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Recent breakthroughs in the valorization of lignocellulosic biomass for advancements in the construction industry: a review

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Extensive use of non-ecofriendly construction materials has already caused much damage to the environment. A novel array of green and sustainable construction materials (GSCMs) is required to address this challenge. Alternatives like Lignocellulosic biomass (LCBs) and other bio-based products have drawn the scientific community's attention over time. LCBs are eco-friendly materials originating from natural resources. Owing to their insoluble nature, morphological properties, and higher dimensional aspects, LCBs can be used to fabricate a wide category of biocomposites that can be consumed by the construction industry. However, for ease of research, there is a need for a review article highlighting up-to-date research connecting LCBs with GSCMs. This review provides a comprehensive examination of the numerous components, including cellulose, silica, lignin, and hemicellulose, that are present in LCBs. Furthermore, the review monitored the following: environmental challenges, novel waste recycling methods, modern valorization techniques, innovative applications of LCBs, durability, and performance enhancement. The importance of LCBs in GSCMs, such as biocomposites, bio-based insulating materials, coatings, adhesives, and various other applications, has been thoroughly examined. Finally, this review encompasses a summary of computational methods and life-cycle assessments (LCA) for the development of next-generation construction materials.

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Shakshi Bhardwaj

Sustainability spotlight

This review emphasizes the innovative uses of lignocellulosic biomass in the construction sector, providing a sustainable substitute for traditional building materials. A thorough comparison is conducted between traditional and sustainable construction material sources bolstered by statistical data that demonstrate the environmental and socioeconomic effects of conventional materials. The study investigates advanced extraction processes and upscaling methodologies, connecting raw biomass to high-value goods and enhancing sustainability and resource efficiency in the building industry.

1. Introduction

Construction has been a fundamental aspect of human civilization since its inception. Having passed through the stone, bronze, and iron ages, we live in the polymer era.[1] In our modern society, technologies are evolving swiftly, and many innovations have already been made in our daily lives. However, there is still a lot of scope for improvement in several sectors of modern society, the construction industry being one of them. In the ancient and medieval periods, people used to build their shelters primarily from wood and stone.[2] In this modern era, those have been replaced by concrete, bricks, steel, and other masonry items. However, these traditional construction methods have several adverse environmental effects (shown in Fig. 1).

Deforestation has emerged as a significant environmental concern in the rural areas of numerous impoverished and underdeveloped nations, as the predominant practice of using timber for constructing houses and household appliances has made the problem even worse.[3] Apart from climate change issues, it is also responsible for the extinction of many *Flora* and *Fauna* species worldwide.[4] According to a survey by the International Institute of Tropical Agriculture (IITA), Nigeria has been at the top of the table of countries with an alarming rate of deforestation. They have marked a worrisome rate of 3.5%

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deforestation, with approximately 400 000 hectares of forestland being deforested annually.[5] A similar trend has also been observed in other parts of the world, the Amazon rainforest stands out as another appropriate example of it, where 20% of the mainland of the Brazilian Amazon has been deforested over the past three decades,[6] as a result, there was an increase of surface temperature up to 3 °C,[7] and by the year 2050, a decrease in rainfall has been estimated around 12–21% in the Amazon basin.[8] Aside from deforestation, soil erosion is also trending upward in metro cities. In undisturbed regions, the rate of soil erosion is approximately 1.4 tons per year under natural conditions.[9] Whereas, at construction sites, the rate might increase significantly from 700 times to as much as 40 000 times.[10] In addition to land-related issues, air pollution has soared severely over the past few decades, due to a high level of CO_2 emission, mainly attributed to many resources and non-renewable energy during unregulated construction activities.[11,12] According to the Global Carbon Project statistics, in 2023, 37.55 billion metric tons of CO_2 were released into the atmosphere,[13] out of which a staggering 37% alone were contributed from the building sector.[14] For apartment units, CO_2 emission was recorded at 424.2–584.2 kg m^{-2} from steel and concrete, only.[15] Apart from the aforementioned issues, several other concerns have arisen, the Urban Heat Island effect,[16,17] Habitat Destruction,[18] Resource Depletion,[19,20] and Waste Generation[21] being the prime ones. Research revealed that construction and demolition work generate trash at 63.74 kg m^{-2} and 1615 kg m^{-2} rate, respectively. It also highlights that the proper recycling of concrete and brick waste has the potential to be transformed into a $ 44.96 million economy.[22]

In light of the current crises related to resource depletion, waste generation, pollution, and sustainability challenges, our society requires some alternative resources that can serve as a greener solution in the construction sector. Here, our main focus would be the utilization of lignocellulosic biomass (LCBs) in the construction industry. Massive annual production of 8.2 billion tons of dry mass of different types of LCBs (shown in Table 1) demonstrates its potential to be utilized in construction and similar sectors where sustainability is a major issue.[23] Nowadays, LCBs have been explored to be employed in many innovative ways. Biofuel production,[24] bioplastic preparation,[25] bioenergy generation,[26] and polymeric materials[27] are the extensive ones. Now, the question is, what are the basic features that made LCBs so significant for the construction industry? Well, LCBs possess many inherent properties that unveil their potential in the construction sector.

(a) Firstly, the abundance, renewability, and easy accessibility empowered it as a viable alternative to non-renewable resources.
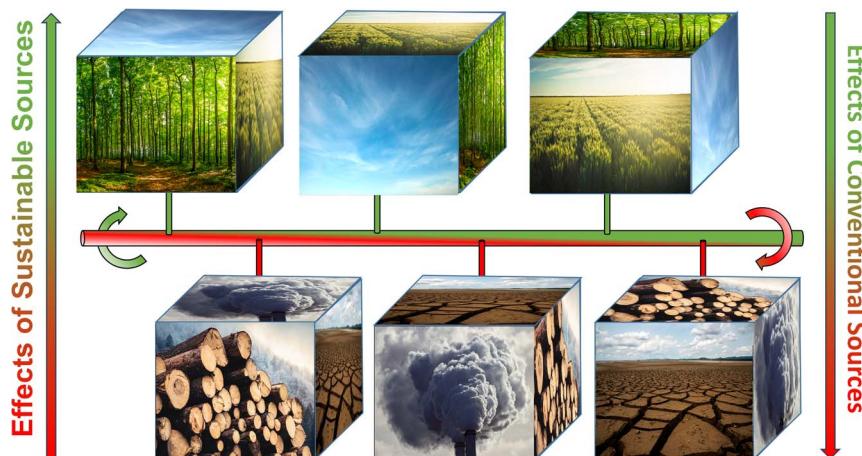
Fig. 1 A comparative illustration of the environmental effects of using conventional sources *vs.* sustainable sources.

Table 1 Global annual production statistics of major agricultural crops

		Weight% of components present within				
Crop	Total dry biomass (million tons)[30]	Cellulose	Hemicellulose	Lignin	Ash[a]	References
Rice	905	37.0	16.5	13.6	19.8	31
Wheat	62	40.2	38.8	17.0	2.3	32
Maize	2724	42.7	23.2	17.5	6.8	31
Sugarcane	1048	41.1	22.7	31.4	2.4	33
Barley	23.46	37.5	37.1	15.8	4.2	34
Soybeans	60.28	36.4	14.3	18.2	4.2	35

[a] Generally, Ash contains 80–95% silica.[36]

(b) Secondly, its biodegradability, low ash content, and elemental composition make it chemically suitable and eco-friendly as well.

(c) Thirdly, from an engineering point of view, several factors like density, high aspect ratio, thermal properties, grindability, flowability, and high energy content put it ahead of other alternatives.[28]

(d) High content of inorganic materials, *e.g.*, salts, silica, within these crops, can act as pozzolanic material, improving the durability and mechanical properties of concrete.[29]

(e) Lastly, the utilization of these materials lays a foundation for many small and medium-sized industries to grow economically following the waste-to-wealth approach.

Apart from the aforementioned points, a detailed discussion was also given below for every component of LCBs in an illustrative way (shown in Fig. 2).

To achieve desirable properties, all of these LCBs components have been used by researchers in some fixed proportion range. Neither all components are appropriate for every purpose nor any proportion of them. Cement and concrete composites generally require nano- or microfibers of cellulose in very small amounts of around 0.05–1 wt%, for reinforcement purposes. An excess proportion typically causes an adverse effect on concrete strength due to the agglomeration effect.[37,38] A similar range of cellulose fiber wt% has also been followed in the case of fiber and plastic composites.[39,40] Generally, in any type of composite

material, cellulose fibers are used as an additional reinforcement, so the proportion is always kept low to fulfill the requirements. On the other hand, in aerogels, cellulose is used as a main structural component. For multipurpose applications like thermal insulation, acoustic insulation, fire-retardancy, *etc.*, a 0.5–2 wt% suspension of cellulose pulp or fibers is considered, and into that other reactants are added in similar minor amounts to maintain the chemical homogeneity. In coatings and adhesives, lignin is generally utilized because of its hydrophobic nature. At maximum, 20–30 wt% lignin is incorporated into polyurethane-based coatings, because a greater amount can introduce brittleness and diminish the mechanical strength.[41] In phenol-formaldehyde resins, around 20–40 wt% of lignin is generally used as a substitute for formaldehyde to maintain mechanical properties with enhanced reaction kinetics.[42] For lignin-based epoxy coatings, optimum results were achieved at a 25 wt% proportion of lignin, whereas for polyester coatings low proportion of lignin (1–5 wt%) is usually maintained to avoid plasticizing and a more heterogeneous effect.[43] In various bio-plastic materials, the application of lignin was also reported. It was observed that in lignin-starch-based foams, a replacement of 20 wt% of the starch by lignin so no adverse effect on the morphological features, besides improving the water-resistivity, elastic modulus, and thermal behaviours.[44,45] The application of bio-based silica is also on trend in several sectors related to the construction industry.
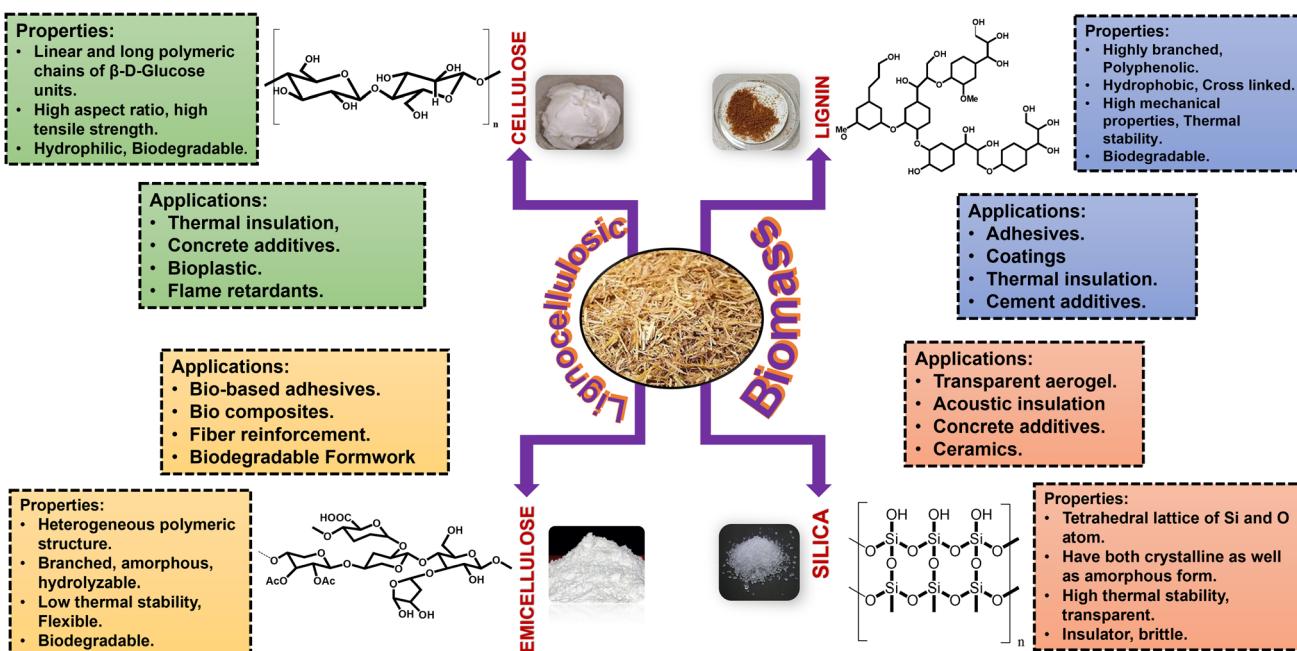
Fig. 2 A detailed discussion of the structure, properties, and applications of cellulose, hemicellulose, lignin, and silica in an illustrative way.

Rice husk ash generally contains 80–90 wt% of silica,[46] which has been vaporized to fabricate low-weight but high-performance concrete materials. Apart from the structural components, silica aerogel is quite famous for its impressive thermal and acoustic insulation properties.[47] Due to compositional dissimilarities, hemicellulose has some limited application in construction fields, although it is highly used in other fields like biomedical, energy applications, adsorbents, *etc.*[48]

The purpose of this study is to highlight the importance of sustainable alternatives in the construction sector. While numerous review journals are discussing the use of LCBs for bioenergy, biofuels, and biogas production, there is a lack of significant reviews on their utilization in the construction industry, despite the presence of many research articles on the topic.

This review aims to bridge that gap by providing a comprehensive overview. In chronological order, after the introduction part, the study begins by discussing the major environmental crises related to conventional construction techniques and emphasizes the importance of substituting traditional materials with sustainable alternatives. In this section, advanced functional materials derived from cellulose, hemicellulose, lignin, silica, and other bio-based resources like bamboo, cork, *etc.*, have been discussed thoroughly. The third section outlines a thorough investigation of cut-edge technologies valorizing LCBs, that is, nothing but the combined process of extraction and subsequent purification methods to achieve the functional form of each constituent. A couple of following sections have been based on a detailed literature review of various construction industry-related products derived from the LCBs components. An additional section has been added based on the computational approach and Life Cycle Assessment (LCA). This

section is completely based on theoretical assessments using various AI-ML tools. Eventually, the study ended with several insightful comments as concluding remarks aimed at challenging the status quo and guiding towards future directions.

2. Sustainable materials from lignocellulosic biomass and their impact on construction

Buildings made from sustainable, eco-friendly sources and that have minimal harmful effects on the environment as compared to traditional sources are termed "Green Buildings" (GB). From
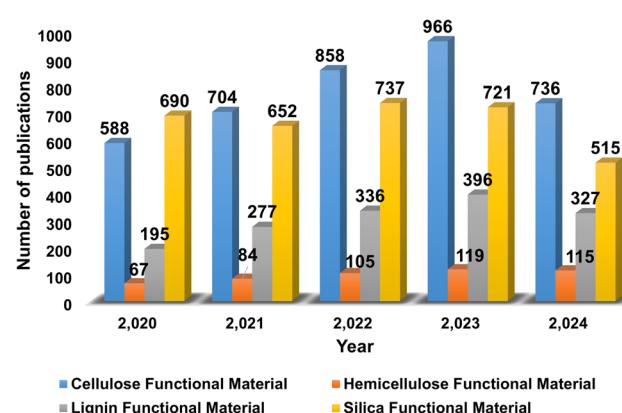

Fig. 3 Number of publications published on LCBs functional material in the last 5 years. According to Scopus, searched on the 8th of August 2024. Search codes: "Cellulose Functional Material", "Hemicellulose Functional Material", "Lignin Functional Materials", and "Silica Functional Materials".

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the production of materials to on-site construction, maintenance, or renovation, and finally, destruction, a GB has to be resource-efficient. Thus, careful selection of source materials, pre-estimation of environmental impacts, resource renewability issues, energy efficiency, and waste recyclability challenges must be a prerequisite in this case. Here, an assessment was done on specific points between conventional and sustainable sources.

2.1. Materials

As compared to traditional construction materials like steel, brick, concrete, *etc.* LCBs are abundant, renewable, and re-processable. However, the major challenge is utilizing the raw forms of LCBs and other biomaterials to produce the desired structural rigidity, which should cross the benchmark to be consumed by the construction industry. So, modifications are often needed in this case. Based on the requirements, this field offers a vast area for pursuing high-end research. A handful of quality journals have been published throughout the past few decades showcasing the ongoing research and the streak of development of advanced functional materials from cellulose, hemicellulose, lignin and silica, as well as the demand is showing an upward trend gradually (shown in Fig. 3). Before going into the detailed discussion, as an overview, the construction industry is a kind of sector where durability, longevity, strength and ductility (in some cases) are the key features that a product must have. A building material should have the ability to withstand the drastic changes in temperature and moisture content in the atmosphere. Thus, robust materials like bricks, concrete, cement, and steel have been used for a long time. But looking at the environmental crisis, it is high time to boost the research on such advanced materials, which is also one of the major objectives of this study. The research community has already explored several ways of the advancement of their materials, like doping, surface coating, tuning of nanostructure, composite fabrication, chemical functionalization, *etc.* Here, we have tried to sum up all of those valuable works concisely and enthusiastically.

2.1.1. Cellulose advanced functional materials. Cellulose is the most abundant source of biomass on a global scale, having a production capacity of more than 100 billion tons annually.[49] A demographic representation was introduced below to show the data on the worldwide production of cellulose in the year 2022 (ref. 50) (shown in Fig. 4). Due to the long chains of the β-*d*-glucopyranose rings, it provides a high aspect ratio to its micro and nanofibers, which proves its potential to be an initial substrate for manufacturing such robust materials. In the plant cell wall, cellulose forms the scaffold of the cell wall due to a thorough hydrogen-bonding network between the long strands of cellulose. This strong interaction is responsible for providing the tensile strength, which is required to endure the internal as well as external pressure to maintain the shape, integrity, and rigidity of the plant cell.[51,52]

Due to the aforementioned properties, the usage of cellulose is conventional in many construction materials for providing additional mechanical strength, durability, and rigidity through reinforcement. Nowadays, in most functional materials, cellulose is usually incorporated in its nano- or micro-dimensional forms. Cellulose Nano Fibers (CNF),[54] Cellulose Nano Crystals (CNC),[55,56] and microfibrillated cellulose (MFC)[57] are the most common forms. For example, Supit *et al.* have very recently developed an ultra-high-performing mortar; they have incorporated CNF and Wollastonite microfibers to improve the microstructure and mechanical properties. They have found that CNF in 0.005–0.030% along with 4.8% Wollastonite microfibers when mixed with 10% silica fume and 90% cement (by weight), compressive strength improved by 13% and flexural strength increased by over 30% than the control mortar. They have described the presence of Ca and Si in wollastonite as helping in the formation of C–S–H gel in a more effective way.[58]

Global Production Statistics of Cellulose (in 2022)

In million metric tons

46.66

6.13

13.62

8.87

46.66

26.73

25.03

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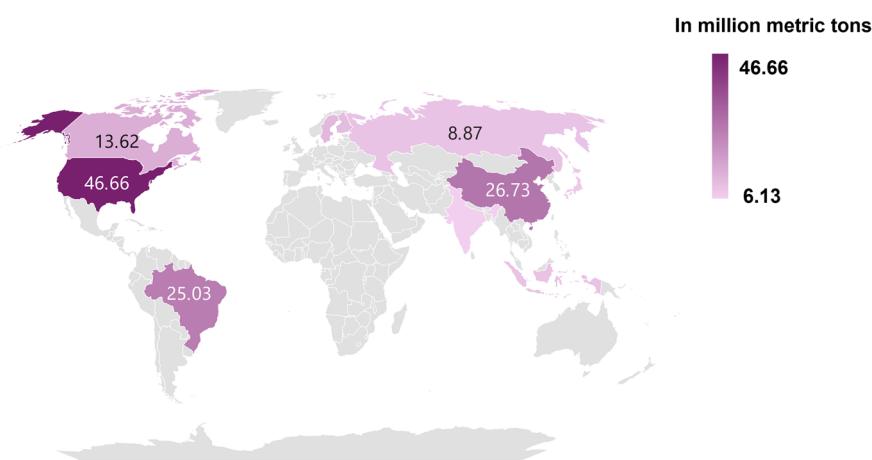
Fig. 4 Global production statistics of cellulose (in 2022) with a demographic representation, data taken from ref. 53.

Another good work was demonstrated recently by Raghunath *et al.*, where they showed improvement in rheological properties, hydration kinetics, as well as mechanical features on the addition of CNCs as their key findings. In this study, they discovered that an amount of 0.02–4% (by weight) of fiber cement enhanced the shear-thinning property of the slurry. Additionally, at a higher % weight of CNC, around 2–4% hydration rate of the cement improved severalfold, also at 4% CNC, the flexural strength of the cement rose to 35.4% more than the unmodified fiber cement.[59] Now, showcasing the efficacy of cellulose fibers of higher dimension, another commendable work has been published this year by Kadea *et al.*, where they used MFC for the development of a laminate biocomposite. They found that a modification of polyvinyl alcohol (PVA) with 3-(trimethoxysilyl) propyl methacrylate (termed as "modified PVA") showed an increase in flexural strength of the laminate biocomposite by 122% as compared to PVA. Further study revealed that the advancement of modified PVA with MFC (termed as modified PVA-MFC) causes an increase of impact strength of 148% as compared to modified PVA, besides mechanical properties, TGA data proved the enhancement of thermal stability as well. In light of all of these features, they claimed that the modified laminate biocomposite is suitable for applications like processing stage floors, furniture, and interior decorations.[60] The discussed works render the utility of cellulose to be applied to the design of more advanced functional materials. More such research was discussed later in an application-oriented manner.

2.1.2. **Hemicellulose advanced functional materials.** Hemicellulose is the 2nd most abundant biomaterial of LCBs. They are highly branched heteropolymers consisting of various pentose (arabinose, xylose) and hexose (mannose, galactose) sugar units.[61,62] They are responsible for binding cellulose with lignin to provide additional structural rigidity to the plant cell wall.[59] It is also responsible for imparting flexibility and porosity to the cell wall. But this random branched structure makes hemicellulose amorphous; as a consequence, it does not show good mechanical strength and chemical resistance properties.[63,64] That is the reason behind a comparatively lower number of available journals on hemicellulose advanced functional materials in comparison to cellulose advanced functional materials. Hemicellulose is more famous in the textile industry, packaging, biomedical applications like drug delivery, *etc.* Amongst very limited construction industry-related applications, Yang *et al.* successfully designed high-strength lignocellulosic fibers from agro-waste. Their fundamental idea was to bring the hemicellulose chains from the core to the surface, where, due to higher branching and the presence of the TEMPO-oxidized carboxyl group, bonding strength and mechanical properties have shown a noticeable change. They reported that the tensile index of the fibers improved from 18.72 N m g^{-1} to 33.28 N m g^{-1}, the tearing index increased from 3.88 mN m^2 g^{-1} to 4.63 mN m^2 g^{-1}, the bursting index enhanced from 1.71 kPa m^2 g^{-1} to 3.04 kPa m^2 g^{-1}, while folding strength went from 3 to 58 times.[65] That shows a perfect representation of processing high-value-added, low-cost products from simple agro waste, which can be further utilized in developing related materials.

