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EFI

Wood-based textiles & modern wood buildings

Environmental impacts beyond climate change

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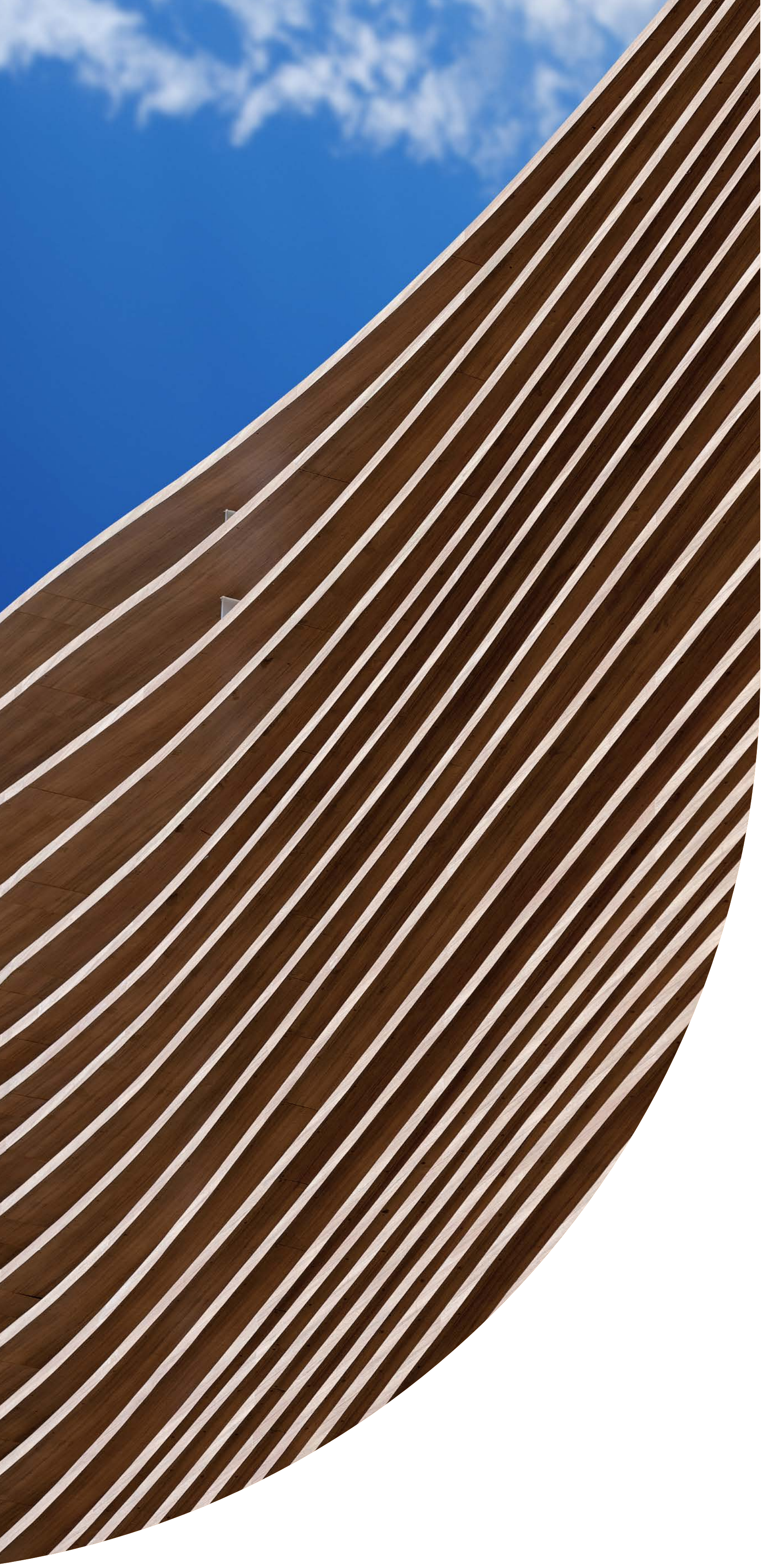

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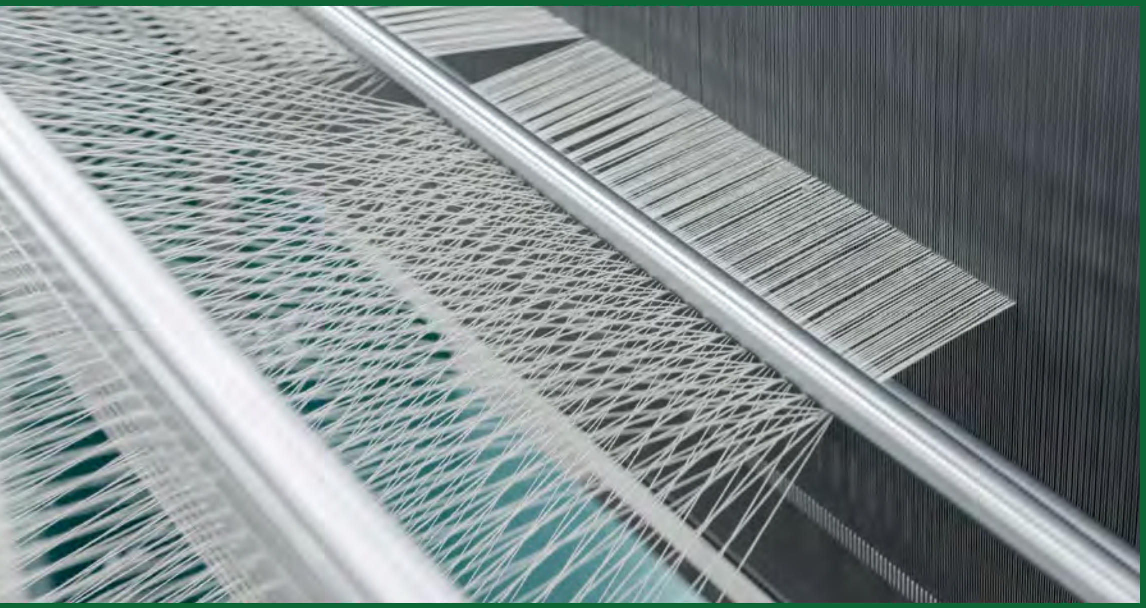

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Executive summary
WHAT IS AT STAKE?

The production and use of wood-based textile fibres and engineered wood products in buildings have been identified as promising areas for carbon storage and greenhouse gas emission reductions. However, a number of other environmental impacts are reported as potentially being associated with the processing, manufacturing, use and disposal of (wood) products, including eutrophication, acidification, photochemical oxidant formation and human toxicity.

Currently the understanding of these impacts is still limited. To date, there are **no systematic studies available that have examined the non-climate environmental impacts** that occur throughout the life cycle stages of wood-based textile fibres and modern wood buildings. This study sets out to explore **the potential non-climate environmental impacts of wood-based textile fibres and modern wood buildings.** Based on comparative life cycle assessment (LCA) studies and interviews with experts, we present the **foreseen technological developments** that support the development of wood-based fibres and modern wood buildings towards environmental sustainability. We also provide insight into the **limitations to the development of wood-based textiles and modern wood buildings.**

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Three lessons can be learned when looking into wood-based textile fibres and modern wooden buildings from a life cycle perspective:

Improvement of the metrics used for quantifying environmental impact indicators is critically important, especially related to the variety of factors that influence the environmental sustainability of forest products. Standard LCA studies that are used to quantify environmental impacts do not represent realistic scenarios for natural systems such as forests, requiring a rethinking of the applicability of these LCA impact assessment methods, indicators, and their metrics.

Investment in R&D to support the development of sustainable materials and circularity of new wood products over their entire life cycle is critical. Environmental sustainability considerations and circularity need to be incorporated in the early stages of product design. The reduction of harsh chemical use and a reduction of the overall chemical input is key.

Investment in technologies to further improve energy efficiency, thus further reducing the reliance on fossil energy is required. The energy mix used in product manufacturing is an important factor that contributes to improving the environmental profile of both industries. Preference should be given to renewable energy sources in the production processes, especially opting for non-woody biomass. Wood should be used as a raw material for products rather than for energy in the production process.

Executive summary
RESULTS ON ENVIRONMENTAL IMPACTS

WOOD-BASED TEXTILE FIBRES

The environmental performance of wood-based textile fibres depends on the benchmark used in the assessments and the value chain's complexity. These findings, however, do not necessarily mean wood-based textile fibres cannot be considered suitable alternatives to synthetic fibres or cotton from an environmental standpoint. The results indicate the need for investing more in environmentally sustainable manufacturing processes to improve environmental performance. Also, more thorough analyses that can capture the entire value chain are required given the global distribution of the wood-based textile fibres value chain.

Limitations identified for the use of wood-based textile fibres are:

- **Pending approval of alternative solvents** to reduce the environmental impacts.
- **Lack of cost competitiveness** for most ionic liquids compared to other solvents (in part due to limited production and consumption).
- **Difficulty to adopt changes for large manufacturing companies** due to the scale and complexity of their value chains.
- **Fashion industry acceptance constrained** as new wood-based fibres have different properties to traditional fibres, especially if producers do not work closely with designers and clothing brands.
- **Business model change needed**, as current consumerism driven by "fast fashion" stimulates the notion of garment disposability, resulting in increasing volumes of waste.
- **Constrained consumer acceptance** regarding **limited options** being environmentally friendly and **increased price** for more sustainable alternatives.

MODERN WOOD BUILDINGS

According to the studies examined, modern wood buildings are often associated with lower environmental impacts compared to building made from other materials. However, this finding depends on the type of building considered, production technology, as well as methodological assumptions and data. Moreover, because new wood buildings and their building systems are comparatively new, evidence/studies are still limited. Buildings are complex systems, involving dozens of products that must meet various technical requirements depending on the building codes. The majority of the LCA studies included in this publication provide results for potential environmental impacts at the building level, i.e., the material composition of the building. This demonstrates that, in addition to the environmental performance of engineered wood products, the sustainability criteria under which the building is designed, as well as product post-use considerations, are critical.

Limitations identified for the wider adoption of wood in modern buildings include:

- **National building codes** are regarded the main impediment to designing buildings with wood as a structural material, although recently national building codes have changed in some countries (e.g., National Building Code of Canada 2020).
- **Limited wood design expertise** among actors in the value chain makes the use of engineered wood as a structural material challenging. This is due to e.g., a lack of systematic cooperation for knowledge transfer, a lack of educational programmes and training.
- **Insurance issues, difficulties to access capital, volatile timber prices, cost of procurement, special fire protection requirements**, and a **shortage in skilled workforce** are all associated with economic factors and increased costs.
- **Technical aspects in relation to fire high risk and wood deterioration** due to moisture are a barrier for using wood in construction.

Executive summary

KEY MESSAGES

WOOD-BASED TEXTILE FIBRES

Invest in the management of chemicals used in textile fibre production by avoiding or considerably reducing the use of harmful chemicals, revamping the production process, and adopting circularity to minimize the generation of toxic wastewater.

Integrate man-made cellulosic fibre mills with pulp mills to improve energy self-sufficiency given that modern pulp mills produce an excess of energy from side streams and waste. A resulting decreased use of fossil fuels, can considerably lower the environmental impacts.

Blend different natural textile fibres, such as cotton with wood-based fibres to help **improve fibre recyclability and,** thus, **reduce waste.** Blending natural with synthetic fibres makes recyclability difficult and costly. Hence, textile companies should carefully consider which fibres are to mix.

New wood-based textile fibres are not meant to be direct substitutes for existing fibres. Future studies should take into consideration the differences in properties of wood-based textile fibres and their non-wood counterparts, as well as the uncertainty in their market uptake when performing calculations on substitution factors and market projections. Calculations on substitution factors should consider which are the alternative wood-based fibres that could technically be considered equivalent to the fibres being displaced, based on available evidence.

MODERN WOOD BUILDINGS

Invest in the development of more environmentally friendly adhesives or technologies that reduce chemical input while maintaining the structural integrity of modern engineered wood. This will aid both in reducing the embodied environmental impacts and increasing circularity potentials.

Apply collaborative working methods for bridging designers, manufacturers and construction companies. Building eco-design is identified as a critical element for modern wood buildings that should be incorporated early in the design process to ensure overall sustainability and support increased wood utilization efficiency at end-of-life.

Develop clear policies and regulations for integrating circularity into value chains to maintain the high value of engineered wood in modern wood buildings. Establishing new value chains that facilitate reuse and recycling at the end of lifecycle could enable circularity and motivate the design of buildings for disassembly.

Modern wood buildings play a critical role in reducing carbon emissions from the construction sector, however, **the emphasis on carbon should be shifted to include other environmental impacts and overall sustainability in wood product value chains.**

The importance of environmental impacts: wood-based textiles and wood buildings

Photo by: © helivideo, Adobe stock

1. The importance of environmental impacts: wood-based textiles and wood buildings

Human impacts on the physical environment have been triggered by economic growth. Overpopulation, the use of fossil fuels and deforestation have all contributed to environmental deterioration through resource depletion, ecosystems degradation, wildlife endangerment and the pollution of air, water and soils. Human impacts on the environment have resulted in climate change and the growing incidence of natural disturbances.

In an attempt to mitigate the effects of climate change, wood and wood-based products have received increased attention for their ability to store carbon and avoid emissions by substituting emission-intensive non-renewable materials [1], [2]. Such substitution effects relate to the use of woody biomass for different applications (e.g., textile fibres or lumber for building elements) instead of other materials (e.g., synthetic fibres, concrete and steel), to reduce the emissions of greenhouse gases (GHG) associated with their production, use and disposal [3]–[6].

The use of engineered wood products (EWPs) in buildings and the production of wood-based textile fibres have been identified as promising sectors for carbon storage and emission reductions [7]–[9]. Many studies that consider wood products and their substitution effects have focused on their impacts related to climate change. However, there are many other environmental impacts associated with the processing, manufacturing, use and disposal of (wood) products. Examples of environmental impacts include eutrophication, acidification, photochemical oxidant formation and human toxicity [10], [11], but the understanding of these impacts is still limited [12], [13]. There are currently no studies that have systematically examined the non-climate environmental impacts that occur throughout the life cycle stages of modern wood products.

