Chapter 2
Biomaterials for Building Skins

Timber, despite being the world's oldest construction material, is now the most modern.

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Abstract Bio-based materials are considered a promising resource for buildings in the twenty-first century due to their sustainability and versatility. They can be produced locally, with minimum transportation costs and in an ecological manner. This chapter describes the potential of biomaterials for use in façades. It presents several examples of natural resources, including innovative alternative materials that are suitable for implementation as a building skin. Novel products resulting from material modifications and functionalization are presented, including a brief discussion on their environmental impacts. Alternative strategies for optimal biomaterials' recycling, reuse, and other end-of-life strategies are presented and supported with case study examples.

2.1 Why Build with Biomaterials?

The current trend for constructing sustainable buildings and increasing environmental awareness is reviving bioarchitecture as an alternative to other construction techniques. The unique properties and the natural beauty of bio-based materials make them desired in various applications, including construction and interior/exterior design, among others. The main advantage of biomaterials is the low environmental impact due to their renewability and cascade use. Only low amounts of energy are needed to manufacture wood. The production of wood as a building material involves only about 10% of the energy consumption required to produce equivalent amount of steel (Odeen 1985). Moreover, it can be processed using simple tools. Biomaterials enable prefabrication and fast installation. Due to a favourable weight-to-load-bearing capacity ratio, they enable erection of multi-storey structures while enabling considerable design freedom. The low thermal conductivity of timber increases its applicability in the façade interface between the inside and the outside (Tapparo 2017).

A. Sandak et al., *Bio-based Building Skin*, Environmental Footprints and Eco-design of Products and Processes, https://doi.org/10.1007/978-981-13-3747-5_2

2.1.1 Unique Characteristics of Biomaterials

Wood is highly recyclable, and several reuse options make it an excellent material for the currently desired cascade use. Wood and other bio-based building material products have the advantage of a significantly lower carbon footprint than steel, glass, or concrete (Tellnes et al. 2017). Since trees absorb CO_2 from the atmosphere and store carbon in the wood tissue, wood generates lower environmental impact in comparison with other building materials. Consequently, biomaterials have become recognized as an attractive alternative to several traditional building solutions, making biomaterials "building materials of the twenty-first century" and "timber a new concrete". Since biomaterials can efficiently sequester carbon, they are counterbalancing emissions from other materials. However, compared with traditional building materials, biomaterials possess some properties that are less understood and remain difficult to control. Natural fibres, for example, are capable of binding the amount of moisture equivalent to between 5 and 40% of their dry weight, depending on the ambient air conditions. These fibres can then act as buffers or humidity/water absorbers within certain building structures. However, the ability to bind moisture influences the hygro-thermal stability of components made of hygroscopic materials. Hygro-thermal stability is an important constraint in certain applications, such as thermal insulation, hydrocivil engineering, cladding, and decking. Hygroscopic properties of any bio-based material are the main reason for shrinkage and swelling, and, consequently, for dimensional distortions. The interrelation between the relative humidity (RH) and equilibrium moisture content (EMC) of a material is usually presented as a sorption isotherm diagram (Willems 2014; Brischke 2017). The moisture content decreases during the drying, until the free water completely evaporates, but the entire amount of bounded water remains. This state is defined as a fibre saturation point (FSP).

Controlling biomaterial moisture content is crucial to avoid decay process. The minimum moisture content stimulating fungal growth is estimated to be from 22 to 24%, depending on the material type. For this reason, building experts recommend 19% as the maximum limit of the moisture content in untreated wood to assure its safe service. The best practice design uses the "4 Ds" to limit the amount of moisture intrusion. The first line of defence is (1) deflection, that deflects water away from the structure. A small amount of water that can pass the cladding should exit the wall via (2) drainage path. All the remaining water should be able to easily (3) dry. Finally, it is recommended to use (4) durable materials, such as naturally decay-resistant species or preserved/modified wood. Excessive moisture in wood structures makes these more susceptible to insect attack. There are several guidelines which include basic protection practices (e.g., in case of termites: maintaining structure dry, applying chemical termiticide to the soil, using barriers and traps). These should be supported by maintenance practices that consist of regular inspections (Reinprecht 2016). With a proper design, construction, and maintenance, timber buildings provide a service that is at least equivalent to other building types (Foliente 2000).

Bio-based materials have the disadvantage of being combustible; thus, they are perceived as less safe than steel and masonry. Combustibility limits their use as a building material due to restrictions in building regulations in most countries, especially in taller and larger buildings (Buchanan et al. 2014). The recently released document "Fire Safety in Timber Buildings—Technical Guideline for Europe" presents the background and design methods for designing timber buildings to assure comparable levels of fire safety to buildings made of other materials (Östman 2010). The most recent report "Fire Safety Challenges of Tall Wood Buildings" by Gerard et al. (2013) is not limited to European contexts but includes case studies of modern timber buildings from around the world. Modern building codes should move towards performance-based design for fire safety, that is, towards designing the building to achieve a target level of performance rather than simply meeting the requirements of a prescriptive building code. The European Construction Products Directive (CPD) has introduced five essential requirements of fire safety. The structures must be designed and built in a way that the load-bearing capacity, in the case of a fire event, will assure structure to remain intact for a specific period of time. The generation and spread of fire and smoke in the building, as well as the spread of fire to neighbouring structures, must be limited. In the event of fire, occupants may either leave the building on their own or be rescued by other means, where the overall safety of rescue teams must be taken into consideration.

Automatic fire sprinkler systems, being the most effective way of improving the fire safety, are especially recommended in tall buildings. Another approach to improve fire resistance is encapsulation (complete, limited, or layered) of timber elements with non-combustible materials. The use of fire-resistant and fire-retardant coatings/treatments is an additional method to improve fire performance of bio-based materials. Fire resistance is a property of a material to withstand fire or provide protection from it. Fire retardants reduce the amount of heat released during the initial stages of a fire and reduce the number of flammable volatiles released during the subsequent fire stages. Fire retardants can contribute to diminishing fire propagation by protecting the surface through insulation layers, changing the pathway of pyrolysis, slowing down ignition and decreasing burning temperatures by changing the thermal properties of the product, reducing combustion by diluting pyrolysis gases, and reducing combustion by inhibiting the chain reactions of burning. In practice, most retardant systems combine diverse mechanisms and, in consequence, increase their own overall efficiency (Russel et al. 2007). On the other hand, fire itself can be used as a protective treatment. The Shou Sugi Ban technique developed in Japan to protect the external cladding made of cedar involves charring a wood surface (Fig. 2.1). Even though this technique was established in the eighteenth century, it is considered a highly interesting treatment for contemporary exterior and indoor spaces (Fortini 2017).

An important advantage of using biomaterials is their naturalness and other assets compatible with the human physiological deactivation. Modern trends in building design tend to move beyond the simple optimization of basic environmental characteristics (such as air temperature and humidity), to more holistic approaches that

Fig. 2.1 Shou Sugi Ban surface treatment of building façades

have a health-supporting role. Biophilic design rediscovers an ancient practice, where humans were a part of a wider ecosystem integrating natural elements into built structures. In architecture, biophilic design is a sustainable design strategy that reconnects people with the natural environment. It focuses more on the human well-being than to green building principles that emphasize the responsibility to the environment and efficient use of sustainable resources. Bio-based building materials can favourably affect occupants of the built environment. Clear benefits of natural materials on human health, childhood development, health care, learning, work efficiency, and productiveness were reported (Kellert et al. 2008; Kotradyová 2013; Kotradyová and Kalináková 2014). It should be mentioned, however, that industrial transformation, post-processing, and modifications may highly affect human perception of material "naturalness" (Burnard et al. 2017).

2.1.2 *Sustainability of Natural Resources*

Wood and other bio-based materials can be produced locally, with minimum transportation costs and in an ecological manner. Forest certification is a recent approach ensuring that forest products are produced sustainably. Certification aims to improve the image of timber producers and explains their involvement to sustainable forest management. Global regulations requiring the exercise of "due diligence" and "risk assessment" are becoming more common. The European Union Timber Regulation (EUTR) prohibits placing on the EU market wood harvested in contravention of the applicable legislation in the country of origin, as well as wood products derived from it. This applies to both imported and domestically produced timber and timber products, such as solid wood products, flooring, plywood, pulp, and paper (ECE/TIM/SP/33 2013). The most common certification marks used in the forest industry are presented in Fig. 2.2.

