per unit volume, facilitating the assessment of safe load-bearing capability, and optimising resource allocation [62]. As displayed in Table A1, the density of polymer-based biocomposites varies from 28.1 kg/m^3 to 1600 kg/m^3, depending on the types of fillers and matrices used. Palumbo et al. [63] observed that hemp fibre composites exhibited the lowest density of 41.1 kg/m^3, followed by corn pith (48.1 kg/m^3), wood wool (60.2 kg/m^3), barley straw (107.5 kg/m^3), and wood fibre (212.2 kg/m^3). Nechita and Ionescu [16] found that the density of samples increased as the dosage of lignocellulosic residue rose, and samples containing starch had a greater density than those without, as starch filled the cavities, resulting in a denser structure. Other studies also found an increasing density of biocomposites with increasing starch [64,65]. The influence of higher filler or fibre dosage on the density of biocomposites was found to be increasing by several studies [60,66–71]. However, using a higher quantity of wood chips with biochar decreased the composite density, which might be due to the increased size and reduced unit weight of wood chips used [72]. Therefore, due to the decreased

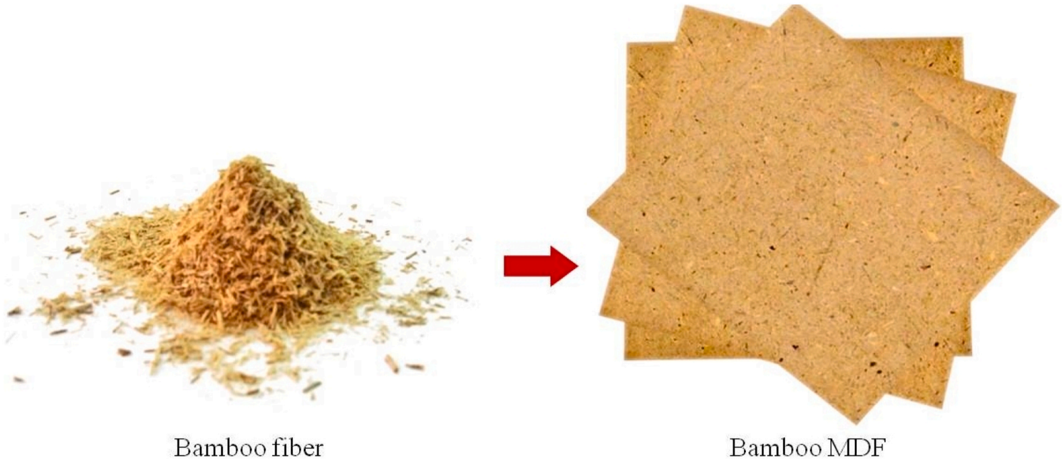

Fig. 5. Bamboo fibre and Medium Density Fibreboard (MDF) made of bamboo fibre [53].

Table 2
Biocomposite fabrication methods with their benefits and drawbacks [7,51].

Method	Benefits	Drawbacks
Spray Lay-Up	Economical	Not appropriate for precise sizes and process reiteration
	Reduced cost tools used	Rely greatly on operator skill
	Less expensive material processing	Rough surface finish on one side
	Appropriate for small to medium-scale products	Not appropriate for high structural prevision
		Low viscosity resins are required
		Not suitable for long fibres
		Fibre quantity and geometry are challenging to control
Wet/Hand Lay-Up	Reduced cost tools used	Composite quality relies on operator skill
	Easy process to perform	Low viscosity resins are required
	Versatile to distinct combinations of materials	Non-uniform resin dispersal in the matrix
	Increased fibres proportions might be used	Hazard and safety issues
	Possibility of using long fibres	Increased porosity of the composite
Filament Winding	Quick processing method	Low viscosity resins are required
	Economical	Restrained to convex shape products
	Enhanced load bearing structure	Expensive tools
	Proportion of resin is controlled by dies or nips	Less smooth external finishing
Autoclave Curing	Uniform dispersal of resin within the matrix	Expensive tools
	Controlled dilution of resin	Higher processing and maintenance expenses
	Smooth finishing	Not appropriate for small components
	Appropriate for large-scale applications	
Pultrusion	Quick and economical	Heating die expenses might be higher
	Controlled resin proportion	Limited to products with smaller cross-sections
	Reduced fibre cost	Restrained to uniform cross-section components
	Smooth finishing	
	Enhanced structural performance	
	Appropriate for large-scale applications	

density of biocomposites compared to traditional construction materials (mortar and concrete), their application for lightweight construction is feasible.

3.1.3.2. Compressive strength. The compressive strength (CS) of composites determines the maximum compression a material can withstand before failure. This property is critical for guiding the selection of materials and the design of structures and load-bearing building elements. The CS of a composite is directly or indirectly linked to various mechanical and durability characteristics [73]. As listed in Table A1, polymer-based biocomposites mostly exhibit lower CS, which might be the main reason limiting their applications to insulation purposes. It has been observed that increasing biofibre or filler dosage in biocomposites led to a decrease in CS [66,68,70,71,74]. The increased fibre content made the cell structure more porous, which, in turn, can lead to a decrease in the cross-linking density of the matrix and consequently compromise the composite strength [70]. In contrast, increasing the dosage of certain biofibres, including hemp, jute, and date, improved biocomposites' CS [75]. The increase in CS is ascribed to the better mechanical properties of natural fibres, which vary according to the specific type of fibre, and the filler action of powder that made the matrix more compact [75]. It was noted that increasing the starch proportion in hemp shive (25 mm and 40 mm) biocomposites led to higher CS. Also, composites comprising smaller-length hemp shives (25 mm) resulted in a higher CS (0.56–1.70 MPa) compared to longer shives (40

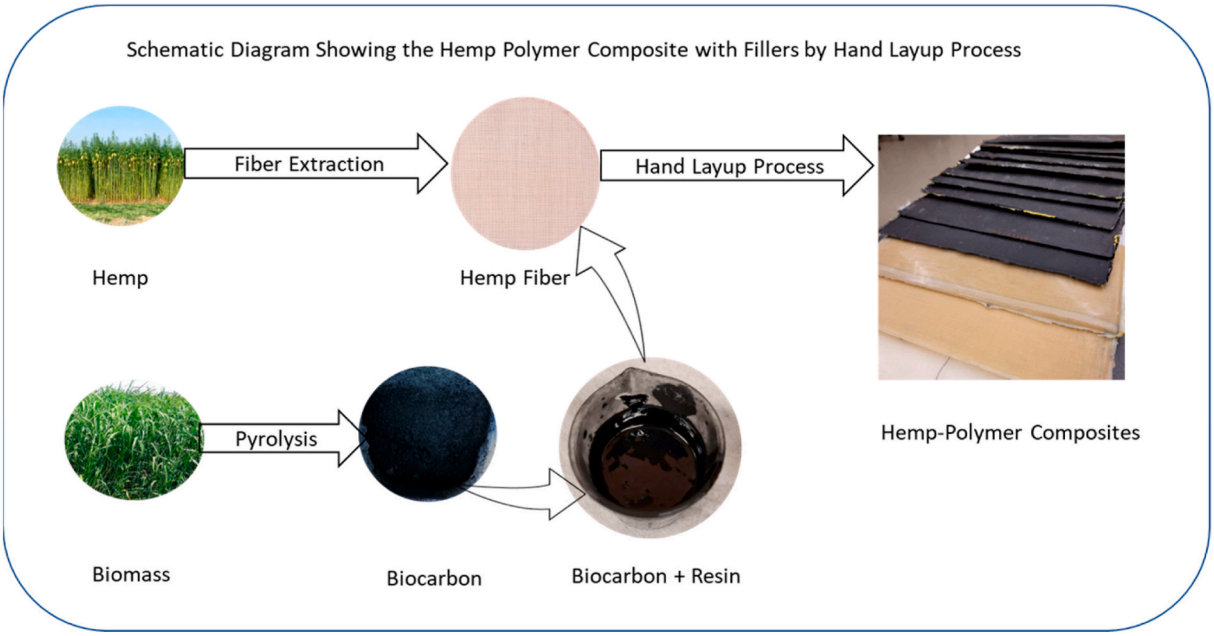

Fig. 6. Hemp-polymer composite preparation using hand lay-up process [54].

mm), which yielded a CS of 0.60–1.40 MPa. This increase is likely attributed to the dense structure of composites with smaller hemp shives [76].

3.1.3.3. Tensile strength. Tensile strength (TS) is also an important mechanical property of composites as it determines tensile stress, deformation, size, and number of cracks that a material may endure while maintaining structural integrity [77]. Limited studies were observed on the TS of polymer-based biocomposites in the retrieved literature. These studies reported a decrease in TS of biocomposites with increasing biofibre or filler content [60,68,69]. An increase in the PLA proportion as a binder from 20 wt% to 80 wt% in sugar palm nanocellulose fibre composites increased the TS from 2.35 MPa to 19.45 MPa [64]. The silane pretreatment of date palm wood fibres showed a favourable impact on the TS of biocomposites with a PLA binder [60]. The fibres are coated with a polysiloxane layer, which improves the compatibility between the polymer matrix and the treated fibre, causing an improvement in TS [78]. The TS of biocomposites needs further exploration for better understanding.

