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# Bio-based materials for eco-efficient construction

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## 13.1 Introduction

Bio-based materials are increasingly recognized as promising for the construction industry. Recent studies have focused on exploring new environmentally friendly alternatives to enhance the mechanical properties of concrete while simultaneously reducing clinker content in cement as a way to lower greenhouse gas emissions related to cement production. Two categories of bio-based materials show significant potential to enhance the mechanical properties of concrete and reduce its CO<sub>2</sub> footprint. The first category includes bio-based resources that serve as supplementary cementitious materials (SCMs) to replace Portland cement. The second category consists of materials composed of fibers from various origins: animal, plant, and mineral. These fibers help enhance the mechanical properties of construction elements and offer several advantages, including mechanical weight/performance ratio and a reduced carbon footprint.

This chapter will explain the various materials applicable to these categories, highlighting their advantages and limitations.

## 13.2 Bio-based materials as supplementary cementitious materials (SMCs)

In the quest for sustainable and environmentally friendly solutions, bio-based materials have emerged as a promising alternative in various industrial applications. Unlike traditional materials based on fossil fuels, bio-based materials are part of a more sustainable approach to industrial production, aiming to reduce carbon footprints, minimize the use of non-renewable resources and contribute to a circular economy. These materials are increasingly being used in sectors such as construction, automotive, packaging, and textiles. Their versatility comes from their ability to offer similar

properties to conventional materials while having a significantly lower environmental impact. Advances in biotechnology have allowed bio-based materials to not only replace synthetic materials but also to enhance performance in terms of biodegradability, energy efficiency, and safety.

The use of bio-based materials aligns with global sustainability goals and the reduction of greenhouse gas emissions. By substituting traditional polymers and compounds, bio-based materials can play a crucial role in the transition toward a greener economy, fostering technological innovation while conserving natural resources. This innovative approach not only promotes the reuse of industrial waste but also opens new avenues for the development of advanced materials with a reduced environmental impact.

### 13.2.1 Biomass ashes (vegetable ashes)

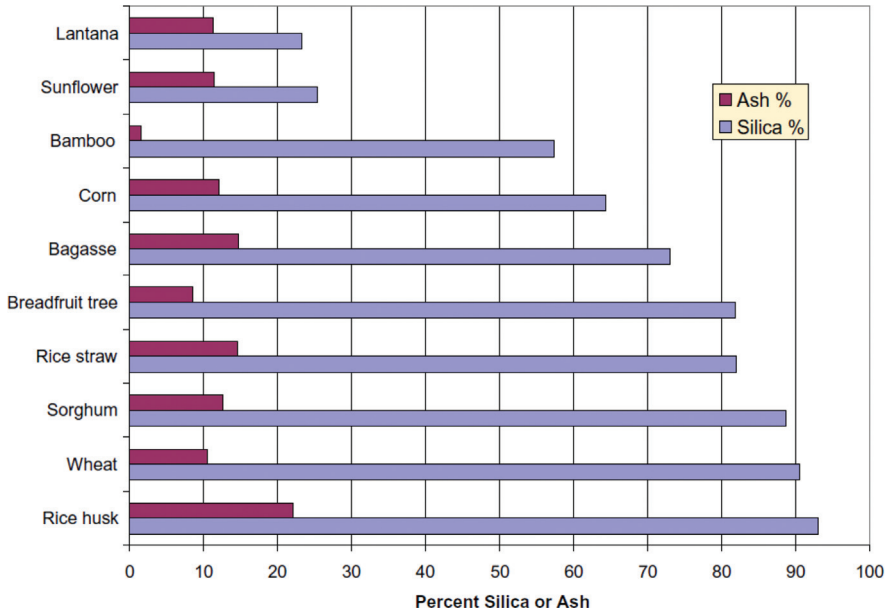
Biomass refers to all organic material derived from plants, including algae, trees, and crops. It is created when green plants convert sunlight into plant matter through photosynthesis. This includes both land and water-based vegetation, as well as all organic waste. Biomass can be considered organic matter in which the energy from sunlight is stored in chemical bonds [1] and plays a crucial role as a renewable, CO<sub>2</sub>-neutral energy source, potentially providing heat, power, and transport energy when consumed at a rate lower than its growth. Approximately 140 billion metric tons of biomass are produced worldwide every year from agriculture [2].

It is reported that flexural strength and compressive strength in mortars and concrete specimens using biomass ash are comparable to the reference material [3–9]. The main agricultural wastes are sugarcane bagasse, paddy and wheat straw and husk, vegetable, food, tea, and oil production residues [10].

Bio-silica (SiO<sub>2</sub>) in agricultural waste is typically concentrated through the firing process. Certain plants are known for having amorphous silica integrated into their structures. Fig. 13.1 highlights the silica and ash content of various plant species. The most suitable plants for bio-silica extraction are those that combine a high silica concentration with a substantial ash percentage, such as rice husk ash and bagasse [11,12].

Vegetable ashes are considered suitable for use as (SCMs) if:

- Their chemical composition meets ASTM C 618 “Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete” requirements that is, the sum of SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub>+Fe<sub>2</sub>O<sub>3</sub> > 70% for N-type pozzolans. Table 13.1 shows the typical chemical composition of rice husk and sugarcane ashes compared to pulverized coal fly ash.
- The occurrence of pozzolanic reaction is proven. Calcium hydroxide consumption in lime-pozzolan systems is a good indicator, and it can be measured directly using a thermogravimetric analysis [13] or estimated by conductimetry [14]. The compressive strength of Portland cement-pozzolan systems is by far the most common indirect way of proving cement particle hydration [15]. There are other methods of assessing reactivity which could also be suitable for vegetable ashes, such as impedance spectroscopy, X-ray diffraction (XRD), and Si magic-angle spinning (MAS) nuclear magnetic resonance (NMR) [11,16,17].



**Figure 13.1** Amount of amorphous silica and ashes in crops [18].

**Table 13.1** Typical chemical compositions of agricultural ashes [11].

	Coal ash	Rice husk ash	Bagasse ash	Straw ash
SiO <sub>2</sub>	56.3	71.74	72.74	59.06
Al <sub>2</sub> O <sub>3</sub>	30.1	5.61	5.26	4.75
Fe <sub>2</sub> O <sub>3</sub>	6.41	3.47	3.92	3.18
TiO <sub>2</sub>	–	0.38	0.32	0.34
CaO	1.16	10.42	7.99	19.59
MgO	0.8	1.98	2.78	2.25
SO <sub>3</sub>	0.26	0.5	0.13	1.37
K <sub>2</sub> O	0.73	3.62	3.47	4.75
Na <sub>2</sub> O	0.07	0.4	0.84	0.73
P <sub>2</sub> O <sub>5</sub>	–	0.89	1.59	1.67
LOI	4.43	0.78	0.77	2.05

### 13.2.2 Rice husk ash

Rice husk ash (RHA) is one of the most extensively studied materials in the field of (SCMs). The application of RHA is not limited to cementitious materials; it can also be utilized as biochar, adsorbent, catalyst, and fertilizer [19]. Typically, rice husks are used as fuel in industrial boilers connected to power generation units, although they are also incinerated under various conditions, including in incinerators or open pit fires [20–21]. In cementitious systems, RHA has been used as a partial replacement for cement, typically substituting between 5% and 30% of cement by mass.

Incorporating RHA into concrete mixes has shown significant benefits, such as enhancing compressive strength and improving resistance to chloride penetration [11]. These properties make RHA a valuable material for construction applications, especially considering its widespread availability due to abundant global production. Rice husks contain a considerable amount of silica, which, when fired, concentrates to levels exceeding 90% by weight in the ash, giving RHA substantial pozzolanic reactivity potential [22].

However, several limitations affect RHA production. These include geographical location, ignition conditions (such as temperature and ignition time), heating rate and the fineness and color of the produced ash [19]. Additionally, the high internal porosity of RHA results in increased water demand in fresh concrete, which can impact the rheology of the concrete mix.

