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Sustainability in wood materials science: an opinion about current material development techniques and the end of lifetime perspectives

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Wood is considered the most important renewable resource for a future sustainable bioeconomy. It is traditionally used in the building sector, where it has gained importance in recent years as a sustainable alternative to steel and concrete. Additionally, it is the basis for the development of novel bio-based functional materials. However, wood's sustainability as a green resource is often diminished by unsustainable processing and modification techniques. They mostly rely on fossil-based precursors and yield inseparable hybrids and composites that cannot be reused or recycled. In this article, we discuss the state of the art of environmental sustainability in wood science and technology. We give an overview of established and upcoming approaches for the sustainable production of wood-based materials. This comprises wood protection and adhesion for the building sector, as well as the production of sustainable wood-based functional materials. Moreover, we elaborate on the end of lifetime perspective of wood products. The concept of wood cascading is presented as a possibility for a

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more efficient use of the resource to increase its beneficial impact on climate change mitigation. We advocate for a holistic approach in wood science and technology that not only focuses on the material's development and production but also considers recycling and end of lifetime perspectives of the products.

This article is part of the theme issue 'Bio-derived and bioinspired sustainable advanced materials for emerging technologies (part 1)'.

1. Introduction

Two of the most severe crises that threaten our society are climate change and the degradation of the environment. Humanity's reckless usage of fossil resources largely contributes to these problems. In a 'take-make-dispose' mentality, our linear economic system is based on their conversion into materials and products that cannot be recycled and eventually are incinerated or end up as landfill. This causes both greenhouse gas emissions and severe environmental pollution. Hence, it is of utmost importance to transform this linear economy towards a sustainable circular one. The use of renewable natural resources instead of fossil feedstock is a cornerstone for this transition. It can help to realize environmental sustainability, which is the use of the resources to meet our needs without compromising the health of the ecosystems that provide them [1]. In the following, our use of the term 'sustainability' will refer to this definition.

Wood is one of the most important of these natural resources. Its renewable and CO_2-storing character has brought it into the focus of sustainable development. It is of major importance in the building sector, in which it is traditionally used as a construction material. Its use has increased in recent years, as the industry relies heavily on wood as a sustainable alternative to concrete. This results in annual growth rates of up to 15% for the production of engineered wood products [2]. Hence, taller and bigger timber buildings than ever before are built and planned globally. Moreover, wood is an important part of the bioeconomy strategy of the European Union [3] and political leaders emphasize its importance: Ursula von der Leyen, president of the European Commission, recently demanded a new era of sustainable building based on the use of wood [4].

In addition to its traditional application for construction, wood has also come into focus in terms of functional material development. Its unique anisotropic porous structure shows a distinct hierarchy over several length scales, which provides the necessary mechanical as well as morphological properties to make wood a promising resource to produce sustainable functional materials. Consequently, various wood-based functional materials have been presented over the last few years. They use wood's unique hierarchical structure where they impart functional agents by chemical modification. The resulting hybrid materials can realize manifold functions and serve for diverse applications [5–7]. They include transparent and optical materials, catalytic materials, filters and adsorbers for waste water treatment, materials for energy storage and conversion, as well as materials with outstanding mechanical properties. With respect to these recent developments, one can even speak of a completely new field of wood nanoscience or wood materials science.

As in the construction sector, one of the main motivations for using wood in functional material development is its renewable nature, due to which it is considered a green and sustainable material. Therefore, it is often claimed that wood-based functional materials can replace conventional materials made from fossil feedstock as a sustainable alternative [5,8,9]. However, there are no investigations into how sustainable the materials really are. The studies mostly focus on the material development and synthesis and give no life cycle analysis or similar assessments of the material's environmental impact. Consequently, the question arises as to whether the use of wood and the developed wood-based materials are indeed sustainable.

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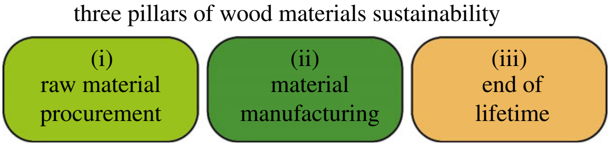

Figure 1. The three stages of the product lifetime that are important to evaluate its sustainability. (Online version in colour.)

Three stages of the lifetime of a wooden product are important to evaluate its sustainability (figure 1). First, there is the raw material procurement. In terms of sustainability, it is clear that wood must not stem from extensive deforestation. Here, we will focus on wood from sustainably managed forests, which are standard in modern European forestry and are considered carbon neutral [10]. Hence, the focus of wood materials sustainability discussed in this paper lies on the manufacturing process and the end of lifetime.

When it comes to the manufacturing process, many applications rely on the chemical modification of wood and its combination with other compounds. In the construction sector, for example, wood is often treated physically or chemically to increase its resistance against environmental influences. It is prone to environmental influences and rapidly degrades under the influence of moisture, UV-light, or microbial attack [11,12]. Therefore, coatings or chemical wood modifications are used to protect wood from these degrading influences. Moreover, wood has a low dimensional stability, which is a major concern for construction applications. It swells and shrinks upon varying humidity, rendering it inapt for precise construction in its natural state [13]. Engineered wood products circumvent this problem by joining layers with different fibre orientations or wood particles of various sizes. Such products are for example cross-laminated timber, particle boards and plywood. These elements require the application of significant amounts of adhesives that bind the wood parts together. Consequently, the technologies required for wood protection and bonding built the fundament of contemporary wood construction. At the same time, wood coatings and adhesives are almost exclusively made from fossil feedstock, diminishing the sustainable character of wood elements [14,15].