3.1.3.4. Flexural strength. Flexural strength (FS) is another critical characteristic to consider during the design process of composite structures, as it significantly influences the materials' brittleness ratio, flexural fracture, shear strength, and deflection properties [79]. Some studies have reported a decrease in the FS of biocomposites with increasing biofibre or filler dosage [69,72,74]. In contrast, a study's test results showed improvement in FS with increasing hemp, jute, and date fibre proportions from 10 wt% to 30 wt% [75]. Biofibre or filler pretreatments with silane and NaOH solution showed a positive impact on the composite's FS [70,74]. The increase in FS can be attributed to the increased interfacial interaction between the matrix and pretreated fibres or fillers and their uniform dispersion [80]. Among the grape pomace, stalks, skins, and crushed stalks used as fillers with starch to produce biocomposites, the crushed stalks biocomposites exhibited the highest FS of 0.61 MPa [81]. Similar to TS, the FS also increased from 3.76 MPa to 35.38 MPa with increasing PLA concentration from 20 wt% to 80 wt% [64]. Although treatments such as silanisation and NaOH and some fibre types have demonstrated potential in improving FS, the research indicates that higher levels of some biofibres or fillers tend to reduce FS, emphasizing the need for balanced composite compositions.

3.1.3.5. Water absorption. The water absorption of biocomposites is a crucial factor as it can significantly affect the material characteristics and structural integrity. Excessive water absorption can lead to swelling, degradation, and weakening of the biocomposite, compromising its long term performance [82]. Understanding and mitigating water absorption is essential in ensuring the stability and dependability of biocomposites for construction, particularly in conditions susceptible to moisture exposure or varying weather patterns. According to previous research (see Table A1), the water absorption capacity of biocomposites varies considerably, depending on the type, size, content, and pretreatment of biofibres or fillers, as well as the type and concentration of binders. Normally, with an increase in the proportion of biofibres or fillers, the water absorption of biocomposites increases, likely due to their hydrophilic nature [16,70]. Using silanised walnut shell powder filler resulted in decreased water absorption of composites (11.7 % at 5 wt% of powder) compared to untreated (15.0 % at 5 wt% of powder) [70]. Considering the impact of binder proportion, it was found that an increase in the binder proportion reduced the water absorption of biocomposites [64,72,76]. As an example, increasing PLA proportion from 20 to 80 wt%, the water absorption of biocomposites reduced from 61.42 % to 5.70 % [64]. Using smaller-size hemp shives (25 mm) increased the water absorption capacity of biocomposites compared to the larger-size hemp shives (40 mm) [76]. However, there is a need for further research on the size impact of shives/fibres on the water absorption of biocomposites.

3.1.3.6. Thermal conductivity. The thermal conductivity analysis of biocomposites determines their insulating capacity within the building envelope. Biocomposites exhibiting low thermal conductivity can enhance indoor comfort, decrease operational expenses, and reduce heating and cooling demands, thereby contributing to energy efficiency [54,83]. Generally, biocomposites show low thermal conductivity (see Table A1) compared to traditional construction materials like clay bricks (0.39–0.63 W/mK [84]), wood (0.11–0.28 W/mK [85,86]), and concrete (0.60–3.30 W/mK [87,88]), making them suitable for thermal insulation applications. It can be inferred that the thermal conductivity of biocomposites is directly proportional to their density, with low-density biocomposites having the lowest thermal conductivity [16,63,65,70,81,89,90]. Higher biofibre or filler proportions have been shown to increase the thermal conductivity of the composite [16,69,70,75]. However, pretreatment of biofibres or fillers can help control the thermal conductivity even at higher proportions, as observed in silanised walnut shell powder composites [70]. Also, increasing the binder proportion in biocomposites showed a positive influence on thermal insulation [64,72,76]. Smaller-size hemp shive (25 mm) composites showed comparatively lower thermal conductivity than longer ones (40 mm) [76]. However, regarding the shives/fibres size influence on the thermal conductivity of biocomposites, the current literature lacks the in-depth studies required for a clear understanding.

3.1.3.7. Acoustic properties. Acoustic properties, such as sound absorption coefficients and sound reduction index, are critical in evaluating building materials' effectiveness in noise control and sound insulation. Materials with high sound absorption coefficients can significantly reduce noise levels within spaces, enhancing occupant comfort and productivity [91]. Fibre type, size, and porosity significantly influence the acoustic efficiency of biocomposites, with porous and longer fibres being more effective [92]. Abaca, cabuya, coir, and totora fibres, coir fibres (60 and 40 mm) exhibited promising sound absorption coefficients of up to 0.95 due to their greater thickness and porosity [92]. Wheat straw oriented strand board exhibited a higher sound reduction value of 35.2 dB compared to commercial oriented strand board (34 dB) due to the sound-absorbing capability of wheat straw compared to wood [30]. Another study showed that the part of the plant used in the biocomposite greatly impacts its sound absorption coefficient [22]. Also, among the various biofillers, (grape pomace, skins, stalks, and crushed stalks with a starch binder), grape stalk biocomposites exhibited the highest sound absorption capability [81]. Typically, increasing the biofibre or filler content in the mix improves the sound absorption capacity [68,69,93]. These findings emphasise that fibre type, thickness, porosity, and biofiller content play a crucial role in enhancing the acoustic efficiency of biocomposites, making them promising sustainable alternatives for sound insulation applications.

3.1.4. *Applications of polymer-based biocomposites*

In recent years, stricter regulations, social and economic considerations, and the growing emphasis on sustainable products by consumers and manufacturers have contributed to the substantial expansion of the global biocomposite market [94]. The market outlook for biocomposites and, consequently, their application domains are influenced by several factors: the availability of renewable resources and raw materials, the scalability and simplicity of manufacturing, biodegradability characteristics (durability, end-of-life treatment, and degradation conditions), and the associated costs [95–100]. Furthermore, there has been a significant increase in demand for biocomposites across various industrial sectors, including, but not limited to, food [101,102], agriculture [103], medical and pharmaceutical [104], textile [105], construction industries [103,106,107] as well as in armour [108] applications. In the construction sector, the potential applications of polymer-based biocomposites include thermal insulation, soundproofing, 3D/4D printing, coatings, lightweight, and retrofitting [109–118]. Figs. 7–9 display products of polymer-based biocomposites used in construction applications.

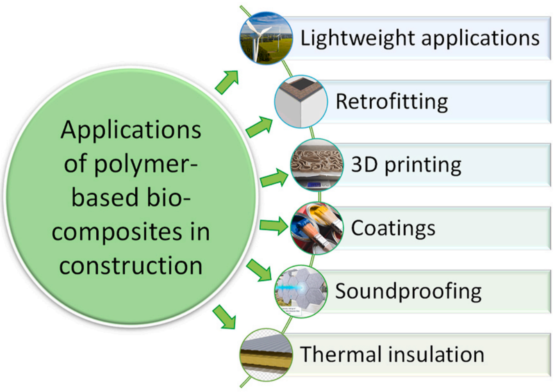

Fig. 7. Construction applications of polymer-based biocomposites.

3.2. Mineral/cement-based biocomposites

Mineral-based biocomposites are produced using biomaterials as raw materials combined with an appropriate matrix or binder. Organic matrix composites, such as oriented strand boards (OSB), fibre boards, and particleboards, differ from inorganic mineral matrix composites by the composition of their matrices. For the latter, materials like ordinary Portland cement (OPC), magnesia, or gypsum are widely used in the construction sector, particularly in reinforced panels and structures. This section, however, focuses on inorganic mineral binder-derived composites designed for construction applications.

3.2.1. Natural fibres for mineral/cement-based biocomposites

Instead of synthetic fibres, natural fibres such as coconut, bagasse, jute, hemp, bamboo, coir, wool, palm, banana, and sisal can be used in cementitious composites [92,120]. However, natural fibres also have certain challenges, such as (i) limited compatibility with matrix materials, (ii) inconsistency in material properties, (iii) concerns about durability, and (iv) reduced workability of fresh mixtures when higher fibre concentrations are used [120–122]. Table 3 lists the characteristics of various natural fibres, while Fig. 10 shows some of the fibre types used in mineral/cement-based biocomposites.

3.2.2. Production of mineral/cement-based biocomposites

Mineral/cement-derived composites are typically processed under ambient temperature conditions using compaction techniques (often by vibration, similar to concrete) or pressure casting. In some cases, additional heat may be applied during curing [125]. Matrix and fibres are combined in various ways to produce biocomposites. The manufacturing process, in addition to the choice of fibre and matrix materials, significantly influences the final properties of the biocomposites. The following key objectives must be achieved to create biocomposites with desirable mechanical properties: (i) the matrix should exhibit uniform fibre distribution; (ii) the bond between fibres and the matrix should be strong enough to prevent fibre pull-out; (iii) the matrix should have low porosity; and (iv) an optimal fibre percentage should be used to reinforce the composite while maintaining the matrix's uniformity [120].

The literature outlines two primary approaches for producing mineral/cement-based biocomposites based on the shape of the fibres: random dispersion of fibres within the matrix or alignment of fibres/fibrous structures [120]. Some researchers have used layering procedures to achieve uniform fibre dispersion in cement-based composites [126,127]. The predominant techniques for manufacturing mineral/cement-based biocomposites with natural fibres in pulp form are derived from the Hatschek method, patented in 1900 [128]. This semi-continuous process involves sheet and board formation, followed by curing, as shown in Fig. 11 by Ref. [129]. The technique results in composites with a well-distributed proportion of fibres throughout the matrix. Fig. 12 displays a schematic of the magnesium-based biocomposite production process [125], while Fig. 13 shows biocomposite specimens produced for various tests in previous research [130].