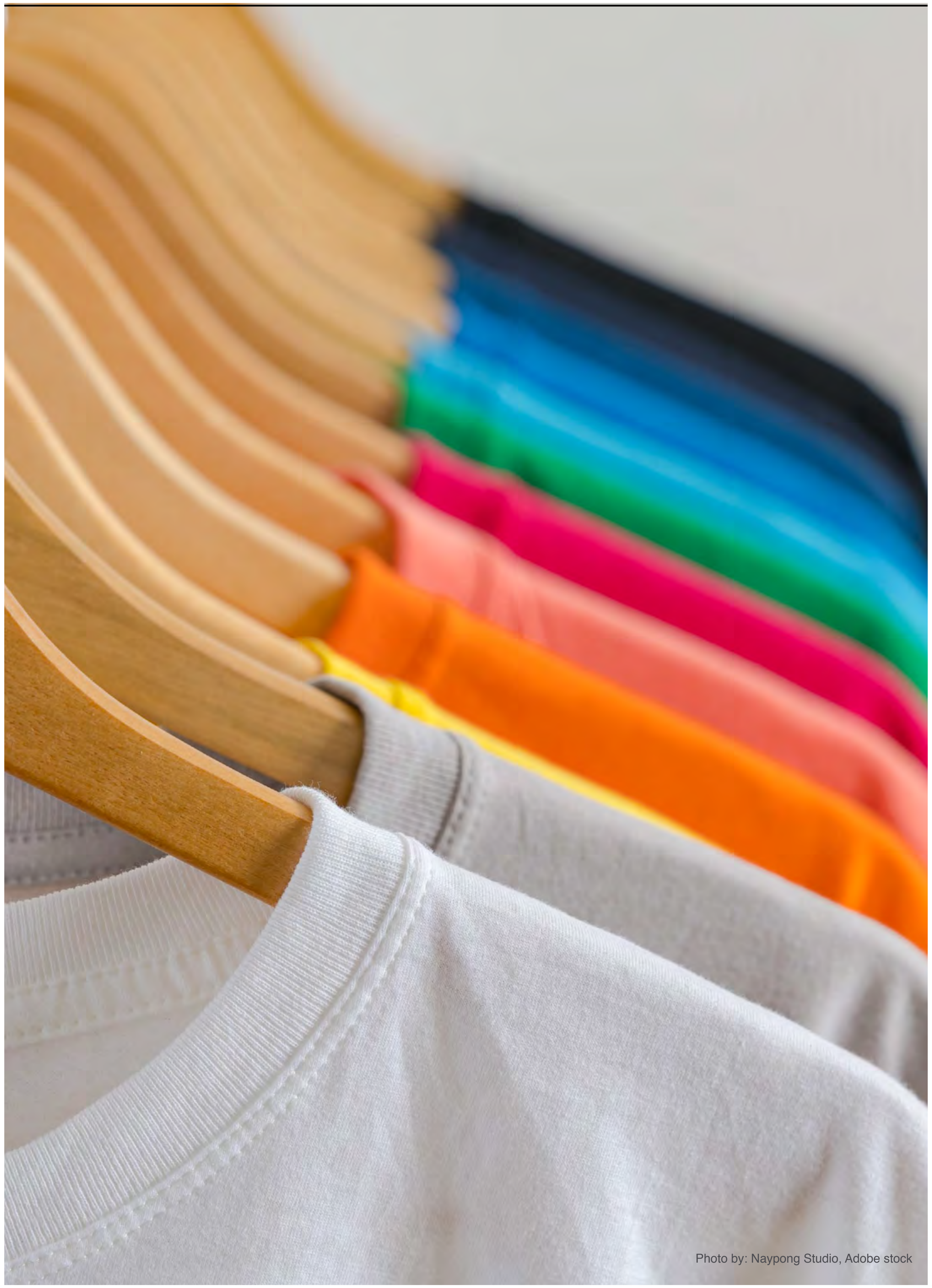
This publication aims to provide insight into the potential environmental impacts of wood-based textile fibres and modern wood buildings, beyond climate change. The present study explores:

the potential environmental impacts of wood-based textile fibres and modern wood buildings;

foreseen technological developments that support the development of wood-based fibres and modern wood buildings towards environmental sustainability;

limitations to the development of wood-based textiles and modern wood buildings.

The intent of this study is not to compare renewable materials (e.g., wood-based textile fibres and modern wood buildings) explicitly and systematically with their non-renewable counterparts (e.g., synthetic fibres and conventional buildings). Nonetheless, non-renewables and other resource-intensive materials, such as concrete and cotton, are at times used in this study as benchmarks to be able to better understand the relative environmental performance of wood-based products.



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Box 1.1:
Terminology and indicators

Life cycle assessment (LCA)
LCA is a systematic method for evaluating a product system's inputs, outputs and potential environmental impacts throughout its life cycle.

Cradle-to-gate
Cradle-to-gate is a partial assessment of a product's life cycle, beginning with resource extraction and finishing at the factory gate, before it is transported to consumers.

Cradle-to-grave
Cradle-to-grave is a full assessment of a product's life cycle, considering the impacts from resource extraction to use and disposal.

Environmental product declaration (EPD)
It is defined by the International Organization for Standardization (ISO) as a declaration that quantifies environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function.

Abiotic depletion -fossil fuels/minerals
Abiotic depletion covers the environmental concerns associated with the overuse of resources such as minerals, metals, fossil and nuclear energy, atmospheric resources, flow energy resources, and in some cases, land and water. Usually reported as kilograms of antimony equivalent (kg Sb eq), kilograms of minerals (kg), or megajoules of fossil fuels (MJ).

Acidification potential
Acidification potential refers to the contribution of chemical compounds that are precursors of acid rain, such as sulfur dioxide (SO_2), ammonia (NH_3), and nitrogen oxides (NO_x). Expressed as kilograms of sulphur dioxide equivalent (kg SO_2 eq).

Climate change
Climate change refers to long-term shifts in temperatures and weather patterns due to human activities. Climate change is expressed as the amount of heat absorbed over a given time period as a result of gas emissions (e.g., carbon dioxide, methane, nitrous oxide and others). Measured in the reference unit of kilograms of carbon dioxide equivalent (kg CO_2 eq).

Cumulative energy demand (sum of non-renewable energy use and renewable energy use)
Cumulative energy demand represents the total primary energy input (direct and indirect) throughout the life cycle of a product, which includes the energy consumed during the extraction, manufacture and disposal. Expressed as megajoules (MJ).

Non-renewable energy use
Non-renewable energy use refers to the demand for energy produced by fossil fuels. Measured in megajoules (MJ).

Ecotoxicity
Ecotoxicity refers to the environmental consequences of some substances, such as heavy metals, which can have an impact on the ecosystem. Freshwater ecotoxicity, marine ecotoxicity, and terrestrial ecotoxicity are the three impact categories that look at toxicity in different environments. Usually expressed as kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DB eq).

Eutrophication potential
Eutrophication potential is abnormal productivity driven by anthropogenic increase of nitrogen and phosphorus inputs to terrestrial and aquatic ecosystems. Expressed as kilograms of phosphate equivalent (kg PO43- eq) or kilograms of nitrogen equivalent (kg N eq).

Human toxicity
Human toxicity reflects the potential harm of a unit of chemical released into the human environment. It considers both the inherent toxicity of a compound and its potential dose. Expressed as kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DB eq) or disability-adjusted life year (DALY).

Land use
Land use impacts refer to effects caused by occupying, reshaping and managing land for human purposes. Usually expressed as square metre of land per year (m^2/a) for land use, and square metre of land (m^2) for the transformed area.

Ozone layer depletion (stratospheric ozone depletion)
Ozone layer depletion refers to the potential consequences of ozone-depleting substance emissions (i.e., CFCs, HFCs, and halons). Expressed as kilograms of trichlorofluromethane equivalent (kg CFC-11 eq).

Photochemical oxidation (Photochemical ozone creation potential)
Photochemical oxidation refers to smog created from the effect of sunlight, heat and non-methane volatile organic compounds (NMVOC) and NO_x. Photochemical oxidation (also known as summer smog) is usually expressed as kilograms of ethylene equivalent (kg C_2H_4 eq) or kilograms of NMVOC (kg NMVOC).

Water use
Water use relates to water use and scarcity, as well as the pollution of water bodies. In LCA, it usually accounts for freshwater use (consumptive use) and is expressed as cubic metres (m^3) of water consumption. The impacts considered here address not only the case of ecosystems and human users losing water, but also the depletion of stock resources, potentially depriving future users of water.

Box 1.2:
Measuring environmental impacts through Life Cycle Assessment

Life Cycle Assessment (LCA) is a standardised and quantitative method to measure the environmental impact of products and services along the life cycle and aids the decision-making process towards sustainability. The leading standards for LCA are ISO 14040 [14] and ISO 14044 [15]. These international standards are primarily concerned with the process of conducting an LCA. The LCA methodology begins with the assessment of used resources and continues through their use until their end-of-life point (**Figure 1.1**).

In LCA, the environmental sustainability of a product or system refers to a number of sustainability aspects connected to human health, the natural environment and natural resources. The sustainability aspects are then assigned to a variety of environmental impact categories and their related characterisation models.

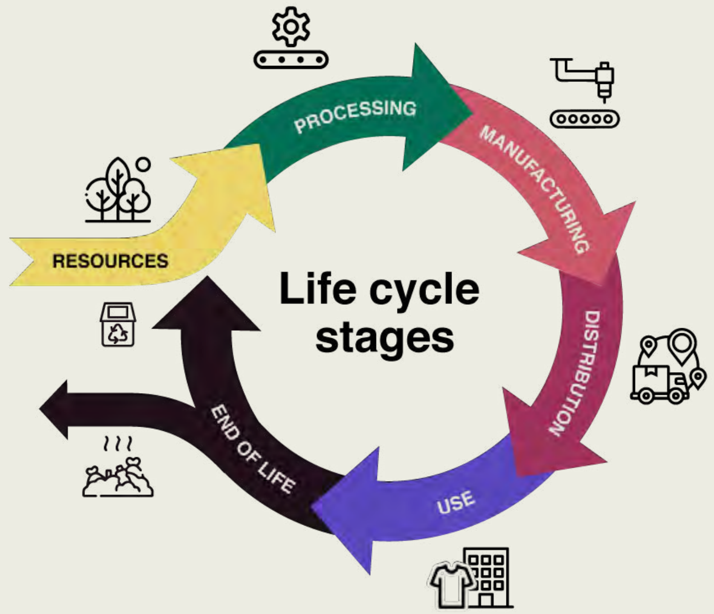

Figure 1.1. Life cycle stages of a product

How can LCA help?

- It can indicate the magnitude of impacts resulting from the studied systems.
- It can help identify processes and activities that make a large contribution to the overall environmental impact.
- It can show in which environmental impact categories the studied system performs worse or better; however, it cannot tell you if one impact category is more relevant than another.

What are the limitations of an environmental LCA?

- It can only give you as good results as the data and models used in the analysis, which leads to problems when assessing emerging technologies.
- It does not assess economic (life cycle cost) or social aspects (social LCA), it purely focuses on the environmental impacts.
- LCA outcomes are determined by the assumptions and scenarios, which are typically simplified representations of the real world.

Box 1.3:
Land use and biodiversity in assessing forest products

The LCA method is widely accepted for assessing environmental impacts. However, it has significant shortcomings for some biophysical effects, such as land use and biodiversity loss impacts [16]–[19]. This issue is especially critical when the LCA method is applied to renewable raw materials. For impacts beyond climate change, these deficiencies mainly relate to the “land use and land use change” indicator, in which biodiversity-related effects are also attributed. Several issues have been reported in relation to this, such as the non-consideration of the transformation of a natural forest to a managed forest, which may result in loss of species diversity, or the change in biodiversity caused by a transformation from a natural area to an urban area [20]–[22]. As a result, LCA of forest products frequently overlooks biodiversity impacts, in addition to not taking into account changes in forest management or harvest intensity [23], [24]. This is a critical issue for forest products, especially when compared to fossil-based counterparts whose background assumptions are inconsistent. Due to the potential for incorrect decision-making based on LCA results, the findings should be interpreted with caution.

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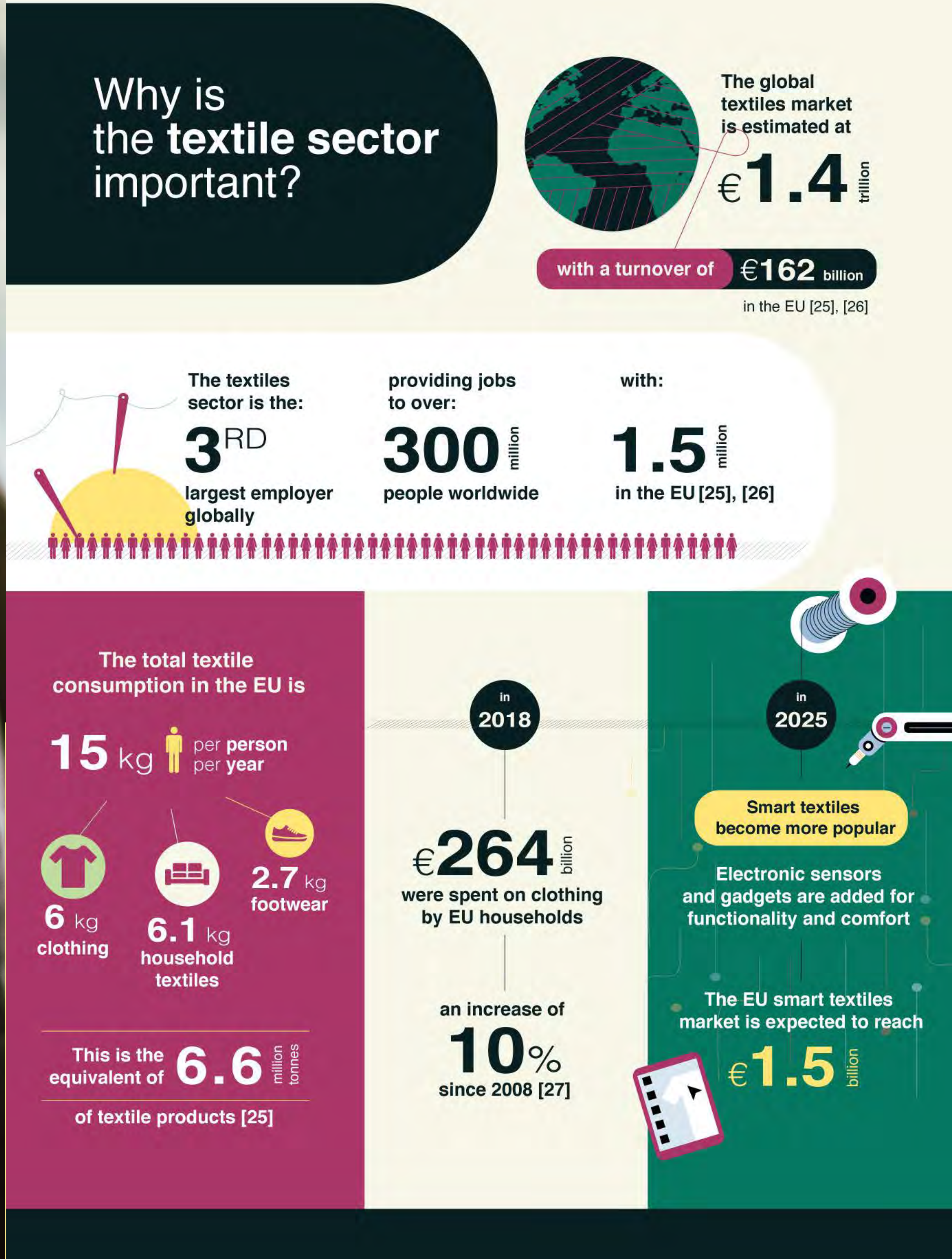
Wood-based textile fibres

Photo by: Daria Minaeva, Adobe Stock



2. Wood-based textile fibres

Many textile and fashion companies are engaging in the circular economy with the objective of reducing the environmental impact of textile production and consumption. The motivation for their engagement includes the companies' corporate social responsibility policies, securing future raw material supply and reducing the consumption of virgin raw materials by closing the loop in the production processes, ensuring opportunities for profit-making, creating 'green' jobs, and meeting consumer demands and expectations [28], [29]. However, only around 50 fashion companies have currently committed to the targets set in the Paris Agreement [30] and much still needs to be done to reduce the environmental impact of the textile sector.