### 13.2.3 *Sugarcane bagasse ash*

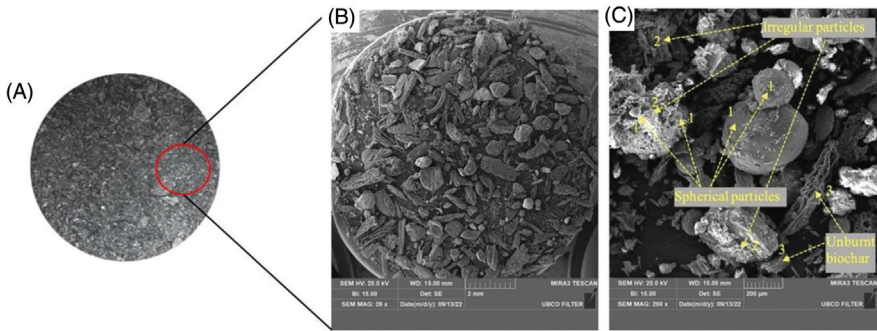
Sugar production generates two primary by-products: bagasse and waste leaves. Bagasse, obtained by crushing the sugarcane stalks and leaves, collected and processed before reaching the mills, is among the most studied waste materials for use as (SCMs) [11]. In particular, sugarcane bagasse ash (SCBA) can replace Portland cement in concrete mixtures at levels ranging from 5% to 20% by mass. Although it is less reactive than RHA, its reactivity can be improved by carefully controlling the calcination process and finely grinding the ash until 80% of the particles are smaller than 60  $\mu\text{m}$  [23]. This allows for up to 20% replacement of Portland cement in high-performance concrete, preserving similar mechanical properties while enhancing workability, resistance to chloride-ion penetration [24] and less thermal conductivity [25].

However, SCBA has limitations, such as variability in its composition depending on the burning process. The temperature must be high enough to eliminate the volatile organic components, while the conditions must be carefully managed to prevent the transformation of amorphous silica into its crystalline form [25]. It can also increase the water demand in concrete mixtures, potentially affecting workability [25]. The most common use of SCBA is a cement replacement.

### 13.2.4 *Wood ashes*

Wood fly ash (WFA) is a by-product generated in power plants from the combustion of forest residues to produce electricity and heat. Due to its pozzolanic properties, numerous studies have investigated its potential as a construction material. The morphology of wood fly ash is irregular, with particles varying widely in size and shape. As shown in Fig. 13.2, some particles are angular with rough textures, while others are more spherical, displaying either smooth surfaces or surface impurities [26]. WFA can be used in the following applications: road construction, soil stabilization, bricks, panels and polyester composites [27].

Wood ash presents several limitations when used in cementitious mixtures. Its irregular shape, porous nature, coarser texture, and larger specific surface area compared

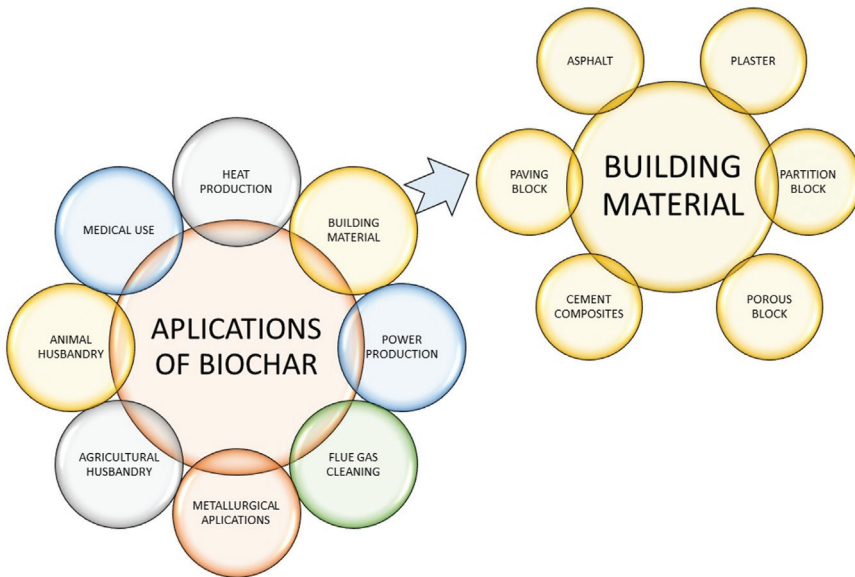


**Figure 13.2** (A) Macroscopic images of WFA, microscopic image of WFA with magnification (B) 26x and (C) 200x [28].

to cement result in a higher water demand to achieve the desired workability [27]. Additionally, the presence of high concentrations of heavy metals in WFA can restrict its use due to potential delays in cement hydration and the risk of excessive leaching of these metals [6]. Moreover, the suboptimal chemical composition of raw WFAs, particularly their high levels of chlorides and alkalis, further limits their reuse as filler or partial sand replacement, making them suitable only for unreinforced or low-quality concrete where stringent requirements are not necessary. However, to reduce these high levels of chlorides and alkalis, controlled combustion and post-processing methods are often necessary, which can diminish the potential environmental advantages [6].

### 13.2.5 Biochar

Biochar is a solid product derived from biomass through three primary processes: hydrothermal carbonization, pyrolysis, and gasification [29,30]. Many organic wastes can be used as feedstock to produce biochar, such as agricultural wastes and municipal solid wastes. Among these, pyrolysis is the most widely recognised and utilized method due to its significant technical and commercial relevance. Pyrolysis involves the thermochemical decomposition of a fuel at elevated temperatures between 300°C and 900°C in the absence of external oxygen [31]. This process yields three main products: permanent gases, one or more liquid phases and a solid residue. The solid carbonaceous product, known as biochar, is of primary interest due to its valuable applications. For slow pyrolysis, typical temperatures are around 500°C, while temperatures in the range of 200°C to 300°C are associated with a process known as torrefaction [29]. The primary goal is to retain and concentrate most of the energy content in the solid residue while also improving the mechanical properties of the biomass. The preparation conditions, including temperature, heating rate, retention time, and air conditions, have an important influence on the physiochemical properties of biochar [31–34]. Biomass is predominantly composed of three organic compounds: cellulose, hemicellulose and lignin. Each of these compounds influences the properties of the final product differently, as they behave distinctly during heat treatment. Hemicellulose is



**Figure 13.3** Applications of biochar [29,36].

the most reactive of the three and decomposes at temperatures between approximately 220°C and 315°C [35], making its decomposition the main process during torrefaction. Cellulose is more thermally stable, decomposing at temperatures ranging from 280°C to 400°C. In contrast, lignin decomposes over a broad temperature range due to its complex structure and numerous functional groups with varying thermal stabilities, starting around 200°C and continuing up to temperatures exceeding 900°C for complete decomposition [29]. In Fig. 13.3, can be seen the different applications of biochar.

Biochar is a promising filler for cement-based composites, enhancing properties like early strength, impermeability and durability. Fine biochar aids internal curing and moisture regulation, while larger particles can affect flowability and increase porosity. Although it improves water retention and thermal insulation, excessive use may reduce strength. Modified or mineral-enriched biochar can offer additional benefits, but further research is needed to optimize its use and maximize performance and sustainability [36]. Biochar-based construction materials provide both environmental and technical benefits. These include regulating humidity and temperature, shielding against electromagnetic interference, trapping contaminants, enhancing indoor air quality, possessing self-healing properties, and offering acoustic insulation [36].

### 13.3 Biopolymers and bio-phase-change material

Polymers that are naturally produced from living matter are referred to as “biopolymers”. This biopolymer is constructed from long chains of monomeric building blocks

**Table 13.2** Types of biopolymers, their properties and applications [38].

Biopolymers	Properties	Applications
Polysaccharides	Less water requirement in mortar, good mechanical and adhesion properties	Used as admixture, modified concrete using plants such as: cactus [39] and guar gum [40]
Lignin	Increased workability, insulating material and protective coatings	Used as a plasticiser, as composite construction material and coating material

that are covalently bonded together to form larger molecules. Biopolymers are produced on a large scale and applied in a variety of fields, such as biomedical, food and drug industries, and building materials [37]. Biopolymers have the advantages of thermal stability, moisture absorption, economy, degradation stability, mechanical strength, availability, and biocompatibility [37]. Typical limitations are high manufacturing costs and low production volume, as well as concerns about service life and biodegradation [37].

There are many different applications for this material, as shown in Table 13.2.