3.2.3. Properties of mineral/cement-based biocomposites

The retrieved literature was analysed to assess the properties of mineral/cement-based biocomposites. Table A2 presents the biocomposite properties examined in this study, focusing on density, mechanical strength, water absorption, thermal conductivity, and acoustic properties. The following sub-sections provide a summary of these biocomposite properties.

3.2.3.1. ***Density***. The density of mineral/cement-based biocomposites depends on several factors, including the type, size, density, pretreatment, and proportion of biofibre and filler. Most studies reported a reduction in composite density with an increase in biofibre or filler [35,132–139]. However, some studies observed an increase in the density of biocomposites with increased biofibre or filler [140,141]. This variation may be attributed to the distinct types and densities of biofibres or fillers used. Regarding the size of biofibres or fillers, it was noted that smaller size materials generally resulted in a higher density of biocomposites compared to larger ones [35,133]. Hydrothermal treatment of biofibres or fillers led to a reduction in the density of biocomposites [141], whereas the use of viscosity modifying agents (VMA) and higher binder content increased the density [142–144]. Overall, the lower density of mineral/cement-based biocomposites compared to conventional building materials highlights their potential for lightweight construction applications.

3.2.3.2. Compressive strength. The compressive strength (CS) of biocomposites (see Table A2) was analysed with respect to biofibre or

Fig. 8. Bamboo-based biocomposite products for construction applications [53].

Fig. 9. 3D printed seashell-based biocomposites [119].

Table 3
Properties of various natural fibres [123].

Fibre type	Density (g/cm^3)	TS (MPa)	Elastic modulus (GPa)	Ultimate elongation (%)
Sisal	1.34–1.45	280–750	13–26	3.0–5.0
Wool	1.3	160	3.5	–
Coconut	0.87–1.4	120–200	19–26	25.0–10.0
Abaca	1.5	400–980	6.2–20	1.0–10
Cotton	1.5–1.6	390–600	5.8–11	6.0–10
kenaf	1.4	223–930	14.5–53	1.5–2.7
Bagasse	1.3	222–290	17–27	1.1
Flax fabric	1.5	500–1500	50–70	–
Coir	1.15–1.46	95–230	2.8–6.0	15–51.4
Bamboo	0.6–1.1	140–800	11.0–32	2.5–3.7

filler content, size, type, and pretreatment. The literature revealed that increasing the biofibre or filler content generally resulted in a reduction in CS [35,132,133,135,136,138,139,141,145–147]. For instance, Boubaaya et al. [145] reported that increasing the content of date palm fibre in mortar from 6 wt% to 30 wt% reduced the CS from 29.0 MPa to 7.0 MPa. The decrease in CS with increasing biofibre or filler content may be due to reduced particle packing density and the weaker mechanical properties of bio-based materials [132]. In contrast, Sophia and Sakthieswaran [140] found an increase in CS when cuttlebone and scallop shell powder were used in gypsum plaster. The size of biofibres or fillers also plays a role, with smaller sized particles resulting in higher CS [35,133]. Smaller particles are better coated by the binder, resulting in higher density and consequently improving CS [133]. Pretreatment of biofibres or fillers, VMA, and higher binder contents also increased the CS of biocomposites [141–143]. Although higher biofibre or filler tends to reduce CS, the use of bio-based powder in gypsum plaster, smaller particle sizes, and VMA can improve CS. Further research is recommended to optimise biocomposite formulations for structural applications.

3.2.3.3. Tensile strength. The analysis of various studies showed an inconsistent impact of different types and sizes of biofibres or fillers on the tensile strength (TS) of biocomposites. Mathavan et al. [148] observed that plant fibres (cotton and silk) resulted in higher TS compared to organic fibres (wool and silk) in mortar, and an increase in fibre content led to a decrease in TS. A similar reduction in the TS with increasing date palm fibre content in mortar was also noted in another study [149]. With varying fibre lengths, shorter fibres (6–12 mm) performed best at 2 wt% and longer fibres (18 mm) at 3 wt% [150]. Although some studies demonstrate higher TS with specific fibre types or sizes, others show reductions, highlighting the significant influence of factors such as fibre content and size on TS. This underscores the potential for future research in this area.

3.2.3.4. Flexural strength. An analysis of the FS results from the literature, as listed in Table A2, indicates that most studies report a decrease in the FS of biocomposites with increased biofibre or filler content [132,135,136,138,139,149]. However, some studies found a positive effect of increasing biofibre or filler content on FS [140,148,150]. The use of cuttlebone and scallop shell powder in gypsum plaster increased FS [140]. Regarding the length of the biofibre, 18 mm fibres showed higher FS at 1 and 2 wt% and 6 mm fibres at 3 wt % [150]. An increase in binder proportion from 199 to 532 kg in the mix increased the FS of rice husk concrete from 0.35 MPa to 1.90 MPa [143]. The FS of biocomposites is influenced by the amount and length of biofibre or fillers. While most studies indicate that increasing content reduces FS, some exceptions show positive effects. Further research is required to better understand the role of fibre length and content in determining FS.

3.2.3.5. Water absorption. The water absorption of biocomposites generally increases with higher biofibre or filler content [138,141,145,148]. This increase in water absorption of biocomposites is likely due to the higher void ratios formed by the increased biofibre or filler content. However, some studies reported improved resistance to water absorption with higher biofibre or filler contents up to a certain level [139,140,149]. A study on the impact of biofibre length on water absorption found that 12 mm long hemp fibres exhibited

Fig. 10. Types of plant fibres for biocomposites production [124] reproduced with permission from Elsevier (license number 5982500265518).

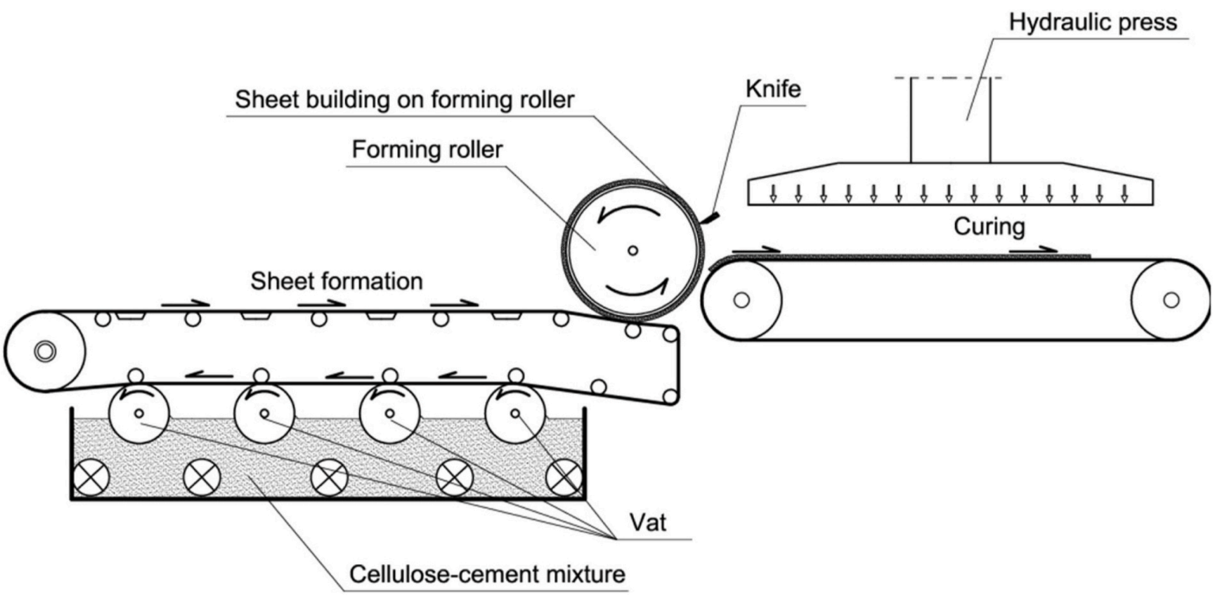

Fig. 11. Schematic illustration of Hatschek process [129] reproduced with permission from Elsevier (license number 5982500532962).

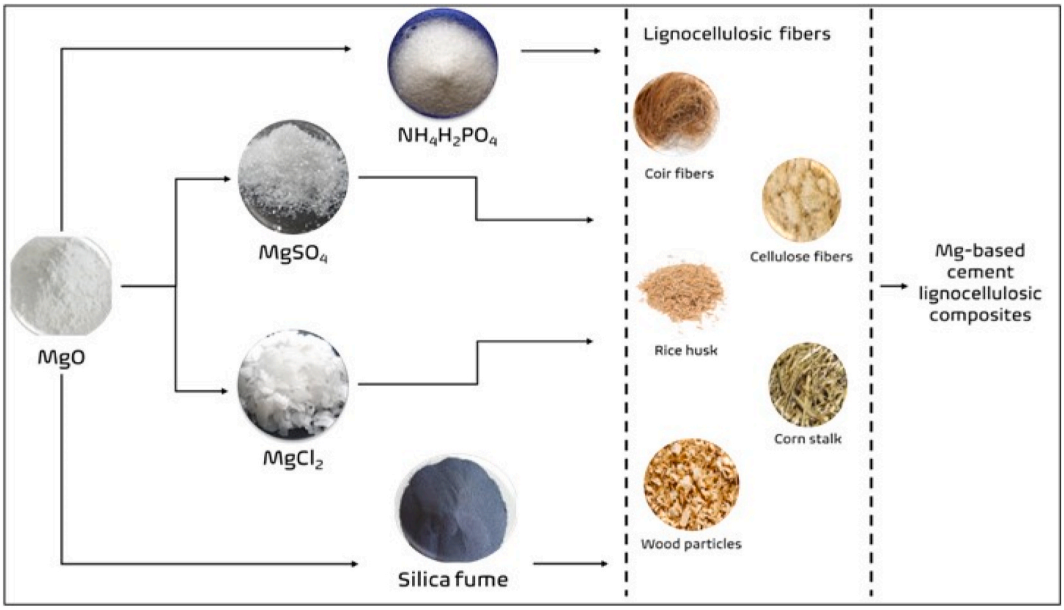

Fig. 12. Illustrative schematic of the manufacturing process for magnesium-based biocomposites [125].