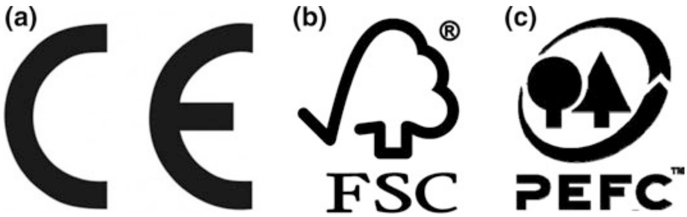


Fig. 2.2 Forest certification marks: **a** "Conformité Européene", **b** Forest Stewardship Council, and **c** programme for the endorsement of forest certification

Frequently used Conformité Européene (CE) indicates that the product conforms to all applicable European legislation related to safety, health, energy efficiency, and environmental concerns. Forest Stewardship Council (FSC) is an international organization founded in Europe in 1993 that provides a system for voluntary accreditation and independent third-party certification. The system permits certificate holders to mark their products and services along the production chain. It confirms that wood products are coming from well-managed forests that provide environmental, social, and economic benefits. The Programme for the Endorsement of Forest Certification (PEFC) is an international non-profit, non-governmental organization endorsing sustainable forest management (SFM). It ensures that timber and non-timber forest products are produced by respecting ecological, social, and ethical standards. PEFC is certified over 230 million hectares of forests in 28 countries (ECE/TIM/SP/33 2013).

2.2 Natural Resources

2.2.1 Timber

Wood is one of the earliest building materials. Its availability, relatively low maintenance cost, and easy processing make it a prevalent construction material in both interior and exterior applications. Various types of load-bearing structures, as well as complementary construction components, such as cladding, decking, doors, and windows were, and still are, frequently made of wood. The performance and strength of wood used in structural applications are influenced by its physical properties, such as density, mechanical resistance, sorption and permeability, dimensional stability, thermal conductivity, acoustic and electric properties, natural durability, and chemical resistance (Mazela and Popescu 2017). In addition, appearance, smell, morphology, roughness, smoothness, and specific surface area, among others, are important material characteristics influencing perception of materials and interaction with them.

All renewable biomaterials are highly naturally variable. This is expressed in their intrinsic characteristics (Fig. 2.3). Wood, for example, exists in a wide range of colours, patterns, and gloss levels, depending on the species and finishing

Fig. 2.3 Variety of colours and textures of biomaterials suitable for use in building façades

applied. Tannins, pigments, and resins make wood more colourful (ranging from white in case of aspen to black in case of ebony). Many hardwood species (maple, oak, beech, elm) have a characteristic lustre that increases their gloss. The wood anatomy—yearly rings, rays, and fibres—provides unique texture that can be additionally highlighted by protective treatments (e.g., oil or wax finishing). The colour of a material (especially if not protected) changes with time and becomes darker (in case of ageing) or greyish (in case of weathering). However, timber does not only vary in terms of appearance. It mainly varies in physical (hygroscopic properties, density, shrinkage-swelling, as well as sound transmission, electrical, and thermal conductivity) and mechanical properties (strength, toughness, hardness, elasticity, plasticity, brittleness, wear resistance).

The density is defined as a ratio of the mass to the volume. Timber species are classified into six classes regarding their density, with "very heavy wood" class consisting of wood dense more than 800 kg/m^3 (represented by hornbeam, yew, or ebony). The opposite, "very light wood" class contains species with the density lower than 400 kg/m^3 (that includes poplar, white pine, and balsa). Different wood species differ in their natural resistance to biological attacks, including resistance to both wood-decaying fungi and wood-destroying insects. In most wood species, the sapwood (the living part of the standing tree involved in the growth of the plant) is not resistant to biological attacks, while the durability of heartwood (central part of the steam not involved in the sap flow) is very variable. The standard EN 350 (2016) "Durability of wood and wood-based products—Testing and classification of the durability to biological agents of wood and wood-based materials" provides guidance in determining and classifying the durability of wood and wood-based materials against biological wood-destroying agents. The following tables provide an overview of the wood classification into diverse durability classes, considering

Table 2.1 Durability classes of wood-based materials: resistance against attack by decay fungi

Durability class	Description
DC 1	Very durable
DC 2	Durable
DC 3	Moderately durable
DC 4	Slightly durable
DC 5	Not durable

Table 2.2 Durability classes of wood-based materials: resistance against attack by termites, marine organisms, and wood-boring beetles

Durability class	Description
DC D	Durable
DC M	Moderately durable
DC S	Not durable

Note In case of wood-boring beetles, there are just two durability classes, DC D and DC C

resistance against wood-decaying fungi (Table 2.1), beetles boring dry wood, termites, and marine organisms capable of attacking wood in service (Table 2.2).

In the building context, mechanical properties are the most important characteristics of wood as a structural material. These encompass wood's ability to resist distortions and deformations (elastic properties) or failure (strength properties). Mechanical properties of timber and engineered wood products are influenced by environmental factors. Changes in moisture, temperature, pH, decay, fire, and UV radiation can significantly change strength properties (Mazela and Popescu 2017).

2.2.2 Non-wood Biomaterials

The use of non-wood materials in the built environment is an area of growing importance. These are successfully used in roofing, wall constructions, wall cladding, insulation, composites, and chemicals used in the built environment. Renewable materials are already utilized on a significant scale worldwide, with an estimated 71 million tons of crop-derived industrial materials produced annually (Hodsman et al. 2005). Fibre crops, such as hemp and flax, are used in textiles, paper, composites, construction packaging, filters, and insulation. The key market sectors for European fibres in the built environment are wood-based panels, fibre-reinforced composites, fibre–cement composites, and insulation products.

Flax, hemp, cereal straw, Miscanthus, sisal, jute, and kenaf have been used in Europe for producing panels (2 million tons in 2010), fibre-reinforced composites (0.25 million tons), and insulation products (no data available) (Hodsman et al. 2005). The technology for manufacturing flaxboards (panels in which shives from the stalk of the flax plant are bonded together with a synthetic resin) is slightly different than the technology in mass-produced particleboards. The flax shives are in a form of particles already after pre-processing and therefore chipping operation is not necessary. Flaxboards are used in dry environments in door cores, fire-check doors, and partitions. Flax fibres are also used in insulation products and as additives in cementitious composites (Réh and Barbu 2017a).

Hemp is another widespread plant gaining interest in the building sector. Its insulation capacity, mechanical resistance of the fibres, and low density (110 kg/m^3) are highly relevant for the construction industry. Hemp is an essential ingredient of environmentally friendly building materials. It is used in the manufacturing of reinforced composites, insulation, hempcrete, and lime–hemp mixtures (Réh and Barbu 2017b).

The traditional use of straw includes roofing, bales in load-bearing walls, and substrates for plasters. Straw is widely available and is considered an affordable building material. Traditional buildings using straw in roofing are present all over the world (Fig. 2.4). When implemented appropriately and protected from the moisture uptake, straw is a long-lasting, durable, load-bearing, and insulating material (Walker et al. 2017).

Reed is a traditional material used mainly in roof construction in various parts of the world. When properly used, it does not require maintenance for relatively long periods of time, typically lasting more than 50 years. However, in case of poor raw material quality and incorrect installation detailing, the maintenance-free period may decrease significantly, in extreme cases to less than 10 years. Previous studies showed that the properties of reed are highly related to its origin as well as to harvesting methods and periods (Greef and Brischke 2017).

Fig. 2.4 Use of straw in roof coverage

Grass is one of the most widespread and available renewable materials. Hay deriving from meadow plants was often stored in attics in order to serve as a feedstock for domestic animals and provide thermal insulation in rural buildings. Currently, several laboratory trials in manufacturing composites and insulation products on the basis of grass are ongoing. It is thus expected that grass-based products will reach the market and gain increased interest in the near future (Teppand 2017).