2.1.3. **Lignin advanced functional materials.** Lignin is the third main component of LCBs. It is a polyphenolic complex organic compound found in plant cell walls. It mainly consists of three primary building blocks (also called phenylpropane units) named *p*-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol.[66] It provides additional rigidity to the plant cell walls and water–repellent properties to the bark and leaves of plants. Highly branched structure, hydrophobic nature, and irregular crosslinking are the key features of this compound.[67,68] Due to these inherent properties, lignin has always been a topic of interest to the scientific community for the synthesis of resins, foams, membranes, coatings, thermoplastics, *etc.*[69] Lignin is highly used in the construction industry for hydrophobic coating and binding agents, or adhesive-related applications. People have also reported the application of lignin as a water-reducing agent in cement composites.[70] Recently, one such application was demonstrated by Choowang *et al.*, where they mixed glycerol and citric acid (as a crosslinking agent) with palm kernel shells (rich in lignin) to synthesize a binder for plywood production. They reported that, at an elevated temperature of 180–200 °C, the molten binder was able to penetrate the rubberwood efficiently, resulting in an enhancement of mechanical and water resistance properties. They also recommended using a 160–200 g m^{-2} amount of the adhesive for the best result.[71] Another excellent piece of work was published by Long *et al.*, where they introduced a lignin-derived hard carbon material having hybrid sp^2-sp^3 bonding. They incorporated microcrystalline units of graphene to generate sp^2 fragments. This hard and hybrid carbon material could be used as an excellent precursor for making resins with tunable porosity.[72] Numerous examples of such advanced materials are derived from components of LCBs that the construction industry can utilize highly.

2.1.4. **Silica advanced functional materials.** Silica is the major component in the ash of LCBs. It mainly remains in its silicate form in a mixture with other inorganic salts like carbonates, phosphates, *etc.*[73,74] Silica can also be extracted *via* chemical treatment, without burning the LCBs.[75] The long polymeric networks of silicates provide some additional stability to the plant tissues.[76] Due to its catenation property and porous structure, there are plenty of novel applications feasible for silica/silicates, like the fabrication of semiconductors, insulators, cement composite, glass, tiles, *etc.*[77–79] This year, one such review has been presented by Pobtocki *et al.*, which summed up some decent works on upcycling the silica fume and fly ash (produced by industrial waste) to valorize geopolymer in a sustainable way that can be used as an eco-friendly building material.[80] Talking about individual research, Mutlu *et al.* have recently published a commendable work. They utilized a high silica content clay to produce Galette tiles. Due to the high silica content, thermal and mechanical properties both improved in galette tiles. As a result, at elevated temperatures, flexural strength increased by up to 19%. Moreover, the unique thing of this work is that when reflectance measurement was done at the UV-Vis region, it revealed that besides improvement of thermal and mechanical properties, it also shows sterilizing properties

under ambient conditions. This phenomenon happens as it is reflected in the UV-C region, and because of all of these, galette tiles produced here are ideal for industrial applications[81]

2.1.5. Miscellaneous. LCBs, in their extracted and modified form, are emerging as a sustainable alternative in the construction industry in modern society. However, from ancient times to the present rural area, different raw forms of plant biomass have traditionally been consumed by mankind. Bamboo, cork, hempcrete, straw bales, and natural latex are a few names under that category.[82] Bamboo plays the same role as concrete pillars in traditional buildings or architecture; due to its low carbon emission rate and three times the growth rate of most other plants, it has a lot of potential as a sustainable alternative to replace concrete slabs, pillars, TMT bars, *etc.* Moreover, due to the highly elastic behavior of the vascular bundle present in bamboo, it shows a 6 times higher tensile strength than steel fiber, and the energy required for the production of the same mass of steel is 50 times higher than natural products.[83] However, limitation emerges due to the poor compressive strength of bamboo than steel fibers. Some comparative data on the mechanical properties of different types of bamboo (found in various regions worldwide) with steel fiber reinforced concrete is given below (shown in Table 2). Now, coming to the flooring alternatives, people generally use cork, which is a sustainable, eco-friendly, and natural material found in the outer bark of Oak trees. Due to its lightweight, compact closed-cell structure, very low permeability for both solid and gas, low thermal conductivity, and chemical stability, it can be used as a green flooring option.[84,85] A comparative study of the properties of the cork and ceramic tiles is provided below (shown in Table 3). Based upon such unique features, cork can be upscaled for many unique applications related to

the construction industry like vibration damping,[86] Volatile Organic Compounds (VOC) adsorbent,[87] sandwich panels,[88] plastic composite,[89] insulation corkboards,[90] cement composite[91] *etc.*

Another frequently used natural material is hempcrete, prepared by mixing hemp fibers with water, cement, and lime.[93] Again, just like cork, hempcrete also possesses some excellent properties that make it an ideal choice for building applications. High density (600–1000 kg m^{-3}) for compact application, low thermal conductivity, acoustic insulation, vapour permeability, low energy demands, and CO_2 adsorbing capacity advocates its potential to replace regular Portland cement.[94,95]

Similarly, Natural Rubber Latex (NRL) can also be applied to reinforcing cement mortars. NRL can be used as a promising agent in substituting commercial latex-like styrene-butadiene, polyvinyl acetate, *etc.* It is very cheap and easily accessible, mostly in South Asian countries. Thus, proper utilization can make it beneficial in several aspects of construction, like improving mechanical properties, filling microstructures, reducing shrinkages, replacing synthetic adhesives, *etc.* Recently, Mathew *et al.* demonstrated NRL's efficacy in upgrading mortar's mechanical properties. They highlighted an increase in NRL : cement ratio from 0.5% to 2%, flexural strength improved from 3.83% to 10.62%, and porosity diminished from 15.2% to 9.9%. Moreover, due to proper entrapment of the inner moisture, drying shrinkage and mass loss were reduced to 40.7% and 51.5%, respectively.[102] On the other hand, a nice work on NH_3-free NRL-based adhesive was presented by Román *et al.* They reported that the peeling strength of an NH_3-free adhesive made from 35% dry natural latex rubber and 65% regular Cellulose-based office glue showed 4 times better adhesion properties than Elmer's glue. The peeling strength of

Table 2 A comparison of the mechanical properties of different species of Bamboo with steel fiber reinforced concrete

Species	Volume fraction of fiber (%)	Native region	Tensile strength (N mm^{-2})	Compressive strength (N mm^{-2})	Reference
Bambusa bambus	—	India subcontinent	239.00	51.33	83
Bambusa vulgaris	—	Southern China and Madagascar	232.09	67.62	
Olchlandra travancoria	—	Western Ghats (India)	149.33	28.60	
Dendrocalamus gigantis	—	Southeast Asia	221.95	53.21	
Steel fiber reinforced concrete	0	—	5.8	85	92
	0.5	—	6.9	91	
	1.0	—	8.7	95	
	1.5	—	10.8	98	
	2.0	—	11.5	96	

Table 3 Comparison between various physical properties of cork and ceramic tiles

Properties	Cork	Ceramic tiles	References
Density (kg m^{-3})	160–240	2500–6000	96 and 97
Thermal conductivity (W m^{-1} K^{-1})	0.045	0.6–1.7	97 and 98
Acoustic resistivity (kg m^{-2} s^{-1})	1.2×10^5	—	97
Specific heat (J kg^{-1} K^{-1})	350	1000	97 and 99
Compressive strength (MPa)	1	125–250	100 and 101
Tensile strength (MPa)	0.85	25–50	100 and 101

said NH_3-free NRL-based adhesive was 23.64 N cm^{-1}, whereas Elmer's glue was just 6.29 N cm^{-1}.[103] From the above discussion, it is not very hard to understand that with proper operating procedures and required modifications, LCBs and natural and sustainable resources can completely replace the synthetic and commercial products from the construction sector.

2.2. Environmental impact and energy consumption

In the current scenario, 30% of greenhouse gas emissions and 40% of natural resources are being consumed by the building sector alone. In developed countries, 70% of electricity and 12% of water have been embezzled by this sector.[104] The demand to make more commercial, residential, and industrial buildings kept rising over the years. Hence, the urge to produce more concrete, steel fibers, bricks, and cement is also moving upward. To cater to modern society's demands, 30 billion tons of concrete are produced every year. To make concrete, we also need to produce Portland cement (binding agent), which is responsible for 8–9% of anthropogenic CO_2 emissions globally.[105] Since the last 5 decades, energy consumption by the building sector has grown 1.8% per year and is projected to be over 4400 Mtoe (184.2×10^{18} J) by 2050.[106] Some relevant data on the current topic is also represented below (shown in Fig. 5(a)–(e)). From this data, we can find some interesting trends. Firstly, countries having the most advanced technologies are mostly responsible for the major portion of Greenhouse gas emissions. Secondly, most residential, industrial, and transportation sectors are the major sectors that contribute to global energy consumption; thirdly, even in this modern era, human civilization is broadly dependent on fossil fuels, which is probably the most important outcome of the study. There is a huge gap in utilizing biomass and other renewable energies to address the sustainability issue in this field. Meanwhile, some other data (shown in Fig. 6(a) and (b)) describes how biomass in different forms on biomass in various continents, as well as globally, has been destroyed, which again turns out to be a major source of pollution. So, the way out is to the proper valorization of that biomass in different forms, to replace the non-renewable energies and non-eco-friendly products from the market.
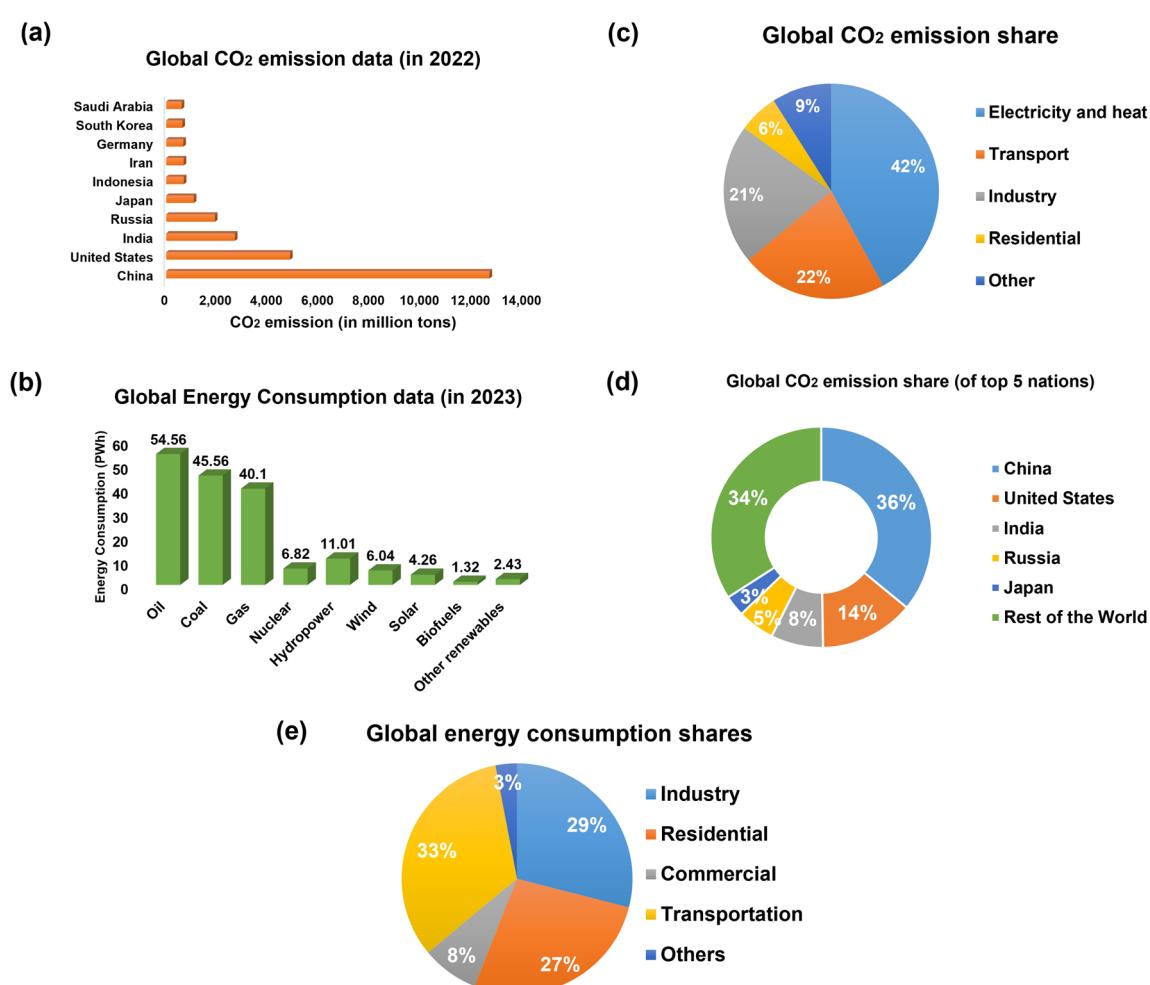

Fig. 5 (a) Global CO_2 emissions data by top 10 countries in the world (in 2022), data taken from ref. 107 (b) global energy consumption data resource-wise (in 2023), data taken from ref. 108, (c) sectoral share of global CO_2 emissions, data taken from ref. 109 (d) share of global CO_2 emissions by top 5 nations *versus* rest of the world, data taken from ref. 107 (e) sectoral share of global energy consumption data resource, data taken from ref. 110.
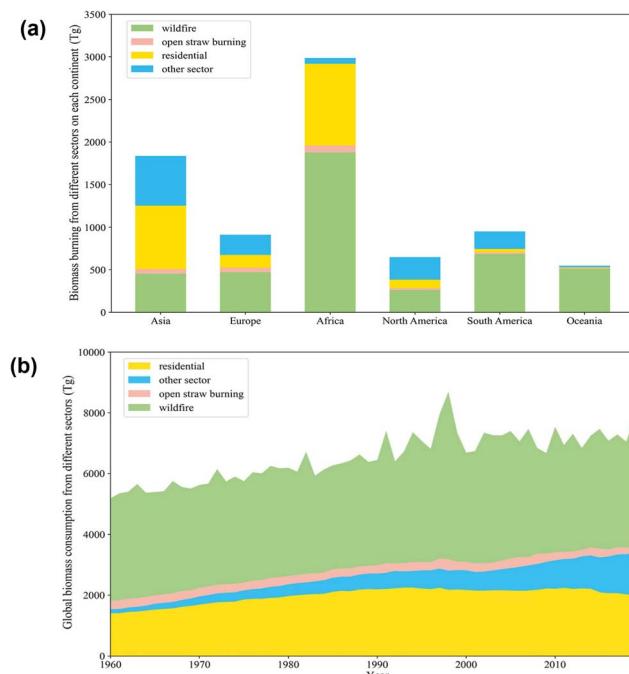
Fig. 6 (a) Continent-wise statistics of the extent of biomass destroyed by burning (in 2019), (b) global trend of total biomass burnt annually over the decades, reproduced from ref. 111 with permission from Elsevier, copyright 2024.

For example, Ardente *et al.* reviewed the role of materials in insulation boards for households by the Life Cycle Analysis (LCA) approach. They compared the Kenaf fibers with some other commercial materials used in making insulation boards, and they found the superiority of Kenaf fibers over other

materials used for the same purpose.[112] Apart from the environmental and energy data, they also considered the carcinogenic nature of some materials to draw their conclusions.

2.3. Durability and performance

Once we are done with the selection of the materials, the estimation of probable environmental and energy consumption parameters, the third and most important aspect is the ultimate performance of that product, and also how durable and sustainable it is! Hence, a thorough review of the product's above parameters is also necessary. In recent times, many good research journals have published on the valorization of LCBs to make value-added products, which can be a direct product or can be added with conventional sources in a composite to enhance their durability, quality, longevity, and performance (shown in Table 4).

2.4. Waste and recyclability

To complete the lifecycle of a sustainable product, starting from the source materials to the production phase to the usage, the last criterion is to properly recycle the waste. That is where most of the commercial polymer materials failed. Polymeric materials can be well-designed to have the desired properties as per the application. But recyclability has always remained an issue, according to a survey of around 350 million metric tons of plastic waste generated every year which is estimated to increase to a staggering figure of 1 billion metric tons by 2060.[120] Hence, pre-planned waste management and recycling protocols should be there for any such product, especially for the thermoset materials. Our future products should have the scope to be recycled into other value-added products after each life cycle, or

Table 4 Enhancement of durability, performance, and quality of construction materials by valorization of LCBs

Amount of biomass (%)	Material type	Effect	References
100%	Lignocellulosic flim	High-performance biofilms were developed from LCBs, with an excellent tensile strength of 132.48 MPa, strain of 9.77%, and toughness of 9.77 MJ m^{-3} also at wet conditions tensile strength was found 70.38 MPa, strain of 7.70% and toughness of 3.76 MJ m^{-3}, which accounts for an outstanding durability. It also has UV-resistance properties	113
0.01–0.1%	Cement mortar	High flexural strength and a greater degree of hydration due to a more porous structure	114
100%	Bioplastic	Honeycomb-like structure, better thermal and water stability, excellent biodegradable properties. It showed 35.67% of mass loss after 15 days	115
0.5–2%	Concrete	The durability of the concrete increased when biochar was added to it, at 0.5–2% weight of the cement in the concrete. Compressive strength increased as high as 16%, decreased in water permeability by 40%, caused less thermal damage, 20% higher strength, and 22–25% water tightness	116
10–20%	Concrete	Due to the mixing of rice husk ash, compressive strength was enhanced by 7.8% and tensile strength by 50%	117 and 118
0–40%	Adhesives	A lignin-doped phenol-formaldehyde adhesive was made for the production of particleboard. Key findings are high viscosity, reduction in moisture uptake, and slight decrease in mechanical properties	118
0–40%	Ultra-high-performance concrete	Sugarcane bagasse ash was used here to develop ultra-high-performance concrete, in which autogenous shrinkage was reduced by 30.25% while maintaining the same mechanical properties	119

Table 5 Different methods of recyclability of polymeric materials

Material	Method of recyclability	Description	References
Poly-trithiocarbamates	Depolymerization	Depolymerization of the polymer to its corresponding monomer is based on sulfur chemistry. The method includes solvolysis by alkali (KOH) at a moderate temperature of 40 °C	122
Unsaturated polyester resin	Self-healing	Carbon fibers were incorporated into unsaturated polyester resins. A fast and good healable property was observed with 75% retention of the original flexural strength. Also, a max of 83% load value was reported compared to the reference sample	123
Polymer composite	Biodegradation	The polymer matrices were made by copolymerization of cyclic esters and bis(1,3-dioxolan-4-one) cross-linker. Fibers were incorporated to generate strength and durability. However, they reported that they can reuse the fibers as the polymer matrices can be degraded to tartaric acid and its oligomers	124
High-performance dynamic material	Decrosslinking and depolymerization	A covalent adaptable network was made to fabricate various functional materials. It showed both rubbery and plastic properties. The disulfide-based ring-opening polymerization technique was utilized here with boroxine chemistry and was also involved in the strategy of cross-linking. It shows self-healing properties at elevated temperatures and can be degraded by treating it with ethanol at 40 °C for 10 min. It can also be reprocessed as and when needed, just by evaporating the ethanol	125 and 126
Epoxy vitrimers	Reprocessing	A fully biobased material was made from carboxy-terminated peach gum polysaccharide and epoxy-terminated itaconic acid. The β-hydroxy ester bond generated hereby exhibited excellent self-healing and reprocessing ability. Also, after getting healed, 92% of original strength recovery was noticed even after 3 processing cycles	126
Geopolymer	Biodegradation	A natural fiber-based biodegradable composite was made for thermal insulation properties. Different natural fibers were tested, and results showed decent insulating properties of all the composites, lying in the range of 0.031–0.047 W m^{-1} K^{-1}	127

they should be biodegradable so that they won't cause any soil or water pollution. This waste and recycling field is a challenging field nowadays. Lots of effort and money have been spent in this field to pursue quality research and find green solutions. As a consequence of it, we got some new fields of research, such as Vitrimerization.[121] As research progresses, many such unique processes of recycling polymer waste are being reported every year. Some selected ones are discussed here also (shown in Table 5), just to give a flavour of the diversity of the available solutions.

3. Innovative valorization techniques for converting LCBs to biomaterials

The meaning of "Valorization" is to make something valuable or extremely useful from ordinary things. That is also our motivation behind writing this paper. We not only sum up the application of LCBs but also draw an overview of some modern valorization techniques concisely. These techniques act as a bridge to obtain valuable biomaterials from various sources in nature. It can be wood, straw, husk, bark, crop, root, leaves, or anything. Most of the time, these items are consumed as food, and the rest are burned as combustibles. This has been a major source of carbon emissions, greenhouse gases, and smoke, which is indirectly responsible for several lung diseases. So, it is utterly important to extract this biomass and valorize it to its corresponding components, which can be further shaped into

different articles. Broadly, these techniques can be classified into 2 categories: (1) physical, (2) chemical methods. Different research can be classified under these two categories. Although a process cannot be fully physical or chemical, because every process needs some basic chemicals and some specific physical conditions. But based on the key step, this classification can be made.

3.1. Physical valorization methods

The physical extraction methods involve thermal and mechanical valorization approaches. These methods are extremely useful for reducing the particle size, increasing the porosity, and surface area while maintaining the chemical composition. Mechanical methods can be like grinding, milling, shredding, *etc.* In high-end techniques, steam explosion, ultrasonication, and microwave irradiation are quite famous for generating fine particles from LCBs. These processes are sophisticated but can be used numerous times with minimal usage of reagents. Some examples have been given below.