The textile sector is an important part of the economy, as textile fibres are a ubiquitous material in our daily lives, used in garments, household items, automotives and many other applications. Textile fibres are produced using filaments or staple fibres from synthetic or natural sources. Filaments are man-made, long and continuous strands produced from synthetic and natural polymers, such as polyester and cellulose, respectively. Staple fibres refer to short fibres of natural origin (e.g., cotton and wool) or fibres that can be formed by sectioning the (natural or synthetic) man-made filaments. The most common types of staple fibres can be classified into four main groups, namely: synthetic fibres, plant fibres, wood-based fibres (also known as Man-Made Cellulosic Fibres, or MMCF), and animal fibres. Over 60% of all textile fibres that are globally produced are synthetic, petroleum-based fibres (**Figure 2.1**).

The current global textile fibre production is around 109 million metric tonnes and is dominated by synthetic fibres (**Figure 2.1**). Among these, polyester is the most common fibre type (52%) [31]. Plant-based fibres, MMCF and animal fibres combined correspond to 38% of global production, with cotton representing a share of 24%. Wood-based textile fibres represent only a share of 6% of the global production, with viscose being the most prominent type [31]. **Box 2.1** presents the differences between wood-based textile fibres.

The textile sector is infamous for many issues that cover – and connect – social and environmental aspects. Cheap labour stimulated by the "fast fashion" industry is arguably the most prominent issue within this sector [39]. The precarious work conditions are directly associated with environmental issues, such as the use of toxic chemicals during the production stage [40], [41] and the improper disposal of chemicals in wastewater [42].

While it is impossible to completely disentangle the social impacts from the environmental impacts, we tried to focus on the environmental impacts based on the LCA impact results.
We also restricted our analysis to the effects related to the textile fibre, from raw material production to material disposal at end of life, without covering aspects related to the manufacture of fabrics and garments. In this study we cover two of the most common types of MMCF used for garments, i.e., viscose and lyocell. (Please note: modal is not covered in detail as it has a small market share [31] and is frequently produced in the same mill as viscose and lyocell).

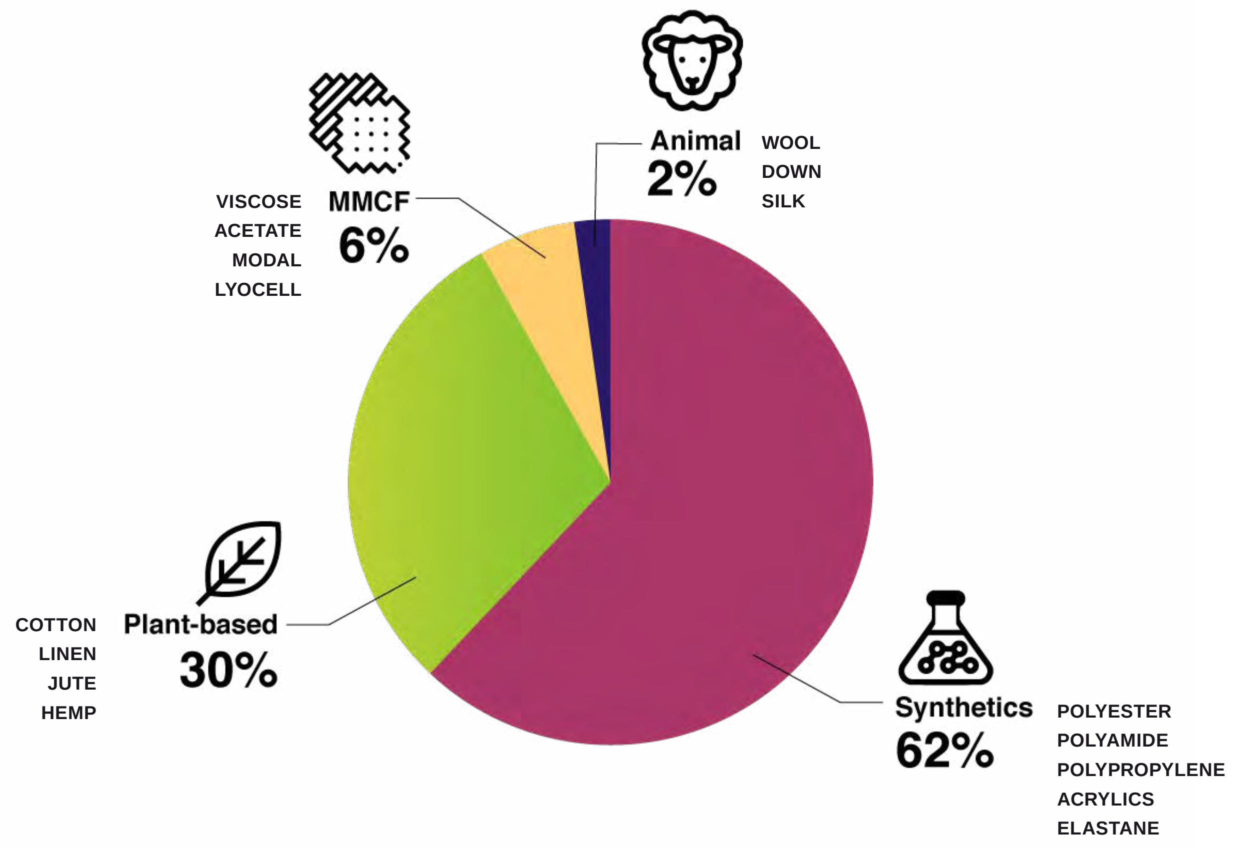


Figure 2.1. Main textile fibre groups, their global market share, and some examples of fibre types (adapted from [31])

Box 2.1:
How do wood-based textile fibres differ from each other?

Consumers have probably heard of the most common MMCF and have most likely purchased products made of them. However, because of the large assortment of textile fibre types in general and the perceived similar characteristics among the different types of wood-based textile fibres, distinguishing regular **viscose** from **modal** viscose and **lyocell** or understanding where **acetate** is used may be difficult.

Regular **viscose** – hereafter simply "viscose" – is the most common MMCF and has been produced for more than a century. Because it absorbs water, it is commonly used in disposable hygiene products. It is also used in garments, linings and to reinforce high-speed tyres [32]. **Viscose** and **modal** viscose – hereafter simply "modal" – are both produced using the viscose process, in which the pulp is dissolved in a process involving sodium hydroxide and carbon disulphide [33].

Modal fibres are made from a high-purity pulp with a higher degree of polymerization from which viscose is made with a composition that allows greater stretching of the filaments in the spinning bath. This results in fibres with a significantly higher wet strength and elasticity equal to that of cotton (hence the name modal fibre).

Lyocell was developed as a solution for producing cellulosic fibres with improved cost-performance and with a smaller environmental impact [33]. Compared to viscose and modal, lyocell uses an organic solvent (N-methylmorpholine N-oxide, or NMMO) to directly dissolve the cellulose [34]. Some advantages of the lyocell process are that NMMO has low toxicity [35] and it can be almost fully recovered and recycled [36]. Compared to viscose fibres, lyocell fibres are significantly stronger (in both their dry and wet state), have a more homogeneous appearance, absorb water evenly over the entire fibre cross-section, which significantly improves wear comfort, and also absorb dyes more evenly due to a uniform nanocapillary structure. However, lyocell fibres are less resistant to changes in shape before breaking than viscose [37].

Cellulose acetate is produced through acetylation and is a thermoplastic polymer, meaning that it is mouldable at a certain temperature. Compared to viscose, it has higher elongation at break, lower abrasion resistance, and higher resistance to pilling [38]. For these properties, acetate filaments are commonly used in clothing, linings and household furnishing, while acetate staple fibres are used in cigarette filters [38].

2.1 Environmental impacts of wood-based textile fibres

Considering that around 70% of the global GHG emissions associated with the fashion industry occur during raw material extraction and product manufacture [30], it is important to understand which environmental impacts are associated with wood-based textile fibres across life cycle stages.

LCA conducted for textile fibres follows the guidance provided by ISO standards 14040:2006 [14] and 14044:2006 [15]. The following sections present the environmental impacts of wood-based textile fibres, as well as how the wood-based textile fibres fare in comparison to their counterparts regarding environmental impacts.

Photo by: Roman, Adobe stock

2.1.1 Environmental impacts across life cycle stages

While most of the global GHG emissions from the fashion industry are associated with raw material extraction and product manufacture [30], environmental impacts occur across all life cycle stages [43]. From a life cycle perspective (**Box 1.1** and **Figure 2.2**), environmental impacts typically occur during the followings stages: (I) raw material extraction, (II) manufacturing, (III) transportation, (IV) product use, and (V) end-of-life.

(I) Raw material extraction

The environmental impacts associated with the production of raw material depend on the source and type of feedstock, whether they come from natural or planted forests, from forest residues, or from industrial side streams. For instance, the sourcing of biomass to produce viscose has been associated in some cases with unsustainable forest management practices, illegal logging and sourcing from endangered forests and sensitive sites [44]. The issue with biomass sourcing is not exclusive to textile fibre production [45], but it is important from a global perspective, considering the textile value chain spreads considerably across the globe.

In LCA (see **Box 1.1**), the "land use" impact category refers both to land used for biomass production and to land occupied by infrastructure. Land use is considered an important

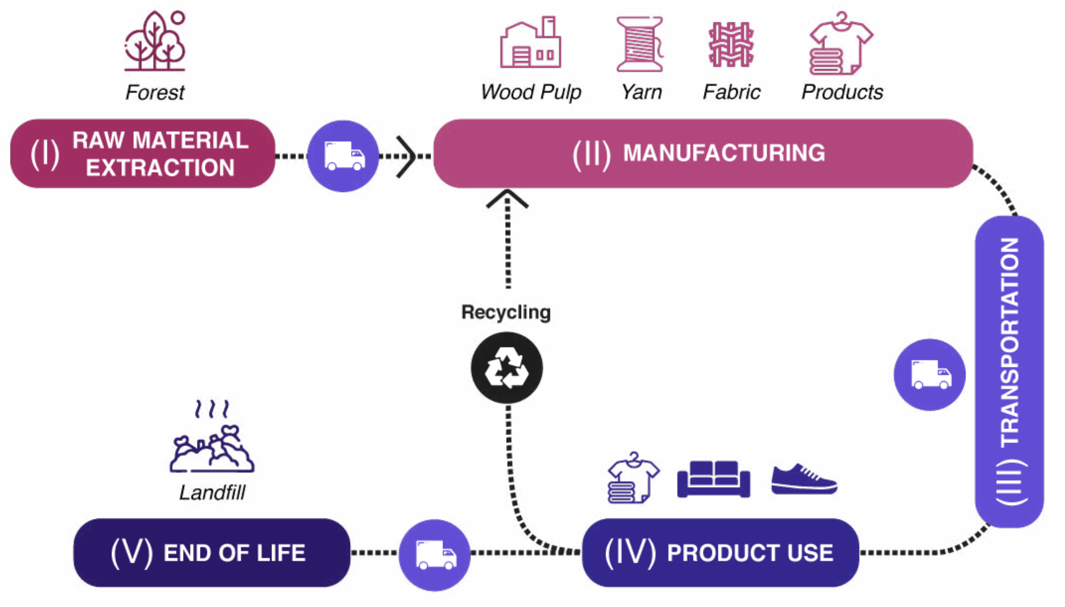


Figure 2.2. Representation of the life cycle stages for wood-based textile fibres

environmental impact due to the competition for land for food, feed and fibre production, and the impact on soil quality and biodiversity [46]. Land use also affects wildlife habitats and frequently reduces plant species biodiversity, although biodiversity impacts are currently not properly considered in LCA methods [47]. Despite having certain consequences for ecosystems, even planted forests (depending on type of harvest, tree species and targeted wood product) are in general associated with higher biodiversity than agricultural crops such as cotton [48], as forests can harbour wildlife and create conditions for the development of plant and mushroom species in between rotations [49]. The impacts are also connected to the land use change (e.g., from natural ecosystems to planted forests and fields) or with the extension of the area needed to produce the biomass feedstock [50].

(II) Manufacturing

The manufacture of wood-based textile fibres starts with the conversion of wood chips into wood pulp through the same process used to produce wood pulp for paper. Traditional wood pulping processes are known for requiring large volumes of chemicals, water, fuel and energy [51], [52].

Pulp mills that produce wood pulp through the kraft process frequently use the resulting black liquor for the mill's internal energy needs [53]. In some pulp mills, fossil fuels are still used as the main energy source in the manufacturing process, contributing to multiple environmental impact categories [50], including air pollution [54]. The pulping process generates sulphur dioxide, which is the main cause of acidification, photochemical oxidant formation and also affects freshwater aquatic ecotoxicity and terrestrial ecotoxicity [55]. Although not quantified in LCAs, the kraft pulping process also emits other sulphurous compounds, such as methyl mercaptan, dimethyl sulphide, dimethyl disulphide and hydrogen sulphide [56]. This makes the wood pulp production a key contributor to the environmental impact in the wood-based textile fibre value chain, with chemical compounds being mostly emitted to air.