A similar picture emerges in the case of wood materials science. The underlying treatments to produce wood-based functional materials mostly disregard the principles of green chemistry. They often rely on the modification of wood with fossil-based compounds or methods that require solvent-based chemistry [16,17].

Moreover, this negatively affects the end of lifetime of wood products. Coatings and adhesives form inseparable composites with the wood, preventing the separation, reuse or disposal of the components. The same accounts for wood-based functional materials, which are mostly hybrid materials, whose individual constituents can hardly be recovered. Therefore, landfill or incineration are often the only end-of-lifetime options for these materials, releasing fossil carbon into the atmosphere [18].

Consequently, the sole use of wood as a natural resource is not necessarily sufficient to guarantee the creation of green and sustainable materials: new methods and technologies have to be developed and employed to use wood as a material for a sustainable future and to unleash its full potential as a resource for a sustainable circular economy.

With this opinion piece, we would like to draw attention to this important topic and to create more awareness of the challenges that lie in the sustainable utilization of wood, which is commonly seen as a sustainable product. We will suggest methods to increase sustainability in wood research that can help to lead to truly sustainable wood-based materials. However, we will not deliver an extensive evaluation of the sustainability of common wood modification techniques. For this, the reader is referred to the excellent review from Akpan *et al*. that was recently published on that topic [19].

Additionally, we will elaborate on wood recycling and reuse for a more efficient utilization of the resource. Our focus lies on the material use of wood and its technical aspects. This means we will elaborate neither on the topic of wood biorefinery nor on political or economic aspects of a wood-based circular economy.

2. Sustainable approaches towards wood-based materials

As a green, renewable and biodegradable material, wood is a valuable resource for the development of more sustainable materials. Currently, innovative wood-based materials become increasingly attractive, and show great potential in several fields:

— Construction (structural and non-structural applications, indoors and outdoors)
— Advanced functional materials (energy, electronics, composites, water treatment, catalysis)
— Mass-consumption products (alternative to disposable items, replacement of conventional engineering materials such as plastics and metals).

For each of these applications, the wood-based material must fulfil very specific requirements. In most cases, it is necessary to modify its intrinsic properties or to add new functionalities to make it an ideally suitable material. To do so, various modification techniques are available. According to the types of properties required for the finished wood product, the natural wood scaffold will undergo a modification triggered by mechanical, [20] thermal, [21] chemical, [22] or biological [23] methods (or a combination of those). The goal of these modifications is always to alter the structure and/or the composition of wood, to obtain enhanced performances or new characteristics for novel applications. However, none of these modification methods are environmentally neutral.

In recent publications about innovative wood products, the authors usually focus on the validity of a concept or the feasibility of an approach using wood as a green raw material. Many of these new wood modifications do not comply with the principles of green chemistry. They rely on fossil-based precursors, solvent-based chemistry, use energy-intensive production methods, or result in hybrid and composite materials that are hard to recover and recycle. Therefore, these approaches diminish the advantages that wood provides over traditional materials: the processes developed have not been optimized in terms of sustainability, and the final products cannot be assumed to be sustainable only because they are based on wood.

According to the principles of green chemistry, [24] we can identify the major challenges that are relevant to design a fully sustainable wood modification:

— Using energy efficient processes
— Using non-toxic, bio-based and bio-degradable chemicals
— Integrating degradation and end-of-life perspectives in the product design (this question will be discussed separately in part 3).

In the next paragraphs, we provide a non-exhaustive overview of the latest technologies used to improve intrinsic wood properties and to provide new functionalities to wood-based materials. We estimate the sustainability of these approaches, discussing their limitations, their challenges and promising approaches towards sustainable wood-based materials.

(a) Wood in construction

Wood has been used for thousands of years as a construction material. Impressive buildings were constructed from wood, such as the Sakyamuni Pagoda, a Buddhist temple in Yingxian (China, figure 2*a*). Built from larch and elm wood, it is still one of the tallest wooden buildings in the world (67 m), although it is almost 1000 years old [25]. However, in the wake of the twentieth century, wood was more and more replaced by steel and concrete. Concomitantly, many studies confirm that wood is the most sustainable building material [26,27]. It is therefore seen as the material