(a) Llorens *et al.* discovered an innovative way to valorize LCBs using supercritical-CO$_2$ (Sc-CO$_2$). They reported the convenience of this green method under conditions of 300 bars, 100 °C and 70% moisture content. A minimal effect was observed on the overall chemical composition and β-O-4 lignin structure. This pretreat also improved the solubilization of lignin for Organosolv extraction to 49% to 79%. In this technique, they took 70% aq. solution LSBs in a preheated chamber
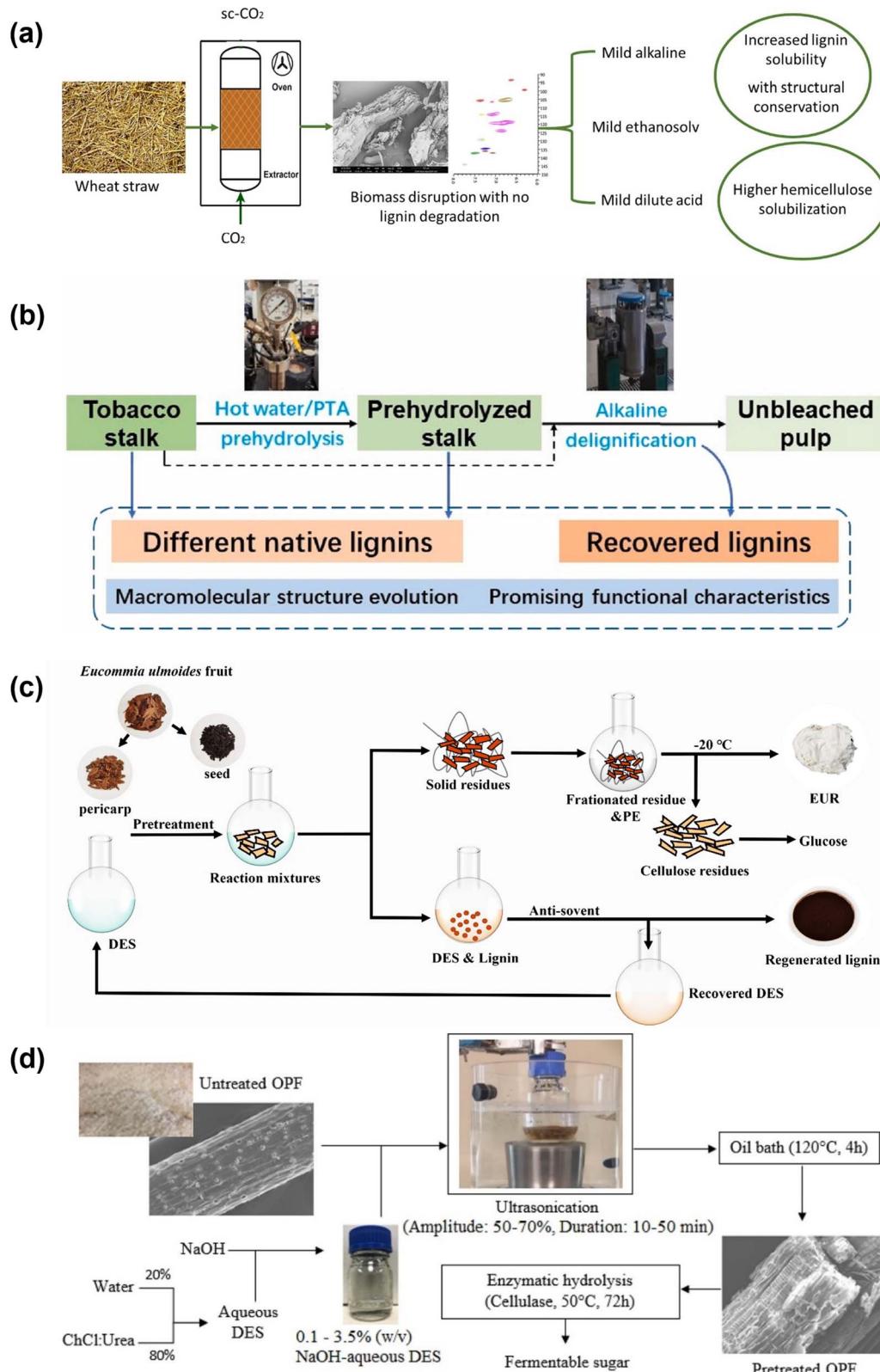
Fig. 7 (a) Schematic diagram of the pretreatment process of wheat straw using Sc-CO₂, reproduced from ref. 128 with permission from Elsevier, copyright 2024. (b) Schematic diagram of phosphotungstic acid-assisted delignification process of tobacco stalk, reproduced from ref. 132 with permission from Elsevier, copyright 2023. (c) Process of valorizing LCBs for the production of *Eucommia ulmoides* rubber *via* the DES method, reproduced from ref. 133 with permission from Elsevier, copyright 2023. (d) Ultrasonication-assisted DES method for the extraction of cellulose and other valuable polysaccharides from palm frond biomass, reproduced from ref. 135 with permission from Elsevier, copyright 2021.

and maintain a constant flow of CO_2 at a 50 g CO_2 per min rate for 2 h. Throughout the experiment, pressure and temperature were maintained at 200–500 bar and 100–150 °C, respectively (shown in Fig. 7(a)). The whole set-up runs in a circular way, where extra-pure CO_2 (≥99.7%) is pumped into the preheated chamber, which carries the extracted materials and then goes into a separation chamber, where materials get separated and gas is left out of the chamber in gaseous form, later condensed and compressed for reuse.[128]

(b) Freitas *et al.* represented an alternative technique to valorize Almond shells to cellulose other than doing Soxhlet extraction using organic solvents. Here, they employed a method called subcritical extraction. The fundamentals of this method are to heat the Almond shell feedstock at the subcritical temperature (150–320 °C) and pressure (20–150 bar). Under these conditions, several properties of water, like surface tension and dielectric constant, varied significantly, which makes it ideal for the extraction of substances that are even sparingly soluble in water. This condition is also ideal for breaking some specific bonds present in agro-waste. This treatment was further followed by a bleaching step of 8% H_2O_2 at 160 °C and 180 °C to remove lignin and hemicellulose. After the whole procedure, cellulose content recovered at 71% and 78%, with crystalline characters at 50% and 62% respectively, at 160 °C and 180 °C.[129]

(c) Aguilar *et al.* reported another unique process of the steam-explosion method. This process is beneficial, especially for those cases where surface modification is also needed. This process involves heating at high temperatures followed by sudden decompression, which generally affects surface properties and porosity. In detail, the process begins with alkali (NaOH) pre-treatment followed by steam explosion, and after that, oxidation by 30% H_2O_2 and 3.7 wt% of NaOCl. 70% of biomaterials have been recovered after the steam explosion.[130]

(d) Singh *et al.* recently described a technique for valorizing LCBs to silica and other biominerals. They talked about the thermal liquefication technique. With this method, they subjected the LCBs to an autoclave cycle equipped with a mechanical stirrer, pressure controller, thermocouple, and a heater. The parameters were set to 150 °C, 5 bar, and stirring was kept on. After the reaction, the instrument was cooled and depressurized. A liquid phase and some solid substances were recovered from it. Solid was dried at 105 °C for a day, and bio-oil was extracted from the liquid. The yield of bio-oil was found to be around 90%, and solid substances were found to be 98% pure, with mostly silica and some other minerals.[131]

3.2. Chemical valorization methods

Unlike physical methods, chemical methods are more specific; here, some selective reagents are used to break some targeted bonds. These techniques are very useful for the selective extraction of a particular component based on its substrate-reagent chemistry. Acid hydrolysis is widely used to selectively break the ester linkages between lignin and hemicellulose, for targeted removal of hemicellulose from biomass. Similarly, bleaching reactions using chlorite, alkali, and peroxides are

known for lignin removal by destroying the chemical structure. In high-end techniques, deep eutectic solvents (DES) and ionic liquids are familiar for selectively dissolving LCBs components. Such methods are discussed below in detail.

(a) Liu *et al.* have highlighted a facile method of extraction of pure lignin from Tobacco stalks. They have utilized a very common hydrothermal method with the unique use of phosphotungstic acid, which helps in the selective removal of hemicellulose units. The hydrothermal process was carried out at 170 °C for 1 hour, and the pretreatment process with 1% (w/v) phosphotungstic acid was performed for the same time at a comparatively lower temperature of 130 °C. After all of these processes, an alkali treatment was done with 14% NaOH and 0.5% Anthraquinone to extract the lignin through "black liquor" (shown in Fig. 7(b)). This process was strategically selected for the fact that lignin, present in Tobacco stalks, has lots of structural similarity with hardwood lignin, which means they are very depolymerized. So, *via* this process, they claimed that they were able to recondense through the hydrothermal and pre-treatment process. A large number of phenol groups and high carbon content were detected in extracted lignin, which makes it ideal to be utilized in many bio-based composites.[132]

(b) Yao *et al.* utilized the DES method (shown in Fig. 7(c)) for valorizing LCBs for the production of *Eucommia ulmoides* rubber, a natural rubber comprised of *trans*-1,4-polyisoprene, which is extremely useful in making various composites. They reported some interesting results with the addition of cellulose and lignin nanoparticles as side products. In this process, they treated their LCBs feedstock with DES (consisting of lactic acid, Zinc Chloride) at 120 °C, 2 hours after the reaction, lignin was extracted from the mixture by a 1 : 1 (v/v) acetone-water mixture thrice. Lignin was precipitated by adding excess water and later recovered by freeze-drying. However, the solid substance obtained after extraction with a 1 : 1 (v/v) acetone-water mixture was subjected to alkali treatment (for neutralization purposes) and subsequent mechanical treatment for recovery of rubber. They highlighted that the process is utterly useful with a yield of 91% and a purity of rubber of more than 99% while maintaining the chemical structure. On the other hand, nano lignin recovered through this process was able to perform superior antioxidant properties than the commercial options.[133]

(c) Rastogi *et al.* developed another enzymatic-based technique for valorizing LCBs to lignin-free polysaccharides. They have used sugarcane bagasse and corn cob as their feedstock and subjected them to an alkali treatment (with 2% NaOH) for the delignification process, followed by xylanases enzyme treatment, which is extracted in-house using *Aspergillus tubingensis* strains. In this method, the substrate loading parameter was set to 2% (w/v), 100–500 U g^{-1} enzyme loading, and incubation conditions were set to 40 °C, 140 rpm, and 72 hours. The yield of saccharification reactions was found to be 81.4%. The result revealed greater saccharification of the hemicellulose fraction than cellulose. The quantity of reduced sugar was determined by the colourimetric method using DNA reagent.[134]

(d) Ong *et al.* combined ultrasonication with the DES process (shown in Fig. 7(d)), to valorize palm frond biomass into

reducing sugar and its derivatives. The ultrasonication pre-treatment was carried out at 20 kHz, followed by DES with a choline chloride: urea mixture. It was established that with the addition of an ultrasonication method at 60% amplitude and 30-minute duration, delignification significantly improved from 30.92% to 47%. Also, upon enzymatic saccharification, glucose content was found to be 90.12%. Overall, the synergistic effects showed much better results.[135]

(e) Fawy *et al.* reported a dual valorization technique to convert LCBs into amorphous silica and activated carbon, which are highly consumed by the construction industry. They employed the pH reduction technique to precipitate silica. On the other hand, thermal treatment with N_2 gas purging was used to generate activated carbon. At first, rice husk and straw were pre-treated with an alkaline solution of 50 g L^{-1} concentration, and then after cooling and filtering, the reaction mixture was neutralized with an acidic solution to make the pH of the solution around 7, resulting in the precipitation of sodium silicate from LCBs, that are further converted to amorphous silica. The pH of the rest of the filtrate was further brought down to near 1–2 range to precipitate components of the biomass; then they were washed, dried, and subjected to the carbonization process in a tube furnace for 8 hours with 800 °C, flow of N_2/CO_2 gas. For confirmation, both silica and activated carbon were characterized by several analytical tools like XRD, SEM, and FT-IR.[136]

4. Application of LCBs-based biomaterials in modern construction

In the previous section, we highlighted several modern-age technologies regarding the extraction of biomaterials like cellulose, hemicellulose, lignin, silica, and many other mineral or valuable inorganic compounds. These methods are also tailored to valorize those biomaterials into different shapes, sizes, forms, and textures according to the application field. Now, passing through the motive of our study, comparison of LCBs with conventional materials, and discussing some novel technologies for valorization, we have reached the advanced functional material stage. That means it's time to focus on our actual purpose, application! The way to utilize LCBs-based biomaterials to serve specific applications is to make commercial products. These products are vast in variety. Still, if we need to categorize the most frequently manufactured products from LCBs, two broad categories must be included in that list: (1) structural and (2) non-structural materials. Further, they can be classified into several sub-categories (shown in Fig. 8). The major ones are discussed below thoroughly.

4.1. Structural materials

Structural components are the backbone of any construction project. These materials are designed to provide the structure for a building. They are responsible for structural support, carrying loads, maintaining the integrity, stability of the structure, *etc.* These materials are tested to withstand stresses like compression, tensile shear, *etc.* Cement composite, fiber
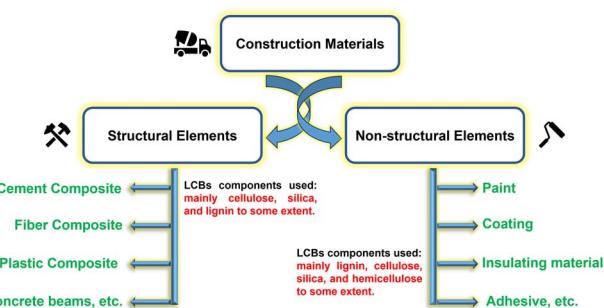

Fig. 8 Classification of structural, non-structural construction material and components of LCBs consumed in the respective fields.

composite, and plastic composites are the major ones from this category.

4.1.1. Cement composite. The idea of incorporating LCBs to improve the microstructure and mechanical properties originated a few decades ago. Research has been on this topic since the previous century. In the 80 s, the number of such journals started to grow slowly year by year. The scientific community revealed a basic yet novel idea that can be extrapolated to tackle the sustainability crises in the future. Just like, Mai *et al.* compared the mechanical properties of cellulose fibers reinforced cement composite, where in one case, bleached cellulose fibers were used in another case, unbleached. They found that bleaching causes an increase in mechanical properties except for the fracture toughness.[137] In the next year, Mai *et al.* published another journal article where they focused on reducing cracks or fractures. They discovered that the rate of crack growth is much lower in wet cellulose fibers, evident from crack growth resistance *vs.* crack extension curves. These modified composites can show an improved value of both ductility and toughness.[138] In the same decade, Thomas *et al.* highlighted the extraction of cellulose fibers from wastepaper and further valorization to the cement composite. They tried the combination of cellulose fibers with Kaolinitic clay and incorporated it into a cement matrix in some fixed proportion. They were able to achieve a compressive strength of 10.3 MPa and tensile strength of 2.8 MPa.[139] As science progressed with time, researchers came up with some more advanced ideas to work on the fundamentals. Bentur *et al.* did thorough research on the aging the cement composites in natural conditions and with a mimicked accelerated condition in higher CO_2 concentration. They found that in accelerated conditions, carbonation of the matrix leads to an increase in flexural strength and E-modulus. However, accelerated aging in normal environmental conditions deteriorates the material quickly, resulting in a decrease in toughness.[140] In the 1990s, Bakula *et al.* investigated the effects of autoclaved cellulose fiber on cement composite, where they reported a 25% increase in bending strength and almost twice the increase in bending toughness.[141] In this period, people started looking for improvement in microstructure also, from micro-level reinforcement to micro-crack filling, and the field became more enriched; Klemm *et al.* demonstrated some modification with cellulose to make

methyl hydroxy ethyl cellulose (MHEC), they mixed it with polyvinyl alcohol (PVA) and applied to the cement composite. This strategy was again taken to cease the deterioration of concrete from moisture and low temperatures. The addition of MEHC helped in retaining the water present within the concrete, whereas PVA improved the adhesion property. All together enabled the concrete to withstand adverse weather conditions and enhanced its longevity.[142]

As we moved from the 20th to the 21st century, other components of LCBs were introduced to this field. People started exploring lignin and, most importantly, advanced silica materials to serve their purpose. Bilba *et al.* utilized lignin extracted from sugarcane bagasse to reinforce the concrete. They mentioned that the incorporation of lignin delayed the setting time of the concrete, and side by side, it also enhanced the hydration temperature. They also stated that a heat treatment at 200 °C enables their cement composite to exhibit similar properties to those we observed in regular Portland cement. Moreover, DSC studies revealed that their cement composite has thermal stability up to 450 °C[143] Similar results were also observed in a study conducted by Morton *et al.*, where they used a 0–4 wt% lignin extracted from slash pine. Their key findings were an increase in flexural toughness from 1.69 kJ m^{-2} to 3.69 kJ m^{-2}, which also shows a similar trend at aging when an accelerated aging test was performed. Apart from that, several other mechanical properties showed an improvement, such as fracture energy, modulus of rupture, lower water absorption capabilities, and excellent dimensional stab.[144] In 2008, Wang *et al.* conveyed a nice study revealing the effects of using fly ash (majorly silica) on mechanical strength, durability, microscopic changes and to investigate its kinetics. Their result highlighted that up to a 25% incorporation of biomass fly ash provides exactly similar compressive strength as that of pure cement and a composite using coal fly ash for up to a year. Microscopic studies revealed a change of smooth surface to rough due to the formation of C–S–H gel when 1-year-old reacted concrete compared with the raw one. Kinetics was found to be indifferent with respect to the consumption rate of Ca for both coal and biomass fly ash. With all of these results, they concluded that biomass fly ash has exactly similar and better performance in some cases compared to coal fly ash, hence potentially being used to make cement composites.[145] Similarly, in this time period, many other good journals have been published explaining the effects of fly ash on mechanical properties,[146] pozzolanic activities,[147,148] hydration kinetics,[116] water permeability,[118] microstructure,[149] durability[149,150] and performance[151,152] *etc.*

In recent years, the number of journals discussing LCBs-based cement composites has increased exponentially. Thought processes have upgraded quite a lot, and new sources, methods, and approaches have been explored vigorously. For example, Huang *et al.* developed a novel Mineralized Cellulose Composite (ML-CCM) through vacuum filling and an *in situ* mineralization strategy (shown in Fig. 9(a)–(c)). This composite has shown excellent thermal insulation, fire retardancy, and a passive radiative cooling effect due to the presence of ZnO nanoparticles. Moreover, the multilevel scaffold, micropores,

and micro-nano minerals present within the ML-CCM enable it to capture CO_2 and Environment Tobacco Smoke (ETS) (shown in Fig. 9(d)–(g)).[153] Taheri *et al.* prepared a composite using CNF and ordinary Portland cement (OPC) in various proportions. They highlighted the significance of homogeneity and the degree of entanglement between fibers in defining various mechanical, thermal, and chemical properties. They found that short CNF played a significant role in improving the mechanical properties, whereas long and entangled fibers reduced the density and thermal conductivity of the composite.[154] Manjunath *et al.* published a very interesting study including electrical resistivity and ultrasonic pulse velocity through cement mortar structure. They first prepared Cashew Nutshell Ash (CNSA) through vigorous processing (shown in Fig. 10(a)) and mixed it with cement to prepare the composite. Results show that CNSA-based mortars have impressive compressive strength, water absorption, and porosity. It was also noticed that ultrasonic pulse velocity and electrical resistivity (ER) have increased with the percentage of CNSA in the mortar (shown in Fig. 10(b) and (c)).[151] In recent times, some journals have also published on the effects of CNF doping on the 3D-printability of cement composites. Like, Fahim *et al.* described the application of alkali-activated CNC, based on their viscosity-enhancing property, a reduction of extrusion pressure by 35%, a maximum 20% increment in mechanical properties, and a 25% increase in the degree of hydration was observed in the composite. The internal curing potential of CNC was enhanced even more when they were heated thoroughly. They mentioned that due to this heating, the unreacted particles have been dissolved, generating a denser and more interconnected structure. Hence, fewer microcracks were observed in the case of heat-cured samples than in seal-cured ones. They concluded that due to the viscosity-modifying effect of CNC, overall improved the overall consistency and buildability of the cement mixture were improved without using any synthetic viscosity-modifier, which enables this composite for 3D-printing applications.[155] Similar applications were also represented by Kilic *et al.* They found a 0.3 wt% of CNF can provide desirable rheological and mechanical properties. Various tests were conducted by them for elucidating compressive, tensile, flexural strength, dynamic yield stress, and viscoelastic characteristics using a model of Bingham plastic material (shown in Fig. 10(d)–(g)). Buildability and printability assessment was done using a 3D-concrete printer facilitated with a screw pump mechanism and nozzle of 10 mm diameter (shown in Fig. 10(h)).[156]

4.1.2. Plastic composite. Considering the accumulation of plastic commodities on land as well as ocean surfaces, there is no need to explain the importance of bioplastic nowadays. Plastic materials are not biodegradable, require high energy for burning and are responsible for the greenhouse effect. It is worth mentioning that when 1 kg of plastic is burnt, it generates 2.8 kg of CO_2.[157] Thus, bio-based or bio-derived plastics are the high demand of our society. To reduce pollution, enhance sustainability and move towards greener alternatives, bioplastics are introduced in the previous century. In the 20th century, Wilde *et al.* published a journal discussing the key
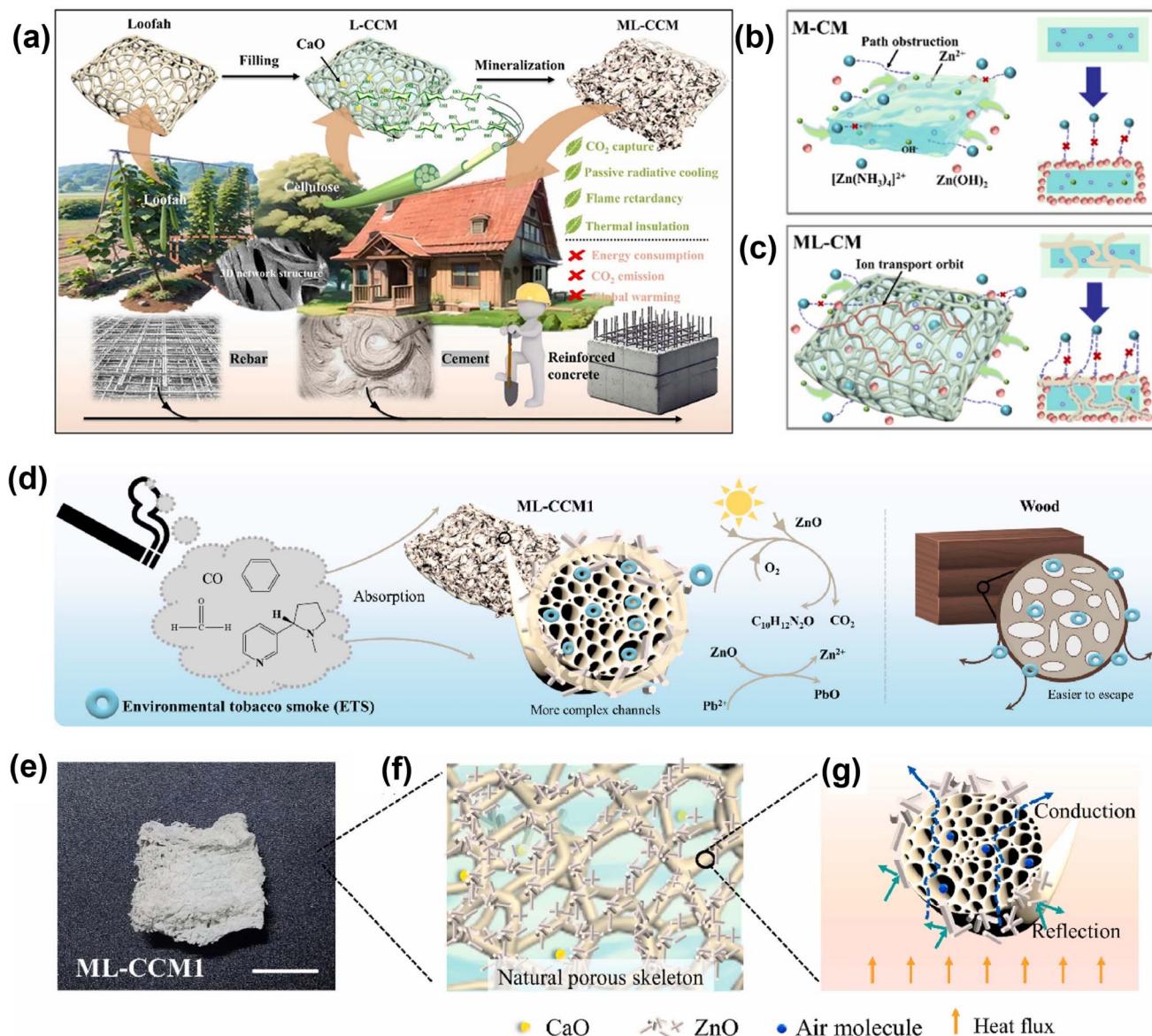
Fig. 9   (a) Fabrication of ML–CCM composites. (b) Mechanism of structural formation of M–CM composite. (c) Mechanism of structural formation of ML–CM composite. (d) Mechanism of absorption and fixation of ETS ML–CCM1. (e) Appearance morphology (scale bar: 2 cm), (f) internal structure, and (g) heat transfer mechanism of ML–CCM1 composite, reproduced from ref. 153 with permission from Elsevier, copyright 2024.

features and prerequisites for a bioplastic to be accepted for daily use applications.[158] In the last decade, Brodin *et al.* published a review of various methods for the production of bioplastics, as well as a detailed discussion on the application of different types of bioplastics and their environmental concerns.[159]