(a) (b)

Fig. 13. Biocomposite specimens: (a) hemp-lime [131]; (b) sugarcane bagasse ash-lime [130].

the highest resistance to water penetration compared to 6 and 18 mm fibres [150]. Additionally, several studies highlighted that the pretreatment of biofibres or fillers and VMA significantly enhanced water absorption resistance [141,142,149]. Hence, understanding the relationships between material type, size, and pretreatment is of the utmost importance for optimising biocomposite formulations for moisture resistance.

3.2.3.6. Thermal conductivity. The thermal conductivity pattern of mineral/cement-based biocomposites closely aligns with their density. Low-density biocomposites exhibited lower thermal conductivity values (see Table A2), contributing to improved thermal resistance. The literature consistently shows that increasing the biofibre or filler content decreases the thermal conductivity of biocomposites [35,132,134,135,137–139,141,145,146,151]. The use of small corn stalks resulted in biocomposites with a higher thermal conductivity compared to large corn stalks [35]. Hydrothermal pretreatment of bio-fillers exhibited the same effect on thermal conductivity as it did on density, leading to an increase in thermal conductivity following pretreatment [141]. Similarly, using VMA and higher binder content in biocomposites led to an increase in thermal conductivity due to the denser structure formed [142–144]. Mineral/cement-based biocomposites display better thermal properties compared to traditional cement-based composites (0.60–3.30 W/mK [87,88,152]). However, while higher biofibre or filler content improves thermal resistance, it can negatively impact strength and water absorption. Therefore, careful material selection is necessary to balance performance for specific applications.

3.2.3.7. Acoustic properties. Mineral/cement biocomposites' sound absorption coefficient varies widely (0.3–0.9), influenced by biofibre or filler type, content, binder type, compaction, surface permeability, and production technique [9,153]. Hempcrete generally outperformed traditional concrete in sound absorption, especially with smaller hemp shives and lime pozzolanic binders [154,155]. The quantity of bio-based material significantly influences acoustic performance relative to the binder used [156]. An increased compaction pressure during manufacturing led to reduced sound absorption for lower epoxy content but improved when epoxy content was higher due to differences in void distribution [157]. Using gypsum instead of epoxy increased the acoustic performance of corn stalk biocomposites, with higher gypsum content enhancing sound attenuation. Porosity played a key role in improving noise reduction, making gypsum an effective binder for acoustic applications [157]. Also, a higher quantity of hemp shives and miscanthus fibres resulted in a higher sound absorption coefficient due to more interconnected pores [136,158].

3.2.4. Applications of mineral/cement-based biocomposites

Recently, there has been growing interest in utilising plant fibres in construction materials, particularly in partition boards of varying dimensions and densities, as well as for their resistance to fire and insects. Biocomposites, due to their aforementioned properties, offer wide-ranging applications in the construction sector. Gypsum and magnesia-bonded biocomposites are primarily suited for interior applications due to their susceptibility to moisture; however, more resilient OPC biocomposites are applicable for both interior and exterior uses [125]. However, due to the lower mechanical strength of biocomposites compared to concrete and bricks, they have limited use in structural applications and are more typical in non-structural construction applications in buildings, such as non-load-bearing walls, insulation, tiles, railings, partition boards, coatings, 3D printing, and window and door frames [4,157, 159–171]. Fig. 14 illustrates various applications of mineral/cement-based biocomposites in construction, while Fig. 15 shows an example of hempcrete wall construction using mortar-less interlocking blocks [172].

3.3. Alkali-activated/geopolymer biocomposites

3.3.1. Alkali-activated and geopolymer binders

Cementitious binders that are alkali-activated (AA) are produced by activating aluminosilicates using extremely alkaline solutions. Due to their reduced environmental impact, AA cement is often chosen as an alternative to OPC. Furthermore, in terms of energy efficiency, resilience, and resistance to high temperatures, AA cement is universally acknowledged to have advantages over Portland cement [173]. Geopolymers have emerged as an environmentally sustainable and low-embodied energy alternative to traditional building materials. They can be produced using natural pozzolanic materials, industrial waste streams, slag, fly ash, metakaolin, silica fume, and calcium or magnesium-containing minerals [174–177]. The scientific community is divided regarding whether geopolymers should be classified as a subset of alkali-activated materials (AAMs). AAMs are "the widest classification, encompassing essentially any binder derived via the reaction of a solid or dissolved alkali metal source with a solid silicate powder," as stated in the state-of-the-art report by RILEM [178]. AA and geopolymer (GP) composites are discussed together for this study and collectively referred to as AA-GP composites.

3.3.2. Production of AA-GP biocomposites

The production of AA-GP composites requires precursor materials rich in aluminosilicates. Various natural materials and industrial and agricultural wastes, such as metakaolin, fly ash, slag, silica fume, and rice husk ash, contain suitable aluminosilicate content for producing AA-GP [179]. To fabricate AA-GP biocomposites, an alkali-activator solution is required to be formed by combining sodium silicate (Na_2SiO_3) with sodium/potassium hydroxide (NaOH/KOH), which reacts with a precursor material to form a binder. Bio-based materials (like plant fibres) are mixed with a binder and aggregates to produce biocomposites [52]. In some cases, initial curing at

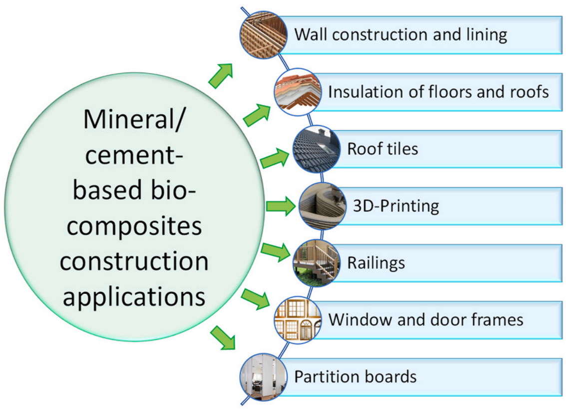

Fig. 14. Applications of mineral/cement-based biocomposites in the construction sector.

Fig. 15. Hempcrete mortar less interlocking block construction [172].

elevated temperatures (heat/steam curing) is necessary to achieve the desired strength [125]. Fig. 16 depicts the manufacturing procedure for AA-GP biocomposites, showing the required constituents, including alkali activators and aluminosilicates.

3.3.3. Properties of AA-GP biocomposites

To analyse the variation in the properties of AA-GP biocomposites with respect to biofibre or filler type, content, size, and pre-treatment, Table A3 has been constructed. TS and acoustic properties were not included in the subsequent discussion due to insufficient data available in the literature.

3.3.3.1. Density. Similar to other biocomposites discussed earlier, increasing biofibre or filler content in AA-GP biocomposites generally resulted in a decrease in density (see Table A3) [180–187]. For example, Che et al. [181] reported a decrease in density from ~1600 to 1250 kg/m^3 when the sorghum fibre proportion in fly ash-based AA-GP biocomposites increased from 1 wt% to 3 wt%.

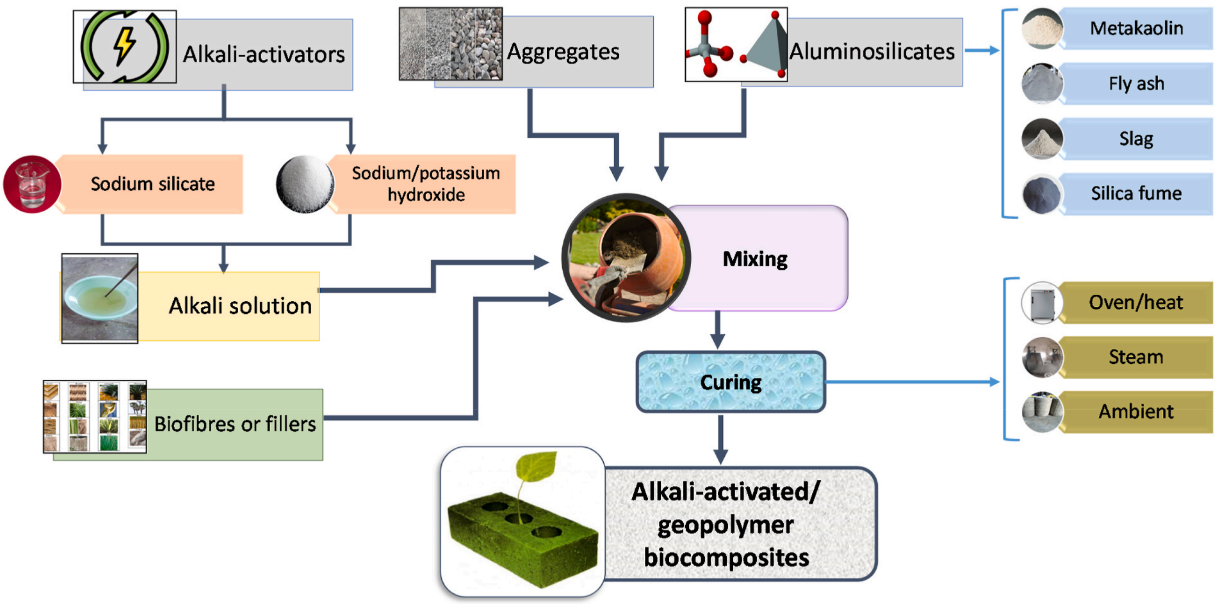

Fig. 16. Manufacture process of alkali-activated/geopolymer biocomposites (reproduced with modifications from Ref. [179]).