### 13.3.1 Lignin

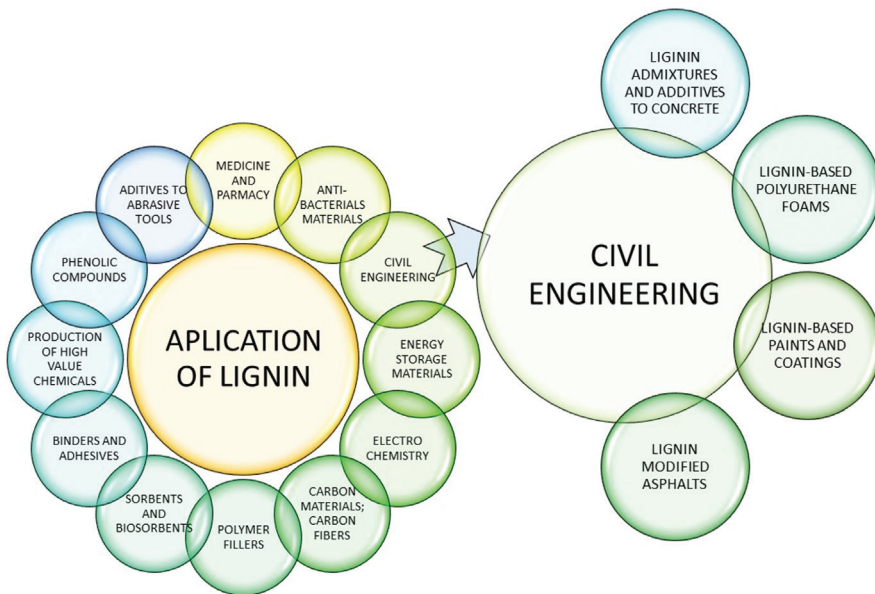
Lignin constitutes about 20% to 30% of plant cell walls and is the most abundant aromatic polymer found in nature. It is a waste product from industrial processes, mainly the paper and pulp industry [41] and it can be used in different fields, as shown in Fig. 13.4.

This biopolymer acts as a plasticizer, improving the workability of concrete without the need for an increased water-cement ratio, thereby preserving its fluidity while enhancing both its strength and durability [38]. Rigid polyurethane foams derived from lignin are used in structural applications, such as insulation and construction, due to their low thermal conductivity, high compressive strength and low density and strength parameters. As a protective coating, lignin offers environmental and health benefits, being a natural substance free from the toxic elements present in many commercial coatings, and it provides superior fire protection [38]. Additionally, lignin-based biopolymer capsules show significant potential for imparting robust self-healing capabilities to concrete, presenting a cost-effective and sustainable solution [42–44].

Despite its advantages, unmodified lignin has low activity and limitations, such as poor durability under conditions including temperature variations. Therefore, modification is necessary to improve its durability [45].

### 13.3.2 Polysaccharides

Biopolymers derived from polysaccharides encompass substances such as starch, hyaluronic acid (HA), cellulose, chitin, chitosan, and various gums. Chitin is a hydrophobic polysaccharide with either acidic or neutral characteristics and is insoluble in water and many organic solvents due to its hydrophobic nature. Conversely, chitosan



**Figure 13.4** Applications of lignin and lignin-based materials [41].

is particularly effective for creating scaffolding materials because of its ability to absorb water, induce cytokines, and biodegrade [46]. Starches, commonly present in root vegetables, potatoes and grains, are processed into thermoplastic starches (TPS) through heat and/or mechanical means. TPS serves as an alternative to conventional synthetic polymers, offering benefits due to their availability, renewability, recyclability, and thermoplastic properties.

Currently, natural polysaccharides and their derivatives are extensively used as admixtures in mortar and concrete mixes. These polysaccharides enhance the water retention capacity of fresh cement-based mortars [38]. By reducing the substrate's absorption of mixing water, they improve the mechanical and adhesive properties of the mortar [47]. Additionally, incorporating polysaccharides into mortar and concrete mixes results in a material with enhanced shear-thinning characteristics, improving the rheological properties of the mortar due to their thickening effects. Furthermore, a biopolymer based on polysaccharides from cactus has been shown to enhance both the fresh and hardened properties of modified concrete [48].

The drawbacks of these materials include increased viscosity, difficulties with dispersion, optical problems, and a higher rate of sedimentation [49].

### 13.3.3 Bio-based phase-change materials

Phase-change materials (PCMs) are a key class of thermoresponsive substances utilized for thermal energy storage in the form of both sensible and latent heat. Their use in energy-related technologies can greatly enhance the efficiency and conservation of sustainable and waste energy. The latent heat storage capacity of PCMs offers high

energy density with minimal temperature variations during the heat absorption and release processes [50]. Most PCMs currently in use are derived from non-renewable sources, contributing to a certain level of carbon emissions. However, innovative PCMs can now be engineered from eco-friendly materials, which have little to no environmental impact [50]. Bio-based PCMs are made from organic substances, often sourced partially or fully from biomass, vegetable or tropical oils or animal and fish fats. While it is commonly assumed that bio-based PCMs are biodegradable, this characteristic requires careful examination for each type. Generally, bio-based PCMs are non-toxic and can be used in a wide temperature range, from as low as  $-80^{\circ}\text{C}$  to as high as  $275^{\circ}\text{C}$ , making them suitable for various applications [51].

The diversity of raw materials allows the production of PCMs from locally available or even waste resources found globally. The most thoroughly researched bio-based PCMs include biopolymers [50], esters [52], sugar alcohols [53], fatty acids [54], and their blends, whether naturally occurring or synthesized in laboratories. Many of these compounds, especially in lower purities, are produced in significant quantities and can meet the cost and availability demands of various industries [51].

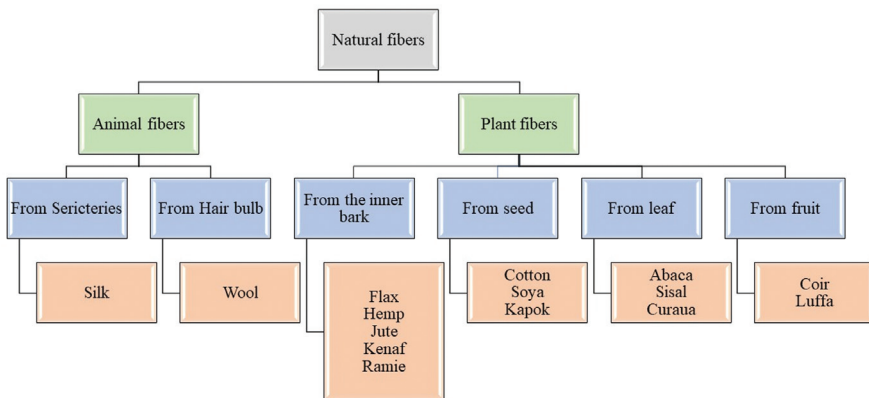
## 13.4 Biofibers

Biofibers, also known as natural fibers, are gaining recognition as a sustainable and eco-friendly alternative in construction materials. Sourced from biological origins such as plants, animals, and microorganisms, these fibers include materials like flax, hemp, sisal, wool, and others. Their application in construction, particularly in the production of composites and reinforcements, has increased due to their ability to reduce environmental impact compared to synthetic or non-renewable materials. These eco-materials offer several advantages, including lower weight for similar performance, biodegradability (also a disadvantage), and a lower carbon footprint [37]. When integrated into composites with polymer or concrete matrices, biofibers enhance structural performance, boosting tensile strength, flexural strength, impact resistance, and fatigue resistance

To optimize the use of fibers in concrete, it is crucial to address the rate of degradation in highly alkaline environments, such as that of cement. While fibers significantly enhance the toughness of concrete, their rapid degradation could diminish this improvement over time. Rather than focusing solely on biodegradability, we should prioritize the selection and development of fibers that, even if they do degrade, do so at a slow enough rate to maintain their structural properties throughout the concrete's lifespan. This will not only ensure the durability and effectiveness of the material but also make the use of fibers in industrial applications more cost-effective and sustainable in the long term. Furthermore, their thermal and acoustic insulation properties have expanded their use in eco-friendly and sustainable building practices [37].