Now, talking about the applications, Orts *et al.* prepared polymeric gels and films using cellulose microfibrils (2–10%) as a reinforcing agent. Several properties, like Young's modulus, tensile strength, and load-bearing capacity, were estimated using different sources of cellulose fibers. At 10.3 wt% of cotton-derived cellulose fibers 5 times increase in Young's modulus was observed.[160] Ganster *et al.* represented the utility of man-made cellulose filament with high tenacity to reinforce

commonly used commercial polymers like polypropylene (PP), poly-(lactic acid) (PLA), polystyrene, *etc.*, for injection molding applications. Compared to glass fiber reinforcement, these cellulose filaments were noticed to improve overall mechanical properties and impact strength due to their low density and anisotropic nature, which provides lower stiffness. Especially, in the case of PLA, a dramatic reduction in brittleness was observed, with excellent biodegradability and mechanical strength.[161] Some research groups also reported state-of-the-art works on the fabrication of wood-based bioplastics. Chen *et al.* fabricated a wood-derived bioplastic where they extracted the latex from *Hevea brasiliensis,* modified it with some vulcanizing agent, and mixed it with delignified balsa. *In situ* vulcanization and densification led to the bioplastic (shown in Fig. 11(a)–(c)).
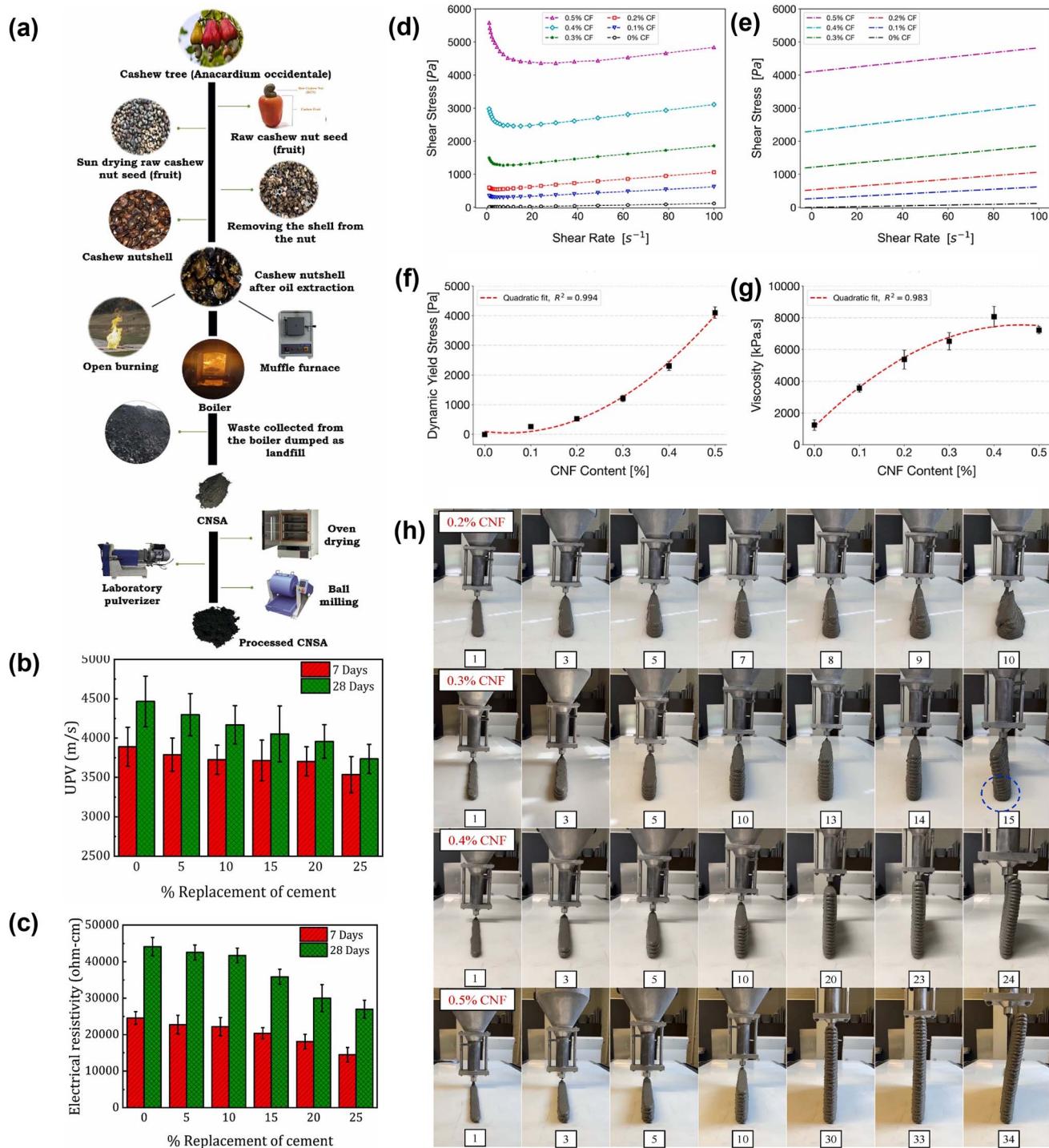
Fig. 10 (a) Procedure for the generation of CNSA. (b) UPV values of blended cement mortar at different CNSA percentages. (c) Electrical resistivity of blended cement mortar at different CNSA percentages, reproduced from ref. 151 with permission from Elsevier, copyright 2023. (d) Flow curves, (e) Bingham model fits, (f) Dynamic yield stress, and (g) viscosity values of the mixes with increasing CNF concentration. (h) Buildability assessment of the mixes with 0.2%, 0.3%, 0.4%, and 0.5% CNF concentration, reproduced from ref. 156 with permission from Elsevier, copyright 2024.

It has shown good mechanical properties, biodegradability, water absorption capacity, and many more. Compared to delignified balsa, the fabricated bioplastic's water absorption capacity was almost 6 times lower (shown in Fig. 11(d)). The tensile strength of the bioplastic has also improved thrice after adding both the natural rubber latex (NR) and vulcanized natural rubber latex (VNR) (shown in Fig. 11(e)). Moreover, this bioplastic also offers an excellent in-built O_2 barrier property, however, the delignified balsa does not have this O_2 barrier property due to the porous structure between the cellulose
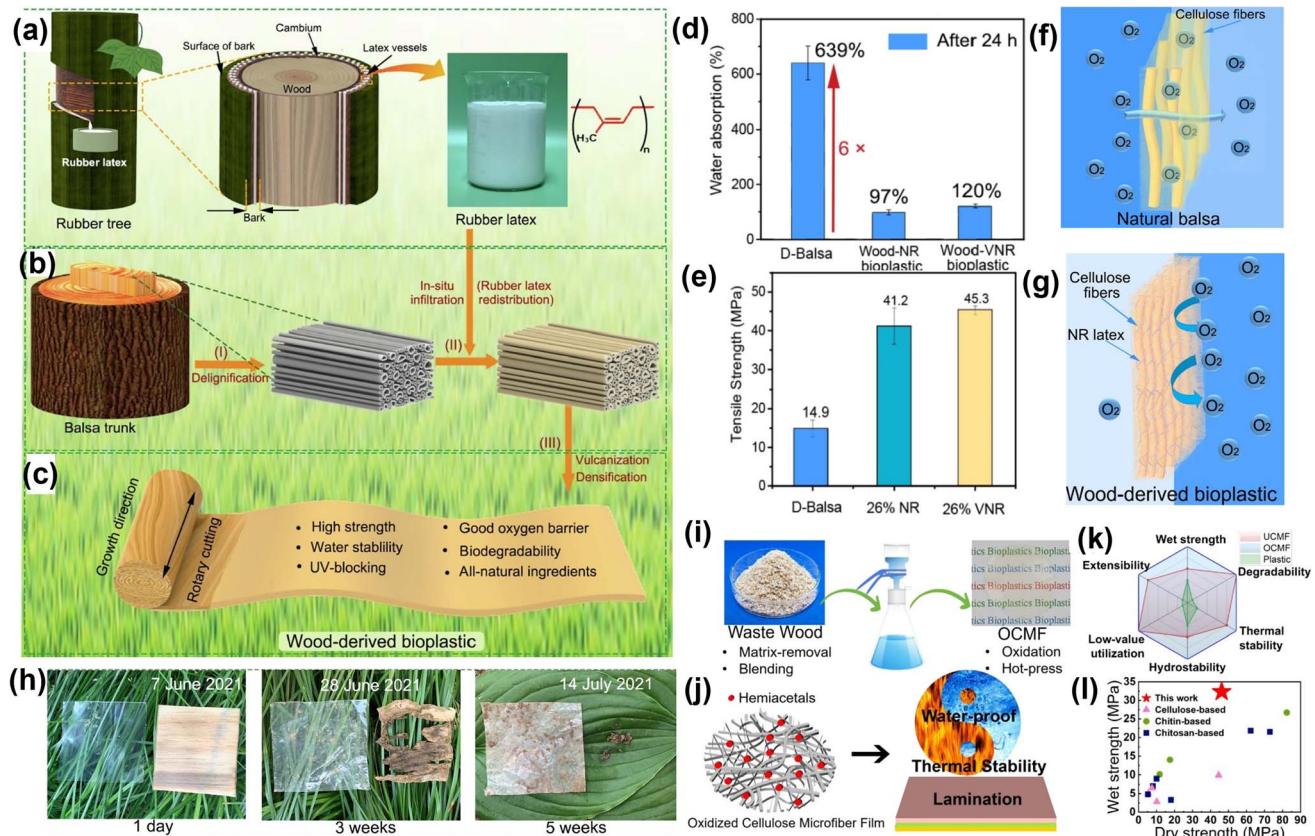
Fig. 11 (a) Schematic of *Hevea brasiliensis* and its radial cross-section showing the latex vessel in the bark. (b) Illustrative demonstration of the fabrication of the wood-derived bioplastic through delignification, redistribution, and vulcanization of natural rubber to make it more porous. (c) Schematic representation of the derivation of the wood-derived bioplastic using a rotary cutting method and demonstration of its unique properties, like biodegradability, water stability, and excellent oxygen barrier. (d) Comparison of water adsorption properties of delignified balsa and wood-derived bioplastics infiltrated with 26% NR and 26% VNR, respectively. (e) Tensile wet strength comparison of the soaked D-balsa and wood-derived bioplastic (26 wt% of VNR and 26 wt% of NR). (f) Schematic of the high oxygen permeability of natural balsa due to the porous structure. (g) Schematic of O_2 barrier property due to the dense packing of cellulose nanofibers. (h) Images of the biodegradability test of the wood-derived bioplastic and PE under moist soil, reproduced from ref. 162 with permission from Elsevier, copyright 2022. (i) Diagram of the conversion process from waste wood particles into OCMF. (j) Schematic diagram of the formation mechanism and performance of OCMF. (k) Qualitative radar plot comparing UCMF, OCMF, and plastics. (l) Wet and dry tensile strength of OCMF compared with the reported works, such as cellulose-based, chitin-based, and chitosan-based films, reproduced from ref. 163 with permission from ACS, copyright 2024.

fibers, but during the processing of the bioplastic, hot-pressing and addition of NR Latex produced a tight packing among the cellulose fibers leading to this O_2 barrier property (shown in Fig. 11(f)–(g)), and talking about biodegradability, it has shown an incredible biodegradable behaviour by decomposing by the soil microorganism in just 5 weeks (shown in Fig. 11(h)).[162] Similarly, Zhou *et al.* developed an entirely cellulose-based bioplastic from waste wood residues through a step-by-step process of matrix removal, blending, oxidation, and hot press (shown in Fig. 11(i)). The fabricated Oxidized all-cellulose Microfiber Film (OCMF) has superior wet strength, transparency, extensibility, thermal stability, biodegradability, and hydrophobicity as compared to unprocessed hydrophilic cellulose fiber-based films and plastics (shown in Fig. 11(j)–(k)). Even compared to other material-based bioplastics like chitin and chitosan, the OCMF has better dry and wet strength (shown in Fig. 11(l)), making this a robust one.[163] Chen *et al.* modified ultra-fine fibers with cellulose acetate and polyethylene glycol

(PEG/GA) composite *via* an electrospinning method for thermal storage applications and to improve water resistance. For further upgradation of thermal and mechanical properties, toluene-2,4-diisocyanate was embodied as a cross-linking agent. Due to this modification, a 10 °C increment in decomposition temperature was recorded in differential thermogravimetric data.[164] Saralegi *et al.* inspected a study on shape-memory-based properties of the incorporation of CNC into segmented thermoplastic polyurethanes. In this study, castor oil and corn cob were used as the source of polyurethanes and CNC, respectively, which were covalently bound to each other. DSC and DMA revealed that the melting of soft and hard phases was responsible for shape fixity and shape recovery, respectively. The thermo-mechanical data confirmed nearly 100% shape recovery in the 2nd cycle. The effect of CNC is nothing but the increase of hard phase crystallinity, generating more network points.[165] Farias *et al.* demonstrated a plasma therapy using either air or pure oxygen to remove the amorphous layer of lignin present on
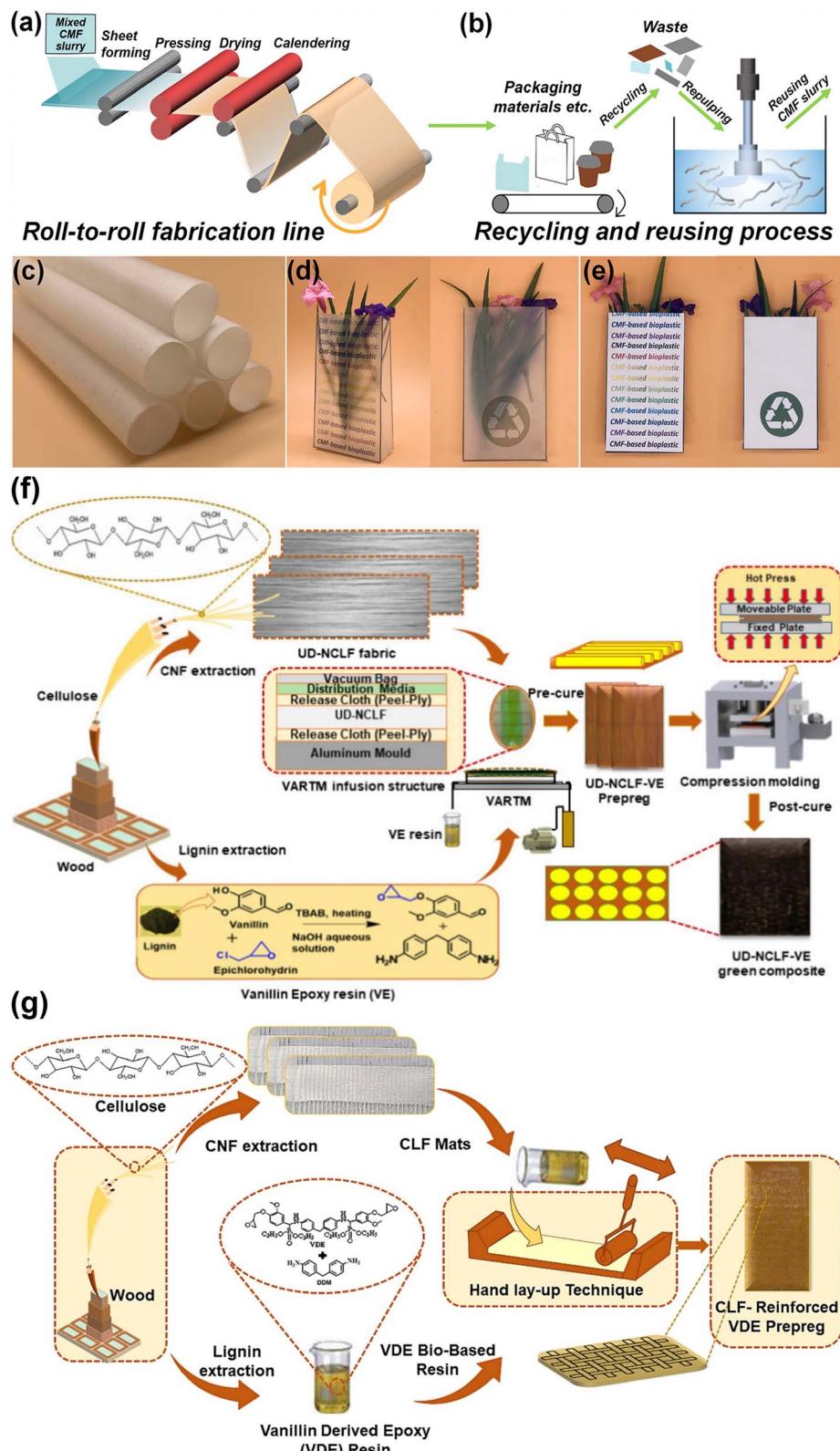
Fig. 12 (a) Schematic of the industrial production process of the CMF/Al$_2$(SO$_4$)$_3$/PAE crosslinked bioplastic film through a roll-to-roll production line. (b) Schematic of the recycling process of the CMF/Al$_2$(SO$_4$)$_3$/PAE bioplastic film. (c) & (d) Digital photos of the CMF/Al$_2$(SO$_4$)$_3$/PAE bioplastic film showing the potential of this film in transparent packaging material. (e) Digital photo of commercial paper-related application of the CMF/Al$_2$(SO4)$_3$/PAE bioplastic film, reproduced from ref. 167 with permission from ACS, copyright 2022. (f) Scheme for the preparation of a UD-NCLF-VE composite using the VARTM process and compression molding, reproduced from ref. 170 with permission from ACS, copyright 2024. (g) Fabrication of CLF-reinforced VDE prepreg preparation using the hand lay-up method, reproduced from ref. 171 with permission from Elsevier, copyright 2024.

the surface of coir fibers to decrease the lignin-to-cellulose ratio, leading to improved mechanical strength. After the plasma treatment, they found a 3 times increase in tensile strength and an almost 20-fold increase in elastic modulus, which is attributed to better fiber-matrix adhesion. They mentioned 80 W and 7.2 minutes as the optimum parameters for oxygen plasma treatment.[166]

Similarly, Lei *et al.* represented a facile method for industry-level processing of dual-crosslinked Carboxymethyl Cellulose Fiber (CMF)-based films with a total preparation time of just 1 hour. They extracted the softwood kraft pulp, bleached it, and treated the slurry with polyamide epichlorohydrin resin and $Al_2(SO_4)_3$ for cross-linking through electrostatic interactions. Later, the slurry was fabricated into bioplastic film through several steps like dehydration, drying, hot pressing, *etc.* (shown in Fig. 12(a)). Apart from excellent mechanical properties in both dry and wet states, transparency, flexibility, and printability, these bioplastic films are easily recyclable by disintegrating the cellulose fibers in water to reprocess the slurry (shown in Fig. 11(b)). These bioplastic films have many applications, like fabricating interior décor, packaging, commercial paper, *etc.* (shown in Fig. 12(c)–(e)).[167] On the other hand, Yeo *et al.* utilized the same lignin with some modification using (3-aminopropyl) triethoxysilane to process a composite with polypropylene-*graft*-maleic anhydride *via* the melt-bending method. Due to the homogenous distribution of modified lignin particles, a 2-fold increase in tensile strength and tensile modulus was observed as compared to pristine lignin. This modification also contributed to greater interfacial adhesion forces. Just like cement composites, 3D-printing domains were also explored in the case of plastic composites.[168] For example, Koo *et al.* focused their research on developing a bio-based thermoplastic elastomer for 3D-printing applications and the production of bio-integrated devices. Keeping an eye on sustainability, they fabricated the elastomer with CNC-doped bio-furans (like 2,5-furandicarboxylic acid). Uniformly distributed CNC acted as the nanofiller, providing a superior tensile strength of 67 MPa that is 7 times greater than synthetic thermoplastic urethanes, as reported. With a significant extensibility of 8.6 folds and almost negligible *in vivo* cytotoxicity, this surely becomes a superior alternative to petroleum-based thermoplastic elastomers.[169]

Apart from bioplastic films, some researches are also focused on the fabrication of semi-synthetic epoxy-composites using cellulose fibers. Like, Adil *et al.* prepared a Unidirectional-Nano-Cellulose-Long-Filament-Reinforced Vanillin Epoxy green Composites (UD-NCLF-VE) through Vacuum-Assisted Transfer Molding (VARTM) and compression molding method (shown in Fig. 12(f)). The prepared UD-NCLF-VE has shown excellent thermal, water-resistant, and biodegradable properties along with comparable flexural properties to pure VE composite, which makes this composite a more sustainable option to overcome plastic pollution and landfill issues.[170] Adil *et al.* published another good work where they made a similar type of Vanillin Derived Epoxy (VDE) composite, which consists of fire–retardant properties along with the previous applications. Here, they extracted the wood-based CNF

and lignin and compounded it with VDE to form the Cellulose Long Filaments (CLF)-reinforced VDE Prepreg using the hand lay-up technique (shown in Fig. 12(g)), which finally shaped into the CLF-reinforced VDE composite through compression molding and some post-cure treatment. The composite has shown a commendable enhancement of 100.9% flexural strength and flexural modulus compared to the neat VDE resin and also secured a V-o rating under the UL-94 test for flame-retardancy.[171]

Apart from those, there are so many journals published on the various applications of LCBs modifying plastic composites. Some selective research areas are lignin-cellulose containing PVA composites for generating biodegradable plastics,[172] active food packaging applications,[173] to generate tribological properties,[174] epoxy vitrimers,[175] transparent UV-protecting films,[176] improving piezo-resistance,[177] *etc.*

4.1.3. Fiber composite. Fiber composites, as the name suggests, are materials manufactured using two or more different types of fibers. The fiber components may vary as per the requirement, such as ultra-tough, ultra-light, chemical resistant, moisture resistant, UV-resistant, or with fine microstructural arrangements. As in this review, our main objective is to find out the available materials that can bear mechanical stress in applications related to the construction industry, as well as those that are sustainable and biodegradable. So, here we have mainly discussed those fibers which are purely natural or semi-synthetic. In this regard, Mohanty *et al.* published a comprehensive review comparing bio-based fibers with glass fibers. It was mentioned that several fibers, especially the hemp and flax fibers, have greater *E*-modulus and specific modulus than glass fibers. Moreover, the advantages of matrix modification and novel fabrication methods with low-energy requirements make the fibers suitable for numerous applications.[178] Lacoste *et al.* investigated the effect of alginate-based adhesives on biofibers. They compared a bunch of aldehyde-based synthetic cross-linkers with alginate-based binders. They reported of development of semi-rigid fiber composites with flexural strength around 0.2–0.54 MPa and compressive strength around 0.4–1.41 MPa, along with a thermal conductivity value of 0.08 W m^{-1} K^{-1}, which stands for the thermal insulation application in green buildings.[179] Ramlee *et al.* developed another robust natural fiber composite using sugarcane bagasse (SCB) and oil palm empty fruit bunch (OPEFB) fibers. They tested several properties like tensile strength, void percentage, swelling behavior, and water resistance capacity. They found that the composite made of 70% OPEFB and 30% SCB showed better UTM results with 5.56 MPa of tensile strength and 661 MPa of tensile modulus. Whereas a composite made with 30% OPEFB and 70% SCB performed better in water adsorption and swelling experiments. Overall, these natural fibers are suitable for green insulation applications, as described in this article.[180]