The use of wool and other animal hair in the building sector is currently limited to thermal and acoustical insulation. Thermal attributes, prevention of vapour condensation and mitigation of global warming, that are related to such materials, make them useful in both traditional and modern constructions. Wool has a moisture buffering effect indoors, where fibres capable of absorbing moisture in wet conditions may release it when the ambient relative humidity is low (Mansour and Ormondroyd 2017).

Bamboo and rattan are abundant, renewable, recyclable, and biodegradable materials available in high quantities, especially in Asia. Bamboo is one of the fastest growing plants in the world, simultaneously having low density and high mechanical strength and stiffness. The natural durability of bamboo is relatively low but varies among different species and provenances. Both bamboo and rattan fibres are widely used in manufacturing composites. In this case, fibres can be used in the native form as well as modified chemically or thermally to enhance the properties of the composite (Knapic et al. 2017).

The latest trends in the development of alternative building materials have resulted in the development of mycelium-based composite materials for the use in design and architecture. The natural ability of saprophytic fungi to bind and digest ligno-cellulose is used to manufacture packaging, textile, edible films as well as building and insulation materials (Attias et al. 2017). Commercial composite board (Myco-board) can be utilized similarly as medium density fibreboard (MDF) with the significant advantage of not containing formaldehyde. Recently designed Hy-Fi Mushroom Tower pavilion at the Museum of Modern Art in New York by David Benjamin is the first large-scale structure to use mushroom brick technology (Fig. 2.5). The 13-m-tall tower was created in order to provide a new definition of sustainability. The lightweight bricks being an innovative combination of corn stalk waste and living mushrooms returned to the earth through composting at the end of the structure's lifecycle. In contrast to typical temporary architecture, Hy-Fi was designed to "appear as much as to disappear".

The Cuerden Valley Park Trust (Fig. 2.6) is a superb example of a building that was erected using local natural resources. It was designed by Straw Works according to the Living Building Challenge standard. It has a hybrid load-bearing straw and a timber frame built by volunteers from straw, timber, cedar shingles, lime plaster, sheep wool, and hemp. The Trust building is a visitor centre enabling close connection with the nature.

Fig. 2.5 Hy-Fi Mushroom Tower pavilion at the museum of modern art in New York Photograph courtesy of Amy Barkow

Fig. 2.6 Visitors' centre in Cuerden Valley Park Trust during the construction (November 2017)

2.3 Modification and Functionalization of Biomaterials

Recent advances in biomaterials research have delivered several solutions for the construction sector. Currently industrialized engineered wood products, such as glue-laminated timber beams (glulam) or cross-laminated timber panels (X-lam or CLT), allow using wood for erecting long-span and/or multi-storey buildings. Biomaterials can act as buffers or sinks for water within certain building structures and provide comfort to occupants of the built environment. On the other hand, their ability to bind moisture influences hygro-thermal stability, which can be an important constraint in certain applications, for example, in thermal insulation, hydro civil engineering, cladding, and decking (Jones and Mundy 2014).

To broaden their applicability, biomaterials need to improve in several of their properties, such as dimensional stability, thermal stability, fire resistance, biotic and abiotic degradation resistance, and mechanical properties. This brings new solutions to the market that assures expected properties and functionality over elongated service lives and reduces the risk of product failure. These include novel bio-based composite materials (e.g., fibreboards, particleboards), as well as more effective and environmentally friendly protective treatments, such as thermal treatments, densification, impregnation, and chemical modifications. The same revolutionary progress is observed in surface treatments, including innovative coatings, impregnations, or integration of nanotechnology developments to protect biomaterials. The latest trends are driven by the biomimicry approach of capturing and exploiting properties that have evolved in the nature. All above-mentioned treatments lead to changes of natural properties of wood or other natural resources.

Biomaterials, originate from nature and thus possess great variability in properties that are manifested in different durability/use classes, density, or appearance. The variation is observed between species, trees, and even within the single tree itself. While possessing several advantages, such as aesthetical appeal and positive weight-to-load-bearing capacity ratio, unprotected wood suffers when exposed to environmental conditions and changes its dimensions and appearance (e.g., colour, roughness, glossiness). Wood modification processes enhance desired properties by applying chemical, biological, or physical agents (Hill 2006). Properties of wood are determined by its chemical composition; therefore, most (but not all) modification processes target material changes at molecular levels.

2.3.1 Thermal Modification

Thermal treatment is an effective way to improve properties of biomaterials. The permanent modification of chemical composition of constitutive polymers is achieved through exposure to elevated temperatures with reduced oxygen availability. Thermally modified timber (TMT) is a result of such a treatment (in the case of wood), where the modification process is defined in CEN/TS 15679 (2007). The usual range of the treatment temperatures is between 160 and 230 °C, depending on the intended treatment intensity. Several modifications of wood chemical components occur due to the thermal treatment. Hemicelluloses are deacetylated, depolymerized, and dehydrated to aldehydes. Cellulose microfibrils are less affected by the thermal treatment due to the crystalline structures that are more resistant to the thermal degradation. However, the overall crystallinity level increases because of the amorphous part degradation. Lignin is softened and cross-linked with other cell wall components, which results in the increase of the apparent lignin content (Esteves and Pereira 2009). Thermally modified wood possesses superior durability against decay and weathering, enhanced dimensional stability, constant colour within the bulk, reduced thermal conductivity, lowered equilibrium moisture content, and increased hydrophobicity. These properties partly result from the reduced accessibility of hydroxyl groups to water molecules. Thermal treatment processes can change non-durable softwood species (class 5 according to European Standard EN 350 (2016)) into the superior durability class 1 (Navi and Sandberg 2012). There are several commercially available technologies differing in terms of treatment conditions (e.g., temperature and duration, steam presence or absence, atmosphere type, use of catalysts, closed versus open system) (Gérardin 2016).

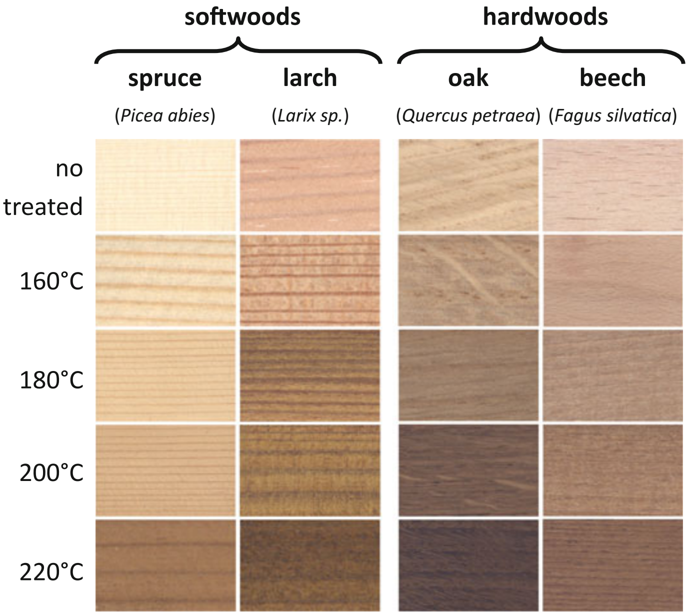


Fig. 2.7 Effect of the thermal modification on the appearance of wood

Properties of TMW depend on the settings of the treatment process and wood species, among other factors. In general, thermally modified wood is not suitable for load-bearing applications. Its dimensional stability is improved with a more hydrophobic surface. This has an effect on the surface finishing procedures and the coating performance. The colour becomes darker as a result of thermal modification although the discoloration is not stable when used in the exterior. The surface of thermally modified wood becomes grey/silver after a short weathering. Even though the decay resistance of TMT is improved, it is not recommended to use it in contact with the ground. The appearance of selected wood species that were modified thermally at different temperatures is presented in Fig. 2.7.