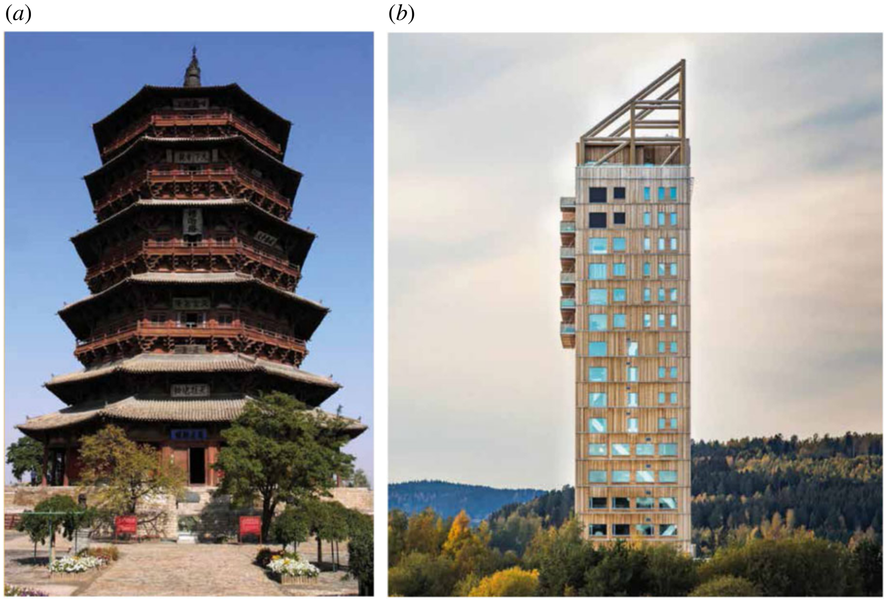

Figure 2. The Sakyamuni Pagoda in Yingxian, China (*a*), tallest old wooden structure and the Mjøstårnet tower in Norway (*b*), currently the highest timber construction in the world. Photo Wikipedia and © Ricardo Foto. (Online version in colour.)

of the future in the field of construction, with spectacular buildings already realized, such as the Mjøstårnet tower in Norway, at 85.4 m the highest timber construction worldwide (figure 2*b*) and many impressive wooden skyscrapers in the planning stage, showing the potential of wood in multi-storey building [28,29].

(i) Wood protection

The protection of wood elements against humidity, fungi, UV or fire is crucial for the design of wood buildings and structures. For both indoor and outdoor uses, surface coatings are often used to protect wood. Aside from the fact that such coatings are mostly derived from fossil-based synthetic polymers, they themselves age and degrade over time and they must be reapplied periodically. A more durable approach to wood protection is to impregnate the material with a compound whose role is to slow down or supress the wood degradations caused by external factors. With this type of modification, the wood material has a 'built-in' protection. Consequently, maintenance is decreased and durability increased.

Acetylation. The first attempts to chemically modify wood date back to the early twentieth century [30]. One of the oldest techniques—acetylation—benefited from decades of research and development and has been optimized and tailored for wood. Acetylation is today arguably the most widely used chemical modification to hydrophobize wood, providing increased dimensional stability and biological resistance. It is a very efficient process that does not require any solvent (pure acetic anhydride is used), combined with full recycling of unused chemicals. Despite the excessive waste production of acetic acid (it is a stoechiometric reaction), acetylation is a good example of a rather sustainable wood modification [31,32]. Acetylated wood is produced industrially and available under trade names such as Accoya [22]. Similar esterification processes use bio-based molecules such as citric acid or itaconic acid, and may be considered even greener [33–35].

Furfurylation. Furfurylation is another attractive reactive impregnation technique, which is considered environmentally friendly. Furfurylation consists of the catalytic polymerization of furfuryl alcohol (FA) in wood. The treated wood is not toxic, and FA is a bio-derived reagent that can be produced from agricultural waste. The modified wood elements have improved long-lasting properties, but they are also more brittle due to the formation of a cross-linked furan resin inside wood. Industrial production is carried out under the trade name Kebony [22].

Impregnation with natural or bio-based products. There are many more wood impregnation techniques, many of which use oil-based chemicals (resins and monomers) and consequently cannot be considered sustainable. However, the utilization of natural products and biodegradable products is becoming more attractive. Nature uses complex molecules such as waxes, extractives, resins and oils to impart specific properties to surfaces and to bulk biological materials [36].

The modification of wood with oils is already well known. For instance, linseed oil is used as a finish to protect wood surfaces. One of the drawbacks is the low retention of oils in wood. Epoxidation of oils (e.g. epoxidized soya bean oil) can help to improve the oil retention, but this requires more complex processes involving potentially harmful chemicals [37]. Other methods such as heat treatment or UV exposure could be used alternatively to cross-link unsaturated oils inside the wood structure.

Waxes have been shown to be useful for wood hydrophobization, but they also suffer from low wood penetration, low reactivity and consequently low durability.

In another approach, the introduction of extractives into the wood leads to improvements in its properties (higher dimensional stability, protection against biodegradation) [38,39]. However, in these studies either a first wood modification with fossil-based products was used, or solvents were needed to allow for in-depth wood penetration.

Finally, the introduction of polymeric material inside wood is of high interest for wood protection. Although polymers can be added to the wood structure, it is desirable to perform the polymerization inside the wood structure. This was demonstrated with several oil-based monomers including styrene and various acrylates, which provided wood with excellent new properties [16,17]. To avoid the use of non-renewable resources, the addition of biopolymers, and in particular polyesters was investigated [40]. Many different polymers could be added to wood, including poly(lactic acid) (PLA), polycaprolactone (PCL) or poly(glycolic acid) (PGA), with acceptable results, mitigated by the complexity of the polymerization process inside wood.