In search of some other applications of fiber composites, we found a recent journal of Charai *et al.* talking about upscaling hemp fibers for green plaster-based construction items. They manufactured plasterboards using Moroccan hemp fibers with a wt% ranging from 0–6%. On comparing the 6% sample with
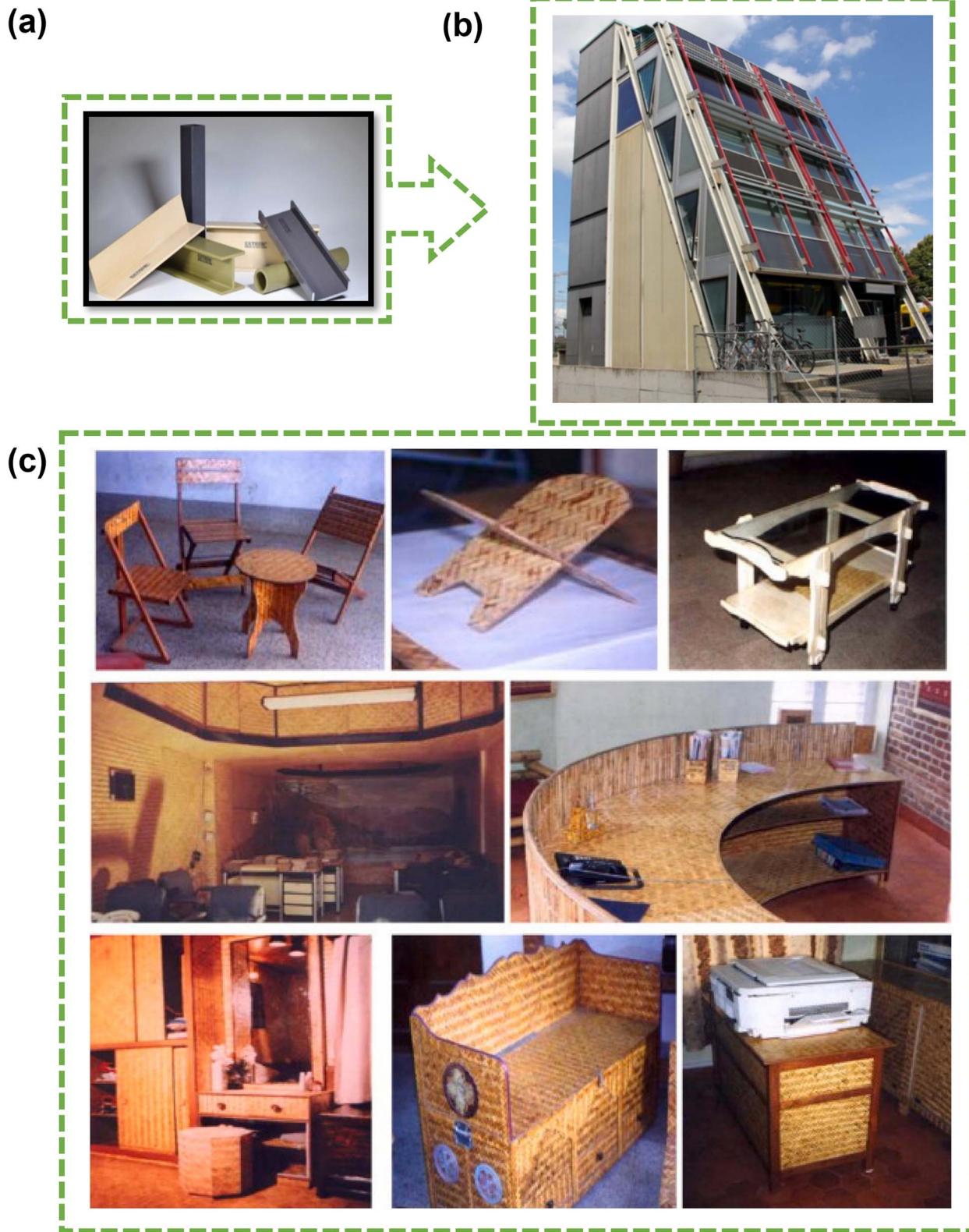
Fig. 13 (a) Various kinds of FRP, (b) five-storey hybrid building made using FRP (Switzerland), reproduced from ref. 184 with permission from MDPI, copyright 2022. (c) Utilization of Bamboo fiber-reinforced composites in sustainable furniture, reproduced from ref. 186 with permission from Elsevier, copyright 2012.

control plasters (without fibers), it was observed that the density has lowered by 24.5%, thermal insulation properties improved by 31.3%, whereas heat transfer reduced by 8.5%. It was also mentioned that the 2% sample stands out to be the best in terms of thermal heat capacity. In conclusion, these biofiber-based plasterboards can be very useful as a green building material, having low weight, low energy demand, and the least environmental impact.[181] Yu *et al.* developed another robust and durable semi-synthetic composite using glass fibers and bamboo scrimbers with various thicknesses. They found an enhancement in every mechanical feature: compressive strength increased by 7%, shear strength improved by 25%, modulus of rupture enhanced by 18%, and modulus of elasticity increased by 22%. Moreover, aging test results prove excellent dimensional stability, and impressive fire–resistance properties were also recorded by the infrared thermal imaging method for these composites, especially the thicker ones. Fire limitation test results also support the IR imaging data, where the limitation duration was found to be increased by 650% and the mass loss rate reduced by 400%.[182] Liu *et al.* prepared some biomass bricks using corn stalk (15%) and $Ca(OH)_2$ (85%) with brown sugar (0.85%) doping. In comparison with the control specimen, these brown sugar bricks showed a 51.03% increase in compressive strength, 40.91% enhancement in tensile strength, and 64.24% improvement in flexural strength. The efficacy of brown sugar was attributed to its ability to disperse the CO_2 within the bricks, ultimately resulting in a slow carbonation rate. Due to this, pore-clogging is delayed around the surface, leading to enhanced mechanical properties of the brick, which makes them the ideal candidate for adhesives and processing of building materials.[183] Qureshi *et al.* reviewed a study on the application of Fiber Reinforced Polymer (FRP) (shown in Fig. 13(a)) in modern-day civil engineering. These FRPs are used to provide additional mechanical strength to the concrete slab, leading to an entire hybrid building structure (shown in Fig. 13(b)).[184] On the other hand, Hasan *et al.* conducted a mini-review on bamboo fiber-reinforced polymer composites, where they represented a wide category of applications of bamboo-based FRPs in buildings and daily households (shown in Fig. 13(c)).[185]

4.2. Non-structural materials

Non-structural materials are not directly involved in load-bearing jobs. They are responsible for surface-finishing jobs like coating, insulation, moisture resistance, fire retardancy, *etc.* So far, we have discussed the modification of structural components by LCBs, which is the first step toward constructing a green building. However, these modifications are only limited to constructing a building; to make this building a home, workplace, or institute, several internal advancements are highly required. For example, a building material that is performing excellently in ambient conditions might not exhibit the same performance in some specific geographical areas with extremely cold, hot, or humid weather, so there we need proper thermal or moisture insulation. On the other hand, if we are constructing some building in an area where sound pollution is

a major issue, like beside some airports, railway stations, auditoriums, stadiums, or even a construction site itself, so there we need some pretty good arrangements of acoustic insulation for living with sound health. Similarly, to protect building material from corrosion, deterioration, and other chemical factors, we need proper water-resistant coatings, also to ensure stable joining between the structural components, it requires strong adhesives. Hence, a growing market for insulation products is observed all around the globe. According to a survey conveyed in 2022, the global insulation market was estimated at around $67 billion, out of which a staggering $29.75 billion, which is projected to expand to a massive economy of $110.6 billion and $48.69 billion respectively, by 2032, with a growth rate of 5.2% between 2022-2032.[187] Here, we have discussed some major categories of non-structural construction materials.

4.2.1. Thermal insulation. The concept of thermal insulation in residential buildings did not originate in recent times. From the ancient period, human civilization has used straws, big leaves, and even wood stems for this purpose. We can still see these types of huts and cottages in rural areas, especially in the continents of Asia and Africa. At present, besides different forms of forest materials, the extracted forms of LCBs are being used as thermal insulating substances.[188,189] Particularly, for thermal insulation purposes, the use of cellulose and silica has been observed the most; apart from that, journals were also available on hemicellulose and lignin. Now, let's do some background study; the first question arises: how does heat conduction occur in different states of matter? Well, it is commonly known that in solids, the heat is conducted through the material due to the combined effect of lattice vibrations and energy transport *via* electrons. Whereas liquid and gas heat conduction occur due to collisions between different molecules and diffusion from one place to another.[190] So, to manufacture some products with specific shapes and sizes, we have to think about the solid state of matter. Now, as lattice vibrations are mostly responsible for heat conduction in solids, we have to keep the density of our solid insulating material as low as possible and porosity as high as possible; these are the primary requirements for a material to use as thermal insulation in buildings. So, researchers have developed ultra-lightweight and highly porous materials like aerogels, foams, *etc.*[191] Bhardwaj *et al.* described the inner mechanism of heat conditioning through the air medium present with a porous structure in aerogel. It was described that if we can reduce the pore size of the aerogels to less than the mean free path of air (70 nm), then we can reduce the heat conduction that occurs due to successive collisions. Hence, this way, we can decrease the thermal conductivity even less than that of air ($\sim$25 mW m^{-1} K^{-1}).[192] To improve the quality of these insulating products, many research groups attempted different methods, for example, Biswas *et al.* tried with nano-PCM (Phase change material) incorporated wallboard for thermal insulation to reduce the energy consumption. In that paper, they fabricated an innovative PCM using graphite nanosheets. They not only show good conductivity but also distribute heat energy pretty well; due to the interconnected structure, they overall have excellent thermal

Table 6 Comparison between different bio-based insulating materials based on their thermal conductivity and other related features

Type of material	Components present	Thermal conductivity (mW m^{-1} K^{-1})	Valuable features	References
Aerogel	Cellulose, Mg(OH)$_2$	56–81	Flame retardant	197
Aerogel	Cellulose	25.5	Low density, high strength	198
High porosity wood	Cellulose	38	Lightweight, noise reduction	199
Bamboo particle boards	Lignin, glue	101–201	Hygrothermal properties	200
Aerogel	Silica, lignin, ethylene glycol polymer	40	Fire resistance, superhydrophobic performance	196
Aerogel	Silica	19–23	Acoustic insulation	201
Aerogel	Konjac glucomannan, silica	21	Ultralight, high mechanical strength, hydrophobic	202
Aerogel	Cellulose nanowhisker	45	Flexible, flame retardant, high mechanical strength	203
Aerogel	Cellulose, PVA	31–42	Ultralow density, high porosity, superhydrophobic	204
Aerogel	Cellulose, graphene confined-zirconium phosphate nanosheets	18	High mechanical strength, fire retardancy	205
Aerogel	Bacterial cellulose	13	Flexible	206
Foam	Wood fiber, phytic acid, polyethyleneimine	33.6–40	Mechanically tough, fire-retardant, self-extinguishing property	207

storage capacity. They tested this modified wallboard with regular gypsum wallboard in extreme conditions throughout the year. Both heat gain and heat loss data reflected lower numerical values for PCM-modified wallboards, proving their capacity to provide better insulation.[193] Similar use of PCM was also discussed in research done by Lee *et al.* They incorporated PCM into building walls, and the result proves a reduction in average heat flux daily is 25.4% for individual walls in four directions (*e.g.*, north, south, east, west). A 20.1% reduction in the hourly average of heat flux was noticed in the sum of all walls.[194] Another great piece of work has been published by Wicklein *et al.* They have prepared some anisotropic foam consisting of Graphene oxide (GO), CNF, and sepiolite nanorods, which performed way better than traditional polymeric insulating materials. It gave an outstanding insulation capacity with only 15 mW m^{-1} K^{-1} radial thermal conductivity. Brilliant mechanical properties with axial specific Young' modulus of 77 kN m kg^{-1} and impressive fire retardancy with limiting oxygen index (LOI) of 34, which means a 60% higher concentration of oxygen than O$_2$ present in the air (21%), will be required to burn the material. Concisely, the performance of these foams, made from sustainable sources, is much better than usual halogenated flame-retardant materials, and due to their anisotropic properties, like greater mechanical strength in the axial direction and lower thermal conductivity in the radial direction, enables them for versatile applications.[195] As the amount of quality research published on this particular thermal insulation topic is huge, we have shortlisted some insulating materials and discussed their thermal conductivity and other relative properties (shown in Table 6).

Apart from the above research discussed in Table 6, a few other recent works show some promising results with a commendable presentation. For example, Ou *et al.* presented a noteworthy work on lignin-silica-based aerogel with a bunch of desired properties like thermal insulation, fire-retardancy, robust structure, superhydrophobicity, durability, *etc.*

Here, they fabricated a silica-mineralized lignin nanocomposite aerogel (LigSi) having a flexible multilevel micro/nanostructure, and the fabrication method is based on an eye-catching water-induced self-assembly and *in situ* mineralization technique (shown in Fig. 14(a)). The composite aerogel has some extraordinary mechanical strength, which can comfortably take a load of a person weighing 65 kg (shown in Fig. 14(b) and (c)). The optimized LigSi has shown an ultrahigh stiffness (a specific modulus of ∼376.3 kN m kg^{-1}), humidity–resistant properties, intrinsic superhydrophobic performance (158° WCA), *etc.* Prepared aerogel composite had some exceptional NIR reflectance properties originating from the multi-scaled morphological structure and hybrid composition of silica-lignin of the composite (shown in Fig. 14(d)), resulting in very low NIR absorption (∼9%), which upscaled the thermal insulation property. Now talking about thermal insulation property, the result revealed that the composite has a low thermal conductivity of ∼0.04 W m^{-1} K^{-1}. To ensure comfortable living, they made a model building where they used their composite as an insulating material; the result was found very satisfactory as recorded in the thermal IR camera (shown in Fig. 14(e) and (f)). To correlate the lower NIR absorbance and thermal insulation property, a photochemical conversion test was also done and recorded through a thermal IR camera, which concludes the excellence of their scheme (shown in Fig. 14(g) and (h)).[196] Boquera *et al.* developed a novel plaster using gypsum and lignin. They evaluated their thermal, acoustic, and mechanical properties. They mentioned that the plaster composite has similar thermal insulation properties as compared to the pure-lignin-based test. However, acoustic performance was reduced with an increase in lignin content, and mechanical properties were found to be better at 50–70% lignin content.[208] Sun *et al.*
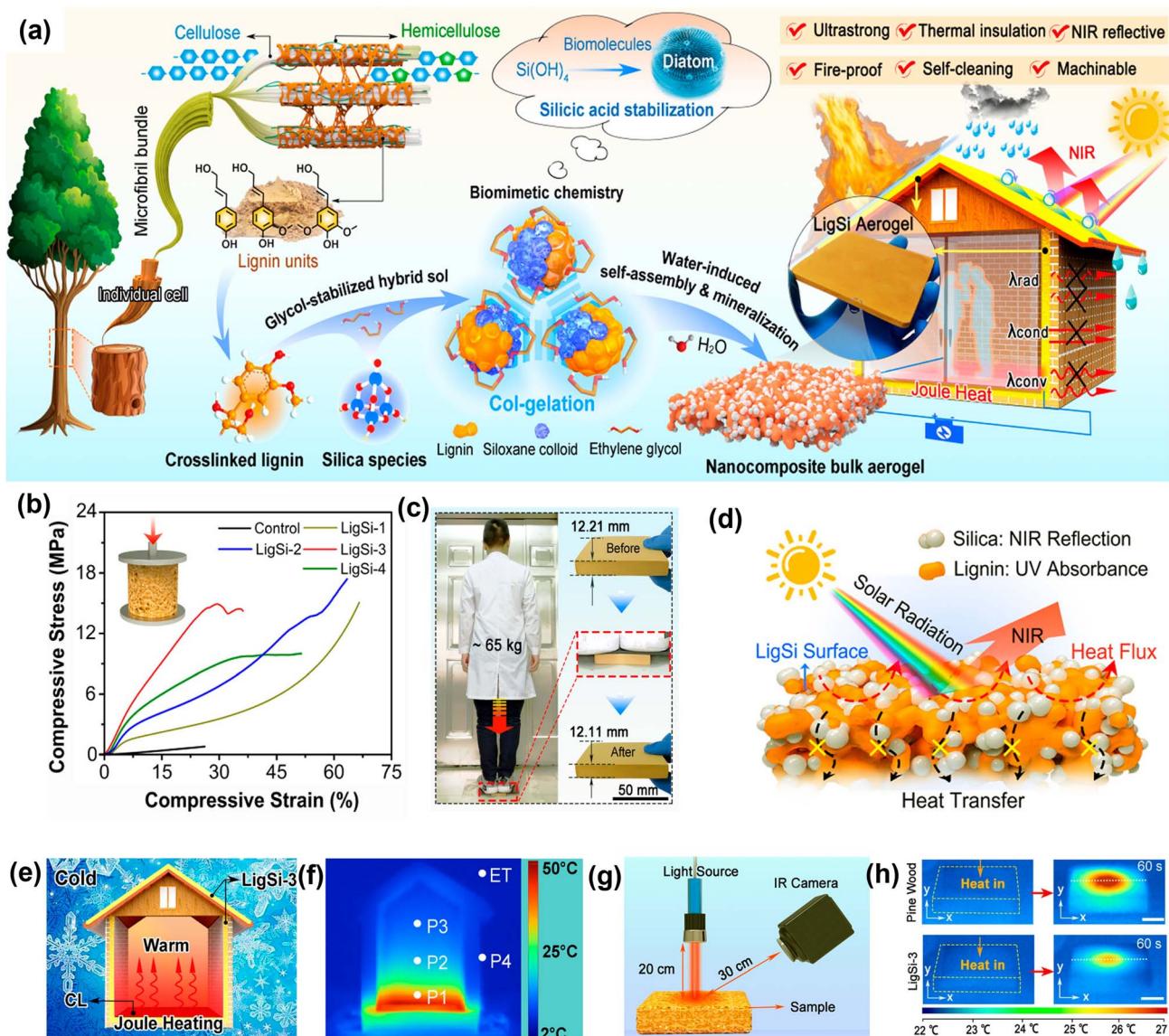
Fig. 14 (a) Schematic illustration of the fabrication strategy of LigSi aerogel composite through the water-induced self-assembly and *in situ* mineralization technique. (b) Compressive stress–strain curves of typical LigSi materials. (c) An example showing the extraordinary mechanical property of LigSi aerogel, which can bear a 65 kg weight of a human, with minimal deformation. (d) Illustration representing the low photothermal conversion. (e) Illustrations of the energy-efficient model building, whose roof, floor, and external sidings are made of LigSi-3 material. (f) Thermal IR photographs of the model energy-efficient building when power is applied (10 V). (g) Schematic setup for testing the photothermal conversion of LigSi-3 samples as compared to pine wood (reference). (h) Thermal IR photographs of LigSi-3 and the pine wood, illuminated by a NIR light (1350–1600 nm), reproduced from ref. 196 with permission from ACS, copyright 2022.

prepared another lignocellulose-based aerogel with multiple exciting properties like thermal insulation, durability, mechanical stability, and fire retardancy. For their synthesis purpose, they have used a recyclable DES, along with incorporating tourmaline particles and ammonium sulfate to form a stable structure through H-bonding. The overall structure formed is highly porous, ultralight weight, impressive flame retardancy, excellent thermal insulation properties with thermal conductivity of 29.67 mW m^{-1} K^{-1} for the TLA-4 sample (the optimized one), and a dramatic enhancement in Negative oxygen ions (NOI) was found to be 74.1%, which signifies its ability to purify the air which is good for our health.[209]

Some research groups also represented the real-life implications of their material for thermal insulation purposes. For example, Baetens *et al.* have represented a collage of such real-life applications of thermal insulating materials in their review. They enlisted a number of photographs of buildings using translucent aerogel for thermal insulation (shown in Fig. 15(a) and (b)). They also emphasize the effectiveness of aerogel in insulating heat by comparing insulated and non-insulated buildings/floors (shown in Fig. 15(c)).[210] Mendes *et al.* reviewed a more specific topic; they selected silica-based aerogel for thermal insulation. There, they represented different designs or protocols for building wall insulation, such as the
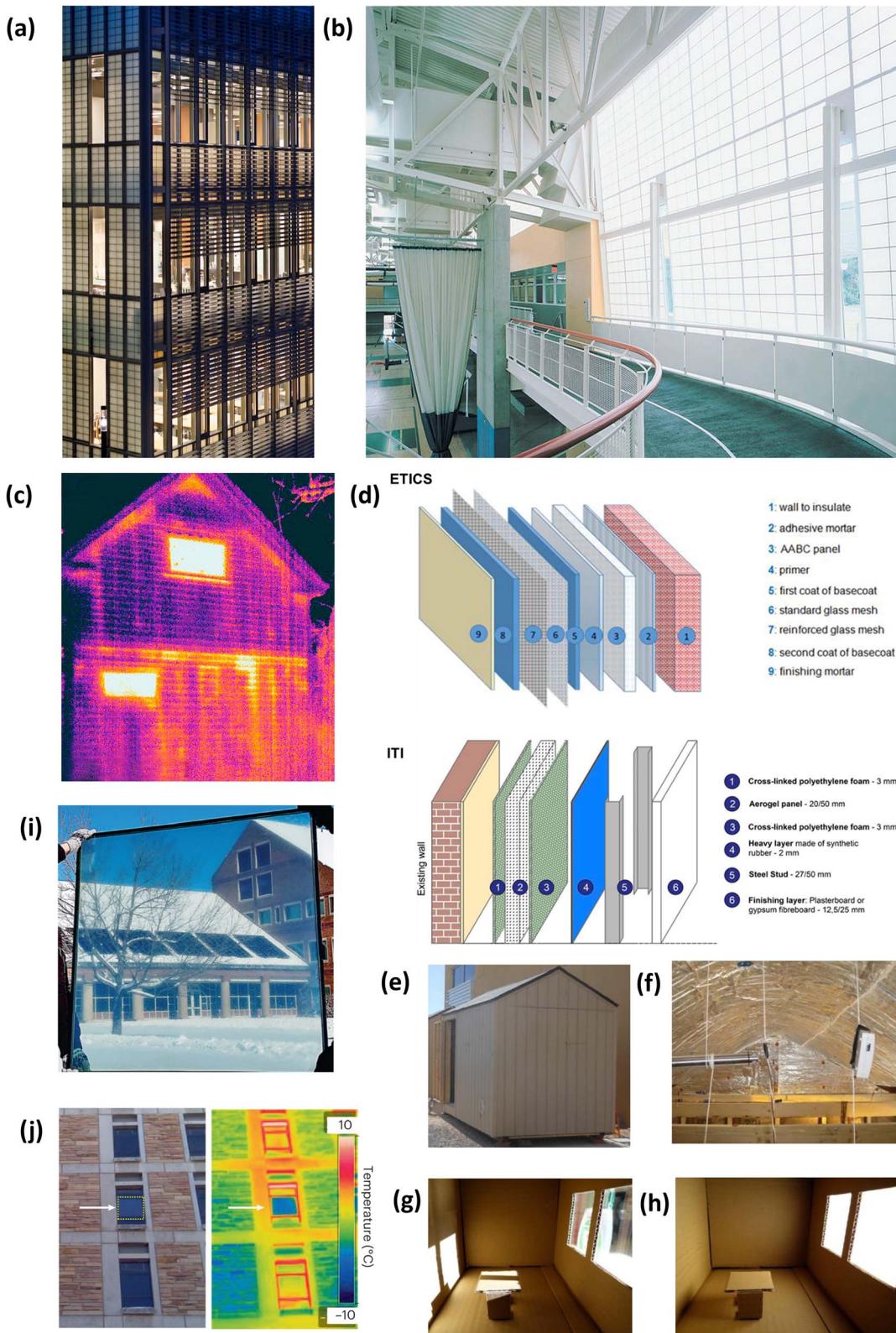
Fig. 15   (a) Real-life application of translucent aerogel used to insulate the curtain wall at the sculpture building of Yale University (USA). (b) Example of thermal insulating performance by translucent aerogel in daylight. (c) A thermographic photograph of the timber wall of a house, where the aerogel insulation was used at the top floor, and the ground floor is kept uninsulated, reproduced from ref. 210 with permission from Elsevier, copyright 2011. (d) Schematic illustration of ETICS and ITI systems, reproduced from ref. 211 with permission from Elsevier, copyright 2019. (e) Test house, (f) attic deck area of that house where the aerogel-based radiant barrier was used, reproduced from ref. 212 with permission from Elsevier, copyright 2018. Representation of (g) double glazing unit and (h) aerogel glazing unit in test house reproduced from ref. 213 with permission from Elsevier, copyright 2016. (i) Real-life images of Double-pane IGU with LoĒ-366 coatings on one glass pane and 3 mm-thick