### 13.4.1 Classification of biofibers

Composite materials consist primarily of two phases: the matrix and the fibers. The matrix is the dominant component and can be made from metals [55,56], ceramics

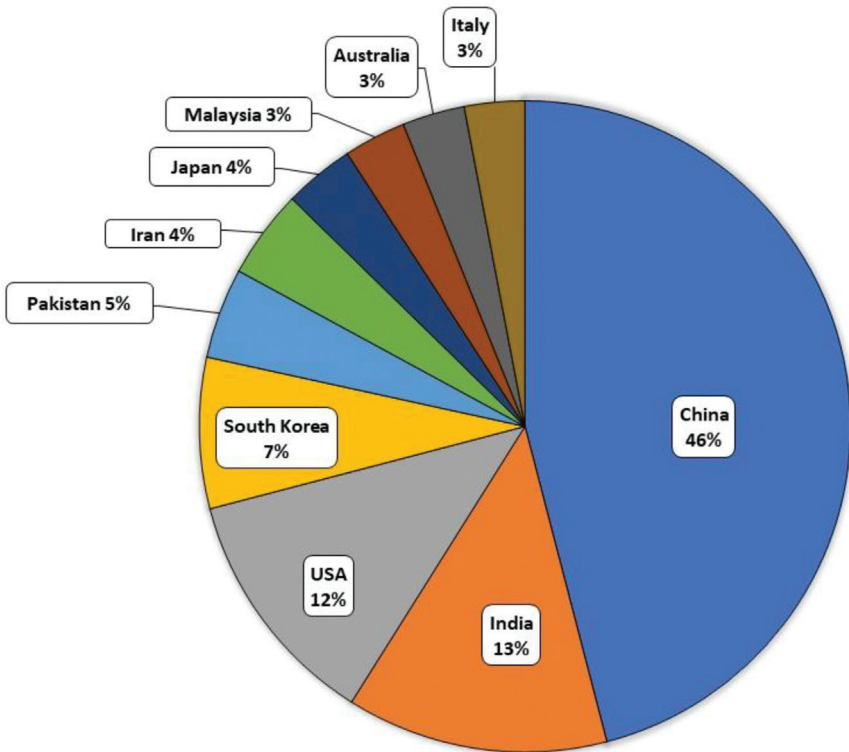


**Figure 13.5** Fibre classification, elaborated based on [67–70].

[57,58], or polymers [59,60]. Typically, the matrix is lightweight and continuous, serving to shape the material and distribute stresses to the fibers. The dispersed phase, composed of particles or fibers, is primarily responsible for the strength and ductility of the material [61,62]. These fibers adhere to the matrix through adhesive forces, which play a critical role in the material's performance. In the case of cementitious materials, the matrix is composed of cement-based materials, which can be applied in the form of pastes, mortars, or concrete [63].

Fibers can be classified into two main categories: Natural fibers and synthetic fibers. Natural fibers are a degradable circular by-product of agricultural industries, whilst synthetic fibers are made from oil refinement processes (mainly polypropylene manufacturing) and are non-degradable. Typically, fibers are employed either as raw strands or woven fabrics. Fig. 13.5 provides a comprehensive classification of these strands. The major users are presented in Fig. 13.6, with China being the leading user of bio-fibers followed by India, the United States and South Korea [64].

This chapter will primarily focus on natural fibers. However, it is important to note that synthetic fibers also exhibit significant structural performance and are applicable in various composite systems, such as fiberglass, carbon fiber or Kevlar, with a matrix like epoxy resin or concrete to create materials with enhanced properties. Examples include fiberglass in epoxy for boat hulls, carbon fiber in aerospace structures and steel-reinforced concrete in construction. These materials offer high strength, lightness, and durability, making them essential in applications like vehicles, infrastructure, and protective gear. Natural fibers, sourced from plants and animals, have gained traction in recent years as a sustainable construction material [65]. There are also steel fibers, which are commonly used in construction materials due to their high tensile strength and durability. These fibers are typically incorporated into concrete to improve its mechanical properties, such as toughness and ductility. Steel fiber reinforced concrete (SFRC), in particular, is known for its excellent resistance to cracking and the prevention of crack propagation [66]. However, it also has some disadvantages, such as



**Figure 13.6** Major consumers of bio-fibers worldwide [64].

increased cost compared to traditional reinforced methods and potential corrosion in certain environments.

Natural fibers are categorized into two primary groups: animal fibers and plant fibers. Animal fibers are generally less favourable compared to plant fibers due to the complexities and challenges associated with their large-scale collection. In contrast, plant fibers offer several compelling advantages over synthetic fibers, including: (1) improved mechanical performance for the same weight (2) low cost, (3) widespread availability, (4) biodegradability (can also be seen as a disadvantage), (5) renewability, (6) desirable aspect ratio and (7) favorable tensile and flexural strength properties [71–74]. When utilizing natural fibers, several critical factors must be considered, including fiber selection (which encompasses type, harvest time, extraction method, aspect ratio, treatment and fiber content), matrix selection, interfacial strength, fiber dispersion, fiber orientation and porosity [75]. The main disadvantage of natural vegetable fibers compared to synthetic fibers is their greater variability in properties. Synthetic fibers, produced through controlled industrial processes, have consistent, well-defined characteristics. In contrast, natural fibers are affected by environmental factors like weather, geographic location, and seasonal changes, leading to inconsistent

**Table 13.3** Summary of physical and mechanical properties of some natural fibers [76].

Animal fiber	Density (g/cm <sup>3</sup> )	Length (mm)	Diameter (μm)	Absorption (%)	Tensile strength (MPa)	Tensile modulus (GPa)
Sheep wool	1.5–2.0	50–127	11.5–22	Varies	120–174	1–4.8
Pig hair	Varies	22.1–60.2	7–230	95	44.5–155.1	3.93–8.08
Silk	1.34–1.38	Varies	5–20	10–12	25–50	2–6

properties. Additionally, durability is a concern for vegetable fibers in cement-based composites. These fibers, composed of organic materials like cellulose, lignin and hemicellulose, degrade in alkaline environments (such as cement), reducing their long-term performance [63].

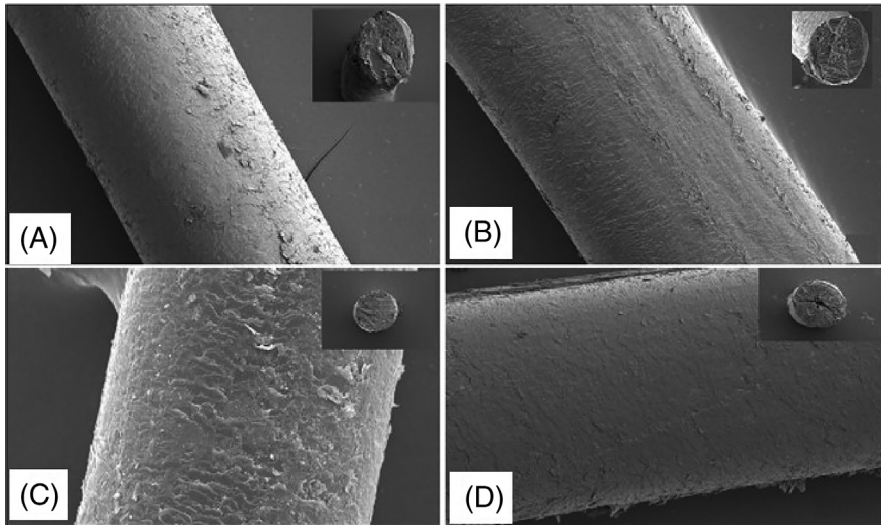
### 13.4.2 Animal-based fibers

Animal-based fibers (AFs) can be classified into two main categories: (1) Silk fibers, which are derived from the cocoons of silkworms or other insect species, and (2) animal hair fibers, typically sourced from the hair or fur of mammals [76–78]. These fibers, whether secreted or derived from hair, are primarily composed of proteins known as keratins. Keratins are categorized into two families: Acidic keratins (40–55 kDa), classified as Type I and basic or neutral keratins (55–77 kDa), classified as Type II [79]. Despite their diverse origins, AFs exhibit similar physical properties, compared to natural fibers, with notable differences in the organization and morphology of the outer cuticle scale cells, as well as the presence or absence of a central medullary core [62]. The cuticle, comprising scale-like cells, constitutes the outermost layer of the fiber and interacts with the external environment. This layer includes an epicuticle, a sublayer coated with an extremely thin film of fatty acids. The thickness of cuticle cells varies, ranging from 1 to 2 layers in finer fibers like cashmere, wool, and mohair, to 8 to 10 layers in coarser fibers such as goat guard hair [62]. Table 13.3 shows a summary of the physical and mechanical properties of some animal fibers.

#### 13.4.2.1 Sheep wool

Sheep wool (SW) is one of the earliest known fibers utilized by humanity and has been extensively employed in textile production and other industrial applications. Sheep yield approximately 2.3 to 3.6 kg of raw wool annually, and it needs to be trimmed for their health care [80]. In the textile industry, SW is favored for its exceptional resistance to elastic deformation and low thermal conductivity [81]. In the context of construction applications, SW-based insulation can be effectively utilized for flooring, where millions of microscopic air pockets formed by crimped wool fibers create a thermal barrier while simultaneously controlling moisture and reducing noise [82].

This fiber offers several significant benefits, including low density, high tensile strength, and excellent thermal and acoustic insulation, within others. However, it also



**Figure 13.7** Scanning electron microscopy (SEM) images showing surface features of pig hair fibre from different breeds ( $\times 500$ ). The inset shows a cross-section of the mid-shaft of the fibre ( $\times 250$ ). (A) Hampshire, (B) Duroc, (C) Ghungroo and (D) Niang Megha [85].

has some drawbacks, such as limited durability, high moisture absorption (30%–40%), and poor compatibility with cementitious matrices [82].