2.3.2 *Chemical Modification*

Chemical modification is the reaction of a chemical agent with wood chemical components resulting in formation of covalent bonds (Hill 2006). Acetylation is the most established treatment, where acetic anhydride reacts with hydroxyl groups of cell wall polymers by forming ester bonds. The reaction replaces hydroxyl groups with acetyl groups and yields acetic acid as a by-product. Acetylation improves UV resistance and reduces surface erosion by 50%, which is important when using wood as a façade material (Rowell 2006). The mechanical strength properties of

Fig. 2.8 Acetylated wood as a material for a building façade. Photograph courtesy of Accsys

acetylated wood are not significantly different than in untreated wood; however, its durability is substantially improved. An example of the use of acetylated wood is presented in Fig. 2.8. Suitability of other reagents as an alternative to the acetic anhydride was investigated for wood modification. Unfortunately, most of those technologies were never implemented as industrial solutions were not commercialized.

2.3.3 Impregnation

Impregnation process leads to locking selected chemicals within the wood cell wall. The cell wall should be in a swollen state to ensure accessibility of the impregnate. The treatment is considered effective when chemical substance used for impregnation is not leachable in-service conditions. Several substances are currently used for impregnation, such as resins (UF, PF, MF, MMF, DMDHEU), furfuryl alcohol, and inorganic silanes, among the others. Some of the processes, like furfurylation (Kebony®) or DMDHEU treatment (Belmadure®), are commercialized, and their products are available on the market. When considering the large variation of the impregnation methods, it becomes clear that the performance of impregnated wood can vary significantly. However, in general, these treatments reduce swelling and shrinking, improve dimensional stability, and increase resistance to biotic degradation. Figure 2.9 presents the use of furfurylated wood in an innovative architectural sculpture inspired by nature.

Fig. 2.9 Furfurylated wood as a material for a building façade. Photograph courtesy of Kebony

2.3.4 Surface Treatment

The above-mentioned treatments are related to modifications occurring within the whole volume of the material bulk. In contrast, several techniques affect only the properties of the surface without interfering with the interior of the material. The changes of the surface functionalities affected by the exterior treatments include UV stabilization (e.g., surface acetylation), increase of hydrophobicity (e.g., reaction with silicone polymers), or improvement of the adhesion (e.g., enzymatic treatment, plasma discharge). In addition, additional processes can be applied to improve biomaterial surface resistance against biotic and abiotic factors, such as surface densification (Rautkari et al. 2010) or surface carbonization (e.g., Shou Sugi Ban).

Façade surface finishing by diverse coatings, waxes, oils, or stains is the most common treatment of the surface that highly influences its service life performance. The systematic comparison between different finishing technologies is presented in Fig. 2.10. The resistance of the surface against deterioration in service highly depends on the finishing product quality (i.e., chemical formulation), surface preparation (e.g., oxidation stage, roughness, wettability, surface free energy), and the application procedure (e.g., industrial coating, immersing, brushing, or spraying). A high variety of commercially available products for surface finishing can produce various differences in appearance, including variations in colour, transparency, and gloss. An example of appearance changes in wood surfaces when treated with different surface coatings is presented in Fig. 2.10. A proper use of the surface finishing technologies may highly contribute to the aesthetical attractiveness of the structures as well as to the changes in appearance along the service life of the façade. The cost of the finish, including proper surface pre- and post-treatment, may be substantial. However, it may be sensible, from a financial point of view, to rise the initial cost of the façade by increasing the thickness of the coating layer, as this may significantly extend the time of maintenance-free use. It has been reported that

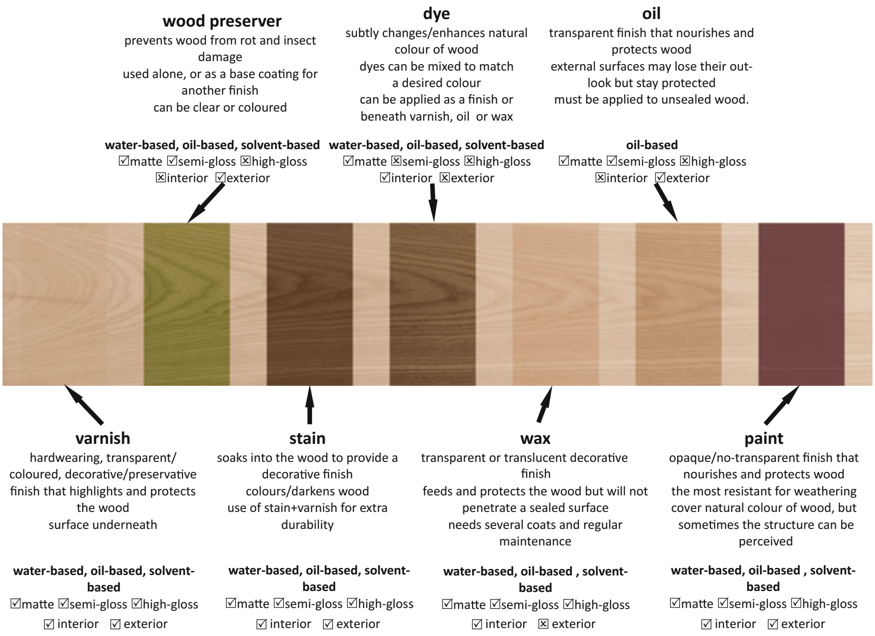


Fig. 2.10 Appearance of the wood surface after diverse coating solutions

the increase of the coating layer thickness from 30 to 50 µm extends the time of the surface resistance against cracking, and the service life period, by a factor of 1.2 (http://www.servowood.eu).

2.3.5 *Hybrid Processes*

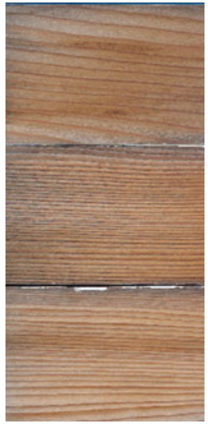
Bulk and surface modification processes may affect one or more functionalities of the biomaterial used in a building façade. Although each modification process improves certain material properties on its own, this positive effect can be multiplied by merging two or more modification processes. Such an approach is a "hybrid process" of biomaterial modification and has become an optimal solution frequently implemented by biomaterials producers. An example of a successful hybrid modification is the surface coating of acetylated or thermally treated wood. The synergic effect of the reduced shrinkage/swelling of the bulk substrate and water protecting coating substantially reduces stresses of the coating film, thus preventing it from cracking. As a consequence, a façade surface remains intact for a longer period of time by preserving its original attractive appearance. Other examples of hybrid modifications implemented at an industrial scale are presented in Table 2.3.

Table 2.3 Hybrid modifications of bio-based materials suitable for the use in building façades

Constitutive treatments	Thermal treatment + water borne penetrating oil impregnation	Acetylation + surface coating	Oil impregnation + biofilm	Melamine impregnation + thermal treatment
Affected properties	• Improved dimensional stability • Better durability • Lower equilibrium moisture content	• Improved durability • High-dimensional stability • Change of the surface colour • Additional protection of the surface	• Increased resistance to biotic and abiotic degradation • Self-healing	• Enhanced dimensional stability • Fire resistance • Improved resistance to weathering
Appearance after modification				

(continued)

Table 2.3 (continued)

Constitutive treatments	Thermal treatment + water borne penetrating oil impregnation	Acetylation + surface coating	Oil impregnation + biofilm	Melamine impregnation + thermal treatment
Appearance after 1 year of natural weathering				

Benefits obtained by merging different materials and treatments are highly useful in addressing design limitations and biomaterial deficiencies. If properly implemented, hybrid modifications can help reduce the environmental burden and economic cost of façades. It has to be stated, however, that some modification processes cannot be merged or may induce undesired changes of other material properties. An example may be the increase of the brittleness of a biomaterial after certain hybrid modifications that affect its machinability or paintability. For this reason, special attention should be directed towards selecting appropriate treatment combinations and extensive quality control of the hybrid modification processes.

2.3.6 Bio-Based Composites

"Composite" is a term used to categorize materials merged with other materials possessing different structures or compositions. According to Rowell (2005), the key advantages of bio-based composites are:

- possibility to utilize waste from wood processing
- utilizing smaller trees
- removing material defects and deficiencies
- creating more uniform materials that are usually stronger than solid wood
- freedom in the shaping and design.