To produce MMCF the wood pulp must be dissolved with chemicals, a process that varies according to the type of textile fibre. In principle, there are two types of cellulose dissolution options: one via cellulose derivatives (for viscose and cellulose carbamate) and another via a direct solvent (e.g., NMMO, water and ionic liquids). The former requires at least three chemicals (i.e., carbon disulphide, caustic soda and sulfuric acid) which undergo side reactions and thus form other sulphurous compounds such as hydrogen sulphide and different types of mercaptans. The latter method is a direct solvent; therefore, the dissolution is a mere physical process where the chemical nature of the solvent does not change during the dissolution procedure.

For viscose production, it is estimated that about 25-30% of the carbon disulphide is not recovered, and that 300-600 tonnes of wastewater and toxic waste residue are emitted for each tonne of staple fibre that is produced [57]. Another important factor associated with the production of viscose is the use of caustic soda. The production of this chemical is associated with freshwater aquatic ecotoxicity and terrestrial ecotoxicity [55].

Unlike viscose, for which there are no alternative chemicals, lyocell uses NMMO as the chemical for dissolving the pulp [58]. NMMO does not cause the same environmental impacts because it is less harsh, and it is recovered and recycled into the process [38], [59]. The small quantity of final waste issued from the lyocell production process is mostly composed of a small amount of NMMO [58] and organic matter, which are biodegraded during water treatment. The organic matter in lyocell wastewater is mostly composed of hemicelluloses (i.e., wood sugars) which decompose during water treatment. The environmental impact of the lyocell production process can still be improved by lowering water use [60].

Similar to the pulping process, the type of energy used to produce textile fibres can lead to air pollution, contributing to acidification and other impacts [50]. The heat and electricity used during textile fibre production can also affect the environmental impact depending on the source (e.g., fossil fuels, coal, natural gas, renewables) and amount of energy required for the processes. In a comparison of LCA between viscose and lyocell fibres, it was observed that the primary energy consumption to produce lyocell is much higher than for viscose due, at least in part, to the high energy demand for evaporating water and recycling the chemicals used in the process [61].

After the textile fibres are produced, they are transported to a mill to be spun into yarn, and then woven or knitted. The energy source and the type, use and treatment of chemicals are important factors influencing the environmental impact during yarn and fabric production. The chemicals used later in the value chain, during dyeing and finishing treatments, are also responsible for a significant amount of resource use and, consequently, increase the environmental impact of textiles [62]. In addition, many post-treatment and finishing chemicals are neither produced sustainably nor are safe for health and environment [63].

One of the main causes of pollution in the textile industry is the discharge of untreated effluents into the water [64], which is associated with water, terrestrial and human ecotoxicities [65], [66]. The colourant discharged in water when there is no adequate wastewater treatment affects light transmission and, consequently, photosynthesis by aquatic plants, reducing aquatic animal and plant biodiversity [67]. Other impacts associated with textile dyes are mutagenicity and carcinogenicity [68]. The type and amount of chemicals used for dyeing and treating the textile fibres vary according to the type of fibre and requirements for the end-product.

(III) Transportation

An important part of the value chain is related to the transportation of raw materials and intermediate products, from the forest to the pulp mill and/or integrated mill, and from the mill to the manufacturing companies. A large part of the impact of viscose is related to petroleum consumption for transportation in the whole value chain [55].

Lyocell is produced from different types of raw material, due to requirements related to the feedstock such as degrees of polymerization [59] and wood pulp purity [60]. Part of the raw material is internationally traded; thus, the environmental impacts of the fibre vary according to the source of the feedstock. Part of the wood or wood pulp used for lyocell is produced in tropical countries (e.g., from eucalypt), where tree growth is faster than in other global regions, and part is produced in temperate and boreal forests from Europe, Russia and North America. Transportation of raw materials or wood pulp from distant sources is frequently done by ship and because of the long distances involved can be considered an important source of pollution.

(IV) Product use

In LCA, the use phase for textiles refers to the number of times the material is used and subjected to regular washing, drying and ironing. In this sense, the durability of the textiles has an important effect on the environmental impact of the use stage, as the longer the material is able to maintain its properties and functions, the higher the potential environmental benefits [69]. Environmental impacts during the use phase of textiles in general are usually associated with the release of microfibres during washing [70], regular “wear and tear”, and the material’s ability and rate of decomposition in the natural environment. Compared to polyester, cotton and viscose release more microfibres during washing, which causes negative environmental impacts on freshwater [71] and seawater [72], [73]. However, the overall impact of cotton and wood-based fibres is considered smaller in the long term, as they do not remain in the environment for long periods of time [74].

Cellulose-based textile fibres, whether they are cotton or MMCF, are generally fully biodegradable. Although MMCF are “regenerated fibres” (i.e., they are created by dissolving the cellulose with chemicals and spun to form new filaments), their chemical composition remains the same, which makes their decomposition similar to unmodified or natural fibres [75]. While MMCF are biodegradable, the conditions and time to decompose vary according to the type of fibre, and biodegradation method and conditions. In general, viscose fibres have high biodegradability rates, both in soil and in wastewater treatment facilities, due to the low crystallinity and low degree of orientation of fibres [76], [77]. In a separate study, lyocell textiles were observed to be biodegradable in the marine environment [78].

(V) End-of-life

The end-of-life stage corresponds to the end-of-life options, such as reuse, recycling, disposal and incineration. A garment is used on average up to ten times before being discarded [62], and the estimated period of active life of garments in general is, on average, four years in Europe [79]. Once textiles reach the end of the period of active life, some of the most common waste management treatments given to these materials are landfilling and incineration [28], [62].

Some other conditions of waste disposal and management, such as in an anaerobic digestor [80] and freshwater [74], have been tested for MMCF with good results regarding the biodegradability rate. However, a better option for end-of-life from an environmental perspective is to recycle the textiles [81], which could be an opportunity for the industry to recover over 88 billion EUR per year in materials that are lost with other end-of-life options [62].

Some factors may impact the feasibility of textile fibre recycling [28], such as:

- poor collection and sorting systems for post-consumer textiles;
- lack of information regarding the mix of fibres in garments and other textiles;
- unattractive market prices for recycled fibres; and
- trade barriers for textile waste.

Photo by: annaspoka, Adobe Stock

2.1.2 Environmental performance of wood-based fibre and their counterparts

Synthetic fibres, such as polyester and nylon, are responsible for large GHG emissions [82] and other environmental impacts. According to estimates, the production of synthetic fibres for textiles uses about 342 million barrels of petroleum each year [62], which is an important cause of freshwater toxicity. In addition, synthetic textiles release microfibres during washing, which results in water contamination by microplastics [83].

The production of cotton is highly GHG emission-intensive and has a large environmental impact associated with land use and chemicals inputs. Cotton requires 60% more land than viscose (integrated mill), 2.3 times more than viscose (separate mill) and 3-5 times more land than lyocell, based on global averages [84]. Cotton has high freshwater and terrestrial ecotoxicities, due to the use of pesticides [55]. Its global production requires around

200 thousand tonnes of pesticides and eight million tonnes of fertilisers per year [62]. It also has the highest eutrophication impact, which is associated with the use of fertilizers [55]. Even though less environmentally impactful types of cotton have been introduced to the market – also called “preferred cotton” – they account for about 30% of total cotton production [31]. Organic cotton is as water-intensive and requires almost as much energy as conventional cotton [85].

MMCF constitute a group of fibres where each type of fibre has distinct impacts on the environment, depending on the production process and end-of-life options. The environmental impacts of MMCF, as well as other textile fibres, depend on several factors, including the source of raw material, geographical location of mills, and energy mix [46].

Table 2.1 presents how MMCF fare in comparison to synthetic fibres (i.e., polyester and polypropylene) and cotton regarding their environmental impacts (other than climate change), according to the few studies that assess multiple types of fibres. The results are presented for specific fibres, with specific locations of the raw material production, energy mix and sources, manufacturing technology and waste management.

In **Table 2.1**, viscose (separate mill) refers to the fibre produced with market pulp from eucalypt planted in the southern hemisphere and represents the state-of-the-art separate viscose plant. Viscose (integrated mill) refers to the fibre produced in an integrated facility in Austria that uses beech wood planted in Europe, representing the best available technology. Modal also refers to the fibre produced in an integrated mill in Austria that uses wood from Europe. Lyocell refers to the fibre produced in Austria with wood pulp from both the integrated mill and produced in other countries [55]. Energy used in the integrated mill is produced with feedstock from the same facility (e.g., bark and black liquor from pulping), external biomass, municipal solid waste incineration and small amounts of fossil fuels [55].

The results come from a review of literature and are colour-coded as follows:

- The impact of wood-based fibres is at least 5% higher than their counterparts
- The impact of wood-based fibres is similar to their counterparts
- The impact of wood-based fibres is at least 5% lower than their counterparts

Table 2.1
Environmental performance of wood-based textile fibres in relation to counterparts, according to cradle-to-gate assessments.

Note: *indicates the weighted average of cotton produced in the USA and China. Colours indicate the wood-based fibres performance, as follows:

Performs worse | Performs similarly | Performs better

TEXTILE FIBRE: Wood-based fibre	TEXTILE FIBRE: Counterpart	GEOGRAPHICAL LOCATION: Wood-based fibre	GEOGRAPHICAL LOCATION: Counterpart	UNIT OF COMPARISON	abiotic depletion	acidification potential	cumulative energy demand	non-renewable energy use	eutrophication potential	freshwater aquatic ecotoxicity	human toxicity	terrestrial ecotoxicity	land use	ozone layer depletion	photochemical oxidant formation	water use	References
Viscose (separate mill)	Polyester	Asia	Western Europe	staple fibre	better	worse	worse	better	worse	worse	better	worse		worse	worse	worse	[55]
	Polypropylene	Asia	Western Europe	staple fibre	similar	worse	worse	better	worse	worse	worse	worse		worse	worse	worse	[55]
	Cotton	Asia	USA/China*	staple fibre	worse	worse	worse	worse	better	better	better	better	better	worse	worse	better	[55]
Viscose (integrated mill)	Polyester	Austria	Western Europe	staple fibre	better	better	better	better	similar	worse	better	better		better	better	worse	[55]
	Polypropylene	Austria	Western Europe	staple fibre	better	worse	better	better	similar	worse	worse	better		better	better	worse	[55]
	Cotton	Austria	USA/China*	staple fibre	better	better	worse	better	better	better	better	better	better	better	better	better	[55]
Lyocell	Polyester	Austria	Western Europe	staple fibre	better	better	better	better	worse	worse	better	better		similar	better	worse	[55]
	Polypropylene	Austria	Western Europe	staple fibre	better	worse	better	better	worse	worse	worse	better		similar	better	worse	[55]
	Cotton	Austria	USA/China*	staple fibre	better	better	worse	better	better	better	better	better	better	better	better	better	[55]
Modal	Polyester	Austria	Western Europe	staple fibre	better	better	better	better	similar	worse	better	worse		better	better	worse	[55]
	Polypropylene	Austria	Western Europe	staple fibre	better	worse	better	better	worse	worse	worse	worse		better	better	worse	[55]
	Cotton	Austria	USA/China*	staple fibre	similar	better	worse	better	better	better	better	better	better	better	better	better	[55]
Viscose	Polyester	-	-	textile fibre			better				better		worse			better	[85]
	Polypropylene	-	-	textile fibre			better				better		worse			better	[85]
	Cotton (conventional)	-	-	textile fibre			worse				worse		similar			better	[85]
	Cotton (organic)	-	-	textile fibre			worse				worse		similar			better	[85]
Viscose	Cotton	-	-	mixed textile waste		better			better	better	worse					better	[86]

While existing assessments can provide an indication of the environmental impacts of different fibres, they cannot be easily generalized:

- **The impact associated with land use can only be compared to cotton,** as both trees and cotton use land (or result in land use change) to produce biomass. However, to produce synthetic fibres it is necessary to extract petroleum, a step that is frequently overlooked during assessments, but that has strong environmental impacts [87]–[89].

- Although not presented in Table 2.1, **processes that use petroleum as input have relatively high impacts on ozone layer depletion** due to the emissions of halon, which is a liquefied, compressed gas used for fire extinguishing, from the crude oil production [55]. This is also an impact that is not always considered. The extraction of petroleum also causes water pollution from surface spills and wastewater disposal and is a cause of drinking-water contamination [90].

- During the use phase, synthetic fibres are also responsible for environmental impacts, especially associated with aquatic toxicity, and possibly to human and terrestrial toxicities. **Microplastics** are considered the worst consequences of the use of polyester [46], but are frequently outside the boundaries during environmental impact assessments. Recent efforts towards the development of pathways that account for the environmental impacts of plastic residues, along with data collection, are likely to change this situation [91].