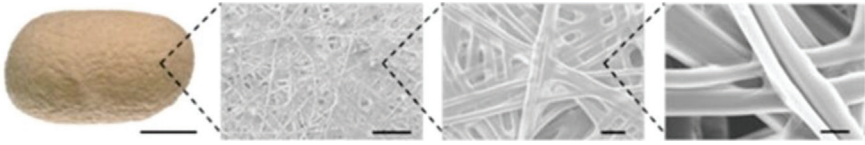
#### 13.4.2.2 Pig hair fibers

The potential use of pig hair fibers (PHFs) as shown in Fig. 13.7 in cementitious materials (CMs) has long been unexplored, mainly because their key properties have not been thoroughly characterized. Traditionally, PHFs have been used in commercial applications, particularly for making brushes and insulation materials [83]. In the pork industry, pig hair is typically regarded as waste. Nevertheless, PHFs are non-toxic and possess morphological and mechanical properties that make them suitable for use as microfibers [82].

The fibrous structure of pig hair is also noted for its favorable thermal properties [84]. One of its significant limitations is the variability in the extraction process and the physical properties, which can be inconsistent.

#### 13.4.2.3 Silk

Silk (shown in Fig. 13.8) is a fibrous material produced by certain animals such as moths and spiders, with mulberry silkworm silk being the most common [37]. Silk fibers are known for their stiffness, strength, elongation, and toughness, largely due to the presence of fibroin and sericin—proteins that contribute to their structural integrity. The properties of silk fibers can vary depending on the animal species. Primarily, silk



**Figure 13.8** Hierarchy of the morphology of a *Bombyx mori* cocoon (scale bar from left to right: 1cm, 200 $\mu$ m, 20 $\mu$ m, 10 $\mu$ m) [80].

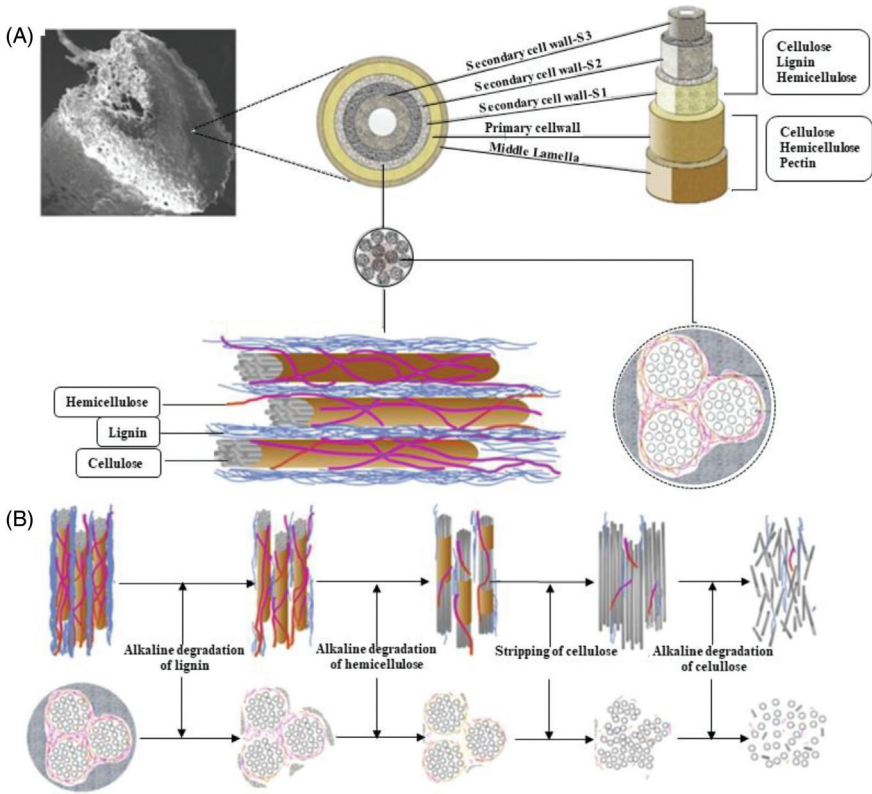


**Figure 13.9** Different types of plant-based fibers [37,98].

fibers are used in tissue engineering and regenerative medicine due to their flexibility, biodegradability, and biocompatibility [82].

#### 13.4.2.4 Plant-based fibers

Plant-based fibers are gaining prominence in the construction industry due to their sustainability and economic benefits. Plant fibers, derived from plants such as coconut, sisal, palm, bamboo, abaca, and jute (see Fig. 13.9) are used as reinforcement in eco-friendly composite materials. While offering similar benefits compared to animal fibers, the primary distinction between these two biomaterials lies in their



**Figure 13.10** Diagrammatic drawing of (A) microstructure and (B) cellulosic fiber's alkaline degradation process [73,100].

composition and biological origin. Plant-based fibers are primarily composed of cellulose, a carbohydrate polymer that provides rigidity and strength to plant cell walls. Table 13.6 presents the average amounts of chemical components (in wt%) of the most used dried plant fibers in the industry. In contrast, as previously mentioned, animal fibers are primarily based on proteins such as keratin and fibroin.

The use of cellulosic fibers can reduce free plastic shrinkage [86] and thermal conductivity [87]. Additionally, these fibers enhance sound and vibration absorption in cementitious materials [88,89]. Despite their advantages, cellulosic fibers face two key challenges:

1. Durability—alkaline environments significantly reduce their lifespan (Fig. 13.10).
2. When used as monofilaments, maintaining volume fractions between 0.2% and 2% is crucial to prevent handling and mixing issues that may cause unwanted porosities.

Variation in their physical properties: Cellulosic fibers exhibit significant variations in chemical composition, diameter, length, and surface roughness, resulting in

**Table 13.4** Factors affecting the mechanical properties of cellulosic fibers [73,99].

<b>Plant growth</b>	<b>Specimens of plant, crop cultivation, crop geographical origin, fibre location, local climate, that is, rainfall and temperature during growth</b>
Harvesting stage	Fiber ripeness, which affects: Cell wall thickness, coarseness of fibers, adhesion between fibers and surrounding structure, size and shape of lumen, porosity, microfibril angle
Fiber extraction stage	Decortication process, type of retting method and separating conditions
Supply stage	Transportation conditions, storage conditions, age of fibers
Measurement conditions	Moisture, temperature and different cross-sections of fibers along their length
Surface treatment	Chemical treatment, water treatment, drying treatment etc.

**Table 13.5** Summary of physical and mechanical properties of some plant-based fibers [64,113].

<b>Plant fiber</b>	<b>Density (g/cm<sup>3</sup>)</b>	<b>Length (mm)</b>	<b>Diameter (μm)</b>	<b>Absorption (%)</b>	<b>Tensile strength (MPa)</b>	<b>Tensile modulus (GPa)</b>
Coconut	1.2	20–150	100–450	40–52.45	131–503	4–6
Sisal	0.7–1.3	50–127	11.5–22	56–230	400–700	9–20
Palm	0.463	22.1–60.2	7–230	1–10	100–400	26–32
Bamboo	0.6–11	100	240–330	40–52	140–230	11–17
Jute	1.3–1.5	1.5–120	40–350	10–12	393–860	10–30
Abaca	1.5	-	179–230	-	430–760	12

considerable scatter in their mechanical properties [73]. Notably, the tensile strength of cellulose fibers tends to decrease with increasing fiber length, as longer fibers are more likely to contain defects and thus may experience premature failure compared to shorter fibers [73]. Additionally, tensile strength can vary significantly based on the maturity level of the fibers [90].

To enhance the durability of cellulosic fibers in cement matrices, several methods have been proposed: Hornification, which improves dimensional stability and reduces water retention [91]. Surface modification with methacryloxypropyltrimethoxysilane (MPTS) and aminopropyl-triethoxysilane (APTS) [92] has been used to increase the modulus of rupture and elasticity of the fiber/matrix interface. The use of silane coupling agents has also been shown to improve adhesion with the matrix and increase durability [93,94]. Additionally, using water repellents or impregnating the fibers with sodium silicate, sodium sulphite, or magnesium sulphate can improve the interfacial adhesion between cellulosic fibers and concrete, thereby enhancing their mechanical properties and durability [95–97]. Table 13.4 shows factors that affect the mechanical properties of plant fibers and Table 13.5 shows a summary of the physical and mechanical properties of some plant fibers.