Thermo-hydro and thermo-hydro-mechanical treatments. In a thermo-hydro modification, wood is heated above 150°C in a controlled atmosphere. The process induces several physical changes in the wood composition, which influence the wood properties. Thermally modified wood has a clear environmental advantage over other modification techniques as no additional chemical treatment is necessary. However, the improved dimensional stability and resistance to biodegradation are obtained at the expense of the mechanical properties [41].

In the thermo-hydro-mechanical process, wood is compressed under controlled humidity and temperature conditions. The goal is to achieve a permanent deformation of the wood structure, thereby decreasing the void spaces in wood, increasing its density, and enhancing its mechanical properties. One of the major challenges is to prevent the shape recovery induced by moisture.

In the mechanical and thermal treatments, there is essentially no need for any additive substances, i.e. no waste products are generated upon manufacturing. The major environmental impact is generated by the energy needs for pressing (mechanical treatment) and heating (thermal treatment).

(ii) Wood assembly

Besides protection issues, the building sector provides another important challenge, related to the assembly of wood elements. To circumvent wood's natural dimensional instability, the construction sector relies heavily on engineered wood products. These are composite materials of smaller wood pieces (strands, particles, fibres or veneers) bonded together with adhesives. Most of the established adhesives used to produce wood components for contemporary construction are not sustainable. Adhesives holding together engineered wood products are based on fossil-based synthetic polymers. Since the adhesives make up from 2% to 8% of engineered wood products, their replacement with more sustainable solutions is a major priority [42].

Many building blocks derived from bioresources such as lignin, proteins and polysaccharides are available and can be added to adhesive formulations, decreasing the content of fossil-based chemicals. Despite their potential, bio-based adhesives and sealants still need to overcome several issues to match with the properties of synthetic-based solutions. Further developments to reach economic alternatives and to design processes fitting to wood industry requirements are needed. This is currently a hot topic in academic research, and the reader will find exhaustive information in recent reviews [43–46].

It is also interesting to mention that a number of smart adhesion concepts have been extracted from the study of plants and animals [47]. Whether it is related to topology, interlocking mechanisms, or surface energy, these concepts are promising approaches that would allow a reduction of the amount of traditional adhesives at the wood interface.

(b) Advanced functional wood materials

So far, we have shown that several sustainable wood modification strategies are particularly suitable to the construction field. Besides that, the application fields for new wood-based functional materials are tremendous. In its natural state, wood is able to act as a water purification device due to its natural anisotropic porosity [48–50]. Other applications for wood-based functional materials are accessible by modification of the wood structure or introduction of functional agents. Many of the concepts and methods developed for wood protection treatments have been reused to bring functionality in wood scaffolds. Additionally, novel approaches have been reported recently. Research has focused on gaining control over the alteration of wood composition and wood structure on the micro-, nano- and molecular scale to create novel macroscopic properties in the resulting hybrids. With this knowledge, it is possible to tune the characteristics of wood-based materials and to design products for innovative applications. Wood-based materials are currently under investigation in areas such as energy, optics, electronics and flexible materials [5,7].

(i) Altering the wood structure

Delignification. Currently, a lot of research is being conducted on what are called ‘subtractive’ chemical modifications, the leading approach being delignification. With this technique, it is possible to remove lignin from wood while maintaining the hierarchical organization of the cellulose fibres. Essentially, the removal of lignin increases the porosity of wood by creating nanovoids and nanochannels in the cell wall, affecting the optical properties of wood, and decreasing the overall mechanical integrity of the composite. All these new characteristics can be exploited for new wood utilizations [51].

The change in porosity is for instance beneficial for new applications where the transport of fluids is of high importance. It is also interesting to alter the thermal properties of wood: the removal of thermo-conductive lignin combined with the higher porosity generates materials with good insulation properties [52]. The delignified material may also be densified, leading to a material with outstanding mechanical properties [53].

The delignification process opens new perspectives on the utilization of wood. Nevertheless, it should be noted that it is not a green process: the most straightforward method is performed with sodium chlorite, a strong oxidant and therefore a highly toxic chemical. Here, industrial methods used in the paper industry cannot be directly applied, because the goal is to maintain the cellulose micro-structure. Further research efforts should therefore focus on the means to scale up this modification step, using green chemistry approaches.

Carbonization. Another way to alter the wood structure is carbonization. Carbonized wood features higher porosity, but also higher electrical conductivity (wood is transformed to pure amorphous carbon), and strong light absorption [54]. It was used to produce materials for clean water production, [55] energy storage [56] and thermal management [57]. Carbonization is a cheap and ecologically friendly approach to tune wood properties, but is generally combined with additional functionalization methods.

(ii) Filling the voids

Another way to create functional composites and hybrids is the injection of functional materials into the porous wood structure. This can be the natural wood porosity or pores created by delignification.

Polymers are widely used to produce such composites. The resulting materials combine the properties of a polymer matrix with the wood structure. In a similar fashion, the injection of a new polymer in the delignified wood scaffold offers many interesting possibilities, such as the development of lightweight composites [58]. When a polymer with matching refractive index is used, transparent composites with attractive optical properties coined as 'transparent wood' can be obtained [59].