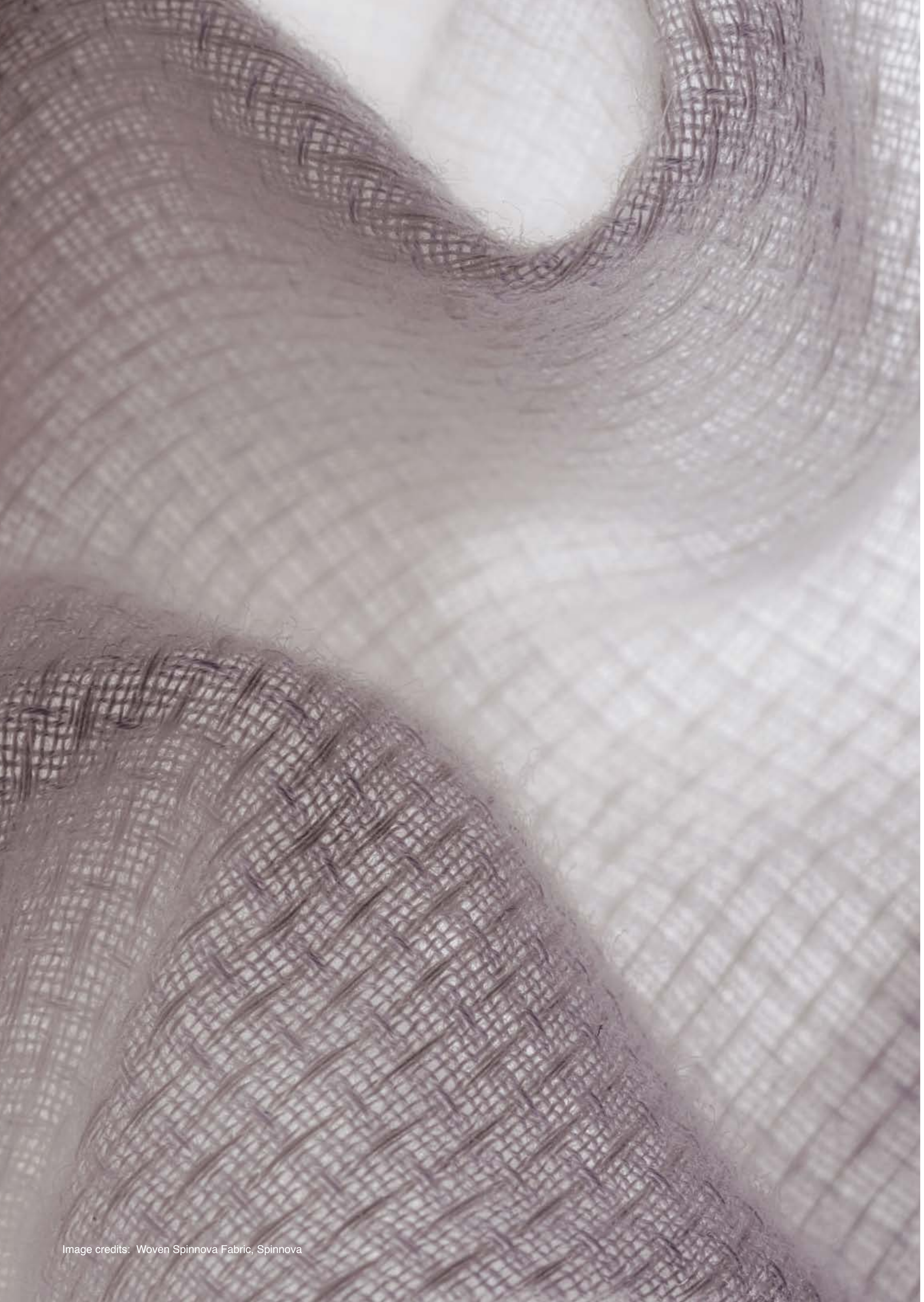


Image credits: Woven Spinnova Fabric, Spinnova

2.2 Latest developments in wood-based fibres

Over the past 20 years the textile industry has developed new production technologies for wood-based textile fibres. This development is linked to interest from fashion brands and consumers in fibres that have less impact on the environment and that contribute to circularity, and improved sustainability.

These new technologies are revolutionizing the textile sector, as consumers will have more options of materials and products, and the production systems could alleviate at least some of the environmental issues from traditional manufacturing processes. In addition to the development of new fibres, research has also focused on the development of recycled fibres.

The new wood-based fibres are not meant to compete directly with synthetic fibres, as these have certain properties that can currently only be achieved with synthetic materials. Despite wood-based fibres not being direct substitutes for synthetic fibres, the industry has been working to improve wood-based fibres' properties to allow for future substitution of synthetics. Currently, the new wood-based fibres represent more options for consumers and can potentially displace cotton (especially from less sustainable sources) and viscose produced using older technologies. Some of the technological developments are presented in **Figure 2.3.**

Photo by: panuwat, Adobe stock

Figure 2.3.

New wood-based textile fibres and potential environmental impacts.

Ioncell-F

https://ioncell.fi/

How is it produced?

Uses several types of raw material, including dissolving and paper pulp. Fibres are produced using ionic liquid as a solvent.
It can be dyed like cotton or viscose.

How can it reduce environmental impacts?[1]

Water and 99% of the ionic liquid can be recycled into the process.

Which fibres can it substitute?

Currently viscose and especially cotton; in the future possibly polyester.

What are possible environmental impacts?[2]

Some ionic liquids have moderate/high toxicity; thus, full recovery and recycling is necessary [92].

Spinnova

https://spinnova.com/

How is it produced?

Kraft pulp is treated through a mechanical process, which turns the pulp into microfibrillated fibre.

How can it reduce environmental impacts?[1]

Does not use harsh chemicals.

Minimal water use.

Evaporated water is the only output, and it is reused in the process.

Minimal raw material losses: fibre yield is 100% (from kraft pulp).

Can be dyed before spinning, helping cut back on water use.

Which fibres can it substitute?

While technically different from any other fibre in the market, the Spinnova fibre can be used in some applications where cotton, viscose, and some synthetic fibres are commonly used.

What are possible environmental impacts?[2]

Use of significant amounts of crosslinkers (e.g., alginate) and binders (e.g., calcium salts) which are hardly recyclable.

Kuura

https://www.kuura.io/

How is it produced?

Does not use dissolving pulp in the process. Fibres are produced using ionic liquid as solvent.

How can it reduce environmental impacts?[1]

Produced in an integrated biorefinery, not requiring transportation of the wood fibre by trucks, ships, etc.

Water and 99% of the ionic liquid can be recycled into the process.

Which fibres can it substitute?

When it reaches the market, it is likely to replace cotton and viscose.

What are possible environmental impacts?[2]

Some ionic liquids have moderate/high toxicity; thus, full recovery and recycling is necessary [92].

TreeToTextile

https://treetotextile.com/

How is it produced?

Produced from dissolving pulp treated in a cold alkaline solution, transforming it into a cellulosic solution. This solution is spun into long filaments and cut into staple fibres.

How can it reduce environmental impacts?[1]

Does not use carbon disulphide or sulfuric acid (as in viscose).

No sulphur emissions during the production.

The water and chemicals are recycled and reused.

Compared to viscose, uses 33% less energy, 80% less water, 70% less chemicals.

Which fibres can it substitute?

Viscose, and certain types of polyester when a strong fibre is not needed

What are possible environmental impacts?[2]

The extent of recovery of the chemicals used in the process, such as NaOH, ZnO and Na_2CO_3 is not known at this stage.

Figure 2.3 is not meant to be a comparison between the different textile fibres, but to point at developments that aim to solve some of the issues related to fibre production for the textile industry.

[1] Based on information available on the websites of organisations involved in the development and manufacture of the fibres.
[2] The described impacts are based on information freely available and do not represent the full extent of the potential environmental impacts as these technologies are still in development.

The technologies to produce most of these new fibres are still in the process of development, and detailed information on fibre properties and the environmental impacts themselves is mostly not yet available. For instance, the extent of recovery of the chemicals used in certain production processes is not yet known at this stage, and it is likely that a certain amount of these chemicals will be discharged into the municipal wastewater treatment. Thus, the environmental impacts of the required chemicals for some of these processes cannot be assessed at this time.

While producing textile fibres using renewable feedstock sources is a crucial part of reducing the environmental impacts within the textile sector, reducing material consumption and increasing recycling of discarded textiles are important steps to reduce the environmental impacts and improve circularity [93]. Even though the recycling of textiles may not be beneficial in some cases, such as when fossil fuels are used as the energy source for the recycling process or when the substituted materials are produced using energy considered “relatively clean” [94], [95], it still has environmental benefits when compared to fibre production using virgin biomass.

According to an LCA performed for recycled cellulosic fibres, virgin cotton and viscose, the recycled fibres had equal or better performance compared to the virgin fibres for the assessed non-climate environmental indicators (i.e., acidification, freshwater toxicity potential, human toxicity potential, eutrophication potential, water use) [86]. In addition, some fibre recycling processes, such as the cellulose carbamate, can be produced in existing viscose factories, which reduces capital investments, making the fibre production even more feasible [94]. **Figure 2.4** presents some of the new fibres that use recycled textiles and materials as feedstock.

Photo by: kucheruk, Adobe Stock

Figure 2.4.
New recycled textile fibres and the potential environmental impacts.

Infinna
https://infinitedfiber.com/

How is it produced?

Cellulose-fibre recycling technology that uses urea to prepare the cellulose to be wet-spun into fibres (known as cellulose carbamate process).

How can it reduce environmental impacts?[3]

Uses old textiles, cardboard or paper as feedstock.

Does not use carbon disulphide.

Uses less water in the production process than cotton.

Which fibres can it substitute?

Cotton, some synthetics and viscose.

What are possible environmental impacts?[4]

Uses large amounts of sodium hydroxide and forms of sodium sulfite [94].

Uses urea in large quantities, which produces ammonia when it decomposes to isocyanate [96]. Because ammonia is extremely soluble in water, there is a risk of contamination if effluents are not treated carefully before discharge. Thus, full recovery of chemicals is necessary.

Refibra
https://www.tencel.com/refibra

How is it produced?

Uses cotton scraps from garment production as feedstock.

Produced in a closed loop.

How can it reduce environmental impacts?[3]

Uses pre- and post-consumer textiles as feedstock; wood comes from sustainably managed forests.

99.9% of the solvent is recovered.

Which fibres can it substitute?

Mostly used to produce lyocell.

What are possible environmental impacts?[4]

Most likely similar impacts as lyocell, such as high energy [61] and water consumption [60].

The technologies for fibre recycling presented in the figure are at different stages of development. Therefore, this is not meant to serve as a comparison between different technologies and products.

OnceMore
https://www.sodra.com/en/gb/pulp/oncemore-by-sodra/the-oncemore-pulp/

How is it produced?

Uses white polyester-cotton blend as main feedstock. The polyester fraction goes for energy production and the cotton fraction is used for new textile fibres. The main output of this technology is 50% recycled dissolving pulp.

How can it reduce environmental impacts?[3]

50% of the feedstock comes from post-consumer recycled textiles and 50% is wood from sustainably managed forests.

Which fibres can it substitute?

It is the technical equivalent to other cellulosic fibres in the market.

What are possible environmental impacts?[4]

Uses dissolving pulp in the fibre mix.

Is associated with the emission of dangerous substances/pollutants [97].

Has low recycling efficiency [97].

Uses energy-intensive process [97].

Circulose
https://www.renewcell.com/en/circulose/

How is it produced?

Uses post-consumer cotton and other cellulose-rich materials to produce dissolving pulp.

How can it reduce environmental impacts?[3]

Uses textile waste instead of virgin biomass.

Has high recycling efficiency.

Lower energy consumption (compared to cotton).

Which fibres can it substitute?

Can be used to produce viscose, lyocell, modal and acetate.

What are possible environmental impacts?[4]

Is associated with the emission of dangerous substances/pollutants [97].

[3] Based on information available on the websites of organisations involved in the development and manufacture of the fibres
[4] The impacts described in this column are based on information freely available and do not represent the full extent of the potential environmental impacts as these technologies are still in development

2.3 Limitations and knowledge gaps

Although there are many technologies for producing new or recycled fibres in various stages of development, the fibre-producing sector still faces multiple challenges. Some limitations to the sustainable development of the sector, from an environmental standpoint are summarized here:

- **Pending approval of alternative solvents:** There are many alternative solvents that can be used in the textile fibre production process and which could help reduce the environmental impacts; however, in many countries these chemicals have yet to be approved for production at large scale.
- **Lack of cost competitiveness:** Most ionic liquids are still not cost-competitive compared to other solvents [92], [98] in part due to limited production and consumption.
- **Difficulty to adopt changes for large manufacturing companies:** Large manufacturing companies may have difficulties to adopt changes in the supply chain due to the scale and complexity of their value chains [99].
- **Fashion industry acceptance:** Because the new wood-based fibres have different properties to traditional fibres such as cotton and viscose, the acceptance of the new materials by the fashion industry can be a constraint to the development of the textile sector, especially if producers do not work closely with designers and clothing brands.
- **No technical substitute:** With some viscose mills expecting to shift their production to lyocell in the near future, this fibre has the potential to increase its market share. However, it is not a technical substitute to viscose, and for this, the fibre properties would have to be improved, especially the issues with fibrillation [38], [57], [60].
- **Business model change needed:** The biggest hurdle for the environmental sustainability of the textile sector is arguably the current business model adopted by the fashion industry, where consumerism driven by “fast fashion” stimulates the notion of garment disposability, resulting in increasing volumes of waste [40], [100].
- **Consumer acceptance and price awareness:** Despite consumer awareness regarding some environmental impacts of textiles, consumers may not want to limit their options or to pay higher prices for more sustainable alternatives [101], [102]. This is due to the high costs regarding raw material and energy, as well as some processes being labour-intensive.

Photo by: triocean, Adobe stock

Assessing the environmental impacts of wood-based textile fibres is difficult due to the complexity of the value chains. This complexity increases as a function of the origin and type of feedstock, the processing technology, the type of textile fibre, the geographical location of mills and refineries, the distance from forest to pulp mill and to refinery, the source and type of energy, the waste management, and the country legislation. Considering this, our study identified two important gaps that should be narrowed to improve the accuracy of environmental impact assessments:

1. **Data for wood-based textile fibres are scarce and incomplete:** Data to perform LCAs of wood-based textile fibres, both from more established technologies (e.g., lyocell) and from newer technologies, are scarce (see Sandin et al., 2019). In addition, databases are incomplete, either not available or only partially available in certain countries (e.g., Asian countries), which adds uncertainty to the results of environmental impact assessments.
2. **Information gap for wood-based textile fibres:** There is a lack of information regarding the technical aspects of the production processes (e.g., input and recovery of chemicals), durability and life expectancy of modern wood-based fibres, as many technologies have not yet reached the market. This gap is likely to be filled as these technologies become available in the market, but for now it hinders a more thorough assessment of their possible environmental impacts.

Modern wood buildings

Photo by: Petair, Adobe Stock

Why is the **construction sector** relevant?

Construction & demolition waste accounts for more than **1/3** EU´s total waste generation and **5 - 12%** of total emissions [105]

Better building construction and use in the EU would influence:

42% of total energy consumption [106]

Buildings are responsible for consuming almost **50%** by weight of all extracted materials [103]

Between **now** and **2050**

The emissions produced by the construction sector between now and 2050 will determine whether we meet **the goals of the 2015 Paris climate accord and prevent the worst effects of climate change,** as the manufacture of building materials makes up

11% of total global greenhouse gas emissions [104]

by **2060**

the world's building stock will double and almost

70% of the global population

is projected to live in urban areas which is expected to **increase the global energy & material demand** [104], [107]

Buildings and construction are responsible for more than

36% of the global energy consumed [104]

3. Modern wood buildings

Combating climate change necessitates a global transformation to decarbonize the world. Buildings and construction play a critical part in this transition due to the need for large GHG emission reductions, and renewable construction materials such as wood are already being investigated as a global solution.