**Table 13.6** Chemical composition of the most widely used plant fibers [108–110].

Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Waxes (wt%)
Abaca	56–30	20–25	7–9	3
Coir	32–43	0.15–0.25	40–45	–
Cotton	85–90	5.7	-	0.6
Flax	71	18.6–20.6	2.2	1.5
Jute	61–71	14–20	12–13	0.5
Kapok	64	23	-	–
Kenaf	72	20.3	9	–
Bamboo	26–43	30	21–31	–
Hemp	68	15	10	0.8
Pina	81	-	12.7	–
Ramie	68.6–76.2	13–16	0.6–0.7	0.3
Sisal	65	12	9.9	2
Bagasse	55.2	16.8	25.3	–
Oil palm	65	–	29	–
Curaua	73.6	9.9	7.5	–
Wheat straw	38–45	15–31	12–20	–
Rice Straw	41–57	33	8–19	8–38
Rice Husk	35–45	19–25	20	15–17

Water retting and dew retting are traditional methods used to extract natural fibers from plants like flax, hemp, and jute. In water retting, plant stems are submerged in water, allowing bacteria to break down the pectin that binds the fibers to the woody parts, producing high-quality fibers. However, this method requires large amounts of water and can be environmentally harmful if not managed properly. Dew retting, on the other hand, involves leaving the plants on the field, where natural moisture and microbial activity break down the binding agents. This method is simpler and eco-friendly, but it depends on weather conditions and can result in variable fiber quality. While water retting produces better fibers, dew retting is less resource-intensive and more sustainable [37].

#### 13.4.2.5 Coconut coir fiber

Coconut fibers typically range in length from 50 to 350 mm and are primarily composed of lignin, tannin, cellulose, pectin, and other water-soluble substances. Due to their high lignin content, these fibers exhibit slower degradation compared to other natural fibers, resulting in enhanced longevity, with field service life extending from 4 to 10 years [101]. Coconut fibers have a water absorption capacity of approximately 130% to 180% of their volume and a diameter ranging between 0.1 and 0.6 mm on average [102]. The rate of degradation is influenced by the embedding medium, with the fibers retaining about 80% of their tensile strength after 6 months of immersion in clay [101]. Coconut fibers are being explored as a sustainable alternative to traditional concrete reinforcement materials.

### 13.4.2.6 *Sisal*

Sisal is a lignocellulosic fiber [103] traditionally utilized as reinforcement in gypsum plaster sheets within the building industry. It exhibits a water absorption capacity of 60% to 70% and a diameter ranging from 0.06 to 0.4 mm. Sisal fibers are extracted from the leaves of the *Agave sisalana* plant, which vary in dimensions from 6 to 10 cm in width and 50 to 250 cm in length. Brazil, Indonesia and East African nations are the principal global producers of sisal fibers [104].

### 13.4.2.7 *Date palm fibers*

Date palm fibers (DFTs), known for their filamentous texture, offer advantages such as low cost, abundant availability, durability, lightweight nature, high tensile capacity, and relative resistance to deterioration. However, fibers extracted from decomposed palm trees tend to be brittle, with low tensile strength, modulus of elasticity, and very high water absorption [105].

### 13.4.2.8 *Bamboo*

Bamboo fiber (BF) is classified as a regenerated cellulose fiber and is notable for its sustainable growth, as bamboo can proliferate without the use of pesticides and is rarely subject to pest infestations or pathogen attacks [101]. BFs are chemically treated to remove lignin and amorphous regions. A common method involves soaking in 4% NaOH for 72 h [106], which removes 38% to 42% of polysaccharides and lignin, producing a pulp that is then bleached with sodium chlorite. Another technique uses HNO<sub>3</sub> and KClO<sub>3</sub> to obtain bamboo fibers that are converted into nanocrystals of 50 to 100 nm after treatment with sulphuric acid. A more complex approach by Xin et al. [107] includes roasting the bamboo, treating it with various chemicals, and then bleaching it to produce refined fiber [108]. Mechanical methods for processing bamboo fibers include high-pressure refiners, super grinders, and homogenisers. Techniques like crushing, heat steaming, and shearing after swelling the bamboo can yield fibers, though crushing requires screening and heat steaming may weaken the fibers [108]. Chemical and mechanical processes are used to extract bamboo fibers in the pulp and paper industry. Methods like compression molding (CMT) and roller milling (RMT) prepare bamboo strips for alkali treatment. CMT compresses the strips between plates, while RMT flattens them between rollers. These strips are then easily separated into individual fibers. Manual decortication and chemical degumming achieve a 33% yield [108].

Bamboo exhibits strong potential as a raw material for both structural and non-structural applications in construction. It serves as a viable alternative to conventional building materials, finding use in areas such as roof structures, walls, flooring, foundations, and scaffolding. Bamboo offers several key advantages: it is lightweight, strong, highly versatile, and cost-effective in comparison to traditional construction materials. Furthermore, it is a self-renewing resource, contributing to sustainability efforts. However, bamboo also presents certain limitations, including its susceptibility

to fire, the difficulty and complexity of forming joints due to its round shape, a considerable tapering in diameter and width along its length, high water absorption, and the necessity of preservation treatments to retain its mechanical properties over time [109].

#### 13.4.2.9 Jute

Jute fibers are increasingly recognized for their utility in the building and construction sectors. Each part of the jute plant has diverse applications: leaves for food and medicine, fibers for industry and households and stalks as fuel. Jute fiber constitutes approximately 7% of global natural fiber production [110]. Its cultivation contributes to soil fertility and enhances air quality by absorbing CO<sub>2</sub> and releasing O<sub>2</sub>.

When integrated into cementitious materials, jute fibers can enhance various mechanical and physical properties, such as tensile strength, flexural strength, and crack resistance [74]. They function as reinforcements within the cement matrix, aiding in shrinkage control and improving material toughness. However, jute fibers are prone to moisture absorption and potential degradation over time [73]. To mitigate these issues, surface treatments or chemical modifications, such as dry heat, autoclaving, and alkaline treatment, are often employed prior to their incorporation into cementitious composites.

#### 13.4.2.10 Abaca

Abaca (*Musa textilis*), commonly referred to as Manila hemp, is a robust natural fiber derived from a species of the banana plant family, predominantly cultivated in the Philippines. As the world's leading producer, the Philippines accounts for approximately 84% of the global abaca supply [111]. Abacá fibers are recognized as one of the strongest natural fibers available and are extensively utilized in various industries, including the production of specialty paper, pulp, twines, and textiles, and it is also used to produce floor panels in automotive manufacturing [112]. Chemically, abaca fibers consist of approximately 60% cellulose, 21% hemicellulose, 12% to 16% lignin, and around 1% pectin [111].

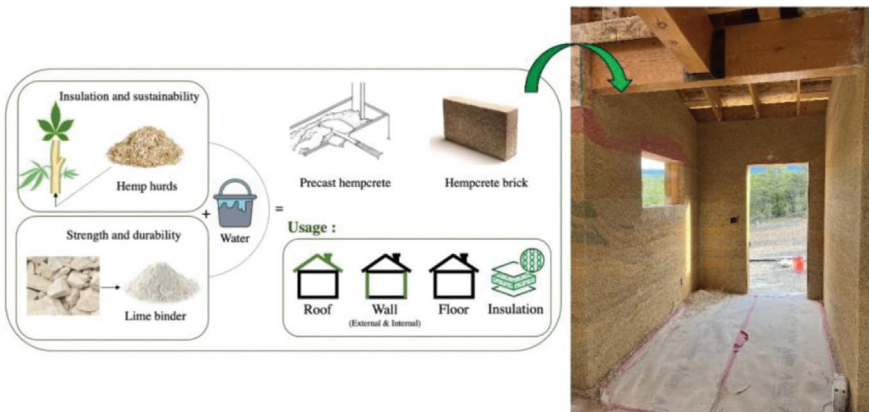
## 13.5 Applications in building materials

Bio-based materials are increasingly being utilized in a wide range of construction applications, such as cementitious composites, filling, and insulating [114].

### 13.5.1 Insulating materials

#### 13.5.1.1 Hempcrete

Hempcrete is a sustainable building material primarily composed of hemp fibers, lime, and water (Fig. 13.11). Although sometimes referred to as “hemp concrete”, Hempcrete



**Figure 13.11** Example of hempcrete wall [115,116].



**Figure 13.12** Construction of a single-storey house using straw [114].

is not used as a structural load-bearing material but is mainly employed for insulation and wall infill. This material is made by mixing hemp fibers with a lime binder and water, resulting in a lightweight (approximately one-eighth the weight of average concrete) and insulating composite. Its sustainability is rooted in the fact that hemp is a fast-growing and renewable plant, and lime absorbs  $\text{CO}_2$  during curing [91], thereby reducing the carbon footprint. While not a structural material on its own and requiring a wooden or metal frame, Hempcrete is widely used as wall infill and to enhance the thermal and acoustic insulation properties of buildings, making it an eco-friendly and efficient alternative to conventional concrete [114].