Although most of the articles dealing with such approaches claim the sustainability of the product, one point must be made clear: the added materials are often synthetic ones derived from non-renewable resources (epoxy resins to obtain materials with high mechanical performance, transparent polyacrylates for optical applications, polymers for thermal properties and conductive polymers for electronics applications).

A more sustainable approach to provide functionality is the use of biomolecules, such as proteins, polysaccharides and nucleic acids. These are promising precursors to achieve green modifications and yield eco-friendly products, as they are non-toxic, biocompatible and can be introduced by aqueous systems.

Multiple examples of biological hydrogels obtained with proteins and polysaccharides can potentially be applied to modify wood's porosity, providing control over the material's properties. One example, which was recently presented, is the impregnation of wood with gelatine to create bio-based membranes with tuneable flux [60]. Similar approaches are conceivable with other natural hydrogels, which provide a variety of triggers to induce the gel formation inside the wood structure.

(iii) Functionalizing the cell wall

In contrast to filling the porosity, it is also possible to modify the wood cell walls to create functional materials. Cell wall modifications are possible with grafting of polymer chains or *in situ* growth of inorganic particles. The resulting hybrids can fulfil various functionalities. Grafting catalytically active compounds or chelating agents for instance is useful in the design of wood filters for water remediation [61,62]. Moreover, such approaches are highly interesting to combat UV degradation and to develop fire-resistant wood materials. Examples of fire-retardant treatment include calcium carbonate or struvite, which are added inside wood using aqueous modification techniques [63,64].

Other inorganic materials have been deposited inside the wood structure, such as metal and metal oxide nanoparticles decorating the cell wall to impart catalytic activity to wood scaffolds, [62,65] or to bring magnetic properties to wood [66,67].

Again, the utilization of bio-based or biological functional molecules for cell wall modification might be a more sustainable approach for the creation of wood-based functional materials. We recently reported the immobilization of enzymes inside the wood structure yielding bio-hybrid biocatalytic membrane reactors [68]. However, this approach also requires the introduction of metal nanoparticles into the wood structure. Hence, more research is required to create fully bio-based functional wood-bio hybrids. The realm of functional biological molecules provides a huge variety of interesting compounds in this regard. Besides the use of enzymes for biocatalytic activity, there is also nucleic acid as a highly interesting class of molecules for the creation of smart materials. They offer distinct, well-understood self-assembly to complex well-defined multifunctional nanostructures. Hence, they have found many applications in materials science over the last 20 years [69–71]. The combination of nucleic acids with a hierarchical material like wood could yield fascinating new green materials.

(iv) The solvent issue

Apart from a few processes, one of the critical steps in the chemical modification of wood is related to the transport of the reactive components in the wood scaffold. In some techniques mentioned above (acetylation, furfurylation, mineralization, etc.) either no solvent is necessary, or an environmentally acceptable solvent is used. But not all reagents can be introduced inside the wood structure with environmentally acceptable solvents. In addition, the efficiency of wood impregnation very much depends on the swelling capacity of the solvent used [72,73]. Water is one of the best solvents in this regard, but others such as pyridine, DMF, or DMSO have an even higher swelling efficiency. Because these are excellent wood swelling solvents, they have been widely used at laboratory scale. However, they are not viable for industrial applications for sustainability reasons. In some publications, promising results are obtained with a given solvent, but they may never be applied to larger scale because the solvent is too toxic, or too difficult to recover and recycle. To avoid the utilization of problematic solvents, a few approaches are possible:

— No solvent approaches
— Full solvent recycling
— Use a green solvent: water, $scCO_2$

The first approach is not always possible as it requires a reagent in the gas phase or liquid phase. The second proposition is usually feasible and is highly relevant when upscaling a technology. Recovering and recycling a solvent may however largely increase the energy consumption and cost of the global process.

In terms of process, it is finally worth mentioning supercritical fluids. As an example, the introduction of biocides for protection against fungi using supercritical CO_2 as a carrier solvent is currently done by a Norwegian company called Superwood [74]. Supercritical fluids are largely used for extraction purposes in the industry, because $scCO_2$ can be easily recovered by decompression-induced phase change and then stored and reused. This green technology holds great promise for wood impregnation processes.

(c) Replacement of mass-consumption and other products: a case study

Finding alternatives to man-made materials—in particular plastics—for everyday consumption is currently a major topic for all stakeholders (governments, industry, the public). Here, the requirements for sustainability do not differ from the ones discussed above. The goal is often to find a cheap, sustainable and efficient way to change the properties of wood so that it at least matches, but preferably exceeds the standard requirements for the material to be replaced. Bringing such products to the market is a long and complex process. In our opinion, this also represents a highly interesting discussion because it provides an excellent example encompassing all three stages described in figure 1: sustainable wood sourcing, sustainable manufacture, and solutions towards a fully recyclable product. There is very little literature available yet. This is why in this section we will present a case study from our experience at Swiss Wood Solutions (SWS).