External Thermal Insulation Composite System (ETICS) and the Internal Thermal Insulation multi-layer system (ITI) (shown in Fig. 15(d)). They also incorporated some journals talking about the characterization of the thermal performance of aerogel-based radiant barrier systems in residential attics (shown in Fig. 15(e) and (f)). Moreover, the journal also consists of aerogel used as the glazing system (shown in Fig. 15(g) and (h)).[215] Abraham et al. have published work on a similar topic, where they developed a highly transparent Silanized-Cellulose Aerogel (SiCellA) for the glazing systems in buildings to boost energy efficiency. They show how a thin coating of their aerogel on the surface of Insulating Glass Units (IGUs) can resist the heat by several folds and provide comfort inside (Shown in Fig. 15(i) and (j)).[214]

4.2.2. Acoustic insulation. Acoustic insulation means protection from sound pollution, indeed, one of the most important topics of discussion. Temperature fluctuation can cause discomfort, but living in an area with noise pollution issues can cause severe mental illness and deafness. So, first, we have to understand how a material can act as an insulator of sound waves. Well, it was well known that in a solid medium, the sound spreads due to the collective vibration of solid atoms and then disperses in all directions. So, the best way to cut off that transmission is to create some structure where the constituent atoms are not heavily connected. Hence, the ideal material might be porous, lightweight, and elastic. The sound insulating properties might be understood from the sound transmission loss, which is nothing but the difference between decibels of incoming and propagating sound. The greater the numerical value, the better the sound-insulating properties will be.[216] In the current scenario, we can find many such advanced building materials providing good acoustic insulation properties. For example, Faustino et al. developed a corn con particleboard; the result indicates that the value of impact sound insulation gain (ΔL_W in dB) is 30, which is very much comparable with the traditional synthetic alternatives used for the same purpose as glass wool (31 dB) and expanded polystyrene (30 dB). So, we can see they can be potentially used to replace the commercial options.[217]

Yeon et al. upscaled the paper waste to process cellulosic materials for superior sound absorption. They evaluated the acoustic insulation capacity by comparing the Noise reduction coefficient (NRC) of their material with synthetic materials, which is nothing but the ability to absorb sound. NRC = 0 means no absorption, while 1 means total absorption of sound, i.e., complete insulation. They found the NRC to be 0.75 for their insulating material with a thickness of 60 mm and density of 36 kg m^{-3}, whereas that of glass wool and polyester are 0.85 and 60, respectively, which again proves the applicability of lignocellulosic material to replace the synthetic ones.[221] Moving one step ahead, Zhu et al. exhibits a lot of modifications within their materials. Firstly, they modified CNC with

methyltrimethoxysilane (MTMS) to synthesize Si–CNC and then mixed it up with red mud and a cross-linking agent, Hexamethylene diisocyanate (HDI), to fabricate novel organic-inorganic materials (shown in Fig. 16(a)–(e)) for various purposes, including acoustic absorption. They depicted that the sound absorption coefficient (SAC) (ratio of incident and propagated sound energy) decreased by around 50.2% on increasing the red mud content by 6 times the weight of Si–CNC compared to the sample having no red mud (shown in Fig. 16(f)). Authors highlighted the fact that ultra-low density, high porosity, and presence of inorganic particles in the form of red mud acted as a natural barrier to the thermal and acoustic waves, leading to superior insulating properties (shown in Fig. 15(g)).[218] Bikumalla et al. incorporated surfactants to fabricate some biodegradable bagasse foams. Although they used various types of surfactants, they reported the ultimate performance for Sodium dodecyl sulfate, which enhanced the acoustic properties of the foam by 200%. The highest sound absorption coefficient reported by them is 0.85. The novelty of this study is the fabrication method, which did not include the use of any sort of synthetic epoxy or other resins.[222] Yu et al. developed another outstanding sound-absorbing material from natural resources like bamboo pulp. They shaped this into a foam with the additional incorporation of halloysite nanotubes, which is an alumina-silicate-based mineral with a hollow structure. They also added chitosan and phytic acid for layer-by-layer arrangement to improve porosity and mechanical properties. This bio-based foam (especially the BPF-4BL variant) displayed excellent sound-absorbing properties with a SAC as high as 0.95 and an impressive self-extinguishing property in the torch-burning experiment.[223] Such a high value of SAC was also found in a recent work of Li et al., where they developed a silica-based flexible aerogel via a sol–gel process. Along with many other properties like elasticity, mechanical, and thermal, this aerogel provides an impressive SAC of 0.91 at 2000 Hz and sound transmission loss of 13–21 dB between 500-1600 Hz.[224] Wang et al. published a very interesting work on the synthesis of lignin aerogel, where they used cellulose as an adhesion agent. In this work, they have taken 1-butyl-3-methylimidazolium chloride (BMIMCl), a common ionic liquid, for simultaneous dissolution and preparation of lignin-cellulose-based gel, which was further solvent exchanged with water and freeze-dried to form a complete aerogel structure (shown in Fig. 15(h)). All the prepared aerogel samples have shown excellent SAC in the mid-higher frequency range of 500–4000 Hz; the highest SAC value was noted as 0.94, which is just wonderful (shown in Fig. 16(i)).[219] Feng et al. also described a similar kind of work of making hybrid aerogels using silica–cellulose; in this paper, additional information was added in terms of a prototype of the SAC measurement set-up (shown in Fig. 16(j)).[220] Last but not least, we would like to discuss another study conducted by Buratti et al. on the effect of the granule size of the insulating

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SiCellA films on the surface of the other glass panes. (j) Evaluation of the thermal performance of a single-pane window retrofitted with a 72.1 cm × 71.4 cm SiCellA 1.5 mm-thick film (in a building on the University of Colorado campus), reproduced from ref. 214 with permission from Nature, copyright 2023.
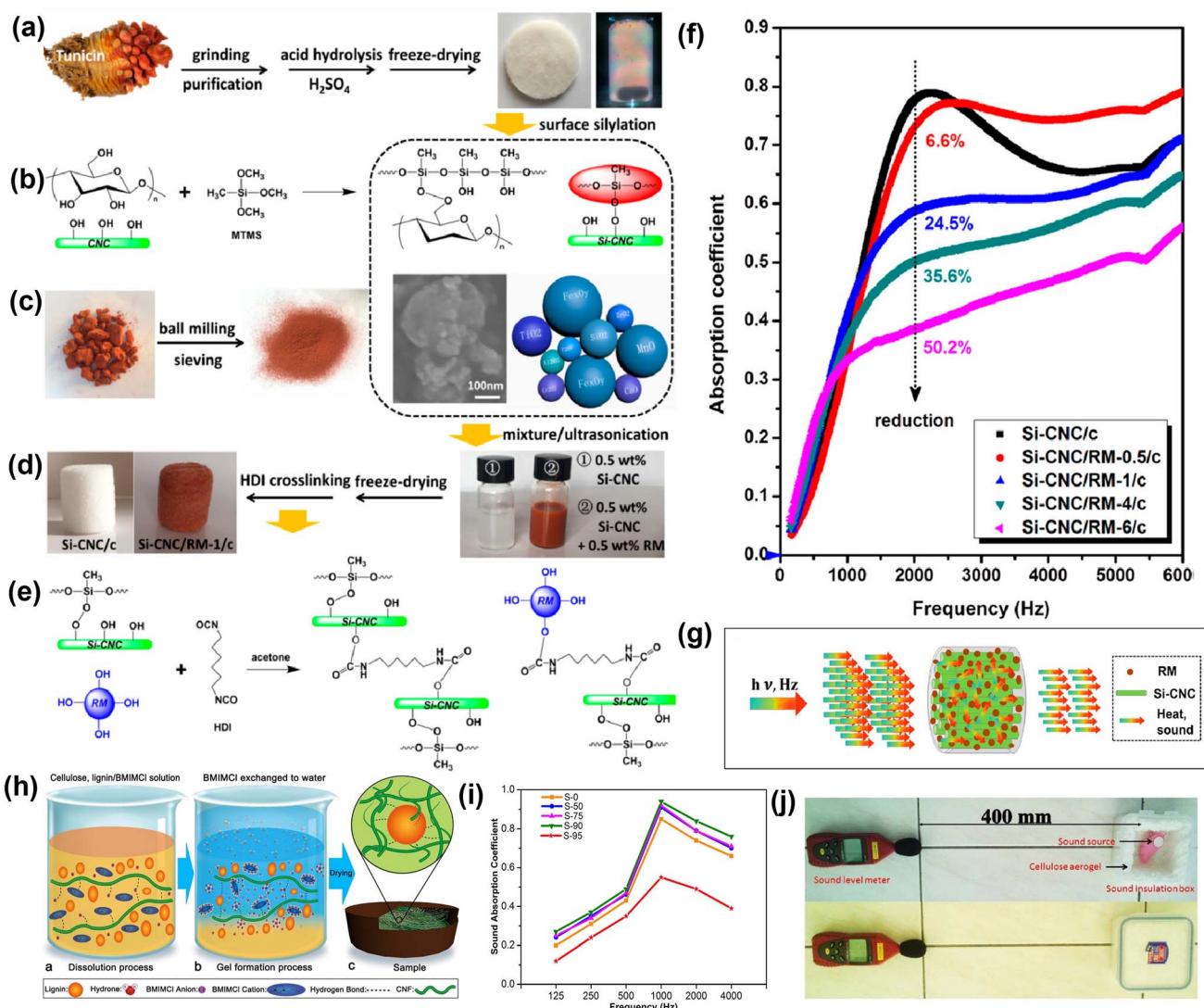
Fig. 16 (a) Isolation of CNC from tunicate through acid hydrolysis. (b) Surface modification of CNC through silylation. (c) Ball-milling process of red mud, along with SEM images and schematics of aggregate formation of red mud particles. (d) Freeze-drying, (e) Cross-linking mechanism of the composite aerogels using HDI. (f) SAC of the series of composite aerogels, and (g) Schematic of the proposed mechanism of thermal and acoustic insulation effect of the composite aerogels containing various RM contents, reproduced from ref. 218 with permission from ACS, copyright 2018. (h) Schematic diagram of the lignin-cellulose gel formation process using BMIMCl. (i) The sound-absorbing performance testing of samples, reproduced from ref. 219 with permission from Nature, copyright 2016. (j) Set-up for quantifying the SAC, reproduced from ref. 220 with permission from Elsevier, copyright 2016.

material on its thermal and acoustic insulation properties. The result showed that the smaller granules (0.01–1.2 mm) are much more effective in enhancing the sound absorption properties than the larger granules (1–4 mm), probably because of more surface area to absorb the sound waves, small interstitial spaces, and multiple scatterings. The values of SAC and transmission loss are 0.95 and 15 dB, respectively.[201]

4.2.3. Moisture insulation. This type of insulating material is comparatively less common than thermal and acoustic insulation. However, the requirement of proper insulation for moisture is not insignificant at all. In humid conditions, especially in tropical regions and also other parts of the globe where a proper rainy season exists, the building materials (both inner and outer), electrical appliances, paint, coatings, and their

respective properties can be severely harmed by the high moisture content in the air. Again, laboratories where a specific range of moisture content should be maintained for experimental purposes also need innovative products that can control the moisture.

So, talking about different methods to generate resistance or insulation against moisture, the first method that comes to mind is superhydrophobicity. Many research groups followed this technique to serve their purpose; let's say Long *et al.* have developed a superhydrophobic composite aerogel using polybenzoxazine (PBOZ) and CNF (shown in Fig. 17(a)). The material formed thereby was ultra-light and super hydrophobic with a negligible water absorption rate throughout the time. The result confirmed the superhydrophobic nature with the highest

contact angle of 162.7° for the PC-24 sample. It was also observed that the Water Contact Angle (WCA) has increased in a very slow manner with the increase in the cellulose content in the composite aerogel from PC-0 to PC-30. Amount of silica present in the aerogel (shown in Fig. 17(b)). However, the presence of silica nanoparticles has a strong influence over the superhydrophobic behavior for the same sample prepared without silica, which has shown a continuous decrease in WCA (shown in Fig. 17(c)), for the same PC-24 sample, the WCA angle was found to be 121.6° for the variant which does not contain any silica (sown in Fig. 17(d)). Also, an almost unchanged water absorption rate was recorded throughout the water absorption test over a long period (shown in Fig. 17(e) and (f)). Similarly, the mass moisture absorption rate also remained invariant at the value of 0.25% over a long period (shown in Fig. 17(g)).[225] A similar type of aerogel was also synthesized by the same group, but this time using fully green materials like silica, cellulose, and Aminopropyltriethoxysilane (APTES) as crosslinker (shown in Fig. 17(h)). This aerogel also performed excellently, with a contact angle of 150.8° and a constant moisture absorption rate of 0.44% with respect to saturated mass over a long period (shown in Fig. 17(i) and (j)); they mentioned that the superhydrophobic nature is mainly attributed to the use of superhydrophobic silica nanopowder.[226] Sobhana et al. represented a different type of strategy for making a superhydrophobic composite material, where they grafted hydrophobic and eco-friendly stearic acid on cellulose fibers through some inorganic crosslinker like Mg–Al layered double hydroxide to generate a sandwich-like structure (between cellulose and stearic acid), via an in situ coprecipitation method. Their result showed a pretty interesting phenomenon of pH-dependent regulation of superhydrophobicity. At lower pH, the contact angle lies between 134–140°, whereas at high pH, it increases up to 144°. They discussed that at lower pH, the sandwich-like double-layered hydroxide structure faces corrosion. Hence, the grafting of stearic acid on cellulose fibers was reduced to some extent, leading to a decrease in hydrophobicity. On the other hand, at higher pH, an additional –OH group is supplied from the solution, which maintains the uniform coverage of stearic acid on the cellulose surface, leading to superhydrophobic behavior.[227] Yoon et al. recently developed a moisture-resistant foam concrete consisting of silica-based nanogel using common silylating agents such as methyltrimethoxysilane (MTMS) and tetraethoxysilane (TEOS). The silica-modified nanogel showed a contact angle of 120.8°, and a 75% lower absorption of water, even after 24 hours, was observed as compared to the conventional sample (shown in Fig. 17(k) and (l)).[228]

4.2.4. Fire and smoke retardants. These kinds of materials are only necessary for exceptional cases like fire hazards or gas leakage. However, that doesn't reduce their significance; these types of materials are very crucial for the safety of lives and other valuable materialistic things, and also very useful to reduce the impact of these types of disasters and to save the building material itself from burning. Now, we have to know the mechanisms by which flame retardants work. Well, talking about the main ones, it can be through some chemical reactions, just like the well-known halogen-based flame retardants,[229,230] which generally emits some heavy gas during the combustion process, to cut off the contact between the material surface and air to extinguish the flame. Some chemical reactions might also be endothermic in nature, which reduces the heat and helps to diminish the impact of the fire.[231] There are also some phosphorus or other inorganic salt-containing materials which, when ignited, react with oxygen to form non-volatile compounds and thus create a protecting layer on the surface of the material to stop the burning process; this is a good example of retardancy by physical barrier.[232,233]

Now, talking about the advanced results obtained from some recent research, Liu et al. developed a Boron nitride nanosheet (BNNS)-based aerogel through an ice-templating method (shown in Fig. 18(a)). In this aerogel, they used L-glutamine grafted BN nanosheets combined with CNF. They tested the flame resistance nature of this aerogel using a butane flame (1400 °C) in the presence of air for 2 minutes, a result of that black layer of char formed mainly originated from BN and carbonized CNF that protects the rest of the material from combustion, they also highlight the different mechanism of axial and lateral burning (Fig. 18(b)–(e)). Less damage was observed with almost negligible change in weight and no emission of smoke (shown in Fig. 18(f) and (g)). This bio-based fire-retardant material is indeed a great alternative to halogenated materials, which produce toxic gases during combustion.[234] Zuo et al. prepared another robust CNF aerogel doped with GO and sodium montmorillonite (MMT) clay to design a novel material that can be used for fire alarms. In this case, the mechanism also includes a physical barrier to the oxygen that GO and MMT produce. He mentioned that a fire alarm made from their material can be triggered within 1.9 seconds of fire contact with the aerogel, which can last up to 137 seconds.[236] Missio et al. fabricated a nanocellulose-tannin-based lighter yet rigid foam that can be used as a flame retardant. These foams, due to their inner humidity content, can be able to reduce the up to 30 °C with just a 5 mm thickness.[237] Wang et al. found a little different solution in the form of a silica fume-based geopolymer coating, targeted to be used on the plywood to make the fire resistant. They commented on the fire retardancy behavior of the coating based on the Fire Performance Index (FPI) and Fire Growth Index (FGI). In brief, FPI is the ratio of ignition time to heat release rate, so the higher the FPI value, the longer the time required for the sample to be ignited. On the other hand, FGI is the ratio of the peak heat release rate to the time required to reach that peak condition. So, here, higher FGI means a greater tendency towards fire hazards. Thus, it should be as low as possible. In their study, they found that at 350 cps kinematic viscosity of silica fume gave them the best possible result with a shift of FPI from 0.83 to 3.80 s m^2 kW^{-1} and a decrease of FGI from 0.34 to 0.17 kW m^{-2} s^{-1}, all of which indicate an improved fire retardancy.[238]

Now, let us explore some smoke suppressors as well, for example, Wu et al. represented an innovative lignin-based material with surfactant modification to form a sandwich-like double-layered structure of hydroxide for smoke suppression and fire retardation. They incorporated this whole system into
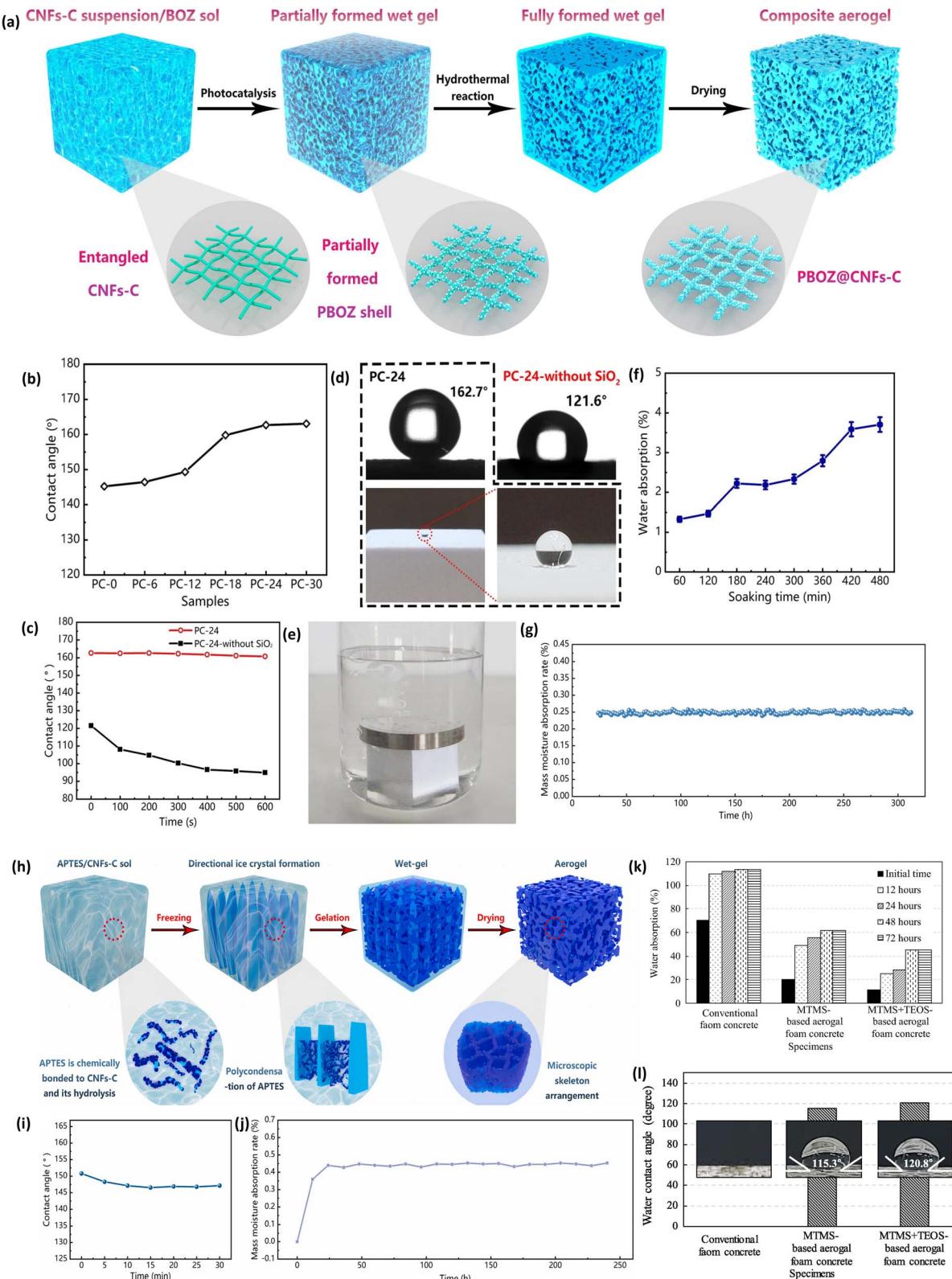
Fig. 17   (a) Schematic illustration of the preparation of the PBOZ@CNFs-C composite aerogel. (b) A static change in WCA from the PC-0 to the PC-30. (c) Evolution of static WCA of the PC-24 sample with and without SiO₂. (d) Difference in static WCA of the PC-24 sample with and without SiO₂. (e) Water absorption test set-up for the PC-24 sample. (f) Change of the water absorption % against the soaking time of the PC-24 sample. (g) Change of mass moisture absorption rate of the PC-24 sample over time, reproduced from ref. 225 with permission from Elsevier, copyright 2023. (h) Schematic diagram of the preparation method of the Silica–Cellulose composite aerogel. (i) Evolution of WCA within 30 minutes. (j) Change in the mass moisture absorption rate over time, reproduced from ref. 226 with permission from Elsevier, copyright 2023. (k) Comparison of water absorption rate of silanized and non-silanized foam concrete specimens over time. (l) WCA comparison of silanized tund non-silanized foam concrete specimens, reproduced from ref. 228 with permission from Elsevier, copyright 2020.
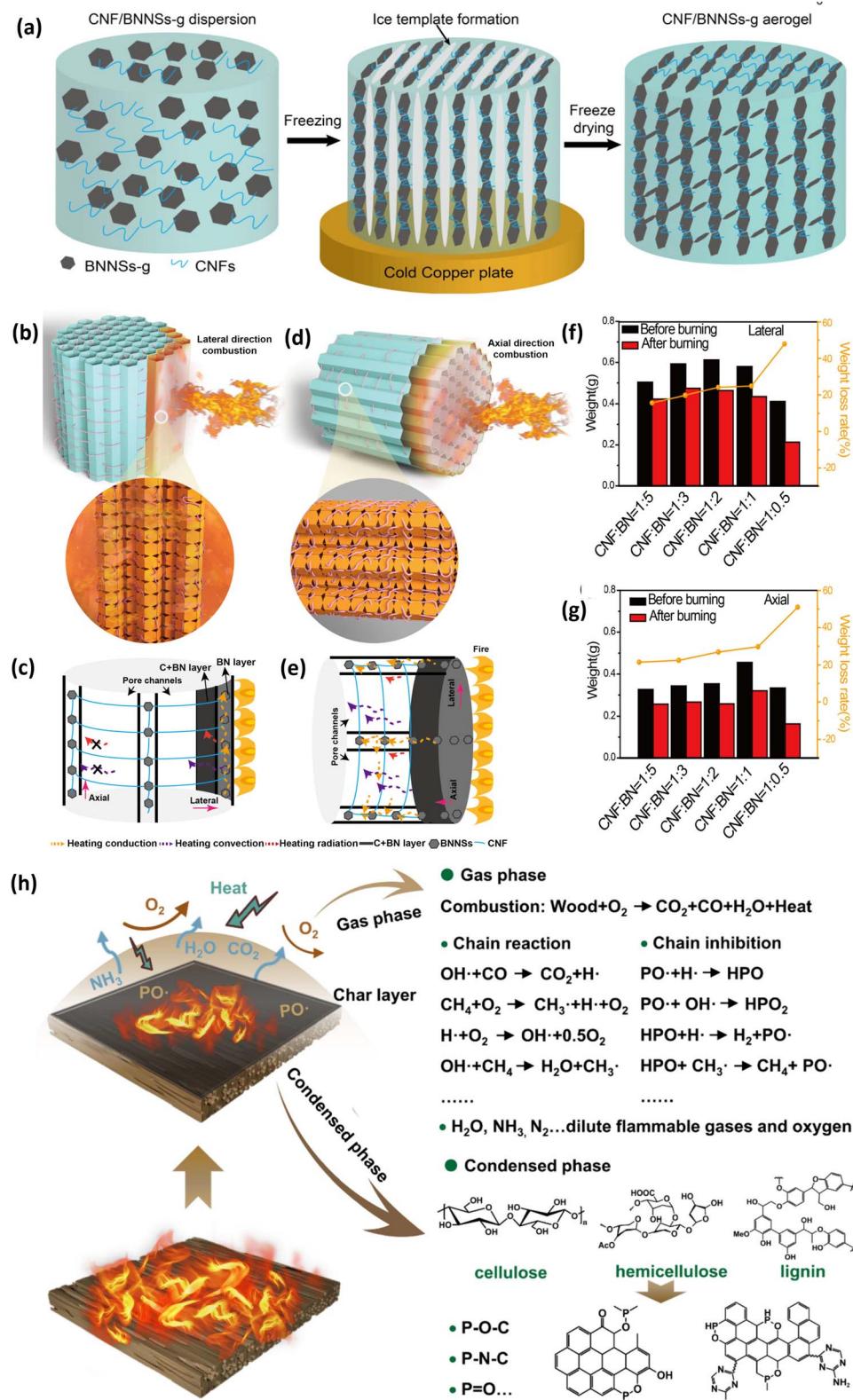
Fig. 18 (a) Schematic diagram of the preparation of CNFs/BNNSs-g aerogel. (b) Illustrative diagram of the lateral flame combustion. (c) Fire-resistant and thermal insulation mechanism of the aerogel in the lateral direction of combustion. (d) Illustrative diagram of the axial flame combustion. (e) Fire-resistant and thermal insulation mechanism of the aerogel in the axial direction of combustion. (f) Weight change and weight loss rate of the aerogel in the lateral direction. (g) Weight change and weight loss rate of the aerogel in the axial direction, reproduced from ref. 234 with permission from ACS, copyright 2021. (h) Schematic diagram of the synergistic gaseous phase-solid phase of fire-retardant mechanism, reproduced from ref. 235 with permission from Elsevier, copyright 2024.