### 13.5.1.2 Straw

Straw is a widely accessible material and is regarded as a practical option (Fig. 13.12). Historical structures featuring straw in their roofing can be found worldwide. Research by Sandak et al. [117] and Falk and Wålinder [118] indicates that in the past, straw was commonly used as a substrate for plasters, roofing, and as bales in load-bearing

walls. As noted in Jones and Brischke [119], when properly installed and shielded from moisture, straw can serve as a durable, load-bearing, long-lasting, and insulating material [114].

### 13.5.1.3 *Biofoams*

Rigid biofoam composites are made from polymeric foams derived from functionalised vegetable oils combined with synthetic or lignocellulosic fibers. These composites are becoming a viable alternative to traditional sandwich composites due to their greater biodegradability and sustainability, making them more suitable for eco-friendly design [120].

### 13.5.1.4 *Cellulose insulation*

Cellulose insulation is an eco-friendly building material primarily made from recycled paper products, such as newspapers and cardboard, which are shredded and treated with fire retardants and pest repellents. This type of insulation is used to enhance energy efficiency in buildings by reducing heat transfer, thereby maintaining stable indoor temperatures and minimizing the need for heating and cooling. Additionally, cellulose insulation offers good acoustic properties, helping to reduce noise between rooms and from outside. It can be installed as loose fill or in panel form, making it versatile for various construction and renovation projects. Generally, cellulose insulation is a cost-effective option and contributes to sustainability by utilizing recycled materials, though its installation must be done correctly to ensure its fire and pest resistance. Overall, cellulose insulation provides an efficient and environmentally friendly solution for improving building performance [121].

## 13.5.2 *Cementitious composites*

### 13.5.2.1 *Cementitious matrix composites with sisal fibers*

Cementitious matrix composites reinforced with sisal fibers offer a sustainable and innovative solution in the construction field. These materials combine the strength and durability of the cementitious matrix with the natural properties of sisal fibers, which are renewable, lightweight, and have good tensile strength. However, a significant challenge is the high alkalinity of the cementitious environment, resulting from the formation of calcium hydroxide during cement hydration. This alkalinity can degrade the sisal fibers through alkaline hydrolysis, reducing their reinforcing capacity and affecting the composite's durability. Despite this challenge, with appropriate treatments, these composites can provide an eco-friendly and more cost-effective alternative to traditional materials, especially in regions where sisal is abundant. In studies such as Veigas et al. [122], an examination is conducted on fibers treated with two different coatings: polyester resin and bio-based shellac. For this study, multiple cubes, cylinders, and beams are used to compare the results with matrices

that did not contain any fibers, resulting in an average increase of 20% and 42% in tensile and flexural strengths, respectively, for the specimens that contained fibers. Sisal fibers were determined to be effective in mitigating plastic shrinkage-induced cracks.

### 13.5.2.2 *Cementitious matrix composites with jute fibers*

In studies by Majumder et al. [98], the aim was to evaluate mortars with jute fiber to enhance both their structural capacity and energy performance in masonry. Composite mortars with jute fibers were produced using different fiber lengths (5, 10 and 30 mm) and four different fiber percentages (0.5%, 1%, 1.5% and 2%) relative to the mortar mass. The study demonstrated that adding fibers increases porosity and reduces density, which in turn lowers thermal conductivity. The results for flexural and compressive strength showed that the addition of fibers decreases mechanical performance, with fiber length being a crucial factor affecting material behavior under external forces, as well as the water-cement ratio. However, the presence of fibers was found to improve deformation energy compared to mortars without fibers, which could be advantageous in scenarios involving seismic activity or extreme load conditions.

### 13.5.2.3 *Cementitious matrix composites with coconut fibers*

The use of coconut fibers in cementitious matrices is reviewed in a study by Ali et al. [123], focusing on various properties, such as workability, hardened density, and flexural and tensile behavior. Regarding workability, six studies [124–129] employ the flow test to assess how coconut fibers affect the workability of the new composite. The results indicate that workability is negatively impacted by the inclusion of coconut fibers due to the balling effect. Additionally, the length and amount of fibers added (relative to the final volume) are crucial factors for the workability and compaction of the concrete mix. It is suggested that incorporating superplasticizers could help reduce voids in fiber-reinforced mixes.

Regarding hardened density, it is concluded that density decreases with an increased content of coconut fibers, as low-density fibers can create voids in the concrete. The reduction in density was more significant with fibers of 25 and 75 mm lengths compared to 50 mm fibers. In terms of flexural and tensile behavior, it is observed that incorporating coconut fibers at a proportion of 1% to 3% improves tensile strength by approximately 10% [124,125,127,130]. However, adding 7% coconut fibers to the weight of cement results in a decrease of about 25% in both tensile and flexural strength. The lower strength is attributed to lower workability, higher voids, and reduced coir bonding capacity. Compressive strength, as well as tensile and flexural strength, shows a slight decrease with a high volume of fiber incorporation. The increase in tensile and flexural strength is primarily due to the enhanced crack-bridging capacity provided by the fiber filaments, which transfer tensile stresses from the concrete to the filaments due to their roughness, resulting in a better bond between the matrix and the fiber.

#### 13.5.2.4 *Cementitious matrix with date palm fiber*

The use of date palm fibers (DPF) in different cementitious materials, including DPF-reinforced mortar, DPF-reinforced concrete, DPF-reinforced gypsum, and DPF-reinforced clay bricks, is reviewed in Adamu et al. [131].

The use of DPF as an insulating material in cement mortar, testing mortars with different DPF sizes (3 mm, 6 mm, and combinations of both) and varying concentrations (5%, 10%, 15%, 20%, 25%, and 30% of the total weight) was evaluated experimentally [132]. Their findings indicated that increasing DPF content reduced both the density and thermal conductivity of the mortar, with a more pronounced effect for smaller DPF sizes. Additionally, the compressive strength of the mortar decreased with higher DPF content. At 5% DPF, compressive strength decreased by 92%, 91.9%, and 95% for 3 mm, 6 mm and combined DPF sizes, respectively. However, acceptable strengths were achieved with DPF concentrations of 15% or less, making these mixes suitable for structural applications and improved thermal insulation.

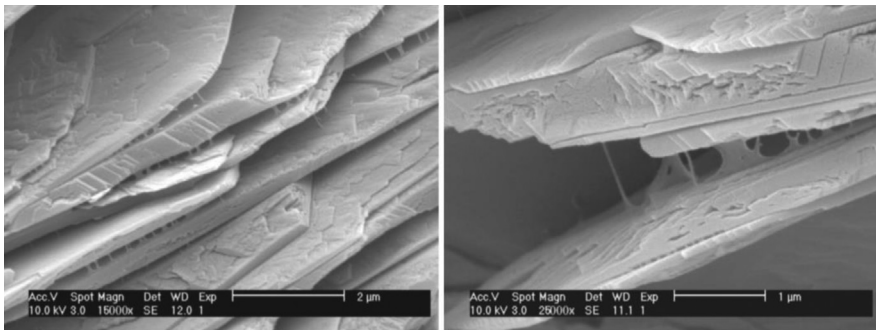
The impact of DPF on the flexural performance of mortar by adding 0%, 2%, 4%, 6%, 8%, and 10% by volume was explored experimentally [133,134]. The results showed that DPF decreased the density, flexural strength, and fracture toughness of the mortar. Specifically, the flexural strength decreased by 9%, 17%, and 52% with the addition of 2%, 4%, and 10% DPF, respectively, due to increased porosity and the lower modulus of elasticity of the fibers compared to the mortar. Fracture toughness also decreased by 7%, 32%, and 66% with the addition of 2%, 6%, and 10% DPF, respectively, attributed to poor bonding between the fiber and the cement matrix. However, the addition of DPF improved ductility, with increases ranging from 27% to 162% as the DPF content increased from 2% to 10%; which could be good for seismic regions.