SWS is a solution provider company: we use our expertise in the transformation of wood to develop innovative, ecological materials with applications in different fields. We started our activity with a product line called Sonowood®. Sonowood® is obtained from the chemical modification then densification of local wood species. The exact nature of the chemical modification is a trade secret; however, it is free from oil-based chemicals, and does not need harmful or environmentally dangerous solvents. We then use the THM process described above to densify the modified wood. With this green process, we manufacture a 100% biodegradable material with superior mechanical and acoustic properties, which advantageously replaces woods from endangered tropical species in the manufacture of music instruments (table 1).

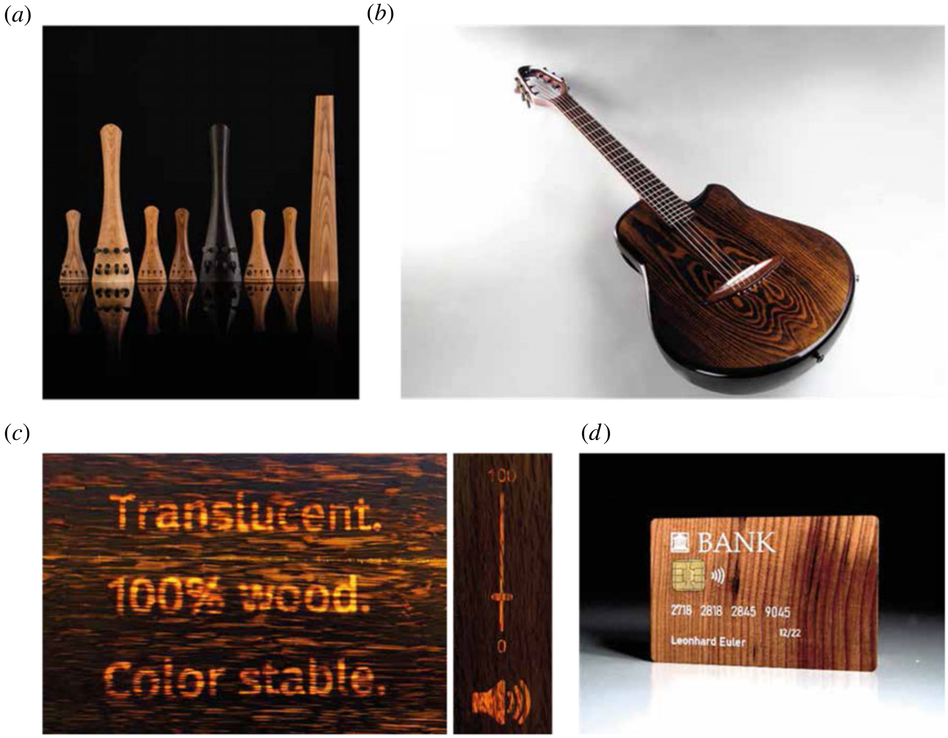

Figure 3. (*a*) Tailpieces for string instruments from Sonowood® spruce, maple and walnut made by Wilhelm Geigenbau (Photo: The Strad Magazine). (*b*) Guitar equipped with Sonowood elements (bridge and fretboard), and a body from Sensoveneer® (made by Canna Guitars). (*c*) Translucency of Sensoveneer® oak, showing the potential for displays. (*d*) 100% wood payment card, made with a densified wood sandwich, with chip and contactless payment options. (Online version in colour.)

Table 1. Characteristics of Sonowood in comparison to ebony.

	Sonowood maple	Sonowood spruce	ebony
density [kg m^{-3}]	1200–1400	1300–1400	1100–1200
Brinell hardness [N mm^{-2}] [a]	90–140	100–150	∼84
sound velocity [m s^{-1}] [b]	>4400	>5500	∼4500

[a] Perpendicular to grain direction.
[b] In grain direction.

Besides solid wood, we have been working with veneers from different species. Using a sustainable modification method adapted from the Sonowood® manufacturing process, we can produce modified and densified veneers showing great potential: they are harder than classical veneers, with high scratch resistance, UV colour stability and translucence. These new materials, called Sensoveneer®, could be used in decorative applications where classical wood veneers are usually employed with a surface treatment involving coatings. They may also find applications as an alternative material for displays due to their translucence (figure 3). Again, these materials are completely natural and biodegradable.

Finally, we have worked on wooden cards to replace plastic payment cards. The majority of the billions of cards issued every year are made of PVC. Despite being a trivial object in our lives, a payment card is a relatively advanced composite material made of several layers, each fulfilling a specific function. The physical characteristics of these cards and their performance in a series of tests are defined by norms. A new card made from wood should fulfil the same requirements while being entirely sustainable, i.e. produced using an environmentally friendly process, with bio-sourced reagents, and finally biodegradable or easily recyclable. At SWS, we have developed a 100% natural card (except for the electronics and chip), made of densified wood veneers and bio-based glues (figure 3). Densification of veneers is performed using a thermo-hydro-mechanical (THM) process. We are currently studying the biodegradation of these cards (end of life scenario) as well as their delamination, which would help to recover and reuse the different materials (wood and metals, second life scenario).