Regarding the size of biofibres, Zhou et al. [187] reported that smaller cotton stalk fibres resulted in a denser biocomposite compared to medium and large sized fibres. Among the different biofibre pretreatment methods explored [187,188], only NaOH treatment significantly reduced the density from 1870 to 1900 kg/m^3, while other pretreatments had negligible effects on density.

3.3.3.2. Compressive strength. Mostly, increased biofibre or filler content negatively impacted the CS of AA-GP biocomposites [181, 183,186,189]. However, some studies demonstrated an increase in CS with increasing biofibre or filler content [182,184,190]. Biofibre or filler size, also impacts CS. Zhou et al. [187] noted that smaller corn stalk fibres (L = 10–30, D = 0.5–1 mm) yielded higher CS compared to medium (L = 20 ± 2, W = 4 ± 0.5, T = 1 ± 0.5 mm) and larger size fibres (L = 20 ± 2, W = 2 ± 0.5, T = 1 ± 0.5 mm). Additionally, corn stalk powder with 0.7 wt% resulted in the maximum CS of ~27 MPa with medium size particles (0.25–0.5 mm), compared to small size (0.1–0.25 mm) and large size (0.5–1 mm) particles [187]. Most biofibre or filler pretreatments, including NaOH [185,187,188], hydrothermal [189], polyvinyl acetate [187], Na_2SiO_3, $CaCl_2$, silane, water, NaOH + ultrasonic treatments [188], resulted in an increase in CS. However, engine oil pretreatment was found to decrease CS [187].

3.3.3.3. Flexural strength. The effect of biofibre or filler content on the FS of AA-GP biocomposites showed inconsistent trends. Some studies reported an increase in FS with higher biofibre content [182,191], others noted a decrease [184,187], and some observed an optimum biofibre or filler content [180,181,186]. This variability is likely due to differences in the types and sizes of biofibres or fillers used. The increase in FS due to fibre incorporation can be attributed to the fibres' ability to resist flexural stresses and crack propagation, while the decrease in FS, especially at higher fibre contents, may be due to the formation of voids and a more heterogeneous composite [180]. The effect of biofibre or filler size on the FS followed a similar pattern to that observed for CS [187]. Additionally, pretreated biofibres or fillers increased the FS of biocomposites due to improved bonding with the matrix [185,188,189].

3.3.3.4. Water absorption. Water absorption of AA-GP biocomposites increased at higher biofibre or filler dosage [184,186,187]. Kielė et al. [186] reported that water absorption of slag-based AA-GP composites increased from 10.75 % to 25.27 %, with increased wood shaving content from 3.5 % to 10.1 % due to the higher water absorption capacity of wood shavings. The impact of cotton stalk fibre size on water absorption was studied [187], and it was observed that larger fibres resulted in greater water absorption in biocomposites compared to medium and smaller fibres. In addition, most pretreatment methods applied to biofibres or fillers to produce biocomposites exhibited good resistance to water and lower water absorption [187,188]. Thus, using smaller sized pretreated biofibres or fillers is necessary to develop biocomposites that achieve enhanced resistance to moisture.

3.3.3.5. Thermal conductivity. There are a limited number of studies focused on the thermal conductivity of AA-GP biocomposites [186–189,192]. It was noted that the thermal conductivity of AA-GP composites decreased from 0.411 W/mK to 0.203 W/mK with increasing wood shavings content from 3.5 wt% to 10.1 wt% respectively, due to the lower density of the composite [186]. As the miscanthus fibre size increased from 125 to 250 μm in AA-GP foam composite, thermal conductivity decreased from 0.0985 to 0.0686 W/mK, which may be due to the inherent structure and configuration within the AA-GP matrix [192]. It was observed that hydrothermal, Na_2SiO_3, $CaCl_2$, and NaOH + ultrasonic pretreatment of bio-based materials caused an increase in thermal conductivity [187, 189], while NaOH, silane, water, and pretreatment caused a decrease in thermal conductivity [187]. In general, the thermal conductivity of AA-GP biocomposites was found to be greater than that of polymer or lime-based biocomposites. However, AA-GP foam composites exhibit low thermal conductivity. Further research is needed to explore AA-GP foam biocomposites for building applications.

3.3.4. Applications of AA-GP biocomposites

Fibre-reinforced AA-GP composites require specific curing conditions for structural and non-structural pre-fabricated components in the building sector. The binder composition and fibre selection in these composites determine their applications, ranging from high-tech and expensive to low-tech and affordable. AA-GP foams are lightweight and have enhanced thermal and sound absorption capabilities [193,194]. AA-GP composites exhibit superior fire resistance than conventional building materials; therefore, they have the potential to be used for high-temperature applications [195]. Fibre-reinforced AA-GPs have also been investigated for their potential use in 3D printing concrete [196]. The 3D printing of AA-GPs technology reduces labour costs, minimises waste, and increases productivity. However, their applicability is currently limited, with only a few prototype components produced to date [197]. Additional potential paths for advancement that could enhance fibre-reinforced AA-GPs for 3D printing include improving printed technology for AA-GP foams and the development of ambient temperature-cured AA-GPs [198]. AA-GP composites have potential use in the production of tiles designed for high temperature resistance [199]. The applications of AA-GP biocomposites in the construction sector are shown in Fig. 17.

4. Circular economy aspects of using biocomposites

Using bio-derived raw materials, recycling or reusing, and determining embodied carbon are the primary facilitators for developing circular biocomposite materials [2,200]. Life cycle assessment (LCA) findings indicated a 50 % reduction in CO_2 equivalent emissions by substituting plasterboard with biocomposite boards [201]. The stages of a circular economy model are illustrated in Fig. 18. The butterfly diagram, sometimes referred to as the circular economy system diagram, depicts a continuous movement of resources. The two primary cycles shown are the technological cycle (right side) and the biological cycle (left side). The biological cycle encompasses

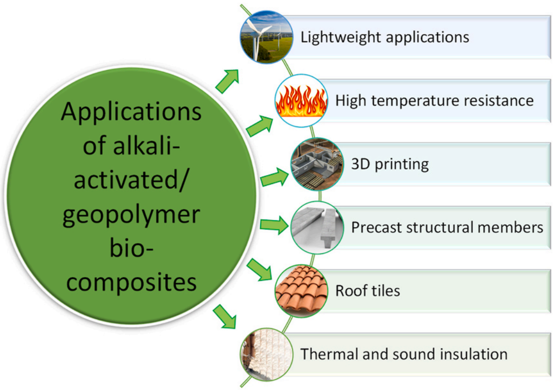

Fig. 17. Potential applications of fibre reinforced AA-Geo biocomposites in the construction sector.

several processes, including composting and anaerobic digestion, which collectively contribute to the restoration of natural resources. Only materials that can safely re-enter the biosphere are appropriate for this cycle. Nutrients from biodegradable materials are returned to the Earth to restore the natural environment [202]. Within the technological cycle, the circulation of materials and products is maintained by reuse, repair, remanufacturing, and recycling.

The growing demand for natural resources in the fabrication of biocomposites is based on the circular economy model due to the use of renewable natural raw materials and the ability to both recycle and reuse [203]. One potential approach to achieve further circularity is to repurpose waste materials for biocomposite production. This would help mitigate the prevalent take-make-use-throw mentality of modern society [204,205]. It also allows for biocomposite waste to be converted to further uses such as energy and beneficial products, following the principals of cascading use and reuse and decreasing volumes of waste in landfills [153,206–209]. Nevertheless, incorporating circular economy principles into end-of-life and waste considerations for biocomposites presents a formidable challenge due to the intrinsic bond between the matrix and filler/reinforcement, which makes separation difficult and