Using engineered wood for constructing buildings helps avoid emissions associated with conventional materials in the short term while also acting as a carbon sink in the long run, as carbon contained in wood is stored over the life of the building [4], [7], [108], [109]. Wood is a renewable resource with one of the smallest carbon footprints of any comparable, newly used building material [110].

The primary factors driving the adoption of engineered wood in new buildings (see Box 3.1) are environmental concerns and a desire for sustainability in the built environment. For instance, Europe´s plan is to become the first climate-neutral continent by 2050. As part of this shift, the EC refers to resource efficiency and the use of low-carbon materials as an alternative for more energy-intensive materials [111], [112].

Photo by: Petair, Adobe Stock

Box 3.1:
Modern Engineered Wood Products: How do they differ?

Modern Engineered Wood Products (EWPs) – what are they? EWPs are value-added wood products made by bonding lumber, veneers, strands or fibres together with adhesives to form building elements. They entered the market in the early years of the twenty-first century, heralding the start of making higher-storey buildings than previously possible [113].

Modern EWPs function as direct substitutes for non-wood construction products due to their more homogeneous technical qualities in terms of load-bearing capability and dimensional stability [9], [114]. Some of the most commonly used modern structural EWPs are cross laminated timber (CLT), glued laminate timber (Glulam), and laminated veneer lumber (LVL) (see Table 3.1), which can replace commonly used materials such as steel and concrete in different applications [115].

EWPs have received recognition for enabling resource-efficient and low-carbon designs, being sustainably sourced and manufactured, accommodating large spans in spaces, and being prefabricated and utilised as hybrid elements when the design requires it.

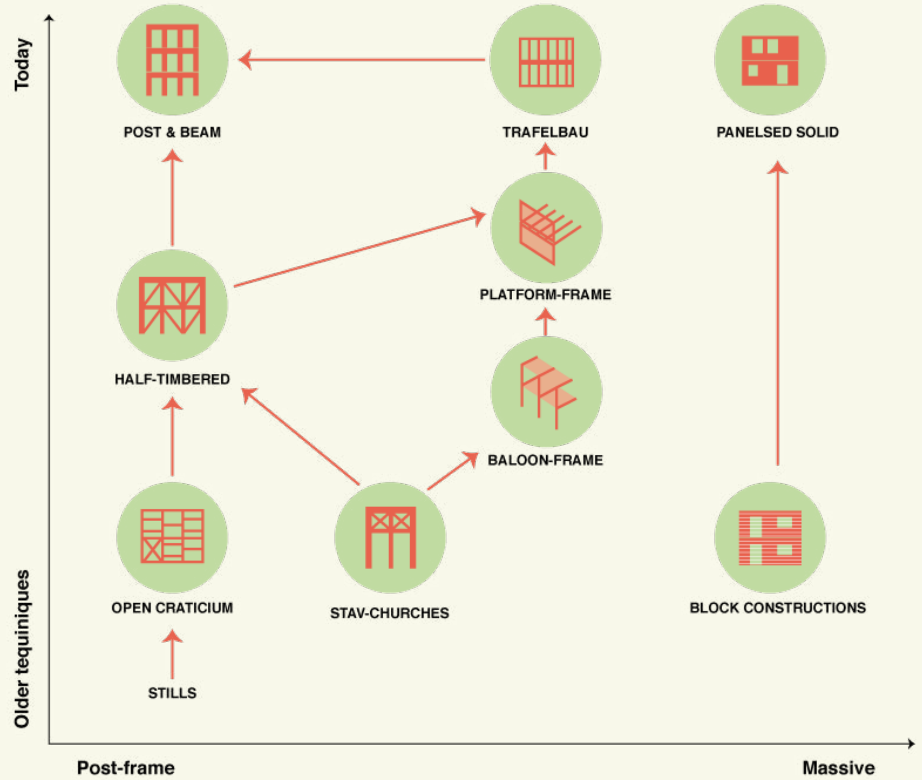


Figure 3.1. Evolution of timber construction (adopted from [117])

Engineered Wood Products

Modern EWPs commonly used in multi-storey wood buildings		
Cross laminated timber (CLT)	**Glued laminated timber (Glulam)**	**Laminated veneer lumber (LVL)**
CLT is formed by gluing cross-angled timber boards together (solid engineered wood panel).	Glulam is made by gluing together a number of graded timber laminations with their grain parallel to the section's longitudinal axis.	LVL is made by bonding together thin vertical softwood veneers with the grain parallel to the longitudinal axis of the section, under heat and pressure.
Traditional EWPs		
Oriented strand boards	**Medium-density fibre boards**	**Particle board**
OSB is formed by compressing layers of wood strands (flakes) and bonding them with resin or another suitable binder.	MDF is created by reducing soft or hard wood pieces to fibres, which are then combined with resin and subjected to heat and pressure.	Particle board is made from wood particles that are pressed and extruded with resin or another suitable binder.

Table 3.1. Selected traditional and modern EWPs

Wood construction systems

Structural systems		
Light-frame construction Balloon and platform framimg techniques	**Post-and-beam** Skeletal framework of massive columns and beams joined together on site	**Massive timber construction** CLT construction, post-and-plank, log construction
		
Prefabrication and automation level		
On-site building Stick-built	**Prefabricated** Elements or sections	**Industrialized construction** Modules
		

Table 3.2. Wood construction systems, (adapted from [116])

Photos by: cherylvb, JoannaTkaczuk, helivideo, eszekglasner, contrastwerkstatt, Jarama / Adobe stock

3.1 Environmental impacts of modern wood buildings

The construction sector can be viewed as an early but slow mover towards reducing its significant environmental impact. Building-related sustainability issues are increasingly being viewed as a critical area for GHG emission reductions.

Standardisation initiatives such as LEED [118], BREEAM [119], DGNB [120] support green construction practices. They have existed for many years and have grown in application and scope in response to current developments. These initiatives facilitated the deployment of life cycle thinking in the building industry in the form of LCA reports or Environmental Product Declarations (EPDs) commissioned by product manufacturers. Several standards have been developed to guide LCAs, these standards include ISO 21930:2017 [121], EN15978:2011 [122], EN15804:2019 [123] and following the principles and requirements described in ISO standards 14040:2006 [14] and 14044:2006 [15], [124]. These standards provide guidance on how to conduct environmental impact assessment of buildings and how to develop EPDs which enable comparisons between building products fulfilling the same function.

In response to current developments in the construction sector, the focus on **the environmental impacts of building materials** from a life cycle perspective (also known as **embodied impacts,** see **Table 3.3**) has received a lot of attention in recent years. Consideration of embodied impacts is critical because it provides a comprehensive picture of the environmental impacts of buildings throughout their life cycle, reduces the possibility of burden shifting between life cycle stages, and guides sustainable building design.

Photo by: bukhta79, Adobe stock

3.1.1 Environmental impacts across life cycle stages

Building embodied impacts include those from material production and transportation, construction activities, component maintenance and replacement, demolition, and demolition waste transport and processing, and are described in EN 15978:2011 substages A1–A5, B1–B5, and C1–C4 [125]. The building LCA stages are illustrated in **Table 3.3**, as described in EN15978:2011 [122]. B6-B7 substages are operational impacts from activities such as energy and water use that occur during the building's use phase and are not covered by this study but are presented to provide a full picture of the impacts.

(A1) Raw material supply

The raw material supply includes all activities performed to raw material sourcing and extraction from the environment. It can typically include forest operations such as site preparation, planting, thinning, final harvest, log transportation to manufacturing sites (see Transportation), and lumber production (if applicable). Wood can come both from primary and secondary forests, as described in **Section 2.1.1.** To avoid issues related to biomass sourcing and ensure that sustainable forest management practices are followed many companies use wood that is certified. These certifications seek to ensure that forest activities provide social, environmental and economic benefits, that competing needs are balanced, and that forest functions are maintained and enhanced now and in the future. A critical aspect is that forests are important carbon stocks, with continuous carbon exchanges with the atmosphere. As a result, forest management practices must be capable of maintaining and expanding forest carbon stocks. Another critical topic in relation to the sourcing of woody biomass is the competition for land use, such as that between forestry and agriculture [127]. This is especially relevant in connection to scenarios that engineered wood demand will grow. This issue is addressed in LCA through the indicator "land use and land use change" and discussed in **Box 1.3.**

(A2, A4) Transportation

Transportation activities relate to raw material transportation from the forest to the mill, internal mill transportation, and construction site transportation. When long distances are involved, emissions may be amplified, accentuating the impacts of the transportation stage [128]–[131]. Transportation impacts are proportional to the distance travelled, the weight of the product, and the fuel consumption of the transportation mode. The use of fossil fuels in transportation is linked to the emission of pollutants into the air (e.g., GHG emissions) [132], [133]. Environmental impacts linked with transportation could be mitigated by diversifying the energy source and mode of transport for forest products [134]. Contributors to the environmental impacts associated with the transportation substages include both the production and combustion of fossil fuels, as well as the infrastructure construction.

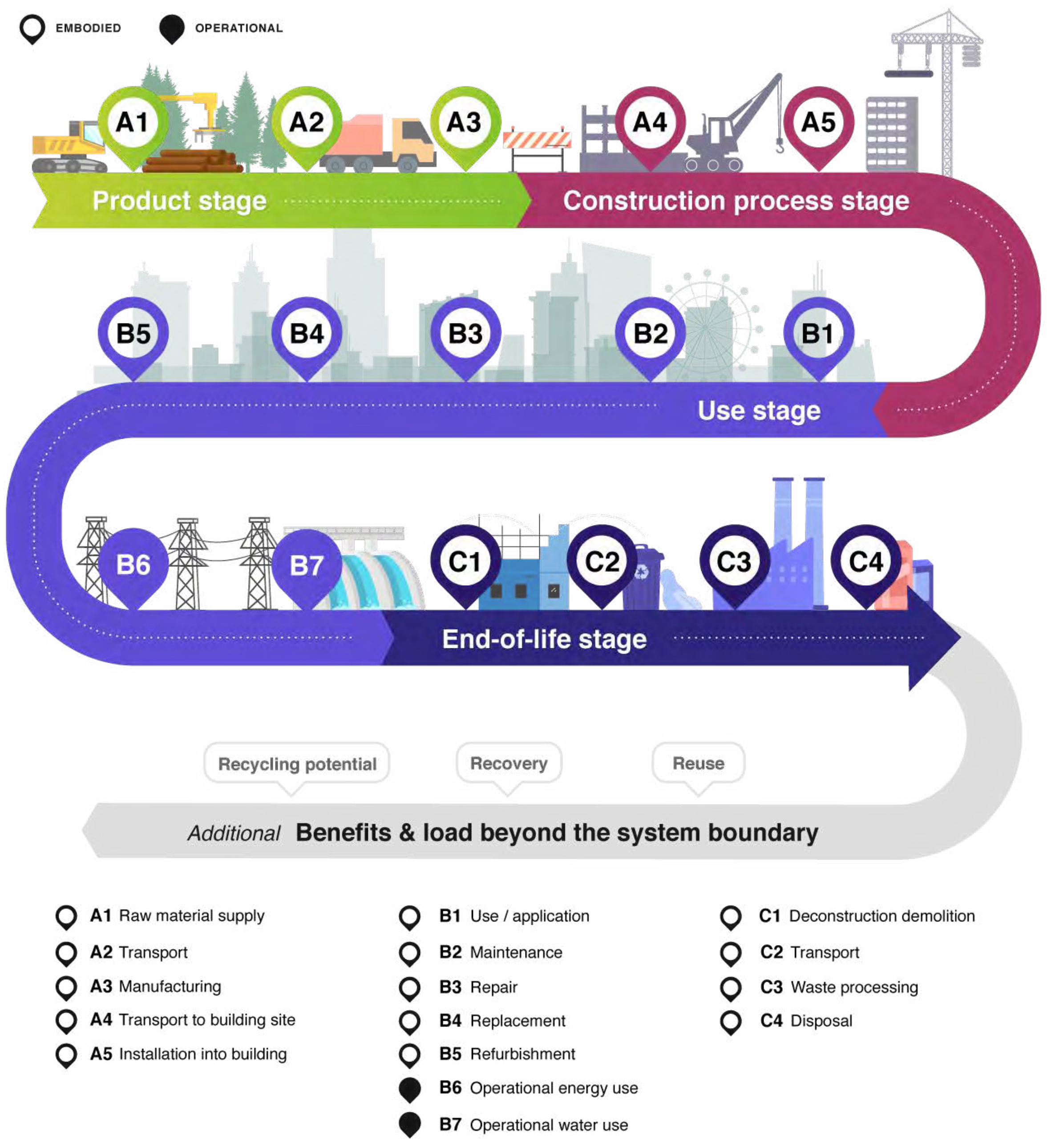


Table 3.3. **Building life cycle stages based on EN15978:2011 (adapted from [126]).**

(A3) Manufacturing

Following substages A1 and A2, materials are transported to final wood product manufacturers for conversion into EWPs. At the product stage, manufacturing (including sawmilling) is a key contributor to the EWPs' life cycle environmental impacts, but it varies according to the LCA modelling choices. The environmental impacts of EWPs at the product stage typically relate to a) the energy required to convert wood into final EWPs and b) the adhesives used to bond the EWPs, which can vary depending on the EWP. The impacts of energy utilization are determined by the amount and type of energy used, the manufacturing conditions (mill capacity), and the transportation distances (and modes of transportation) involved (see Transportation) [135]–[138]. EWPs are manufactured by using adhesives to bond wood boards, veneers, strands, or flakes to make panels or other formed structural products. In general, manufacturing activities include heating, cutting, drying, forming, pressing, and gluing. The production of selected EWPs is presented in **Box 3.1**, and **Figure 3.1** indicates a more detailed description of the CLT production steps.