polypropylene *via* the melt bending method. They found a decrease in peak heat release rate, total smoke release rate, and total smoke release rate by 62.9%, 25.1%, and 43.3%, respectively, as compared to pure polypropylene samples. They described that during a fire hazard, the sandwich-like bilayer structure collapsed due to heat generated from the fire, which produces bimetallic oxide and amorphous carbon in large amounts. Later, they transform into char and stay on the surface without decomposing, resulting in the breaking of contact between oxygen and the material surface.[239] Yu *et al.* worked on another great piece of work, where they modified the

wood sample with carboxymethylated alkali lignin, and to enhance the fire resistance property, they doped phytic acid and melamine-urea-glyoxal resin as a source of phosphorus and nitrogen, respectively. These modified and viscous wood shows a synergistic gas phase and solid phase extinguishing mechanism (Shown in Fig. 18(h)), which stops the combustion very rapidly, resulting in a reduction of heat and smoke. Due to the presence of a dense layer of lignin, it generates a lot of char, which helped in diminishing the flame by a physical barrier; on the other hand, in the gas phase, a dilution effect was observed for oxygen due to the formation of CO_2, several N and P
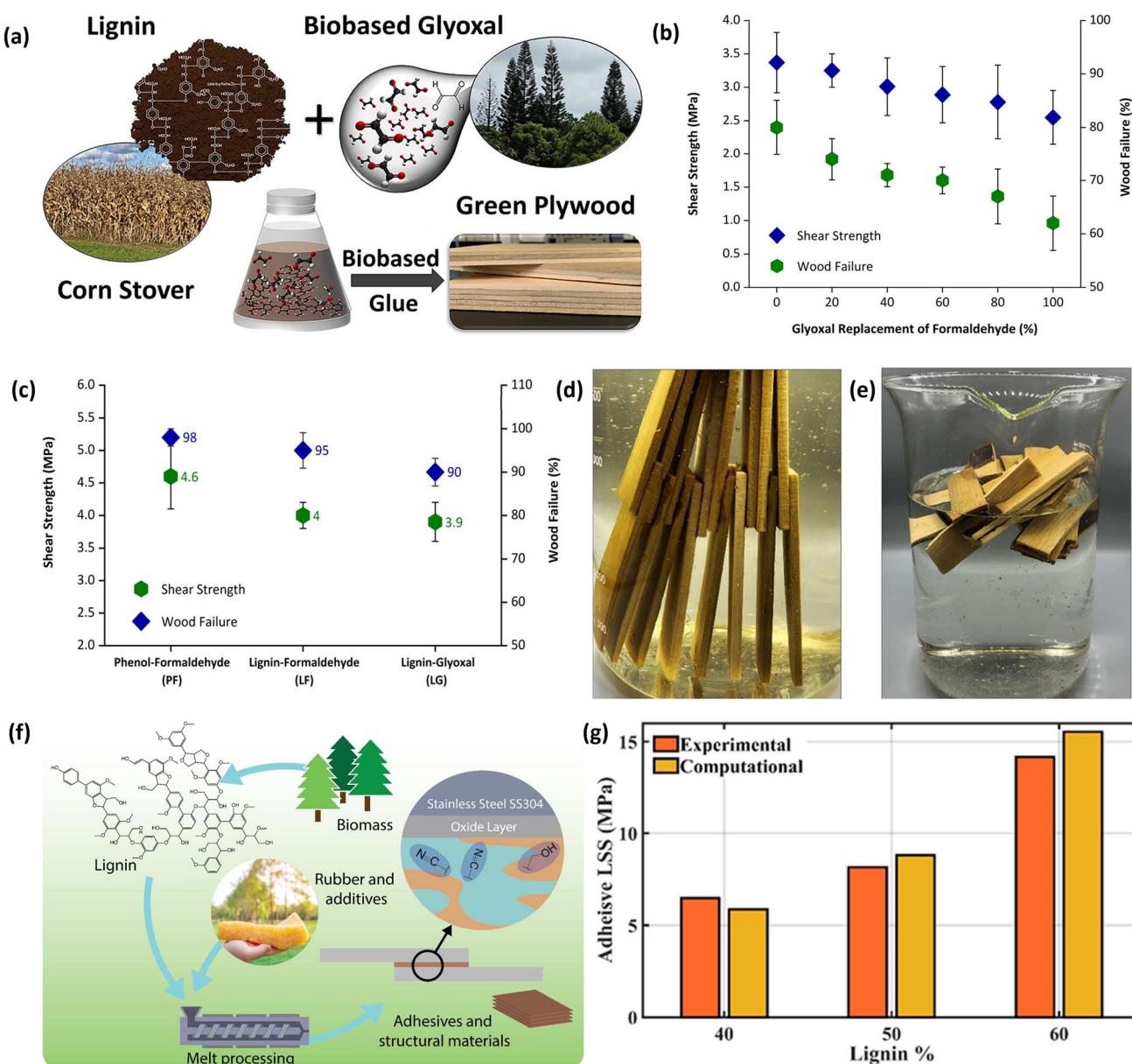
Fig. 19 (a) Schematic illustration of the synthesis of lignin-glyoxal base adhesive. (b) Change in shear strength and wood failure of lignin-based adhesives with the replacement of glyoxal content with formaldehyde. (c) Comparison of dry adhesion performance between phenol-formaldehyde (PF), optimized lignin-formaldehyde (LF), and lignin-glyoxal (LG) adhesives. (d) Wet strength test and (e) failure of wet strength in boiling water, reproduced from ref. 244 with permission from ACS, copyright 2022. (f) Illustrative diagram of the synthesis of lignin-derived adhesive. (g) Comparison of the leap shear strength test results obtained from experiment and computational analysis through CZM, reproduced from ref. 245 with permission from Elsevier, copyright 2023.

containing gases evolved as well as, which inhibits the chain reaction of combustion. Based on all of these, an impressive reduction of 56.8% was observed in heat release, a remarkable decrease of 92.3% was obtained in smoke generation, while LOI also improved significantly from 23.6% (natural wood) to 41.5% (modified wood sample).[235]

4.2.5. Bio-coatings and adhesives. We have discussed structural components of the buildings like bricks, concrete, floorings, fibers, and different plastic composites. We have also pointed out some useful insulation materials and fire and smoke retardants required to protect the building and the lives residing within. Then what's next? Well, to finish the building and to make it ready to move, all we need to do is paint it and put in some coatings and adhesive as and when required. Hence, in this section, we have discussed some advancements in bio-coatings and adhesives; these types of materials are mostly hydrophobic; thus, unlike other products, here we can see extensive use of lignin rather than cellulose. For example, Wang et al. developed a semi-synthetic coating for the protection of cementitious material; in this coating, they incorporated lignin into the polyurethane matrix. In this research, their fundamental objective was to develop a self-healing coating because it was generally observed that the coating, which is used for the protection of building materials, itself got deformed due to various factors like harsh environmental conditions, UV radiation, drastic temperature differences, and chemical corrosion. So, to tackle that problem and to generate self-healing properties, they mixed aniline and ammonium persulfate with lignin, leading to the preparation of lignin-based coating with remarkable self-healing properties due to dynamic S–S bonds. This adhesive was mixed with polyurethane by the physical blending method until a homogenous solution was obtained and molded to a dumbbell-shaped structure to examine its self-healing properties. The result revealed that the self-healing efficiency of tensile strength was enhanced and

crossed the maxima at 86.42% at 60 °C, while the same in the case of elongation first goes upward and then reduces after crossing the maxima at 93.77% at 40 °C Apart from that, the coating also offered an excellent abrasion resistance property and hydrophobicity. After 40 circles, the contact angle just decreased by 10.4%, from its initial value of 139.4° to 124.2° (at the end of the 40th cycle).[240] Borisova et al. fabricated a purely biobased coating with a modification of regular kraft lignin (brittle) by spider-silk-inspired protein, which not only enhanced the mechanical property of kraft lignin but also improved its interfacial bonding property. Due to this overall physiochemical advancement.[241] Henn et al. focused their research on the fabrication of a purely bio-based adhesive made of lignin. They utilized interfacial catalysis to modify unmodified kraft lignin to synthesise epoxy kraft lignin and later mixed it with biocolloids to obtain lignin nanoparticles, which showed exceptional mechanical as well as adhesive properties. The adhesive, when applied through a hot press at 130–160 °C for just 3–5 minutes, results in a shear strength of 13 MPa and also performs pretty well in wet conditions despite having formaldehyde in it. This adhesive also stood out in thermal stability and even displayed flame–resistant properties. The authors also projected a production cost of around 600 € per ton, thus, there is a high chance of scalability.[242] Scarica et al. also utilized lignin with succinic anhydride (through ester bonding) to fabricate a novel thermosetting polyester coating. Due to this cross-linking, the thermal stability of the coating was enhanced remarkably. The hydrophobic character and hardness (around 0.6 GPa) are due to high-lignin content.[243]

Another bio-based formaldehyde-free glue was produced by Siahkamari et al., where they used lignin-glyoxal chemistry (shown in Fig. 19(a)). This bio-based glue also has excellent dry adhesion properties with an adhesion strength of 3.9 MPa in dry conditions with optimized resin formulation. In a comparison of shear strength and wood failure on replacing glyoxal with

Table 7 Miscellaneous applications of LCBs related to green building

Bio-material used	Application	References
Microcrystalline cellulose	Thermochemical energy storage-based solar panels	246
Lignin nanoparticles	Electromagnetic shielding and superior fire safety	247
TEMPO-oxidized bacterial cellulose	Humidity sensor and triple-stimuli-driven actuator	248
Ethyl cellulose-based phase change material	Thermal energy storage	249
Rice straw-based lignocellulosic fibers	Insulation boards for the wood-based panel industry	250
Cellulose acetate	Fluorescence-based ultra-sensitive humidity sensor	251
Bamboo-based cellulose	Electromagnetic shielding for energy-efficient buildings	252
Cellulose nanofibers	Antifungal-resistant foams	253
Bacterial cellulose	Cooling material for building	254
Cellulose	Highly transparent phosphorescent materials for LED optics application in buildings	255
Lignin, cellulose	UV-blocking capacity, useful in light management, is the ability to scatter and absorb light	256
Silica	Anti-reflecting material for high-rise buildings	257
Nanocellulose	Ceiling tiles	258
Silica micro/nanoparticles	Weather resistance and daytime radiative cooling	259
Silica microsphere	Building integrated optoelectronic applications	260
Cellulose nanofibers	Furniture construction	261
Cellulose	Strain sensor and triboelectric nanogenerator	262

formaldehyde, a downward trend was followed (shown in Fig. 19(b)). However, as compared to commercial lignin-formaldehyde glues. The present adhesive has lower shear strength and wood failure of around 2.6 MPa and 62%, respectively, which has improved up to 3.9 MPa and 90% on changing the formulation (shown in Fig. 19(c)). It was found that and also showed promising results in wet conditions in water immersion tests (shown in Fig. 19(d)). However, this glue was limited to the hot water boiling test (shown in Fig. 19(e)), but at room temperature, in wet conditions, the adhesion remained intact for more than a week. Overall, this non-toxic, purely bio-based glue can surely be used for interior purposes like furniture, wood joints, *etc.*[244] Kanbargi *et al.* published a very interesting work; they worked on a renewable lignin-based thermoplastic adhesive that can be potentially used for steel joining (shown in Fig. 19(f)). About their key findings, they reported that the highest adhesive strength was obtained at around 13.1 MPa, at 60% lignin content. They also conducted a computational study to evaluate the adhesive leap shear strength of the dry adhesive through the Cohesive Zone Model (CZM). The results have shown a good resemblance to the theoretical and experimental values (shown in Fig. 19(g)).[245] There are plenty of journals published, especially in the last few years, covering the same topic of bio-based adhesives and coatings for wood or similar materials. We might not be able to cover all the novel research, but we at least try to give a flavor to different products, methods, and modifications. Apart from these major applications, LCBs have many other applications related to the construction industry that might not fall under any category. So, here, we also include some of such novel applications under the miscellaneous category (shown in Table 7).

5. Emerging trends in utilizing simulation and machine learning in the construction industry

Besides experimental works, a handful of computational works have been published yearly. To cross-verify the experimental results or to make assumptions about the probable outcomes, many research groups have come up with some interesting numerical methods, computational models, artificial intelligence, and even machine learning. Here, we have summarized some of such works contributing to the different aspects of the construction industry. Kaplan *et al.* recently embodied Carboxymethyl cellulose (CMC) and Microcrystalline cellulose (MCC) in their cement composite. Other than the experimental result, they have also represented some valuable theoretical data acquired by the response surface method, where firstly they plotted their experimental data by taking the reference of the theoretical curve (shown in Fig. 20(a)), which helped them to calculate the ratio of variance (R^2). Later, they illustrated the surface plots in 2D and 3D space (shown in Fig. 20(b)) to highlight the correlation between increasing cellulose content and various properties like compressive strength, flexural strength, *etc.* They mentioned in this methodology that the

value of R^2 tends to 1, more will be the reliability of the data. There, they ended up with R^2 values of 0.9031, 0.9299, and 0.9785 in the cases of compressive strength, flexural strength, and ultrasonication pulse velocity result respectively.[263] Su *et al.*[264] employed the Holmquist–Johnson–Cook (HJC) model to explain the uniaxial compression failure behaviour of their rice husk-glass powder-doped concrete on a mesoscopic scale. The strength parameters were evaluated using the normalized stress equation (shown in eqn (1)).

$$\sigma^* = [A(1 - D) + BP^{*N}][1 + C\ln(\varepsilon^*)] \leq S_{\max} \tag{1}$$

where σ^* is the normalized equivalent stress, A, B, C, and N are material constants, $P^* = P/f_c$, represents normalized pressure, D is the damage parameter, ε^* is the dimensionless strain rate, and $S_{\max}$ is the normalized maximum strength.

They have also calculated the damage parameters using the damage model. Validation of the model was proved by an excellent correlation between the experimental and model values (shown in Fig. 20(c) and (d)). Combining all outputs from the HJC model, the proposed final failure mode of each sample. The OC sample, which does not contain any glass powder and rice husk, was found to show a brittle failure (shown in Fig. 20(e)) whereas, the RGC2 and RGC3 samples, which have both rice husk and glass powder were observed to show plastic deformation at initial stages which later transformed into ductile failure characteristics (shown in Fig. 20(f)).[264] She *et al.* investigated the effect of pore sizes and shapes on the thermal behaviors of cellular concrete using a 2D Finite Element model (FEM). The model also offered the variation of Effective Thermal Conductivity (ETC) with pore orientations and distribution, which is generally very difficult to determine from some experimental methods. As evidence of their research, it was found that ETC was reduced when triangular ones replaced the circular pores; they highlighted the increasing tortuosity as the probable reason. However, other shapes, like square, hexagon, pentagon, *etc.*, were found to have minimal effect on ETC. Results have shown that the shape change in pores has a more pronounced effect on ETC than the pore sizes. On the other hand, ETC was found to be higher along the principal axis direction for the aligned pores. The distribution of temperature and heat flux was also represented in this journal (shown in Fig. 20(g)).[265] Computational research was also conducted on the recycling of concrete; recently, Ning *et al.* conducted a simulation study on the effect of Static Pressure Crushing (SPC) on reinforced concrete beams. They found this method to be a low-carbon technology for recycling concrete beams (shown in Fig. 20(h)). Before the real-life implementation of this method, they conducted this numerical analysis using FEM and traditional erosion algorithm. In this case, the experimental result also supports the simulation data to the fullest (shown in Fig. 20(i)).[266]

There are also a couple of excellent works published recently on the use of AI tools in predicting compressive strength of concrete. Anwar *et al.* show the utilization of a regression machine learning model in determining the compressive strength of CNF-modified sustainable concrete composite. They
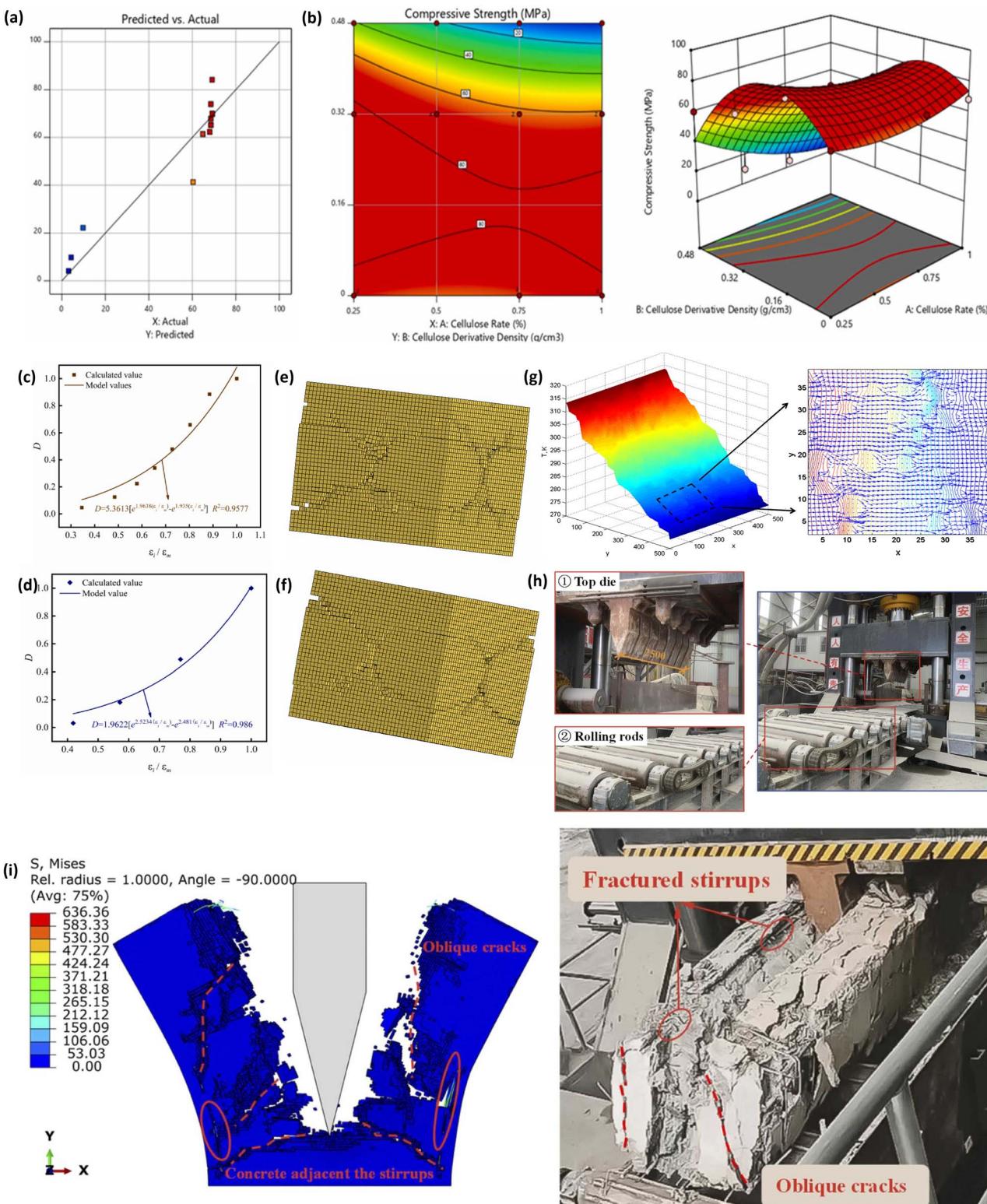
Fig. 20 (a) Comparison between experimental and theoretical data for compressive strength of the concrete. (b) The combined effect of cellulose rate and cellulose derivative on the compressive strength of concrete is represented by 3D and 2D response surface plots, reproduced from ref. 263 with permission from Elsevier, copyright 2024. Comparison of damage model data with experimental results for (c) OC and (d) RGC2. Illustration of final failure mode for (e) OC and (f) RGC2, reproduced from ref. 264 with permission from Elsevier, copyright 2024. (g) Illustration of temperature distribution and heat flux of the 2D reconstructed structure, calculated using numerical analysis, reproduced from ref. 265 with permission from Elsevier, copyright 2018. (h) Demonstration of different parts of the SCP unit. (i) Comparison between simulation and experimental result of the application of SCP on a reinforced concrete beam, reproduced from ref. 266 with permission from Elsevier, copyright 2024.