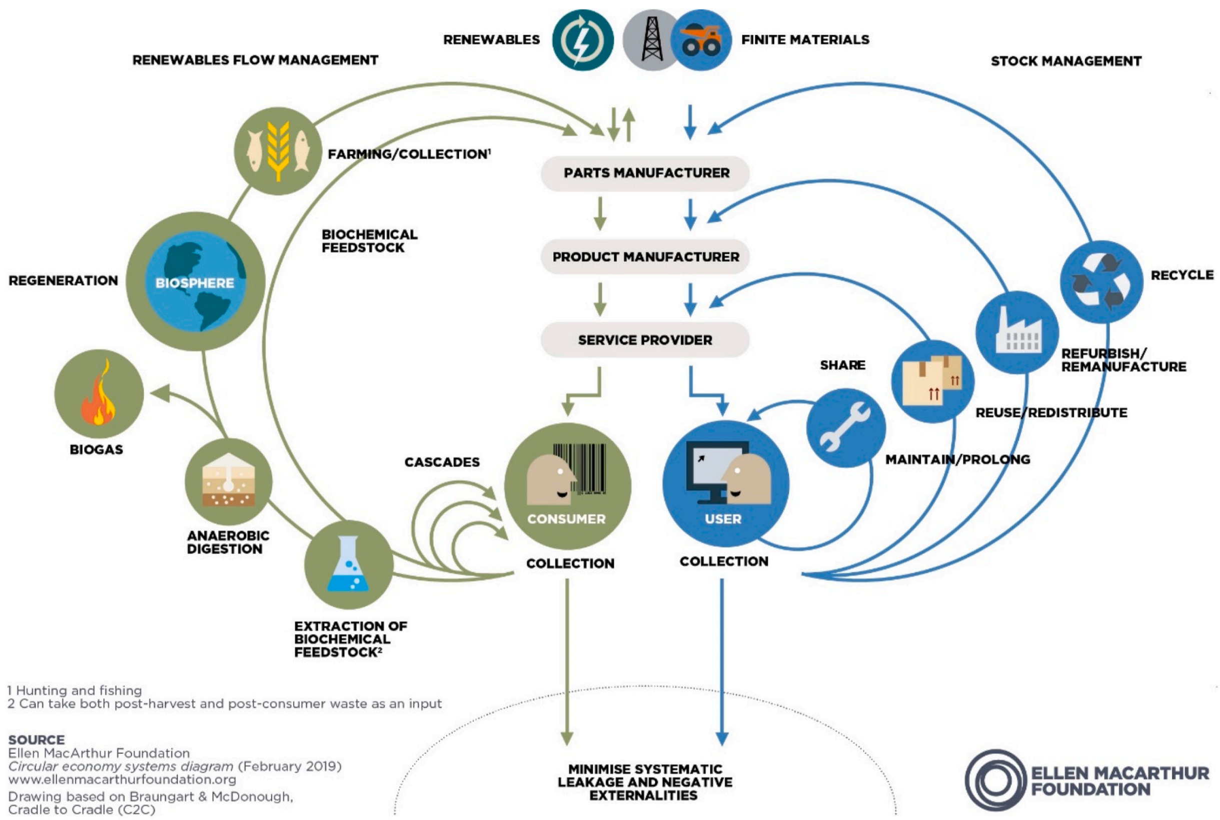

Fig. 18. A circular economy model [202].

costly [209]. Therefore, It is critical to create business opportunities for recycling and reusing such materials and products [210]. Furthermore, new biocomposite material and product developments should follow circular principles, considering all stages of the first life cycle and beyond.

5. Limitations and future prospects

5.1. Biofibre or filler degradation

The lignin, hemicellulose, and cellulose contents in biofibres or fillers were observed to decrease when subjected to solutions containing saturated lime, NaOH, and water [211]. Using these corroded fibres in a biocomposite matrix resulted in a decline in mechanical properties [212–214]. As a result, numerous strategies to prevent the deterioration of these fibres in biocomposites have been investigated, which include using supplementary cementitious materials [215–218], fibre pre-treatment like acrylation, alkali treatment, silane treatment, pulping, acetylation, hornification, and coating [216,219–223]. However, pretreatment can increase costs [224], underscoring the need for cost-effective, scalable pretreatment techniques.

5.2. Low mechanical strength of biocomposites

The limited mechanical strength of biocomposites across various formulations restricts their structural applications. This limitation arises from increased porosity for higher biofibre contents, weak mechanical characteristics of bio-based materials, and inadequate particle packing density [66,70,132]. Future research may address these challenges by exploring innovative reinforcement methods, optimising particle packing, analysing alternative additives, and understanding the relationship between biofibre or filler proportions, size, and pretreatment to enhance strength while maintaining the desired lightweight and thermal properties.

5.3. Sensitivity of biocomposites to moisture

Excessive water absorption is a significant challenge for biocomposites, affecting their characteristics and long-term structural integrity. Water absorption typically increases with higher biofibre content, potentially leading to swelling and degradation over time [82]. Strategies such as using pretreated biofibres or fillers, adjusting binder proportions, and incorporating additives can effectively reduce water absorption, essential for ensuring biocomposite reliability in diverse environmental conditions [64,70,142]. Further research could focus on developing innovative pretreatment techniques and material combinations to minimise water absorption.

5.4. Flammability of biocomposites

Evaluating flame retardancy is essential to understanding the flammability characteristics of biocomposites, given the potential fire risks [225]. There is a scarcity of information about the fire-resistant characteristics of biocomposites [226]. Biofibres containing a greater proportion of cellulose exhibit increased flammability compared to those with a larger proportion of hemicellulose. Conversely, the presence of char is often more prevalent in biofibres with a higher concentration of lignin [227]. The fire resistance of biofibres is influenced by their microstructure, including crystallinity and polymerisation levels [227]. Various coatings or additives might be used to enhance the resistance of biocomposites to fire [228,229]. Intumescent systems, including ceramics, phenolics, silicone, ablatives, glass mats, and others, are commonly used as fibre barriers in biocomposites when exposed to high temperatures [227,230]. Adding zinc borates, natural clays, phosphorous flame retardants, and intumescent zeolites to composites has significantly enhanced fire resistance [7,231,232]. Also, mycelium-based biocomposites exhibit better fire/heat resistance properties [233,234]. Hence, further in-depth investigations are required to develop a cost-effective and reliable method for enhancing the fire resistance of biocomposites.

5.5. Commercialisation of biocomposites

Biocomposites are predominantly used in the construction and automotive industries, which represent the primary markets. While interest in biocomposites is growing, the fundamental difficulty is substituting traditional composites with biocomposites that demonstrate equivalent structural and functional stability [6]. The commercialisation and market potential for biocomposites are anticipated to expand due to the increasing environmental and social awareness among producers and consumers, the discovery of new applications, and advancements in processing technologies. Until recently, a significant barrier to commercialising biocomposites has been the lack of acknowledgement of research and development efforts in developing nations, where bio-based materials are abundant. Many developed nations, especially in Europe, have successfully surmounted this obstacle and have emerged as leaders in this field [50]. Materials researchers still face challenges defining acceptance criteria for biocomposites, particularly regarding cost and performance. Establishing product standards that ensure consistent performance is also crucial [235].

6. Conclusions

This review sought to identify research gaps and consolidate current knowledge on biocomposites for construction applications. A diverse range of biocomposites were investigated, including those based on polymers, mineral or cement, and alkali-activated or geopolymers, with a particular emphasis on the construction industry. The mechanical and functional attributes of biocomposites, raw materials, and production methods were examined. Furthermore, the context of biocomposites within the circular economy was discussed. The following are the conclusions of this study.

- The abundant availability, lightweight nature, energy efficiency, health benefits, biodegradability, and sustainability of biocomposites make them optimal material alternatives for a variety of applications and help mitigate environmental impacts.
- Polymer-based biocomposites offer promising potential in construction, particularly for lightweight structures, insulation, and partitioning, due to their low density, thermal conductivity and better sound absorption properties. However, their suitability for load-bearing purposes is limited due to reduced strength. Efforts to optimise biofibre or filler content, pretreatments, and binder proportions can enhance their performance and expand their applications.
- Mineral/cement-based biocomposites demonstrate versatile properties influenced by biofibre or filler content, size, type, pretreatment, and binder proportions. Generally, increasing biofibre or filler content reduces density and increases thermal conductivity but compromises strength and increases water absorption. Smaller size biofibre or filler and specific pretreatments can enhance strength, offering pathways for optimisation for specific applications to achieve a balance between structural integrity, thermal performance, and moisture resistance.
- Alkali-activated (AA) or geopolymer (GP) biocomposites exhibit varying properties based on biofibre or filler content, size, pretreatment, and binder characteristics. Increasing biofibre or filler content generally decreases density and thermal conductivity; however, it may also reduce strength and water resistance, although exceptions exist. Hence, optimising AA-GP biocomposite formulations requires careful consideration of these parameters to achieve desired properties for specific applications.
- The poor resistance of biofibres to alkaline pore solutions and degradation currently restricts their practical implementation as reinforcements in biocomposites. However, pre-treatment techniques such as acrylation, alkali treatment, pulping, acetylation, silane treatment, hornification, using supplementary cementitious materials, and specialised composite processing can help resolve these issues.
- The flammability of biofibres is also a significant challenge for biocomposites. A variety of additives or coatings can be employed to reduce the combustibility of biocomposites, including ceramics, silicone, phenolics, glass mats, and ablatives.
- Potential applications of biocomposites in the construction sector include insulation, 3D-printing, tiles, precast structural components, lightweight applications, high temperature applications, partition boards, railings, window and door frames, and walls (bricks/blocks).
- Adopting circular practices for biocomposite, such as design for recyclability, repair, reuse, and recycling, along with the development of suitable technologies, are promising strategies for enhancing the circularity of biocomposites and offering significant benefits for society, the economy, and the environment.

Future research should prioritise exploring cost-effective and scalable pretreatment techniques for biofibres or fillers to prevent the degradation of biocomposites. Enhancing the mechanical strength through innovative reinforcement methods and optimising particle packing density is essential, along with reducing moisture sensitivity while maintaining structural integrity. Developing effective fire-retardant coatings or additives to enhance flame resistance, establishing product standards, and overcoming cost barriers will be crucial for facilitating commercialisation. The less explored areas, such as 3D printing and bio-aerogels, need to be investigated for construction applications.

CRediT authorship contribution statement

Waqas Ahmad: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Sarah J. McCormack:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization. **Aimee Byrne:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

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.

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Appendix A

Table A1
Properties of polymer-based biocomposites.