Bio-based Panels

The most widespread wood composites include glue-laminated beams, cross-laminated timber (CLT), plywood, oriented strand boards (OSB), particleboards, and fibreboards, among the others (Curling and Kers 2017). Not all of these are suitable to be used as façade elements. Tricoya® panel products, made from Tricoya® wood elements, are a groundbreaking construction material. In panel form, Tricoya® is opening new markets where wood-based panels would never have been considered before, such as wet interiors, kitchen carcasses, art installations window components, door skins, and building façades (Fig. 2.11). Tricoya® panels demonstrate significantly enhanced durability and exceptional dimensional stability. Tricoya® wood chips exhibit the same sustainable qualities such as longer lifespan and CO_2 sequestration, as its sister product Accoya® solid wood. Tricoya® is also guaranteed for 50 years above ground and 25 years in ground or fresh water due to its outstanding performance and properties.

Composites produced from alterative ligno-cellulosic materials, such as flax, hemp, straw, reed, wool, grass, bamboo, or rattan, are currently used in building interiors (e.g., flooring and siding) or as insulation in walls and roofs. Nevertheless, bamboo claddings (Fig. 2.12) and straw roofs (Fig. 2.13) have been recently frequently used in the building sector due to their unique and attractive appearance, sustainability, cost-effectiveness as well as the local identity (Knapic et al. 2017; Kotradyová 2015).

Fig. 2.11 Use of bio-based panels (Accoya® and MEDITE® TRICOYA® EXTREME) in the building façade

Fig. 2.12 Use of bamboo as a building façade material. Photograph courtesy of Kul-bamboo

Wood–Cement Composites

Inorganic materials proved to be a highly valuable component to be combined with natural materials. Gypsum–wood boards or cement–wood are examples of composites successfully utilized in the construction sector. These possess a high-dimensional stability, high durability against biotic and abiotic factors as well as high resistance against fire (Jorge et al. 2004). The addition of biomaterials reduces composite density and therefore makes the construction lighter. To produce panels, it is possible to use wood residuals, including waste from demolitions or

Fig. 2.13 Use of straw as the roof cover in a modern building

wood preserved even after its service. Similarly, recycled fly ash (residual from the combustion) can substitute up to 30% of the cement. Biomaterials other than wood are also used to produce composites, for example, palm, rattan, or bamboo, among the others. Cement–wood panels are frequently utilized as a siding of building façades. Even when compared to other bio-based solutions, cement-based façades are more expensive, heavier, and more difficult to assemble.

Wood–Plastic Composites

Wood–plastic composites (WPCs) are complex materials manufactured from different resins and wood powder/flour used as a filler (Kers and Ormondroyd 2017). Thermoset and naturally derived resins, such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polyvinyl alcohol (PLA), are used in the majority of currently offered WPC products on the market. Wood–plastic composites have gained great interest of the resource-intensive building industry; however, according to Friedrich and Luible (2016), reliable technical data regarding application-oriented properties are still missing. On the contrary, WPCs are perceived by customers as maintenance free and have an excellent reputation regarding their durability and environmental friendliness (Morrell and Stark 2006). Recent studies performed by Turku et al. (2018) revealed that WPC weathering performance (e.g., changes in tensile strength and flexural properties) is influenced by its chemical composition. New improvements in WPC production are related to optimization of the manufacturing processes (extrusion, injection, or compression moulding) and the WPC composition (including the use of modified wood, non-wood fibres, nanoparticles, or fire retardants) (Gardner et al. 2015).

An important concern regarding the WPC is its environmental impact that may vary depending on the composite configuration and end-of-life scenario. In general, use of petroleum-based polymers results in a highly negative environmental impact. Conversely, renewable resource-based and biodegradable polymers with a high share of the wood filler are more environmentally friendly. Further reduction of the environmental impact can be achieved when wood used in WPCs comes from primary production side streams or is recovered from wood products (Schwarzkopf and Burnard 2016).

High-Pressure Laminate

High-pressure laminate (HPL) is a flat panel consolidated under heat and high pressure. It is made of wood-based layers impregnated with resin in a wide range of colours, finishes, and patterns. High-pressure laminate panels contain up to 70% natural fibres and do not require frequent maintenance after installation. Relatively high weather protection is provided by a coating with acrylic or polyurethane resins. An example of a building façades covered by the HPL is presented in Figs. 2.14 and 2.15.

Fig. 2.14 Use of HPL as a building façade. Photograph courtesy of Ewa Osiewicz

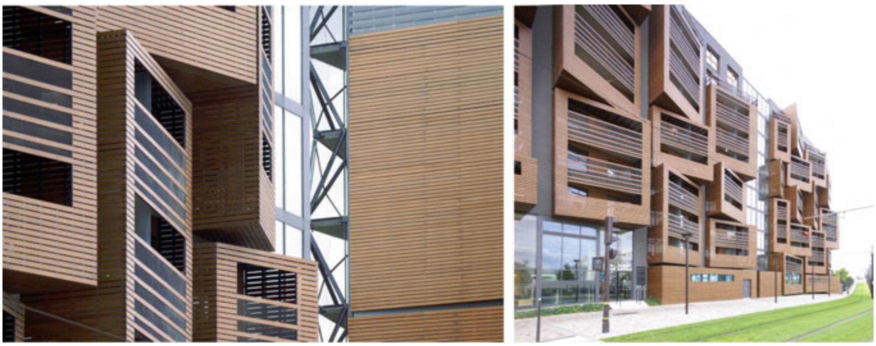


Fig. 2.15 Use of HPL in a building façade of Basket Apartments in Paris (OFIS Architects)

Engineered Wood–Glass Combination

The latest trend in building façade design is to provide multi-functionality and high energy efficiency at the same time. Particularly, the use of renewable materials with low environmental impact and attractive natural appearance, such as wood, coupled with large glazed areas, has recently gained increased interest (Tapparo 2017). An example of such a façade system, where timber load-bearing elements are merged with a protecting glass, is presented in Fig. 2.16. In this case, the glass layer protects the biomaterial from the direct wetting by the rain brought by wind as well as filters UV radiation present in the sunlight. As a result, the surface weathering kinetics are minimized, and the original biomaterial appearance is preserved. This is in line with the biophilic design approach, while assuring desired wood appearance not altered by environmental factors. Engineered wood–glass combination (EWGC) is thus a highly interesting solution in the modern architecture, especially where active and adaptive envelopes are desired.

2.3.7 Green Walls and Façades

Implementing greenery as the integral part of a building façade is a great solution to positively impact human well-being and to increase satisfaction of city occupants. Diverse configurations and implementations of this paradigm have been proposed by architects, creating a new trend of "living walls" or "vertical gardens". In general, such installations can be divided in two categories as described below.

Green Wall

Green wall is a part of the building intentionally covered by the living vegetation where plants are distributed on the whole surface of the façade. In this case, both the grooving media (usually soil) and the dedicated irrigation system are spread and

Fig. 2.16 Combination of the glass and biomaterials as a composite building façade of Bayerische Vereinsbank in Stuttgart (arch. Behnisch and Sabatke)

Fig. 2.17 Green wall implemented as a building façade

cover the whole area of the green wall (Fig. 2.17). Living (green) walls require specific supporting elements, growing substrate and efficient watering system. An important positive effect of the green wall is its capability to maintain consistent temperature and relative humidity on the inside of the building. Moreover, such installations decrease the wall temperature during summer time and provide thermal insulation in winter. Living plants offer shade, improve air quality, and dampen the effects of wind and noise. In some cases, greenery may cover a top of the building, thus creating so-called green roofs, as presented in Fig. 2.18.

Green Façade

In contrast to the green wall, the soil container necessary for plants to grow on the green façade is located at the base of the building façade. The plants covering the wall are therefore climbing on its face creating an external layer of vegetation.

Fig. 2.18 Green roof

Fig. 2.19 Green façade of Nagoya City Science Museum (arch. Nikken Sekkei)

The main challenge of green façades is their maintenance and investment costs as well as their installation (Besir and Cuce 2018). However, as highly attractive in terms of architectural and aesthetical aspects, green façades and walls are interesting alternatives for urban buildings of the future (Fig. 2.19).