Table 8 Use of simulation and machine learning in the construction sector

Method used	Objective	Key findings	References
A new constitutive material model	Evaluation of damage caused by various dynamic loads on steel fiber reinforced concrete (SFRC)	In this study, shear deformation and volumetric deformation were taken separately for a more accurate description of strain hardening and softening behaviour. The radial rate enhancement method was implemented to elaborate on the effect of strain rate on the material characteristics of SFRC.	272
Drying shrinkage model	Evaluation of shrinkage-induced initial damage on the frost resistance of concrete in cold regions with low relative humidity	It was found that, as compared to samples cured at standard conditions, the samples that had been cured at 40% relative humidity experienced more critical freeze-thaw damage, like higher apparent deterioration, greater mass loss rates, and a more pronounced decay in compressive strength	273
A numerical simulation model based on the Mohr–Coulomb failure criterion and plastic failure height prediction	A study on the 3D-printability of eco-friendly concrete reinforced by carbon fibers	This model was found to be a desired tool to predict the feasibility of printing new mixtures, ensuring they meet structural requirements before printing. This study also explained the crucial role of adjusting water-to-binder ratios and superplasticizer dosages to enhance the workability and printability of carbon fiber-reinforced eco-friendly concrete	274
A mathematical model of fresh concrete particle packing	Simulation study to optimize the concrete mix proportion based on fluidity	As a result of this study optimal sand-to-aggregate ratio can be determined. Moreover, from this model, we can also predict the quantitative design of a concrete mix proportion, including water consumption, based on the required criteria	275
A three-phase model of concrete based on the boundary element method	Simulation analysis of chloride-induced corrosion of steel-reinforced concrete	The model was found to be more accurate than FEM. Results showed that chloride attack was more susceptible to the coarse aggregate content and less affected by the interfacial transition zone (ITZ) diffusion coefficient. It might be due to the higher volume of aggregates in concrete than ITZ.	276
Machine learning model using Monte–Carlo simulation, capacity-spectrum method, and seismic Vulnerability assessment	To develop a machine learning-based assessment model for the seismic vulnerability of reinforced concrete frame buildings	The study has successfully developed a machine-learning-based approach to predict the seismic Vulnerability of reinforced concrete buildings for future earthquakes	277
Riedel–Hiermaier–Thoma (RHT) constitutive model	To design ultra-high-performance concrete	The study suggests that an enhancement in the strength of longitudinal reinforcement could help to regulate the maximum deflection of the slab in the reinforcement design. Whereas, in the case of transverse reinforcement, low-grade reinforcement should be used, and the ratio of reinforcement should be reduced appropriately.	278

Table 8 (Contd.)

Method used	Objective	Key findings	References
A system combining deep learning and building information modeling	To detect the underwater cracks of concrete structures	The result offered the coordinate transformation relation between the real world and the sonar images. Moreover, the crack coordinates were mapped to the BIM model, based on Dynamo's secondary development for Revit. The model was found to be an appropriate one to detect underwater cracks and so the damage in the concrete structure	279

have used numerous machine learning models like Random Forest, Support Vector Regressor, Gradient Boosting Regressor, Bagging Regressor, Decision Tree, etc. All models are applied to an experimental data-based dataset having 695 data points, which are further divided into two categories – training data (70%) and testing data (30%). Seven independent variables and five metrics were employed to measure the ability of the models. As a result, 7 out of 10 models were predicted to assess the effectiveness of CNF addition in enhancing the compressive strength of concrete materials with an R^2-value greater than 0.6. Sensitivity analysis data by the Random Forest model was specifically found to be quite impressive in determining that the water and cement proportion are the key factors to the compressive strength of reinforced concrete, while the addition of coarse aggregates affects the compressive strength negatively. As a conclusion, the Random Forest model, along with the Bagging Regressor and Decision Tree model, are found to be the superior ones in this research.[267] On a similar topic, Sun et al. examined a study with an identical machine learning approach. In this study, they employed 3 models – K-nearest neighbour, linear regression, and artificial neural network, on 282 data points to evaluate the effect of various parameters on compressive strength of cementitious material. The conclusion was made on R^2-value and statistical error analysis. Among all models, the artificial neural network model stood out to be the best one with an R^2-value of 0.885. Similar to the previous study, this research also predicts water-to-cement ratio to be the most crucial factor in determining the compressive strength of concrete, followed by curing time, coarse and fine aggregate proportions.[268] Similar to Anwar et al., Kashyap et al. also concluded that the random forest model is the best machine learning model to evaluate the compressive strength of concrete. They tested over 54 different concrete mixes and drew their conclusion based on several parameters, like R^2-value, mean absolute error, and mean square error. For the random forest model, these values came to 0.95, 1.05 kN mm^{-2}, and 5.25 kN mm^{-2}, respectively. With a little extension to the previous models, they designed this model in such a way that the model can help in providing the highest possible mechanical properties with minimal use of resources to reduce water pollution and land degradation-related issues.[269]

A little different from the above studies, Bashir et al. developed a new hybrid machine learning model with explainable artificial intelligence methods to determine the optimal water-to-binder ratio to improve the durability, performance, and sustainability of concrete. They did a similar survey with multiple machine learning models, including a random forest model. They used a database having 192 datapoints, each representing different environmental conditions and mixed proportions of the concrete. They concluded that the addition of an AI algorithm to these hybrid machine learning models has a significant impact on optimizing properties over fresh as well as hardened concrete mix.[270] Like this research, Liu et al. did an identical machine learning driven study to predict and regulate fluidity and rheological fresh cement-based materials. They investigated a 233-sample database, varied by proportion of cement, water, superplasticizers, silica fume, sand, and hydroxypropyl methylcellulose. They have included Shapley Additive Explanations (SHAP) and Partial Dependence Plot (PDP) analyses, which worked excellently in achieving rapid and accurate control over the workability of fresh cement-based materials.[271] More such interesting works focused on different aspects of the construction industry are given below (shown in Table 8).

6. A summary of LCA approaches towards sustainable infrastructure

After combining all aspects of the construction sector, this discussion perfectly concludes with an LCA comparison between the traditional buildings and GBs. There are a lot of journals present on this topic. Research groups like Wu et al. talked about the utilization of wood components in the modern construction industry as a sustainable solution to global warming. They surveyed a cradle-to-grave LCA approach for a qualitative as well as quantitative analysis of various environmental footprints in terms of global warming, natural resource depletion, pollution, and habitat destruction from production and disposal methods of transparent wood (shown in Fig. 21(a)). Their result showed that the usage of transparent wood in building structures has reduced the propensity toward
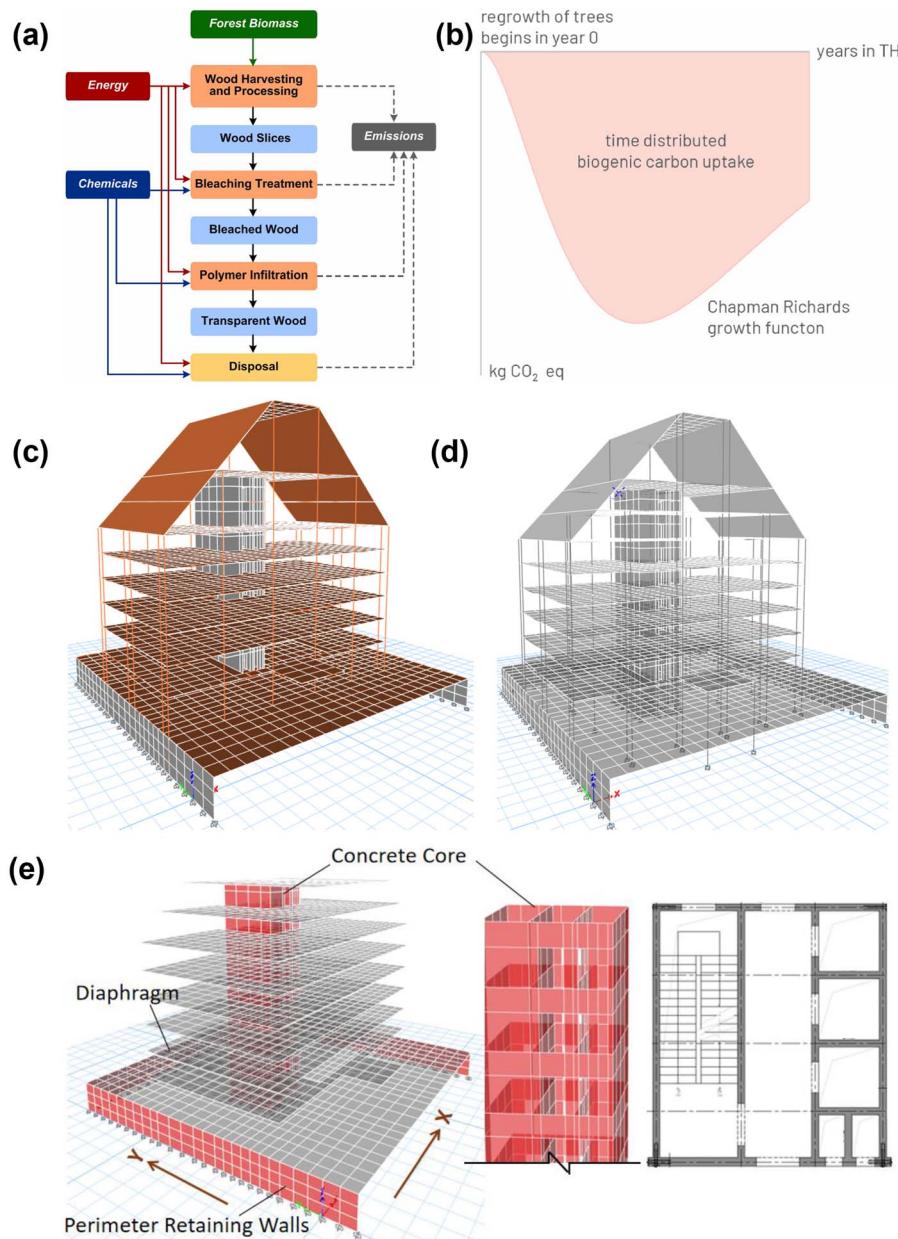
Fig. 21 (a) System boundary for processing of transparent wood, reproduced from ref. 280 with permission from Elsevier, copyright 2024. (b) The conceptual illustrative plot of time-distributed biogenic carbon uptake of dry wood against time horizon (TH) using the Chapman-Richards function, reproduced from ref. 282 with permission from Elsevier, copyright 2024. 3D-ETABS model of (c) hybrid and (d) concrete building. (e) Schematic model of the lateral-load bearing system for both types of buildings, reproduced from ref. 283 with permission from MDPI, copyright 2023.

global warming by 57%, 57%, and 13% as compared to the transparent polymethyl methacrylate, polycarbonate, and polyethylene terephthalate, respectively. So, the conclusion is that transparent wood can potentially replace petroleum-based items from the building sector, leading to sound planetary health.[280] Andersen *et al.* also worked on the same topic; they conducted an LCA on the incorporation of forest resources in modern buildings to minimize the adverse environmental impact. They reported a highest 81% reduction in greenhouse gas emissions from buildings.[281] The same group conducted another survey specifically on the wooden and bio-based

buildings regarding their environmental effects. In this study, they considered the biogenic carbon footprints and temporal emissions, which are most of the time ignored in other LCA. So, they combined all the emissions into a single pulse emission according to their methodology. The estimation of time-dependent biogenic CO_2 uptake of dry wood (shown in Fig. 21(b)) using the Chapman-Richards growth function. They used both static and dynamic LCA methods for their study of 45 cases of bio-based buildings. It was reported that the environmental impact of these buildings is very sensitive to the method applied, and dynamic LCA has been found to have less impact

on the total emission result.[282] Zhang et al. compared concrete buildings and Timber-concrete hybrid buildings in terms of seismic performance. For this study, at first, they virtually constructed two such kinds of buildings using ETABS software (shown in Fig. 21(c) and (d)). They also embodied lateral load-resisting systems for both systems to overcome the seismic shear (shown in Fig. 21(e)). As a result, they described that upon substituting the concrete structure with wooden materials, a 30% weight reduction was recorded. Moreover, a substantial decrease in base share was found to be 37% and 27% in the X and Y directions. The more interesting fact was noticed in terms of inter-story drift, which was reduced by up to 50% in hybrid buildings than in traditional concrete buildings. Talking about the environmental aspect, the result of this LCA study suggested a 65% lower emission of greenhouse gases, which has a much lower impact on global warming.[283]

Apart from this topic, there are many LCA studies on some other topics related to the construction industry. For example, Katebi et al. studied a cradle-to-gate LCA on the reuse of temporary buildings. They found that reutilization of disassembled parts of the building can reduce the environmental damage and associated costs by 79% and 77%, respectively.[284] Miao et al. conducted a more specific LCA study on lignin-based building blocks. These composites were found to have similar strength and structural properties to lightweight concrete. These building blocks are sustainable and have a much lower carbon footprint. The authors described that these materials could be potentially used as the inner applications of buildings, like inner walls, façades, and even roof tiles.[285] Last but not least, recently, Gay et al. worked on developing a digital tool for LCA of construction projects. Their results have shown how a digital tool can influence the decisions taken during LCA. This tool can also efficiently measure the global warming impact for a particular construction project in the early stages and can effectively diminish product-based CO_2 emissions by up to 40%. Moreover, calculations received from this digital tool were found to be more accurate and quicker than most of the manual methods already reported in the literature.[286] Jiang et al. surveyed a very crucial LCA study concerning the current scenario. They evaluated the effect of low-carbon-based mortars on the performance and durability of cementitious material. Chloride-induced deterioration has been a long-term problem with concrete materials. They have used multiple low-carbon-based mortars like calcium sulphoaluminate cement (CSA), CO_2-cured calcium sulphoaluminate cement (CSA-C), alkali-activated slag (AAS), and limestone calcined clay cement (LC^3). Using these materials, they fabricated a series of concrete materials having identical compressive strength and subjected them to various corrosive tests like mercury intrusion porosimetry, chloride ion diffusion, hydration phase analysis, and water permeability tests. Results show that alkali-activated slag and limestone calcined clay cement have a more pronounced effect on reducing carbon emissions than ordinary portland cement (OPC). Production of both of them causes a much lower carbon emission than OPC. Moreover, AAS and LC^3 mortars possess superior resistance to chloride penetration and water permeation, which is why they require less annual maintenance and lower repair time than OPC, which again stands for

their superior nature as compared to OPC.[287] A similar study was also conducted by Sbahieh et al. on different concrete mixes with partial and total replacement of OPC based on sustainability. The study was done by substituting OPC with different Supplementary Cementitious Materials (SCMs) like fly ash, silica fume, metakaolin, ground granulated blast furnace slag (GGBS), etc. They also applied geopolymer concrete for the same purpose. The result reveals that among SCMs, GGBS has the highest effect in CO_2 reduction, which was found around 28.7%, which is higher than other SCMs like silica fume (28.3%), fly ash (17.25%), and metakaolin (15.1%). On the other hand, geopolymer concrete has a more pronounced effect than SCMs, fly ash, and GGBS-based geopolymer registered a 67% and 54% reduction in carbon emission. However, geopolymers have some negative impact on other environmental issues, like fossil depletion, human toxicity, and ozone depletion, due to the emission of sodium silicate and sodium hydroxide. So, in conclusion, SCMs are a better alternative as a substitute for OPC to reduce CO_2 emissions; however, geopolymer could be a more sustainable option if the challenges mentioned earlier can be addressed.[288]

A bunch of similar research was also performed to improve the various properties of cement composites. Khan et al. performed a study to develop sustainable concrete from artificial lightweight aggregate originating from sand-plastic composite. In this paper, they replaced the natural coarse aggregate with artificial lightweight aggregate at different replacement levels. They found an overall 84.5% retention of compressive strength at 30% replacement level, while 100% replacement brought down the compressive strength to 52% of the original. At 100% replacement level, only a 34.7% and 20% reduction was found for tensile and flexural strength, respectively. As a result of the LCA study, they concluded that using these artificial aggregates, we can reduce the potential of global warming up to 54.83%, which is a step towards a sustainable future.[289] Benzal et al. assessed the performance of commercial steel fibers, recycled steel fibers with treatment, and without treatment, to examine the mechanical, environmental (cradle-to-gate), and economic impacts. Their findings highlight that recycled fibers are a superior choice to commercial fibers for reinforcement purposes from any aspect. They have shown a 19.2% reduction in shrinkage along with a 37.7% increase in flexural strength. Moreover, from a circular economy and environmental perspective, it diminished CO_2 emission and production cost by 23.4% and 14.5% respectively. Overall, it leads to a more eco-friendly and sustainable industry.[290] Similar to recycled fiber waste, Scioti et al. published another identical work on the production of construction materials from stone waste. They have varied the amount of sludge, water, cement, and compaction pressure to observe the effect on compressive strength. According to their key findings, the production of artificial stones helps in recycling a huge amount of waste material. The artificial blocks well passed the threshold value of compressive strength required for a building construction, the compressive strength lies within the range of 29.9 to 13.12 N mm^{-2}. The presence of these artificial mortars reduced the brittleness of the construction materials. Optical microscopic study reveals that the slurries made thereby are very cohesive with tiny voids inside. Overall, these materials stand out as an

excellent and sustainable replacement for building blocks.[291] Another study was performed by Nawaz *et al.* in utilizing the Municipal waste incinerator bottom ash (MIBA) in fabricating alkali-activated concrete materials; they reviewed their mechanical performance and conducted an LCA study on them. The main focus of this study examine the replaceability of MIBA with AAS or fly ash. To assess this, they used several parameters like compressive strength, SEM analysis, and dry density test, while LCA was evaluated on environmental impact and sustainability. Although mechanical properties did not appear as expected, to keep the compressive strength above a threshold value, only 15% replacement is allowed by MIBA; however, LCA study demonstrates that its contribution towards sustainability by decreasing Terrestrial Acidification Potential (TAP) and Marine Eutrophication Potential (MEP) by 16% at 5% replacement, 45% at 15% replacement, and 60% at 20% replacement level.[292]

7. Challenges and future pathways

For the shake of advancement, science also required some critical comments that open the doors for many future pathways, so some critical comments were also given below:

(1) In this review, we have scrutinized research covering various sources, methods, products, and applications. During this process, it was realized that the number of publications of fully biobased products is comparatively lower than that for biobased composites. Most of the research products were made in such a way that they still consist of one or more synthetic, harmful, non-eco-friendly components.

(2) Though in terms of insulating capacity, adhesive properties, or flame retardancy, fully bio-based products performed exceptionally well over commercial products due to a perfect overlap of the requirements of the products and characteristics of biomaterials. But in the case of structural products where mechanical strength and robustness are the prime criteria, their fully bio-based products limit themselves. In most cases, they have just been used as an additional reinforcement of synthetic materials with a minor wt% of 0.1–5 (commonly).

(3) In biocomposites, after a certain limit, LCB components have shown a decreasing order of values corresponding to various mechanical and durable properties.

Hence, as a future perseverance, we might explore the following bulletins:

(1) More emphasis on the valorization of agricultural waste rather than cutting living plants, which ultimately leads to several disasters related to deforestation.

(2) Production of fully bio-based products using some other bio-based source as reinforcement should be explored.

(3) Amongst the components of LCBs, mainly the utilization of cellulose and lignin was observed; we should focus more on the total use of biomass, including hemicellulose, bio-based silica, pectin, *etc.*

(4) Last but not least, we must also keep an eye on the maintenance of these bio-based products because, due to their fully organic nature and moisture present within, they might be decomposed by bacteria and fungi, which severely deteriorate the material, leading to decay in performance.

8. Concluding remarks

In this review, we have tried to portray a current scenario on global research trends on valorization and application of LCBs components in construction materials. While many review articles focus on biofuels, bioenergy, some particular component of LCBs, or some specific category of product materials from them, our study stands out by providing.

A comprehensive overview of modern valorization methods, contribution of LCBs-based products towards the construction of "Green Building", computational approaches, and comparison of conventional and sustainable sources of construction.

To conclude, here are a few key takeaways:

(a) LCBs are sustainable and renewable, unlike fossil fuels and mined materials. Greater adoption of them in the modern construction industry will help in conserving non-renewable resources for the future.

(b) LCBs-based material requires significantly less energy for extraction, processing, and upscaling, indirectly cutting down fossil fuel consumption.

(c) LCBs are versatile; they can be easily modified to meet diverse structural and functional requirements.

(d) Most importantly, they're biodegradable, offering an eco-friendly alternative to conventional materials like plastics, which pollute ecosystems and harm wildlife.

Abbreviations

Green and sustainable construction materials	GSCMs
Lignocellulosic biomass	LCBs
Green building	GB
Cellulose nano fibers	CNF
Cellulose nano crystals	CNC
Micro fibrillated cellulose	MFC
Polyvinyl alcohol	PVA
Volatile organic compounds	VOC
Natural rubber latex	NRL
Life cycle analysis	LCA
Supercritical-CO_2	Sc-CO_2
Deep eutectic solvent	DES
Methyl hydroxy ethyl cellulose	MHEC
Polyvinyl alcohol	PVA
Carboxymethyl cellulose	CMC
Microcrystalline cellulose	MCC
Ordinary Portland cement	OPC
Polypropylene	PP
Poly-(lactic acid)	PLA
Phase change material	PCM
Graphene oxide	GO
Limiting oxygen index	LOI
Negative oxygen ions	NOI
Noise reduction coefficient	NRC
Methyltrimethoxysilane	MTMS
Sound absorption coefficient	SAC
Boron nitride nano sheet	BNNS
Montmorillonite	MMT

Fire performance index	FPI
Fire growth index	FGI
Holmquist–Johnson–Cook	HJC model
Effective thermal conductivity	ETC
Finite element model	FEM
Static pressure crushing	SPC
Steel fiber reinforced concrete	SFRC
Interfacial transition zone	ITZ
Riedel–Hiermaier–Thoma	RHT constitutive model
Mineralized cellulose composite	ML-CCM
Environment tobacco smoke	ETS
Cashew nutshell ash	CNSA
Life cycle assessment	LCA
Oxidized all-cellulose microfiber Film	OCMF
Carboxymethyl cellulose fiber	CMF
Unidirectional-nano-cellulose-long-filament-reinforced vanillin epoxy green composites	UD-NCLF-VE
Vacuum-assisted resin transfer molding	VARTM
Cellulose long filaments	CLF
Fiber reinforced polymer	FRP
External thermal insulation composite system	ETICS
Internal thermal insulation multi-layer system	ITI
Silanized-cellulose aerogel	SiCellA
Insulating glass units	IGUs
Hexamethylene diisocyanate	HDI
1-Butyl-3-methylimidazolium chloride	BMIMCl
Polybenzoxazine	PBOZ
Water contact angle	WCA
Aminopropyltriethoxysilane	APTES
Cohesive zone model	CZM
Shapley additive explanations	SHAP
Partial dependence plot	PDP
Calcium sulphoaluminate cement	CSA
CO_2-cured calcium sulphoaluminate cement	CSA-C
Alkali-activated slag	AAS
Limestone calcined clay cement	LC3
Ordinary Portland cementOPCSupplementary cementitious materials	OPCSupplementary cementitious materialsSCMs
Granulated blast furnace slag	GGBS
Municipal waste incinerator bottom ash	MIBA
Terrestrial acidification potential	TAP
Marine eutrophication potential	MEP

Data availability

The authors confirm that the data supporting the findings of this study are available within the article. It will also be shared on request.

Author contributions

Nilanjan Dey: writing – original draft, investigation, formal analysis, data curation. Shakshi Bhardwaj: writing – review & editing. Pradip K. Maji: writing – review & editing, validation, supervision, resources, project administration, funding acquisition, conceptualization.

Conflicts of 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.

Acknowledgements

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