Ref.	Biocomposite	Biofibre/ filler/ binder content	Density (kg/ m^3)	CS (MPa)	TS (MPa)	FS (MPa)	WA (%)	Thermal conductivity (W/ mK)
[157]	Cornstalk-epoxy	–	–	–	–	–	18.75–28.12	0.075–0.1588
[63]	Wood fibre-additives	–	212.2	–	–	–	–	0.054 (dry) and 0.054 (wet)
	Wood wool- adhesive and additives	–	60.2	–	–	–	–	0.038 (dry) and 0.039 (wet)
	Hemp fibre- adhesive and additives	–	41.1	–	–	–	–	0.040 (dry) and 0.040 (wet)
	Barley straw-corn starch	–	107.5	–	–	–	–	0.042 (dry) and 0.046 (wet)
	Corn pith-sodium alginate	–	48.1	–	–	–	–	0.038 (dry) and 0.038 (wet)
[16]	Expanded perlite, lignocellulosic residues-natural polymers	5-50 wt%	480–600	–	–	–	70–88	0.152–0.183
	Expanded perlite, lignocellulosic residues-starch and natural polymers	5-50 wt%	675–740	–	–	–	70–130	0.180–0.195
	Expanded perlite, lignocellulosic residues-natural/ synthetic polymers	20-50 wt%	331–566	–	–	–	18.12–125.18	0.054–0.106
[66]	Açaí fibres-polyurethane foams	5-20 wt%	–	0.16 ± 0.03 to 0.19 ± 0.01	–	–	–	–
[70]	Walnut shell powder-polyurethane foams	1-5 wt%	40 ± 2 to 46 ± 1	0.29–0.25	–	0.37–0.41	12.2–15.0	0.034–0.036
	Silanised walnut shell powder-polyurethane foams	1-5 wt%	39 ± 2 to 42 ± 3	0.33–0.28	–	0.42–0.52	10.7–11.7	0.030–0.031
[71]	Pineapple fibre-polyurethane foams	1-5 wt%	52–55	0.34–0.22	–	–	–	–
[74]	Bamboo fibre-polyurethane foams (untreated)	5-20 wt%	800–900	0.39–0.54	–	0.52–0.72	–	–
	Bamboo fibre-polyurethane foams (NaOH treated)	5-20 wt%	890–905	0.46–0.55	–	0.60–0.76	–	–
[72]	Wood chips-biochar	2-10 wt%	630–670	–	–	7.67–11.42	6.10–6.80	0.093–0.096
[68]	Waste seashells-polyurethane foam	5-30 wt%	28.1–29.8	0.0157–0.022	0.12–0.14	–	–	–
[69]	Beech wood fibre-PLA	10-50 wt%	1175–1220	–	15.2–21.0	30–40	–	0.075–0.095
	Basalt fibre-PLA	10-50 wt%	1250–1600	–	19.5–29.0	46–67	–	0.085–0.095
	Beech wood and basalt-PLA	10-50 wt%	1250–1350	–	10.7–39.0	26–80	–	0.080–0.100
[114]	Desert cotton-epoxy	–	–	–	2.0–3.0	3.0–4.0	–	0.0451–0.0483
	Areca nut husk fibre-epoxy	–	–	–	7.0–8.0	7.0–10.0	–	0.0404–0.0427
	Sandwich desert cotton and Areca nut husk fibre-epoxy	–	–	–	6.0	6.0–8.0	–	0.0386–0.0438
[234]	Wood-veneer-mycelium	–	140 ± 8 to 1180 ± 75	1.2 ± 0.12	–	0.13 ± 0.02 to 21.99 ± 2.01	–	–
[81]	Grape skins-starch	–	433 ± 78	3.0 ± 0.1	–	0.30 ± 0.07	–	0.0793 ± 0.0033
	Grape pomace-starch	–	308 ± 32	5.9 ± 0.2	–	0.43 ± 0.03	–	0.0759 ± 0.0067
	Grape stalks-starch	–	227 ± 47	5.6 ± 0.1	–	0.45 ± 0.06	–	0.0693 ± 0.0039
	Crushed stalks-starch	–	345 ± 35	5.6 ± 0.1	–	0.61 ± 0.06	–	0.0776 ± 0.0015
[76]	Hemp shiv-starch (40 mm shiv)	–	175–218	0.60–1.40	–	–	155–182	0.60–0.063

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Table A1 (*continued*)

Ref.	Biocomposite	Biofibre/ filler/ binder content	Density (kg/ m^3)	CS (MPa)	TS (MPa)	FS (MPa)	WA (%)	Thermal conductivity (W/ mK)
	Hemp shiv-starch (25 mm shiv)	–	185–230	0.56–1.70	–	–	162–190	0.0593–0.061
[236]	Hemp and flax shivs-starch	–	208–215	0.22–0.82	–	–	–	0.53–0.62
[64]	Sugar palm nanocellulose fibre-starch-PLA	20-80 wt%	1290–1410	–	2.35–19.45	3.76–35.38	5.70 $\pm$ 0.37 to 61.24 $\pm$ 0.85	–
[60]	Date palm wood fibres-PLA (untreated)	10-40 wt%	1290–1410	–	8.5–13.5	–	–	0.077–0.083
	Date palm wood fibres-PLA (silane-acetone treated)	10-40 wt%	1340–1390	–	7.4–25.0	–	–	0.086–0.088
	Date palm wood fibres-PLA (silane-ethanol treated)	10-40 wt%	1350–1410	–	7.5–31.0	–	–	0.091–0.105
[237]	Wood fibre-adhesive	–	110–180	–	0.010–0.016		–	0.038–0.055
[75]	Hemp fibre-epoxy resin	10-30 wt%	43.1–55.0	–	–	42–80	–	0.063–0.090
	Jute fibre-epoxy resin	10-30 wt%	40.1–70.0	–	–	40–62	–	0.051–0.073
	Date fibre-epoxy resin	10-30 wt%	50.5–64.0	–	–	50–60	–	0.061–0.082

CS: compressive strength; TS: tensile strength; FS: flexural strength; WA: water absorption.

Table A2
Properties of mineral/cement-based biocomposites.

Ref.	Biocomposite	Biofibre or filler content used	Density (kg/m^3)	CS (MPa)	TS (MPa)	FS (MPa)	WA (%)	Thermal conductivity (W/mK)
[157]	Cornstalk-Gypsum and cement	–	–	0.11–0.29	–	0.04–0.13	12.0–24.12	0.10–0.20
[132]	Date palm fibre mortar	21-51 vol%	1217–1992	3.5–6.0		1.2–3.8		0.243–0.795
[238]	Date palm concrete	15 wt%	954	–	–	–	–	0.185 (dry) and 0.243 (wet)
[63]	Hemp hurds-lime	–	286	–	–	–	–	0.64 (dry) and 0.075 (wet)
[35]	Large corn stalk magnesium phosphate cement concrete	5-30 wt%	557–1657	1.7–11.8	–	–	–	0.051–0.643
	Small corn stalk magnesium phosphate cement concrete	5-30 wt%	709–1854	2.6–28.4	–	–	–	0.099–0.998
[133]	Hemp shiv-lime	42.8–71.4 vol%	250–660	0.20–1.95	–	–	–	–
[239]	Hemp-magnesium phosphate cements	–	600–1984	0.7 $\pm$ 0.11 to 12.4 $\pm$ 0.49	–	–	–	0.10–0.265
[240]	Hemp with various mineral binders	–	531–627		–	–	–	–
[134]	Hemp-gypsum plaster	2-6 wt%	1051–1235		–	–	–	0.364 $\pm$ 0.001 to 0.485 $\pm$ 0.001
[241]	Lavender straw-metakaolin with slaked lime	–	577–661	0.08 $\pm$ 0.015 to 0.13 $\pm$ 0.01	–	–	–	0.142–0.162
[242]	Hemp shiv-lime	–	–	0.46–0.94	–	–	–	0.094–0.101
[140]	Eggshell powder-gypsum plaster	2.5–15 wt%	1290–1380	15.5–17	–	2.4–2.5	16.1–17.7	–
	Conch powder-gypsum plaster	2.5–15 wt%	1280–1370	12.7–15.0	–	1.95–2.25	17.55–20.25	–
	Cuttle bone powder-gypsum plaster	2.5–15 wt%	1420–1515	16.0–18.0	–	2.5–3.15	16.9–17.5	–
	Scallop powder-gypsum plaster	2.5–15 wt%	1430–1530	16.0–19.5	–	2.55–2.75	15.8–16.5	–
[135]	Date Plam fibre mortar	6-30 wt%	790 $\pm$ 0.77 to 1417 $\pm$ 2.13	5.40–25.90	–	2.80–3.82	9.0–50.0	0.055–0.585

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Table A2 (*continued*)