The effects of different types of date palm fibers (male and female) on concrete properties were tested as well [135]. The authors found that male palm DPF, which exhibited the highest tensile strength and elongation, was the most suitable for reinforcement. Adding 2% or 3% of this DPF to concrete, with fiber lengths of 15 mm and 60 mm, decreased compressive strength but improved ductility. Flexural strength also decreased with higher fiber content. At 28 days, concrete with 3 to 60 mm DPF had a 65% lower first crack load compared to the control concrete. They recommended treating the DPF before use to enhance performance. Common chemical treatments include alkaline treatment or acetylation, both of which enhance the fibers' properties for better integration in composites.

#### 13.5.2.5 *Cementitious matrix with abaca fibers*

The mechanical properties of cement matrices using recycled aggregates and abaca fibers were compared to reference matrices with traditional polypropylene fibers in [74]. The toughness of beams with abaca fibers is 48% of that of beams with polypropylene fibers.

The dynamic modulus of elasticity is a valuable measure for assessing how materials respond to dynamic forces, influencing their application, design, and long-term



**Figure 13.13** Polymer films between layered  $\text{Ca}(\text{OH})_2$  crystals [136].

performance. Disks with abaca fibers exhibited 15% of the control samples' value for the dynamic modulus of elasticity, while disks with recycled aggregates showed 30% of the control samples' value.

#### 13.5.2.6 Water soluble polymers

The modification of cement mortars with small amounts of water-soluble polymers (1%), such as polyvinyl alcohol-acetate (PVAA), methylcellulose (MC) and hydroxyethylcellulose (HEC), was investigated by Knapen and Van Gemert [136]. The main objective was to analyze how these polymers influence the microstructure of the mortar and its mechanical properties, such as flexural and compressive strength. Through thermal analysis and SEM (see Fig. 13.13), it was observed that the polymers not only improve the rheological properties of fresh mortar but also form polymer bridges between  $\text{Ca}(\text{OH})_2$  crystals, reinforcing the weaker areas of the cement matrix. The results showed that while the compressive strength was reduced due to increased air content, flexural strength significantly improved in dry-cured mortars due to the formation of polymer films. This study highlights the importance of water-soluble polymers in optimizing cement mortars in terms of mechanical performance and durability.

## 13.6 Concluding remarks

Bio-based materials are increasingly recognized for their potential to enhance the sustainability and performance of construction materials. They address key challenges in the industry by improving the mechanical properties of concrete and reducing its environmental impact. The primary categories of bio-based materials with significant promise include:

- *Supplementary cementitious materials (SCMs)*: Derived from agricultural residues such as (RHA) and sugarcane bagasse ash, SCMs can partially replace Portland cement in concrete. Their use helps lower  $\text{CO}_2$  emissions associated with cement production and enhances

**Table 13.7** Overview of bio-SCMs advantages and challenges.

Aspect	Advantages	Limitations
Source	Derived from renewable or sustainable sources such as agricultural by-products or industrial waste	Raw materials may vary in availability and quality; sourcing may be inconsistent
Environmental impact	Reduces carbon footprint compared to traditional SCMs; can lower greenhouse gas emissions	May require energy-intensive processing; potential land use issues depending on source
Performance in cement composites	It can enhance the properties of concrete, such as strength, durability and resistance to chemicals	Performance can vary; it may not always achieve the same properties as traditional SCMs
Waste utilization	Often made from industrial or agricultural by-products, helping to reduce waste and promote recycling	Some sources of bio-SCMs may not be fully recyclable or biodegradable
Cost	It can be cost-effective if sourced from local or abundant by-products	Initial costs may be higher; processing and transportation costs can affect overall cost
Compatibility with portland cement	It can be compatible with various types of Portland cement and other SCMs; often used to improve concrete performance	Compatibility issues may arise with certain formulations or in specific applications
Sustainability	Contributes to circular economy by utilizing waste materials, often more sustainable than conventional SCMs	Sustainability depends on the lifecycle of the SCM and its impact on resource use
Durability	It can improve the durability and longevity of concrete, reducing maintenance needs	Long-term durability and performance must be verified through extensive testing
Applications	Used in a variety of concrete applications, including construction, infrastructure and repair	Limited availability and application in some regions; may require adjustments in mix design

the sustainability of concrete. Biomass ashes like RHA provide pozzolanic properties that improve concrete strength and durability. However, their effectiveness is contingent on factors like chemical composition and reactivity. An overview of bio-SCMs advantages and limitations is summarized in [Table 13.7](#).

- *Bio-based fibers*: These include fibers from plants, animals and minerals, which offer benefits such as reduced weight, biodegradability, and a lower carbon footprint compared to synthetic fibers. Examples include sisal, jute, coconut, date palm, and abaca fibers. While they enhance concrete properties like tensile and flexural strength and crack resistance, challenges like degradation in alkaline environments must be addressed through appropriate treatments and selection. An overview of bio-based fibers is summarized in [Table 13.8](#).

**Table 13.8** Overview of bio-based fibers: Advantages and challenges [37].

Aspect	Advantages	Limitations
Source	Derived from renewable resources such as plants, animals	Raw materials may require significant land and resources; impact on food supply if derived from crops
Biodegradability	Typically biodegradable, leading to reduced environmental impact	Degradation conditions may vary; some biofibers may degrade too quickly in certain environments
Strength and durability	Can offer high tensile strength and durability; some biofibers are stronger than conventional fibers	Strength can vary widely depending on the fibre and processing methods
Sustainability	Generally more sustainable compared to synthetic fibers; lower environmental footprint in production	Production processes may still involve significant energy and water use
Applications	Used in textiles, composites, automotive parts and construction materials	Limited availability and higher costs compared to synthetic fibers
Processing and cost	It can be processed using traditional methods; offers potential for innovation in sustainable materials	Higher production costs and lower production volumes compared to synthetic fibers
Physical properties	Lightweight, often with good insulation properties; some fibers can be engineered for specific needs	Variability in fibre quality and properties; may require specific processing techniques
Environmental impact	It can reduce reliance on petrochemicals; often less harmful to the environment in disposal	Some biofibers require large amounts of water or land, potential impacts on ecosystems if not managed responsibly

- *Biopolymers*: Polysaccharides and lignin, derived from renewable sources, are used to improve the mechanical and rheological properties of concrete and mortar. They enhance workability, bonding, and reduce water demand, contributing to more sustainable building practices. An overview of biopolymers is summarized in [Table 13.9](#).

Together, these bio-based materials offer a range of environmental and performance benefits. They help lower greenhouse gas emissions, support the circular economy and reduce reliance on non-renewable resources.

## 13.7 Outlook

The future of bio-based materials in construction holds considerable promise, with several key areas for development:

**Table 13.9** Overview of biopolymers: Advantages and limitations.

Aspect	Advantages	Limitations
Source	Derived from renewable resources (e.g. plants)	Production can require significant resources (e.g. water, land)
Biodegradability	Biodegradable, reducing environmental waste; can be modified or blended with other polymers	Degradation conditions can be specific and are not always achievable in natural environments
Biocompatibility	High biocompatibility; used in medical implants, drug delivery and food packaging	Prone to fungi and bacterial attack; anti-microbial and anti-fungal components may be required
Performance in cement composites	Improved workability, crack reduction and sustainability	Degradation, water sensitivity, cost (compared with other conventional additives) and lower durability compared to synthetic polymers
Applications	<i>Versatile</i> : Food packaging, medical implants, electronic applications; high surface strength for printing	High manufacturing cost; low production volume; service life and biodegradation issues
Production and cost	It can be engineered for various applications; potential in reducing carbon footprint	High manufacturing costs; blending with plasticisers needed; proper disposal required for biodegradation

- *Enhancing performance*: Research should continue to address the raw material properties of bio-based materials, including improving their reactivity, mechanical strength, and durability. For example, optimizing the processing of biomass ashes and developing new treatments for biofibers can enhance their performance in construction applications. At the composite level, interface properties between fibers and binder matrix are crucial for bio-materials performance.
- *Scaling production and standardization*: Efficient production methods and industry standards are essential for the widespread adoption of bio-based materials. Establishing standardized quality control measures will ensure consistent performance and reliability and align with shifts in industries to move to a circular economy. Since there is no one-size-fits-all solution -much like in cementitious materials- sustainability efforts must be tailored for both large-scale industrial applications and local contexts. This approach ensures a broader, more effective impact across diverse industries and regions. Comprehensive life cycle assessments are needed to fully understand the environmental benefits and trade-offs of bio-based materials. These assessments will guide best practices and support the development of sustainable building technologies.
- *Expanding applications*: Exploring additional agricultural and industrial residues for use as SCMs or fiber reinforcements can broaden the range of sustainable materials available, that are highly dependent on locally available raw materials, technology, and practices.

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