The general production process of modern EWPs involves (glue) adhesives (e.g., for CLT – at least three bonded single-layer panels arranged at right angles to each other). The use of adhesives aids in the preservation of wood products and their formation into structural products, but their constituents **typically have a negative environmental impact and can limit the end-of-life reuse potential** [133], [139]. Formaldehyde-free polyurethane is typically used in EWPs, while other adhesives (such as phenol-resorcinol formaldehyde, moisture-curing polyurethane and emulsion polymer isocyanate) can be used depending on the technical and wood species requirements [6], [140]. Typically, formaldehyde-based adhesives are associated with toxicity and volatility which lead to acid rain and smog formation, as well as global warming. However, restrictions on their use have been imposed, resulting in a limitation of these adhesives in wood products. These constraints, combined with a general attitude to reduce reliance on petrochemical-based sources, prompted the development of renewable adhesive formulations [141]. Some of them, for example, are lignin-based adhesives (e.g., Stora Enso's NeoLigno®, WISA® BioBond by WISAPLYWOOD) that can partially or completely replace petrochemical-

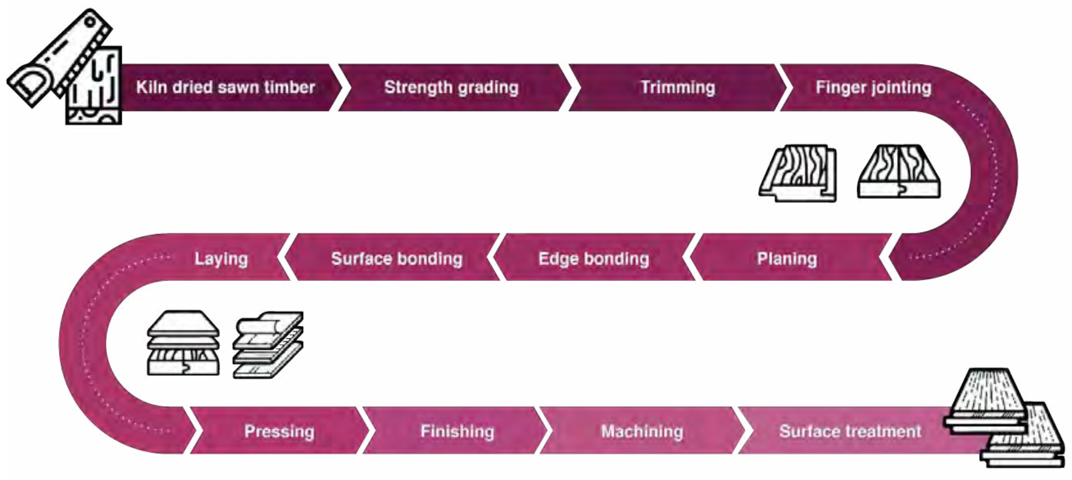


Figure 6. CLT Production steps

based phenols [6]. Recent research also investigates the development of other environmentally friendly solutions such as adhesive-free engineered wood [139].

(A5) Construction

The construction stage includes transportation of materials from factory to construction site (see Transportation) and construction work, such as product installation and groundwork. The installation of wood buildings often requires less energy and produces less waste (when compared to steel or concrete structures) because of the prefabrication possibilities and lighter weight [22], [142], [143]. When compared to concrete and steel structures, the need for less energy and the production of less waste results in less pollution of the air, water, and soil. Furthermore, one of the most common advantages of building with wood is the possibility of a shorter construction time and less noise pollution [144].

(B1 to B5) Use Stage

Use stage includes the application, maintenance, repair and replacement during use phase. EWPs used as load-bearing elements should require no unusual maintenance, repair or replacement. Similar to timber-framed buildings, the building design should include deflection devices to protect the engineered wood elements from direct moisture and decay. Due to the assumption of functional equivalence and, in some cases, a lack of empirical data, **the use phase is frequently omitted from comparative LCAs.**

(C1 to C4) End-of-life

The end-of-life stage typically includes energy use of the demolition equipment, materials transportation from site to waste sorting and processing facilities, to landfill and disposal equipment energy use. Following demolition, wood construction products can be recycled or reused (D stage), disposed of in a landfill, or converted to usable energy (incineration with energy recovery) [116], [145].

The majority of EWPs are incinerated with energy recovery, but some are landfilled or recycled at the moment [146]. During incineration, combustion gases can be released, resulting in impacts such as acidification, eutrophication and smog. Depending on the adhesives used, when incinerated, they can also cause ecotoxicity as well as human toxicity [133]. These impacts, however, are dependent on the specific incineration systems, which can result in differing levels of environmental impacts. Incineration waste is then landfilled, causing land use impacts and soil ecotoxicity.

Landfill is considered the least favourable scenario compared to reuse or incineration [116], [146], [147]. Direct landfill has a consequence on land use and may have an impact on freshwater ecotoxicity. If anaerobic decay is incomplete, as it may be with wood, it will result in long-term carbon storage in landfill [148]. In recycling, and more precisely, when prolonged use is assumed (no additional transformation occurs), the same biomass resource is used, resulting in no new raw material supply impacts [133]. Lastly, compared to its utilization for energy recovery (incineration), cascading allows for the efficient utilization of the resources which contributes to less environmental impacts mainly because it reduces the use of virgin wood in the production chain [149]. The key technical obstacle to cascading wood is ensuring strength and safety in terms of structural safety (standardised criteria to guarantee its mechanical properties) in a subsequent use in buildings [150].

3.1.2 Environmental performance of modern wood buildings and their counterparts

Typically, to determine which of the assessed systems fulfilling the same function has the lowest environmental impact, functionally equivalent buildings or products are evaluated from a life cycle perspective. Studies are site- and design-specific and reflect the study's system boundaries, methodological choices and data used, thus, it is difficult to draw firm conclusions that can be generalized. They can, however, reveal the hotspots and magnitude of the environmental effects of the systems under study.

When looking at the building life cycle stages in combination with the different materials the following should be considered:

(1) Buildings are complex systems involving dozens of products that must meet various technical requirements depending on the building codes. Newly introduced technologies, such as EWPs in multi-storey buildings, usually account for more stringent building codes. In modern wood buildings, the extra requirements usually relate to fire regulations or appropriate acoustic performance and involve the use of larger amounts of e.g., gypsum which mainly contributes to photochemical oxidation and acidification. This results in additional potential environmental impacts derived from the building's material composition [131], [145], [151], [152].

(2) The cumulative energy demand (CED), which is used to determine and compare the energy intensity of processes, appears to be similar or higher with the non-wood counterparts due to the use of a large volume of timber and the associated use of adhesives in the production of EWPs [131], [145], [152], [153]. However, wood buildings consume a far higher proportion of renewable energy than non-renewable energy [136], [145], [152], [154], [155]. This is due to the fact that the mills that manufacture the elements use a greater amount of bio-based energy derived from wood residue for steam or electricity. Concrete's poor performance is commonly attributed to the intensive energy demand during its ingredients' manufacturing, emissions during the cement manufacturing process, as well as extensive materials consumption, requiring significant transportation.

(3) LCAs of wood-based buildings consider all the materials used in the structure, including gypsum, which is typically required for fire safety. This contributes to additional environmental impacts that are not directly related to EWPs but rather to building design regulations. Since modern EWPs are still relatively new products, technological fire protection solutions are expected to be developed, which could potentially improve the environmental impacts of multi-storey modern wood buildings [151].

(4) The inclusion of the end-of-life stage in the LCA of EWPs, as well as the modelled post-use management assumptions (whether wood will be recycled, incinerated or disposed of in landfill), is critical, as they can significantly influence the studied impact categories [146], [153], [156]. The environmental consequences of these end-of-life decisions can be substantial at the building level, accounting for up to 50% of the total life cycle impact of the building [157]. For the case of steel frames, recycling can help achieve considerable reductions in the overall environmental impact [153], [156].

Table 3.4 provides a brief overview of how modern wood buildings perform in relation to conventional buildings in terms of different environmental impact categories.

The results come from the reviewed literature and are colour-coded as follows:

- (pink) The impact of modern wood buildings is at least 5% higher than their counterparts
- (yellow) The impact of modern wood buildings is similar to their counterparts
- (green) The impact of modern wood buildings is at least 5% lower than their counterparts

Table 3.4
Environmental performance of modern wood buildings in relation to counterparts.

Note: Colours indicate modern wood building performance (compared to counterpart) based on LCA results, as follows:

Performs worse **Performs similarly** **Performs better**

Wood-based product or application	Fossil-based counterpart	Geo-graphical location	Unit of comparison	Life cycle stages	acidification potential	freshwater eutrophication	marine eutrophication	ozone layer depletion	photochemical ozone creation potential	abiotic depletion (fossils)	abiotic depletion (minerals)	human toxicity	freshwater ecotoxicity	terrestrial ecotoxicity	marine ecotoxicity	cumulative energy demand	non-renewable energy	water use	land use	references
CLT building	Concrete building	Europe	m² of floor area	ABC	worse	better	better	similar		better	better	better	worse	better	worse			better	worse	[151]
CLT building	Concrete building	Europe	m² of floor area	A1-A4	better	better	worse	better	better	better	better	better	better	better	better			worse	worse [6], worse [7], better [8]	[158]
CLT building	Concrete building	Greenland	m² of floor area	ABC	better	better	similar	worse	better	better	better	better	better	better	better			better	worse	[159]
LVL structural frame	Concrete frame alternative	Australia	entire building	ABC	better	better				better		better						better	worse	[153]
LVL structural	Steel frame	Australia	entire building	ABC	better	better				better		worse								[153]
Massiv– Holz– Mauer (MHM) wall system	Traditional brick wall	Europe	m² of exterior wall	A1-A3				better	better			better								[160]
Roof construction glulam beams	Roof construction steel frame	Europe	Internal roof construction	A, C		better			better							similar	better	better		[156]
Mass timber building	Concrete building	U.S.Pacific Northwest region	m² floor area	ABC	worse		better	similar	similar								similar			[136]
Mass timber building	Concrete building	U.S.Pacific Northwest region	m² floor area	A1-A5	worse		better	similar	worse							similar	better			[131]
Mass timber building	Concrete building	U.S.Pacific Northwest region	entire building	ABC	worse		better	better	worse											[143]
Hybrid CLT with fireproofing	Concrete building	U.S.Pacific Northwest region	m² of floor area	A1-A5	similar		better	better	similar							similar	better			[152]
Hybrid CLT with charring	Concrete building	U.S.Pacific Northwest region	m² of floor area	A1-A5	better		better	better	better							worse	better			[152]
CLT Building	Concrete with steel building	Quebec, Canada	entire building	ABC	similar		better	similar	worse							worse	better			[161]
CLT/Glulam structural frame	Concrete building	British Columbia, Canada	entire building	A1-A4	better		better	better	better	worse		better	better			worse	better	better		[145]

Some observations about the impact assessments of modern wood buildings:

- The most frequently reported environmental impact categories in studies are **acidification, eutrophication, photochemical oxidation, ozone depletion, and to a lesser extent, abiotic depletion, and toxicological effects.**
- The effects of **eutrophication (both freshwater and marine) appear to be less for modern wood buildings,** as the wood building case study performs better in almost all cases. The same pattern holds true for ozone depletion, abiotic depletion and toxicities, where wood outperforms the counterpart in the majority of cases.
- Some indicators, such as toxicities, are only explored in a few studies, limiting the potential for understanding trends. However, **using adhesives containing formaldehyde and other chemical preservatives in the manufacture of EWPs has negative human and ecological impacts.** For example, the human toxicity for the LVL structural frame in which phenol-formaldehyde adhesives are used can be higher than that of the steel counterpart [153].
- Environmental impacts such as **acidification, ozone depletion, and photochemical oxidation are mainly better or similar for the modern wood building case study,** but in general, these categories are attributed to petroleum-based fuels and the gas released into the air during the product's life cycle, whether for transportation or manufacturing.

The results show that no option produces the best LCA-based environmental performance in all impact categories. It can only be observed that modern wood buildings appear to outperform their non-wood counterparts in most impact categories.

[6] Agricultural land occupation
[7] Urban land occupation
[8] Natural land occupation

3.2 Latest developments in wood buildings

Recent years have seen the development of principles which enable the creation of sustainable buildings. This was motivated by the need to make buildings that are socially inclusive, environmentally friendly and economically viable for all. Under general sustainable principles, circularity has also emerged as a critical criterion in building design.

In connection to these sustainable principles in building design, timber buildings have seen significant technological advancements in recent years. These advancements have been primarily focused on prefabrication possibilities [162], which have become more precise, or the combination of timber with other materials such as steel and concrete, which has enabled new possibilities for engineered wood as a building material.

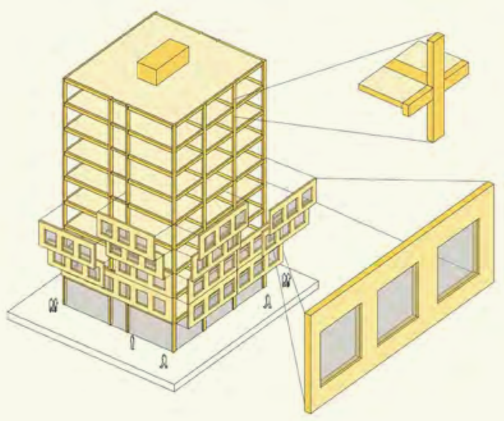
The use of wood in buildings often happens in combination with other materials, for example by incorporating timber-concrete, timber-steel, and timber-concrete-steel elements into their load-bearing system. This hybrid approach to construction enables the best material combinations and techniques to be used while retaining the best characteristics of each material [163]. Building hybridization is influenced by a variety of factors, including regulatory, design flexibility, technical and economic considerations (see **Box 3.3**). Between 2016 and 2019, the number of multi-storey hybrid-timber-based buildings has seen an increase particularly in Europe, North America and Australia, and this trend is likely to continue in the coming years (Salvadori, 2021).

Wood prefabrication possibilities were developed to enhance productivity and deliver consistent, standard solutions that reduce the need for one-off designs. Industrial wood construction enables complex construction assemblies and systems that high-performing environmentally conscious buildings require. Industrial wood construction also enables modular structure dismantling, increasing the circularity of buildings. While prefabrication and modular design are not new concepts, wood prefabrication and modularity have been recognized for their potential to reduce environmental impacts by increasing material efficiency and minimizing waste, shortening construction time, and reducing accidents due to production in controlled environments [164]–[166].

Solutions that relate to automation and the use of robotics play a critical role in digital prefabrication [167]. These technical advancements are part of the industrial revolution of the construction sector, which has significant automation potential but remains one of the least automated industries, relying heavily on manual labour. According to the interviewed experts, the suitability of EWPs for computer numerical control machining, digitalization, transportation and circularity has emerged as a way to boost productivity in the construction sector while potentially indirectly reducing environmental impacts.

Box 3.3:
Innovative modern wood buildings

Build-in-Wood Horizon project (on-going)



ADAPTABLE FOR

MULTI-STOREY
Buildings between 4 and 10 storeys

Different uses
(office, residential, hotel, etc.)