Ref.	Biocomposite	Biofibre or filler content used	Density (kg/m^3)	CS (MPa)	TS (MPa)	FS (MPa)	WA (%)	Thermal conductivity (W/mK)
[243]	Lime hemp concrete	–	688 ± 11.0	2.20	–	–	–	–
	Lime rice husk concrete	–	731 ± 6.0	1.30	–	–	–	–
[142]	Hemp concrete (untreated)	–	455	0.50	–	–	27	0.108
	Hemp concrete (VMA treated)	–	480	1.25	–	–	7.5	0.12
	Rapeseed straw concrete (untreated)	–	590	0.9	–	–	34	0.09
	Rapeseed-straw concrete (VMA treated)	–	610	1.5	–	–	16	0.10
[136]	Hemp shiv-lime	5-20 vol%	1092–1245	1.5–3.45		0.625–0.746		0.537 ± 0.057 to 0.601 ± 0.064
[137]	Alfa fibres-plaster	1-4 vol%	1295–1299	–	–	–	–	0.225–0.346
[138]	Spent coffee powder-mortar	2.5–17.5 vol %	1450–1590	0.45–2.52		0.42–1.42	12.5–20	0.306–0.515
[244]	Hemp shiv-magnesium	–	201–576	–	–	–	–	0.056–0.159 (dry) and 0.091–0.241 (wet)
[141]	Scots pine bark-cement paste (untreated)	30-50 vol%	1116–1118	4.67–11.16	–	–	17.0–37.5	0.26–0.40
	Scots pine bark-cement paste (hydrothermally treated)	30-50 vol%	415–467	4.15–11.18	–	–	18.5–32.0	0.22–0.45
	Black pine bark-cement paste (untreated)	30-50 vol%	1104–1777	5.06–11.04	–	–	19.0–34.0	0.32–0.43
	Black pine bark-cement paste (hydrothermally treated)	30-50 vol%	506–891	8.91–17.77	–	–	14.0–25.0	0.27–0.43
[170]	Hemp shiv-lime	–	550–750	0.21–0.60	–	–	–	0.080–0.98 (dry) and 0.101–0.123 (wet)
[151]	Washingtonia filifera biochar-gypsum	1-3 wt%	–	–	–	2.23–4.24	–	0.33–0.45
[245]	Rapeseed straw-cement and lime	–	352–608	0.07–0.22	–		–	0.071–0.087
[246]	Mussel shells-cement	–	1380–1650	2.04–5.95	–	1.9–2.95	12.8–17.5	0.35–0.43
[145]	Date palm fibre (untreated) mortar	6-30 wt%	1375–1700	7.0–29.0	–	–	7.0–57.5	0.100–0.800
[139]	Spent coffee powder-mortar	2.5–15 vol%	1490.53 ± 77.71 to 1616.12 ± 21.63	0.32–12.03	–	0.14 ± 0.04 to 1.26 ± 0.07	6.5–15.7	0.262 ± 0.04 to 0.367 ± 0.03
[146]	Rice husk and straw-lime	33-100 wt%	446 ± 8.7 to 635 ± 15.3	0.48–1.75	–	–	–	0.087–0.116
[247]	Giant reed-lime and cement	–	870.85–1152.31	0.073–1.029	–	0.075–0.829	–	0.191–0.245
[148]	Cotton and linen fibre mortar	1-3 vol%	–	6.84–9.72	4.92–6.84	2.99–3.22	10.74–19.21	–
	Wool and silk fibre mortar	1-3 vol%	–	7.88–9.48	5.48–7.20	2.57–2.86	9.90–14.47	–
[149]	Date palm fibre (NaOH treated) mortar	0.5–2 wt%	–	20.5–34.0	1.7–3.1	8.2–10.2	4.8–6.2	–
[150]	Hemp fibres (6 mm)-mortar	1-3 wt%	2110–2118	23.62–31.39	5.45–5.86	2.75–3.02	6.40–6.88	–
	Hemp fibres (12 mm)-mortar	1-3 wt%	2149–2156	30.69–35.05	5.08–5.82	2.57–4.10	5.69–6.40	–
	Hemp fibres (18 mm)-mortar	1-3 wt%	2104–2103	30.45–30.72	5.47–5.87	3.15–3.35	6.65–6.96	–
[248]	Bamboo particles-cement	45-50 vol%	693–786	3.22–4.57	–	–	–	0.32–0.52
[143]	Rice husk concrete	–	703–1156	0.56 ± 0.03 to 5.41 ± 0.05	–	0.35 ± 0.01 to 1.90 ± 0.00	–	0.070–0.129

CS: compressive strength; TS: tensile strength; FS: flexural strength; WA: water absorption; VMA: viscosity modifying agent.

Table A3
Properties of alkali-activated/geopolymer biocomposites.

Ref.	Biocomposite	Biofibre or filler content used	Density (kg/m^3)	CS (MPa)	FS (MPa)	WA (%)	Thermal conductivity (W/mK)
[180]	Cotton fibre-Fly ash	0.3–1 wt%	1800–2000	–	10.25–11.7	–	–
[190]	Cotton fibre-Fly ash	0.3–1 wt%	–	27.5–45.7	–	–	–
[191]	Cotton fabric-Fly ash	3.6–8.3 wt%	–	–	11.5–31.7	–	–
[181]	Sorghum fibre-Fly ash	1-3 wt%	1450–1600	25.1–20.40	3.2–5.5	–	–
[182]	Sawdust-Fly ash and metakaolin	5-20 wt%	1590–1970	61.5–68	8–11	–	–
[183]	Palm oil fuel ash-Fly ash	5-100 wt%	1671–1770	18–35	–	–	–
[184]	Hemp fibre-Fly ash	0.5–1 vol%	1829–1833	20.76–23.93	4.83–5.7	14.17–14.19	–
	Hemp fibre-Fly ash and slag	0.5–1 vol%	2067–2075	32.54–33.14	6.39–5.96	10.97–11.61	–
[185]	Rice straw (untreated) -Slag	1-3 wt%	1727–1865	29–36	4.9–5	–	–
	Rice straw (NaOH treated)-Slag	1-3 wt%	1818–1880	39–45	5.75–6.70	–	–
[186]	Wood shavings-Slag	3.5–10.1 wt%	1000–1800	3.5–21.5	3.3–10.7	10.75–25.27	0.203–0.411
[189]	Wheat straw (untreated)-Fly ash and slag	1-3 wt%	–	30–50	8.7–10.8	–	1.2
	Wheat straw (Hydrothermal treated)-Fly ash and slag	1-3 wt%	–	31.5–56.5	9.1–9.8	–	1.4
[187]	Cotton stalk fibres (L = 10–30, D = 0.5–1 mm)-Fly ash	0.5–2 wt%	1460–1540	20.8–22.8	2.8–3.52	8.0–9.5	–
	Cotton stalk fibres (L = 20 ± 2, W = 4 ± 0.5, T = 1 ± 0.5 mm)-Fly ash	0.5–2 wt%	1500–1550	17.2–21.8	2.2–2.8	8.1–11.5	–
	Cotton stalk fibres (L = 20 ± 2, W = 2 ± 0.5, T = 1 ± 0.5 mm)-Fly ash	0.5–2 wt%	1505–1555	15.3–21.0	1.5–2.6	8.5–13.9	–
	Cotton stalk fibres (Untreated)-Fly ash	1 wt%	1496	22.7	3.52	8.59	–
	Cotton stalk fibres (NaOH treated)-Fly ash	1 wt%	1479	23.8	3.98	6.72	–
	Cotton stalk fibres (PVA treated)-Fly ash	1 wt%	1508	22.9	3.76	6.94	–
	Cotton stalk fibres (Engine oil treated)-Fly ash	1 wt%	1517	21.5	2.91	7.43	–
	Cotton stalk powder (0.1–0.25 mm)-Fly ash	0.3–0.9 wt%	–	23.5–26.5	2.40–2.83	–	–
	Cotton stalk powder (0.25–0.5 mm)-Fly ash	0.3–0.9 wt%	–	24.0–27.0	2.5–3.0	–	–
	Cotton stalk powder (0.5–1 mm)-Fly ash	0.3–0.9 wt%	–	22.5–25.0	2.30–2.84	–	–
	Cotton stalk powder (Untreated)-Fly ash	0.7 wt%	–	27.0	3.0	–	–
	Cotton stalk powder (NaOH treated)-Fly ash	0.7 wt%	–	27.7	3.1	–	–
	Cotton stalk powder (PVA treated)-Fly ash	0.7 wt%	–	28.5	3.0	–	–
	Cotton stalk powder (Engine oil treated)-Fly ash	0.7 wt%	–	26.0	2.85	–	–
[188]	Sisal fibres-Slag and biomass bottom ash	1 wt%	1940	10.0	2.6	5.0	0.70
	Cellulose fibres- Slag and biomass bottom ash	1 wt%	1950	10.0	3.2	4.5	0.73
	Olive pruning fibres (untreated)-Slag and biomass bottom ash	1 wt%	1870	7.3	2.9	6.7	0.68
	Olive pruning fibres (Na_2SiO_3 treated)-Slag and biomass bottom ash	1 wt%	1870	8.7	3.5	7.2	0.74
	Olive pruning fibres ($CaCl_2$ treated)-Slag and biomass bottom ash	1 wt%	1875	8.4	3.4	7.0	0.72
	Olive pruning fibres (NaOH treated)-Slag and biomass bottom ash	1 wt%	1900	9.3	3.5	5.8	0.66
	Olive pruning fibres (Silane treated)-Slag and biomass bottom ash	1 wt%	1880	9.3	2.75	6.5	0.63
	Olive pruning fibres (Water 5 cycles treated)-Slag and biomass bottom ash	1 wt%	1875	9.1	3.3	6.6	0.63
	Olive pruning fibres (Water 10 cycles treated)-Slag and biomass bottom ash	1 wt%	1880	9.3	3.2	6.0	0.63
	Olive pruning fibres (NaOH + ultrasonic treated)-Slag and biomass bottom ash	1 wt%	1880	9.3	1.8	7.3	0.60

CS: compressive strength; TS: tensile strength; FS: flexural strength; WA: water absorption L: length; W: width; T: thickness; PVA: polyvinyl acetate.

Data availability

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

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