3. Wood recycling and end of lifetime perspective

When it comes to the end of the lifetime of wood products there are three main possibilities, namely landfill, incineration and recycling. Landfill must be avoided from a sustainability point of view, as it can lead to the release of harmful compounds to the environment, and to the generation of the powerful greenhouse gas methane by wood rotting [26]. Luckily, landfill plays no role in European wood disposal. Waste wood is either incinerated for energy production or regained for additional material use. Material use focuses on the production of particle boards with about one third of the wood supply for the European particle board production stemming from recycled wood [75]. However, the amount of incinerated waste wood often exceeds the amount of reused wood. In Germany, for example, only 20% of all waste wood is reused, whereas the other 80% is directly incinerated [18].

Incineration of waste wood has positive environmental effects, if it replaces fossil fuel incineration. The CO_2 that is emitted during wood incineration was previously captured by the growing tree [76]. Hence, this process is carbon neutral when the entire wood lifetime is considered. However, waste wood not only contains wood but also other components such as adhesives and coatings. Burning these components releases additional greenhouse gases into the atmosphere, which is especially problematic when they were produced from fossil resources. This shows the importance of developing adhesives, coatings and other wood treatments that are bio-based and therefore also carbon neutral upon incineration.

Material reuse increases the positive environmental effect of wood use compared to direct incineration of waste wood. It decreases the required amount of primary wood and leads to carbon sequestration for a longer period. After reuse, the wood will be incinerated for energy production, adding to the positive environmental effect. In this regard, it is important to minimize material loss during the sorting and separation process [77]. In the near future, the urge to reuse a bigger amount of waste wood will intensify, as the demand for wood will soon exceed the supply [78].

Wood cascading is a concept of wood reuse that increases the efficiency of the wood life cycle and can help to meet the wood demand. The term wood cascading describes a system in which wood is sequentially used for multiple products and applications before it is finally incinerated (figure 4). After each product lifetime, the wood is regained and either recycled for the same kind of product it was used before or further processed to fit into another product. During this process, the wood pieces will decrease in size as the wood is disintegrated into smaller pieces during the regaining process. Hence, solid wood products (e.g. boards) are followed by particle-based products of various particle sizes (e.g. oriented strand boards, particle boards), which are then followed by fibre-based products (e.g. fibre-plates, cardboard). Afterwards, the wood can be chemically disintegrated to use its molecular components, before the products made from wooden biomass are finally incinerated for energy production.

The concept is already applied to allocate wood resources, which are regained from waste wood, to the pulp and paper industry or for energy production [79]. However, these are only very basic cascades with few steps. By intensifying wood cascading, the resource efficiency can be substantially increased because multiple material demands and energy needs can be satisfied with one primary resource. Cascading has the potential to reduce the global warming impact of

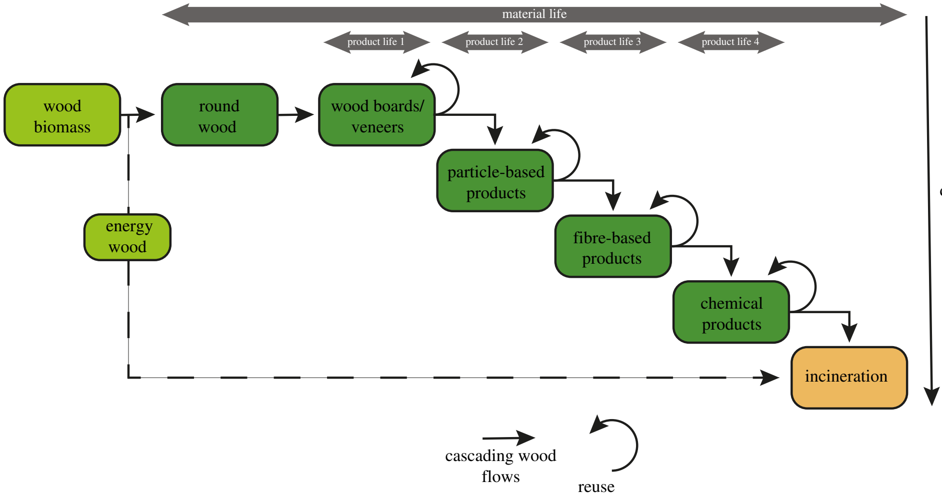

Figure 4. Illustration of the concept of wood cascading (simplified and idealized material flow). (Online version in colour.)

wood utilization by 7% and the primary wood use by up to 14% [80]. The environmental benefit of wood cascading will be particularly high when wood demand increases and the products in the cascade replace non-wood products [81,82]. Consequently, the cascade should include high-quality secondary wood products such as medium density fibreboards (MDF) and oriented strand boards (OSB), whereas the use of primary wood for energy production (energy wood) should be omitted. In this regard, the recent intensification of wood material science leading to the development of novel wood-based materials adds more possible steps to the cascade. However, up to now recycled wood has been mostly used for particle board production [83].

Whether a wood product is recycled and the wood reused depends on a multitude of factors. The most important of these are technical aspects, such as the pollutant content, the technical feasibility and efficiency of the recovery, and the quality of the waste collection and sorting process [84].