Different european
climatic requirements

Different european
regulatory requirements

Different european
market requirements

Retrofitting to existing buildings
(Facade element only)

OPTIMISED FOR

MAXIMUN USE OF
Timber and Natural material products

Re-use, dia-assembly and recycling

Resource efficiency

Use of components which are readily available from multiple sources

Photo by: © Waugh Thistleton Architects

The Build-in-Wood project and project partner Waugh Thistleton Architects developed a timber building system that optimizes the best available technologies and products and is in accordance with European regulatory requirements. It has the goal of making timber the common choice of building material.

Flexible design for flexible use, and an integrated timber structural system with prefabricated façade panels primarily made of wood are examples of this new design, which allows for the technology to change according to the span of the building. There is digitalization within this project that can be used for the different levels of regulatory requirements that various Members States have.

The focus is on material efficiency, evolution on how timber is approached while maximizing its adaptability and multiple uses. The design includes modular elements that can be plugged into the system, as well as a series of other connection materials to overall avoid full demolition of the building. At the end of their lifetime, all of the systems could be dismantled and in parts reused. The design enables the construction of 4-10 storeys on a building size suitable for most EU countries – something that is more feasible with a “post and beam” structure (also called timber frame structure) than with a modular or CLT platform structure. Significant environmental benefits of this design include the design-for-disassembly feature, which enables the reuse of wood at the building’s end-of-life.

3.3 Limitations and knowledge gaps

Wood is supported as a more environmentally friendly structural material than steel and concrete, which is usually the primary driver for its use in buildings [168]. However, the construction industry develops very slowly, resulting in long timescales for new developments to be implemented, and legislation and authorities frequently failing to quickly adopt new technologies and revived building codes [168], [169]. The most common limitations on the development of modern wood buildings include:

- **National building codes** are regarded as the main impediment to designing buildings with wood as a structural material, although recently national building codes have changed in some countries (e.g., Australia's National Construction Code of 2016, the International Code Council of 2019, and National Building Code of Canada 2020). This issue is related to the most common misconception about wood-based buildings, which are thought to have low fire resistance, thereby limiting the maximum height authorized [168], [170]–[172].

- **Limited wood design expertise** makes the use of engineered wood as a load-bearing material more challenging. This barrier, however, is more social in nature and includes factors like a lack of cooperation for knowledge transfer among actors in the value chain (manufacturers, designers, construction companies), a lack of educational programmes and ongoing training, and a lack of expertise in wood that limits architects' and engineers' ability and willingness to use wood. A lack of expertise also limits knowledge of emerging wood-related technologies.

- **Insurance issues, difficulties to access capital, volatile timber prices, cost of procurement, special fire protection requirements,** and a skilled workforce shortage which can affect construction costs are all associated with economic factors and increased costs [168], [172]–[174].

- **Technical aspects in relation to fire high risk and wood deterioration** due to moisture are considered a barrier for using wood in construction [171], [172].

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Lessons learned

Photo by: CreativePhotography, Adobe Stock

4. Lessons learned

The textile and construction sectors are at the centre of the EU´s transformative Green Deal agenda to reduce reliance on non-renewable, unsustainable resources while also enhancing ecosystem services and sustaining and promoting biodiversity [175]. Many studies have indicated that wood and wood-based products have, on average, lower climate impacts than their non-wood counterparts.

However, given the emphasis on assessments focusing on climate change, there is a risk of overlooking critical impacts that can negatively influence environmental sustainability and contribute to surpassing the planetary boundaries. This study presents the environmental impacts (other than climate change) in current value chains and points out the gap in the scientific literature on trade-offs between various environmental impacts.

LCA results indicate that modern wood buildings have, on average, similar or lower environmental impacts than their counterparts, supporting the recent investments in modern wood buildings across the globe. The overall results for wood-based textile fibres, on the other hand, are somewhat inconclusive. The perceived performance of wood-based textile fibres is highly dependent on the benchmark used in the assessments. However, these findings do not necessarily indicate that wood-based textile fibres should not be considered suitable alternatives to synthetic fibres or cotton from an environmental standpoint. They demonstrate the need for more investment to improve manufacturing processes that are underperforming in terms of environmental sustainability. In addition, considering how the value chain of wood-based textile fibres is spread across the globe, more in-depth assessments that can capture the full value chain are needed.

The improvement of metrics used for quantifying environmental impact indicators, especially in the case of natural systems, is critically important. Standard LCA studies do not represent realistic scenarios for natural systems such as forests, requiring a rethinking of the applicability of these LCA impact assessment methods and indicators. This also relates to the fact that overall sustainability in forest value chains is dependent on a variety of factors such as biomass source, biodiversity and carbon balances.

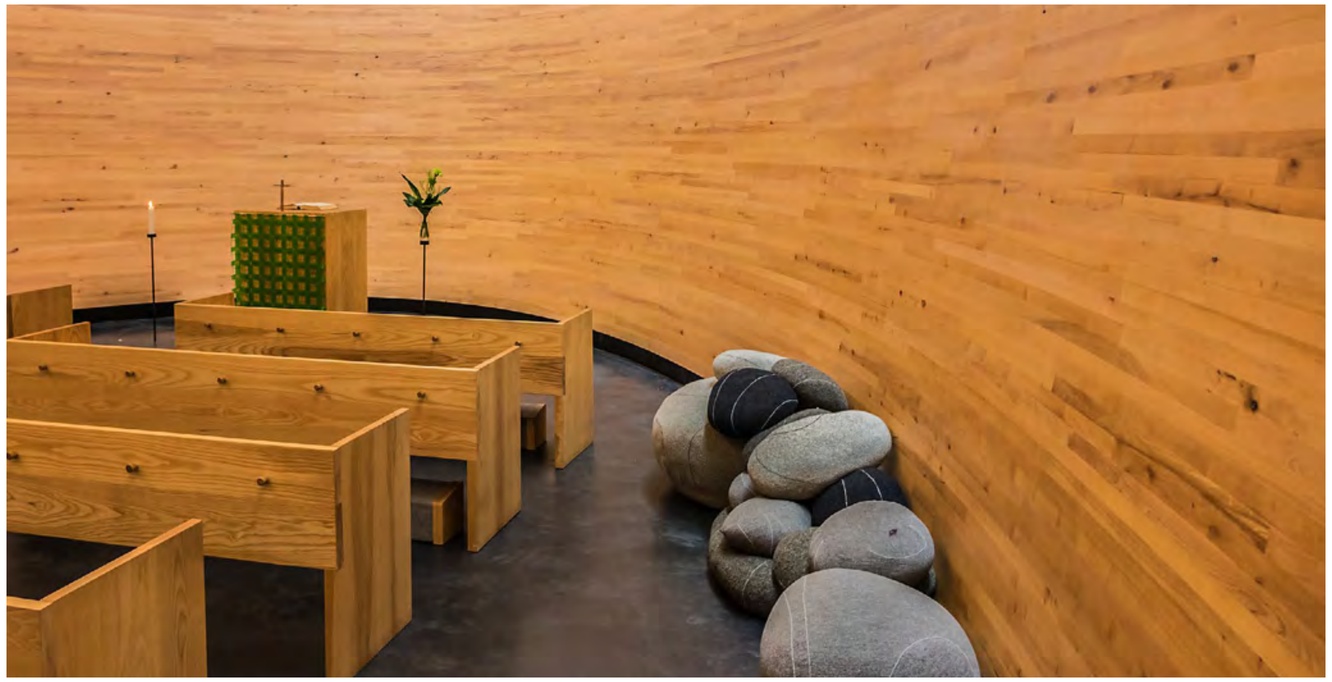
Investment in R&D to support the development of sustainable materials and circularity of new wood products over their entire life cycle is needed. It is important to incorporate environmental sustainability considerations and circularity in the early stages of product design. Investing in product eco-design should consider the environmental impacts over the entire product life cycle and beyond (e.g., reuse, recycling). This includes designing long-lived products that can be repaired or modified for different needs, and that can be fully recycled at the end of the life cycle.

To improve the environmental performance of wood-based textile fibres and modern wood buildings, it is important to avoid the use of harsh chemicals and reduce the overall chemical input. As observed in this study, one of the major sources of environmental impact is associated with the use of solvents, glues and other chemicals in the production of wood-based textile fibres and engineered wood products.

Investment in technologies that aid in further improving energy efficiency and reducing the reliance on fossil energy is required. The two most energy-demanding processes are related to drying of wood, pulp, and wood-based products, as well as the recovery and recycling of chemicals. The development of technologies to improve energy efficiency could target the processes that have additional environmental benefits, such as improving circularity by recycling of chemicals. It is also important to take more steps toward energy self-sufficiency. This includes using a larger share of renewable energy in the processes, preferably from sources other than woody biomass, as well as making use of excess energy from adjoined mills, in the case of integrated mills.

The energy mix used in product manufacturing is an important factor that contributes to improving the environmental profile of both industries. In particular, it is crucial to reduce reliance on fossil energy, and diversify the use of renewable energy sources, especially opting for non-woody biomass. Wood should be used as a raw material for products rather than for energy.

While some commonalities in terms of energy use and source, management of chemicals and eco-design can be observed between the two sectors, the following sector-specific key messages can be drawn out from this report.



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Key messages about wood-based textile fibres

Investing in the management of chemicals used in textile fibre production, by avoiding or reducing considerably the use of harmful chemicals, revamping the production process, and adopting circularity, can minimize the generation of wastewater with toxic chemicals.

Integrating MMCF mills with pulp mills can improve energy self-sufficiency given that modern pulp mills produce an excess of energy from side streams and waste. A decreased use of non-renewable energy sources (e.g., fossil fuels, coal, natural gas) can considerably lower the environmental impacts in the textile fibre production process.

Blending textile fibres of similar nature (e.g., cotton with wood-based fibres) could help **improve fibre recyclability** and, consequently, **reduce waste.** Blending fibres of different nature (e.g., wood-based fibres and synthetic fibres) makes recyclability more difficult and costly due to their different reactions to mechanical and chemical recycling processes. Textile companies should carefully consider which fibres are mixed and opt for options that can improve recycling at the end of lifecycle.

New wood-based textile fibres are not meant to be direct substitutes for existing fibres. Due to their different properties, and because their market uptake is still uncertain, future studies should take these points into consideration when performing calculations on substitution factors and market projections. Calculations on substitution factors should consider which are the alternative wood-based fibres that could be considered technically equivalent to the fibres being displaced, based on available evidence.

Key messages about modern wood buildings

Investing in the development of solutions that will enable the wider **use of environmentally friendly adhesives or technologies that reduce chemical input while maintaining the structural integrity of modern engineered wood.** This will help both reduce the embodied environmental impacts and increase circularity potentials.

Circularity is critical for maintaining the high value of engineered wood in modern wood buildings, but clear plans for integrating it into value chains are still lacking. Strategies for improving circularity at the product and building levels are critical for a better environmental performance. For engineered wood products, it appears that there are no established mechanisms such as secondary value chains that can enable circularity or commitment to design buildings for disassembly.

Building eco-design has been identified as a critical element for modern wood buildings that should be incorporated early in the design process to ensure overall sustainability and support increased wood utilization efficiency at end-of-life. To accomplish this, **collaborative working methods and bridging of designers, manufacturers and construction companies** is essential.

The current emphasis on modern wood buildings is motivated by a desire to reduce carbon emissions. Because all sectors must focus on reducing carbon emissions, **the focus for modern wood buildings should be expanded to include reducing other environmental impacts and improve overall sustainability.**

Methodology

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Methodology

This study was conducted following a qualitative approach, based on mixed sources, in two stages: (i) review of scientific and grey literature, review of websites of organisations working on the development and manufacture of products; and (ii) interviews with experts active in the wood construction and textile sectors.

Literature review

A literature review on the current scientific understanding of the potential environmental impacts of wood-based textile fibres and modern wood buildings was carried out. The purpose of the study was to provide evidence on how wood-based textile fibres and modern wood-based buildings perform in comparison to functionally equivalent buildings and materials in categories other than climate change. Most of the literature was obtained from online databases such as Google Scholar, JSTOR and Elsevier Scopus using blocks of keywords.

The search for literature on wood-based textile fibres used the following blocks of words:

Block 1: environmental impact OR environmental assessment OR LCA

Block 2: textile fibres OR viscose OR lyocell OR tencel OR modal OR man-made cellulosic fibres

The search for literature on modern wood buildings used the following blocks of words:

Block 1: environmental impact OR environmental assessment OR LCA OR comparative building LCA

Block 2: mass timber building OR CLT building OR high-rise timber building OR engineered wood OR laminated timber

The general criteria for including literature were based on the following:

Objective: studies should present results of environmental assessment of wood-based products from the wood construction and textiles sectors, including indicators other than "global warming potential".

Studies should present results for both wood-based products and their counterparts.

Location (i.e., where the production of the functional unit occurred): Europe, North America, Asia and Australia.

Method: based on experimental studies, systematic reviews or meta-analysis.

Publication date: since 2010.

Language: English.

The review covered a total of 60 studies (35 studies for modern wooden buildings and 25 studies on wood-based textile fibres). For wood-based textile fibres, the few reviewed studies covering relevant environmental impacts other than "global warming potential" focused on Europe and Asia. Most of the reviewed studies on wood buildings focused on case studies from Europe and North America, and very few were from Asia.

Based on the LCA results presented in the literature, we assessed how the targeted units of analysis for the two sectors (i.e., wood-based textile fibres and modern wood buildings) fared in terms of environmental impacts in comparison to benchmarks. The results of this assessment are presented in Tables 2.1 and 3.4 (for wood-based textiles and for modern wood buildings, respectively), indicating if the targeted units of analysis performed better, alike, or worse than the counterparts. Information from websites of organisations working on product development in the two sectors was also analysed. The list of organisations was based on expert knowledge, including well-known companies and research institutes that were active in the development of new technologies.

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Expert interviews

Between June and August 2021, 20 interviews (13 interviews with experts on wood construction and seven with experts on textiles) were performed. The interview sessions lasted for about one hour. The anonymised information on the geographical location of the experts, their position in the value chain, as well as their occupation is presented in **Table A1.**

Occupation of experts	Expert position in the value chain	Countries
Architect Chief Executive Officer Development Manager Director of Materials Strategy Director of Sustainability Head of R&D Life Cycle Assessment practitioner Product developer Researcher Senior Structural Engineer Sustainability expert University professor	Academia and Research Consultancy Industry Product development	Austria Canada Finland Germany Sweden United Kingdom United States

Table A1. Information on expert interviews

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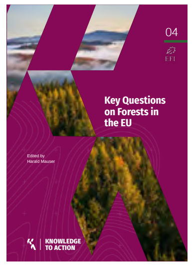

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