2.4 Environmental Impact and Sustainability

2.4.1 Environmental Assessment

To provide solid evidence for supporting policy decisions, such as policies to encourage building with wood (particularly versus the use of non-renewable materials), the objective assessments of environmental impacts should be used. The claimed benefits of using renewable materials compared to non-renewable materials are backed by strong evidence when the whole life cycle of materials is considered. The life cycle of the renewable materials can reach the closed loop leading to closing the biological and technical metabolism (Fig. 2.20), while the life cycle of non-renewable materials cannot (Fig. 2.21). Benefits of renewable materials can be supported by an objective environmental impact assessment. The life cycle assessment (LCA) that considers the use and disposal as well as the reuse of materials and products is an objective measure of the environmental impacts of materials and products in their life cycle.

The LCA is a tool that has been developed to analyse and quantify the environmental burden associated with the production, use, and disposal of a product (Hill 2011). Furthermore, the LCA enables comparison of the environmental impacts of different products (Audenaert et al. 2012; Ding 2008; Forsberg and Von Malmborg 2004).

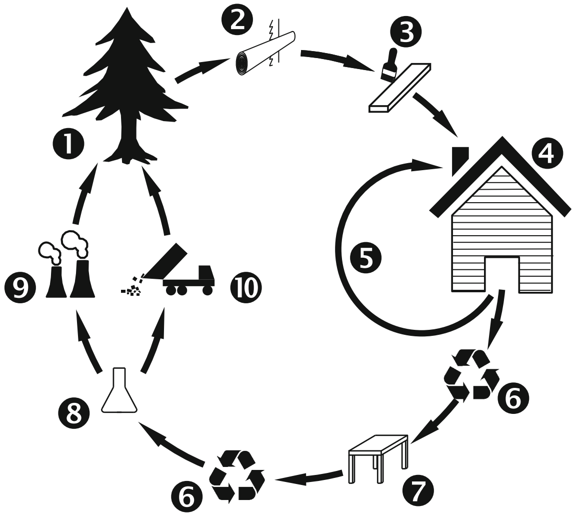


Fig. 2.20 Life cycle of renewable materials: ❶ harvesting, ❷ primary processing, ❸ secondary processing, ❹ use phase, ❺ reuse, ❻ recycling, ❼ second use phase, ❽ cascading to tertiary use, ❾ energy generation, ❿ landfilling, closing the biological and technical metabolism

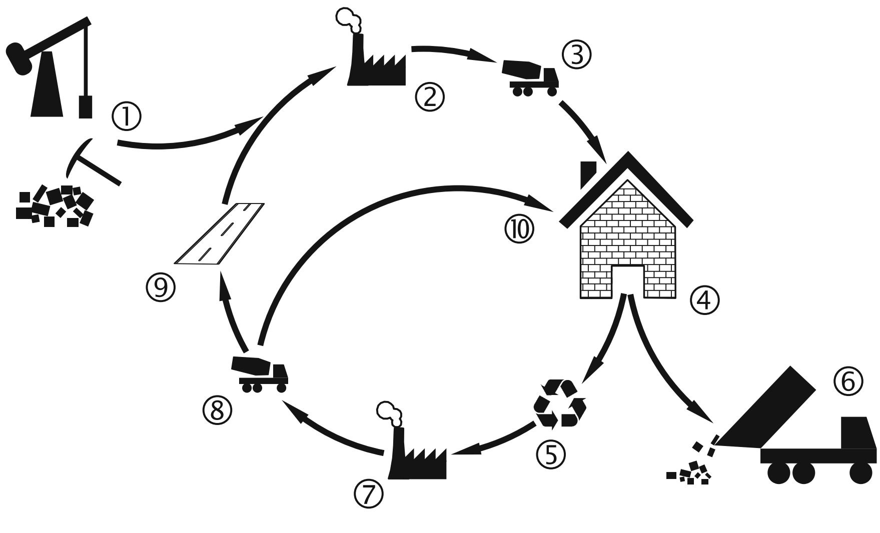


Fig. 2.21 Life cycle of non-renewable materials: ① extraction of raw material, ② manufacturing, ③ processing, ④ use phase, ⑤ recycling, ⑥ landfilling/waste production, ⑦ secondary manufacturing, ⑧ secondary processing for reuse, ⑨ second use phase, ⑩ second reuse phase

LCA Methodology

The LCA methodology is defined in ISO 14040 (2006a) and ISO 14044 (2006b). The most common methodologies to classify, characterize, and normalize environmental effects are focused on the following environmental impact indicators:

- acidification
- eutrophication
- thinning of the ozone layer
- various types of ecotoxicity
- air contaminants
- resource usage
- greenhouse gas emissions.

The LCA analysis is conducted by defining the goal and scope of the analysis that include the system boundaries and the functional unit. When materials are compared only until installed into a building, the system boundary is defined as "cradle to gate". Here, the environmental impacts are evaluated from the point of manufacture of a specific product in a factory to the point at which it leaves the facility. This corresponds to modules A1-A3 in the European Standard EN 15804 (2012). It provides the most accurate LCA because this phase of a product life cycle involves the fewest assumptions and the data gathering process is relatively straightforward. However, a low-impact product, as determined through a cradle-to-gate analysis, may require a lot of maintenance during the in-service phase of the life cycle, or there may be serious environmental impacts associated with its disposal. A full appreciation and understanding of the environmental impacts associated with a product choice therefore require the entire life cycle to be considered (Fig. 2.22). This invariably introduces a higher level of uncertainty into the process because there may be aspects of the life cycle that are not well understood, thus requiring assumptions to be made. These assumptions may have a very significant impact on a LCA, and a bias may be introduced if different products are being compared.

Furthermore, recycling and disposal may be analysed as well. The purpose of the LCA may be simply to report on the environmental burdens associated with a product or process, referred to as an attributional LCA, or to examine the consequences of changing various parameters or adopting different scenarios, referred to as a sequential LCA (Frischknecht and Stucki 2010; Gala and Raugei 2015).

The initial step in the LCA is also a determination of the subject of the LCA, that is, a declared unit or a functional unit. When cradle-to-gate is the system boundary of the analysis, it is referred to as the declared unit. When the analysis additionally includes other parts of the life cycle, it is referred to as the functional unit. In addition, the timescale included in the study and the allocation procedures are defined in the first step of the LCA.

When the goal and scope are defined, the life cycle inventory (LCI) phase of the analysis is performed. It requires a compilation of all information about the selected process. All material and energy inputs and outputs are quantified. This process is

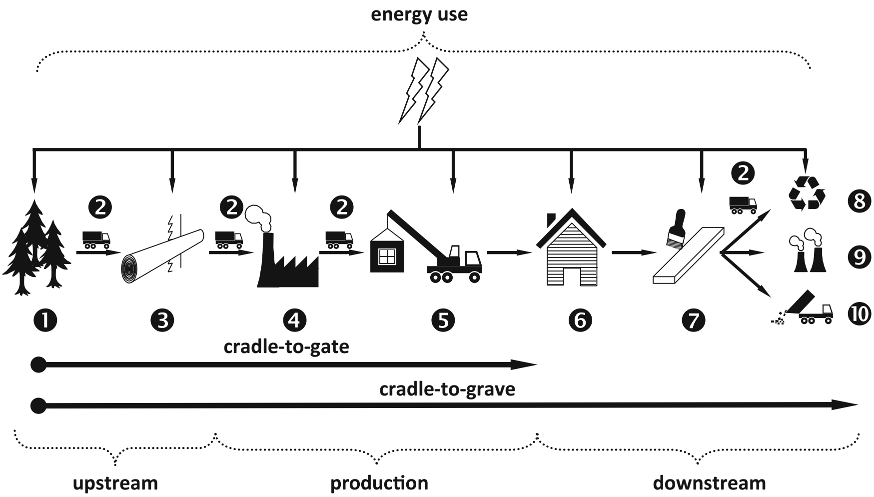


Fig. 2.22 Cradle-to-gate and cradle-to-grave concepts as the LCA system boundaries: ❶ harvest of raw material, ❷ transport, ❸ primary processing, ❹ secondary processing, ❺ construction/assembling, ❻ use phase, ❼ maintenance, ❽ recycling/reuse, ❾ energy generation, ❿ landfilling

divided into different life cycle stages, including manufacture, service life, end-of-life, and disposal. Data fall into two principal categories: primary (foreground) and secondary (background) data.