This puts the spotlight again on the wood product manufacturing techniques and the chemical components used. Today waste wood is often considered as toxic waste, as it is contaminated with potentially harmful adhesives, coatings and other chemicals [18]. It is laborious and costly to separate the wood fraction from other components. Hence, this kind of waste wood does not fit into the concept of wood cascading. Novel sorting and separation processes could help solve this problem, but they are expensive and difficult to implement. Therefore, they could even impede the material reuse of wood [83].

Moreover, in the case of composite wood products, such as particle boards, the non-wood components and the energy needed to produce the products are the main contributors to their environmental impact [77,85]. Therefore, it is required to develop novel components and technologies for wood product manufacturing that allow easy regaining and recycling of wood. This comprises bio-based and biodegradable adhesives and coatings, non-toxic chemical treatments and removable modifications. Wood polymer composites with bio-based polymer matrices are one promising example in this regard [85]. Concomitantly, the more secondary wood is used in such composites, the lower is their environmental impact [86].

For the development of novel wood-based functional materials, the principles of green chemistry must be standard. This comprises, as described above, the selection of green solvents and chemicals, the utilization of non-harmful compounds, and the minimizing of waste during the production. In addition, the end of lifetime perspective must be considered during material development. The materials must allow recycling and regaining of the constituents or a completely CO_2-neutral incineration. This requires a holistic approach that covers not only material development and synthesis, but also develops concepts for the materials' recycling and end of lifetime perspective. The concept behind this approach is known as 'ecological design' (eco-design) and means designing products with special consideration for their environmental impacts over their whole lifecycle [87]. There is some research into the eco-design of furniture made from wood [88]. However, all fields of wood materials research and production have to apply this concept to develop truly sustainable wood-based products and lead the wood industry towards a sustainable circular economy.

4. Conclusion

Wood is the most important natural resource and one of the cornerstones for changing our society. Not only can it be helpful in the construction sector to build sustainable buildings, but it can also act as a raw material for the development of novel functional materials. The application of wood will be particularly important to mitigate climate change, if wood-based materials replace materials from fossil feedstock, such as petrol-based plastics, and materials that require a high amount of energy or emit CO_2 during their production, such as concrete.

However, there is an urgent need to change the way in which wood is used and to develop and implement sustainable production methods to create truly sustainable wood products. For almost all uses, wood is processed, modified and combined with other materials to fulfil the needs of the application. Concomitantly, established adhesives for wood gluing, coatings for wood protection, and modifications to produce wood-based functional materials are mostly not sustainable.

While sustainable approaches exist and are already commercialized, they are not widely applied. Others are still in development and it is unclear whether they can fulfil their potential. In our opinion, sustainable wood-based materials must be entirely bio-based. Bio-based adhesives and coatings have been known for a long time but suffer from certain disadvantages. However, a lot of research is currently allocated to further developing bio-based adhesives and coatings to fit industrial requirements. Moreover, bio-based materials and biomolecules have a high potential for applications in wood-based functional materials. There is an overall trend in material science towards smart, programmable and adaptive materials. In this regard, the combination of wood with its unique structure and biomolecules with their huge plethora of possible functions holds tremendous potential for the development of entirely bio-based materials.

Additionally, a holistic approach in wood materials science is necessary that considers recycling and end of lifetime perspectives for the developed materials. For this, life cycle assessment and material flow analysis should be applied. However, this is rarely done in wood materials science. The focus is mainly on the presentation of novel concepts and functional materials, without considering the end of lifetime and environmental impact of the produced hybrid or composite materials.

In the wood industry, eco design must be the future standard to develop products that blend into a circular economy. This will facilitate wood recycling and cascading and will further increase the positive environmental influence of wood utilization. It will also help decrease pressure on primary wood demand, which will exceed supply in the coming years. In this regard it will also be important to keep regulations as well as recycling techniques up to date. When wood-modifications with non-toxic compounds will be standard, waste wood cannot be considered as toxic waste anymore. Consequently, more opportunities for the application of recycled wood will open up. This is also an opportunity for the wood recycling industry to develop innovative processes that convert waste wood into value-added products.

At the end of its lifetime, it is an established strategy to incinerate wood waste for energy production. The incineration of wood is carbon neutral as the CO_2 that is emitted during the process was previously captured from the atmosphere by the growing tree. Hence, it can help reduce GHG emissions, especially if it replaces fossil energy sources. Therefore, it is necessary to avoid the use of fossil-based resources for wood adhesion, protection, or modification so that no fossil carbon will be emitted into the atmosphere upon incineration.

Besides the utilization of wood as a material discussed in this article, biorefining can help to use wood as a resource for a more sustainable economy. Biorefining consists of the chemical decomposition of wood to molecular building blocks and the subsequent chemical synthesis of value-added products from these compounds. It can help to fulfil the vision of making wood the 'oil of the twenty-first century'. However, it will also increase the wood demand. Hence, it is desirable to include wood derived from cascade usage into biorefining strategies instead of exclusively relying on primary wood.

This shows that wood can and most certainly will be a very important resource for a future sustainable society. However, advancements in many different fields are necessary to develop and apply truly sustainable wood products that blend into a circular economy. In addition to the technical aspects that we discussed in this paper, this requires adequate policies as well as economic incentives.

Data accessibility. This article has no additional data.

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