The LCI phase is followed by the life cycle impact assessment (LCIA) phase, and the environmental burden is quantified. The impact categories selected should provide useful information about the product or process while considering the goal and scope of the study. When selecting the impact categories, it is also necessary to select characterization factors, which are the units used to report each environmental burden.

LCA in the Wood Sector

The reported LCA studies of primary wood products mostly dealt with cradle-to-gate approach. This is due to the lack of data related to use phase maintenance, repair, refurbishment/replacement, as well as to deconstruction, demolition, waste processing, reuse, recovery, and recycling.

Kutnar and Hill (2014) discussed the environmental impacts of primary wood products and included a review of the LCA studies in the wood sector. They concluded that the research of timber processing and the resultant products focuses more on the interactive assessment of process parameters, developed product properties, and environmental impact, including recycling and disposal options at the end of the service life.

The fossil fuel consumption, potential contributions to the greenhouse effect, and quantities of solid waste tend to be minor in wood products compared to competing products that are used in the building sector (Werner and Richter 2007). However, impregnated wood products tend to be more critical than comparable products with respect to toxicological effects and/or photogenerated smog depending on the type of preservative. Bolin and Smith (2011a, b) compared environmental impacts related to borate-treated lumber and alkaline copper quaternary (ACQ)-treated lumber used for decking with a cradle-to-grave life cycle assessment. When compared to galvanized steel framing, the impacts of borate-treated lumber framing were approximately four times lower for fossil fuel use, 1.8 times lower for GHGs, 83 times lower for water use, 3.5 times lower for acidification, 2.5 times lower for ecological impact, 2.8 times lower for smog formation, and 3.3 times lower for eutrophication. The cradle-to-grave life cycle assessment of ACQ-treated lumber used for decking and façades was performed with the assumption that the ACQ decking has a service life of 10 years and that it is demolished and disposed in a solid waste landfill after the end of use. The study included the comparison with the wood–plastic composite (WPC) decking, which is the main alternative product to the ACQ decking. For the WPC, it was also assumed that the service life is 10 years. In both compared decking materials, maintenance, such as chemical cleaning and refurbishing, was not included in the LCI. The results of the cradle-to-grave life cycle assessment showed that ACQ-treated lumber impacts were fourteen times lower for fossil fuel use, almost three times lower for GHG emissions, potential smog emissions, and water use, four times lower for acidification, and almost twice lower for ecological toxicity when compared with WPC decking. Impacts were approximately equal for eutrophication.

The preservation or wood modification is extending the service life of materials. Hill and Norton (2014) compared different wood modification treatments. They defined the carbon neutrality—the point at which the benefits of life extension compensate for the increased environmental impact associated with the modification. Increased maintenance intervals of modified wood products help to lower the environmental impacts of the modified wood in the use phase.

2.4.2 Measures of Environmental Profiles

Environmental impacts of materials can be objectively compared when adequate guidelines are followed. ISO 14025 (2006) describes the procedures required in order to acquire Type III environmental product declaration (EPD). This allows comparability of environmental performance between products. The EPD is based on the principle of developing product category rules (PCR), which specify how the information from a LCA is to be used to generate the EPD.

The EPDs developed in Europe are mostly based on the PCR for "wood materials", which was released by the German Institute for Construction and Environment (Institut Bauen und Umwelt e.V.) in November 2009. PCR outlines five impacts on the environment: global warming potential, acidification potential, eutrophication potential, smog potential (photochemical oxidation), and ozone depletion potential (ozone layer depletion). ISO 14025 demands reporting of the

Table 2.4 Environmental product declaration programmes in Europe (summarized from Suttie et al. 2017)

Institut Bauen und Umwelt e.V.	IBU: created in Germany in 2006; includes 41 categories
bre	BRE EN 15804 EPD: created in UK in 1999; includes all construction products
epd®	EPD Norge: created in Norway in 2002; includes 19 categories
EPD® THE INTERNATIONAL EPD® SYSTEM	EPD Environdec: created in Sweden in 2007; includes 13 categories
inies	Inies—Fiche de déclaration environnementale et sanitaire (FDES) created in France in 2004

environmental impacts of the production phase (cradle to gate) of the life cycle. The standard allows for other life cycle stages, such as the in-service stage and the end-of-life stage, to be included (but they are not compulsory). There has been a range of EPD programmes (Table 2.4) initiated since the publication of ISO 14025 (Del Borghi 2013). At the same time, a large number of PCRs were published. These PCRs, however, are not completely in agreement with each other (Subramanian et al. 2012).

The environmental performance of products that are relevant in the construction sector is also a subject of other standards. ISO 21930: 2017 provides the principles, specifications, and requirements to develop a PCR and EPD for construction products and services, construction elements, and integrated technical systems used in any type of construction work. In Europe, however, the EN 15804 (2012) was introduced as an alternative. It defines a core PCR for building products in more detail than the preceding ISO 14025 (2006). Here, the life cycle stages are divided into modules. Modules A1-A3 cover the production stage, A4-A5 the construction process, B1-B7 the use stage, and C1-C4 the end-of-life stage. In addition, stage D is used to analyse the product "after-life". Suttie et al. (2017) describe the main environmental impacts associated with each of the modulus for bio-based building materials and discuss the carbon accounting and benefits of using timber as a substitute for construction materials with higher embodied energy.

Besides the EPDs that are defined in the ISO 14025 (2006) as Type III Environmental Declarations, there is also an environmental label Type I corresponding to ecolabelling. These labels are based on a multi-criteria approach indicating the overall environmental performance of a product. Type I environmental labels are

Table 2.5 Examples of Type I—ecolabels (Summarized from Suttie et al. 2017)

	Nordic Ecolabel (1989): set up by Nordic Council of Ministers; official ecolabel of the Nordic countries; More information: http://www.nordic-ecolabel.org/
	Blue Angel (2013): set up by German Federal Minister of the interior; More information: https://www.blauer-engel.de/en
	NF Environment (1991): set up by AFNOR certification; French ecolabel scheme; More information: http://www.ecolabels.fr/en/the-nf-environnement-mark-what-is-it

provided by several programs established and operated in line with the requirements of ISO 14024 (2018). The environmental criteria that are taken into account are, for example, energy usage, climate aspects, water usage, source of raw materials, use of chemicals, hazardous effluents, packaging, and waste, among the others. Some examples of ecolabels used in different European countries are provided in Table 2.5.

Building materials and their environmental impacts are important also for assessments at the building level. In this case, the analysis includes a comprehensive assessment of environmental impacts and in most cases encourages the use of EPDs. The three most popular building assessment certifications are presented in Table 2.6.

Table 2.6 Examples of building certification schemes

	BRE environmental assessment methodology (BREEAM)
	Leadership in energy and environmental design (LEED)
	DGNB or German sustainable building council

2.4.3 Circular Economy, Reuse and Recycling of Biomaterials

Circular Economy Concept

Climate change and awareness of needed actions to satisfy multiple aspects of sustainability have led to the development of several political strategies defined at the European Union level. The "Waste Framework Directive" published in 2008 was one of the first such actions taken. The objective of this strategy was to reduce waste generation as well as to encourage increased use of waste as a resource.

Secondly, the "Roadmap 2050" was published in 2011 aiming to provide a practical, independent, and objective analysis of pathways to achieve a low-carbon economy in Europe. The document described a strategy that is in line with the energy security, environmental, and economic goals of the European Union. By the year 2050, Roadmap 2050 aims to reduce greenhouse gas (GHG) emissions to at least 80% below the levels present in 1990.

The "Bioeconomy Strategy" that addresses the production of renewable biological resources and their conversion into vital products and bioenergy was published in 2012. It is structured around three pillars:

- investments in research, innovation, and skills
- reinforced policy interaction and stakeholder engagement
- enhancement of markets and competitiveness.

The forest-based sector is a key pillar of Europe's bioeconomy. Using wood products can contribute to significant CO_2 saving in terms of greenhouse gas emissions, embodied energy, and energy efficiency (Hill 2011). The three above-mentioned documents—Waste Directive, Roadmap 2050, and Bioeconomy Strategy—provide a prospect for the increased use of biomaterials in general, but especially in the construction sector. The increased use was further promoted by the Circular Economy Package published in 2018. The Circular Economy Package includes revised legislative proposals on waste to stimulate Europe's transition towards a circular economy which will boost global competitiveness, foster sustainable economic growth, and generate new jobs. The proposed actions should contribute to "closing the loop" of product life cycles through greater recycling and reuse and bring benefits for both the environment and the economy. The specific measures to promote reuse and stimulate industrial symbiosis are described with a special emphasis on turning a by-product of one industry into a raw material for another. Biomaterials are directly fulfilling aims of the Circular Economy, assuming that harmful chemicals are not involved along the life cycle.

The advantageous aspects of using biomaterials as building materials are also related to the list of goals as defined in the recently published "Research and Innovation Roadmap 2050—Sustainable and Competitive Future for European Raw Materials" (Reynolds 2018). The policy aims to secure a sustainable and competitive supply of raw materials, boost the sector's jobs and competitiveness, and contribute to addressing global challenges as well as the needs of the society. The priority areas and required activities are directed towards the supply of raw resources, production of raw materials, "closed loops", as well as innovative products and applications. A further opportunity for the development of the bio-material sector is finding solutions for substituting critical raw materials, along with the development of new bio-based products, such as composite materials.

Cascade Use of Resources

Reducing waste is a fundamental element in protecting the natural environment. The general concept in minimizing the amount of waste is based on "reduce–reuse–recycle" paradigm. The "reuse" is a preferred option and includes the transformation and the development of new products with minimal cost. Since the materials are used in their original form, efforts related to these conversions are minimized. An example of the material reuse is the manufacture of flooring or furniture from building cladding or the use of parts of demolished buildings in other structures. Another example is the Circular Pavilion in Paris designed by studio Encore Heureux, where the façade of the pavilion is crafted from 180 recycled wooden doors (Fig. 2.23). Even though this was produced as a work of art, it brought high public attention to the benefits of a low-waste, circular economy.

Reused engineered solid wood products, such as cross-laminated timber or glue-lam recovered from large structures, are a highly valuable source of construction materials. Such resources are of high graded quality, with the optimal hygroscopic properties and relaxed internal stresses. Recycled constructional wood can thus be used in the timber housing industry. Casa MAI—Modulo Abitativo IVALSA, presented in the Fig. 2.24, is a perfect example of the pioneer implementation of the reuse paradigm. It is an experimental transportable house constructed entirely from cross-laminated timber panels recovered from the building structure of the SOFIE project. MAI prototype was designed by DUOPUU and

Fig. 2.23 Recycled wooden doors used as a building façade

Wood building design lab of CNR-IVALSA within a research project on sustainable buildings carried out in collaboration with Ceii Trentino and with the support of Provincia Autonoma di Trento. The goal of the project was to design and build a small wooden prototype house (about 35 m^2 floor area) that can be built and prefabricated in a controlled area (factory), easily transported by truck to the final destination and finally assembled to form a real house in a few hours. The MAI prototype, when leaving the factory, was ready to be assembled and used: The heating–ventilation–air-conditioning system, electric installation, plumbing, interior finishing, lights, appliances, and furniture were already installed. All the construction phases in the production area have been optimized to reduce the waste of materials, control air and water pollution, and achieve a highly efficient building process with respect to the environment and the workers (Briani et al. 2012).

Recycling aims to convert waste timber into usable products. There are three distinct types of recycling—direct, indirect, and energy recovery. Direct recycling includes all processes where one sort of timber products is recycled to other sorts of timber products, usually to laminated timber, wood-based panels, or wood–plastic composites. Indirect recycling changes timber products into other types of products, such as animal bedding, landscape mulch, cement boards, or compost. Energy recovery is a process aiming to make use of embedded calorific energy stored in waste biomaterials. Processes of energy recovery are relatively simple and include preparation of fuel (chips, pellets, or briquets), combustion, co-firing, co-generation, pyrolysis, or gasification.

Fig. 2.24 Casa MAI as an example of a building constructed with reused cross-laminated panels. Image courtesy of Romano Magrone and Paolo Simeone—DUOPUU

A sequential use of a certain resource for different purposes is termed “cascade use”. It enables using the same material unit in multiple high-grade material applications occurring consecutively from the most complex to the simplest. The ultimate stage of the cascade use is usually energy conversion. The majority of wood-based products at the end of service life are in the state that allows straightforward further use (Fig. 2.25). Study of Höglmeier et al. (2013) demonstrated, for example, a great potential for cascading of wood recovered from building deconstruction. By utilizing recovered wood, the time span of carbon storage in the wood products increases and consequently delays the contribution to the greenhouse effect. Unfortunately, in many real-world cases the recovered wood is currently considered as not usable for cascade use and is simply burned or landfilled.

The amount of CO_2 wood releases into the atmosphere during burning or in-field decomposition is comparable to the amount absorbed by the tree during its growth. However, even if incineration of wood products at the end of life provides various environmental benefits, the research demonstrated that the use of forest residues in manufacturing particleboards is more sustainable than when they are used as fuel (Rivela 2006). It was shown that manufacturing particleboards from waste wood produces per 1 ton of the final product 428 kg CO_2 equivalent less than particleboard manufactured from fresh wood. Cascading through several life cycles prior to incineration is therefore a fairly better option for the end-of-life of bio-based materials. Table 2.7 summarizes the suitability of diverse waste processing

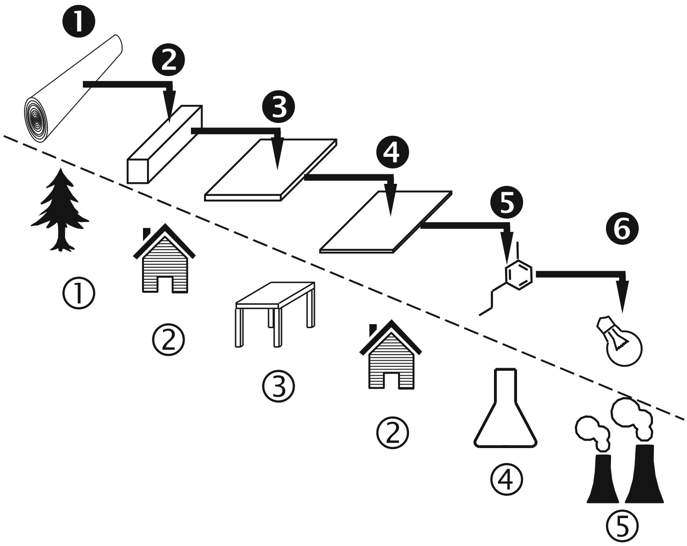


Fig. 2.25 Cascade use of biomaterials: ❶ log, ❷ large dimensions solid or engineered timber assortments, ❸ strand-/particle-based composites, ❹ fibre-based composites, ❺ chemicals, ❻ energy, ① resource extraction, ② first life cycle, ③ second life cycle, ④ chemicals processing, ⑤ energy generation

Table 2.7 Processing technologies for bio-based building residuals

Processing technology	Feedstock flexibility	Conversion efficiency	Market value of product
Combustion	High	Low	Low
Digestion	Low	Medium	Medium
Fermentation	Low	Medium	High
Pyrolysis	High	Medium	Medium
Gasification	Medium	Medium	Medium
Platform molecules	Medium	Medium	High
Liquefaction	Medium	Low	High
Composites manufacturing	High	High	High
Animal bedding	High	Medium	Low
Pelletizing	High	High	High
Insects conversion	Medium	Medium	High
Fungal conversion	Medium	Medium	High

technologies that are available for bio-based building materials. The restrictions identified are related to the feedstock flexibility, efficiency of the process, and the value of final products on the market. It should be stated that some of the listed technologies are still at the development stage; however, their validation and upscaling is only a matter of time. It is expected that intelligent concepts for the reuse and recycling of valuable materials at the end-of-service life will reduce the amount of landfilled waste. So far, landfilling is a most frequent path of the waste transformation, even if it is recognized as a less than optimal solution.

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