SCIENTIFIC BACKGROUND PAPER

Sustainable use of wood in construction, textile and packaging sector towards a carbon-neutral bioeconomy

July 2024

Editors: Elisabeth Gerhardt, Martin Greimel

Contributing Authors:
Mohammad Azarmi, Alex Berg, Sonja Geier, Elisabeth Gerhardt, Martin Greimel, Daniela Groiß-Fuertner, Felipe Guzman, Henrik Heräjärvi, Anu Laakkonen, Joona Lampela, Rahman Mostafizur, Niels Müller, Sabine Ober, Tahiana Ramananantoandro, Andry Clarel Raobelina, Martin Riegler, M. Jahan Sarwar, Pascal Wacker

BOKU UNIVERSITY

IUFRO
Interconnecting Forests, Science and People

Forest Fund
Republic of Austria
An initiative by the Federal Ministry of Agriculture, Forestry, Regions and Water Management

SCIENTIFIC BACKGROUND PAPER

Sustainable use of wood in construction, textile and packaging sector towards a carbon-neutral bioeconomy

July 2024

Editors: Elisabeth Gerhardt, Martin Greimel

Contributing Authors:
Mohammad Azarmi, Alex Berg, Sonja Geier, Elisabeth Gerhardt, Martin Greimel, Daniela Groiß-Fuertner, Felipe Guzman, Henrik Heräjärvi, Anu Laakkonen, Joona Lampela, Rahman Mostafizur, Niels Müller, Sabine Ober, Tahiana Ramananantoandro, Andry Clarel Raobelina, Martin Riegler, M. Jahan Sarwar, Pascal Wacker

This report is part of the project “Wood for Globe - Towards a Global Wood Policy Platform: Sustainable Wood for a Carbon-Neutral Bioeconomy", led by IUFRO and funded through the Forest Fund of the Republic of Austria”. The views expressed within this publication do not necessarily reflect the views of IUFRO or the official policy of the governments represented by these institutions/agencies or the institutions to whom the authors are affiliated.

Contents

Introduction

The currently dominant approaches to bioeconomy focus mainly on the replacement of non-renewable material (e.g. fossil resources, scarce metals) by bio based or renewable raw materials. As the production of biomass is restricted, a replacement is limited by the area available to produce it. A full substitution of non-renewable material with biomass would need three to four times the surface area of the earth. Therefore, the holistic concept of a transformative bioeconomy calls for a social change. This means that viable solutions must be found accompanied by a growing awareness of the connections between humans, nature and technology and an increased acceptance of the necessary transformation steps.

The bioeconomy is designed to reduce the entropic degradation of natural resources through a consumption-minimized and circular utilization of feedstock, based on transdisciplinary knowledge-creation through plural ontologies of global lifeworlds, and aimed at intergenerational justice and fairness across the world[1].

The most promising material in this context is wood. Not only the sequestration and storage effect of carbon dioxide over a long-term period (like in wooden buildings) is enormous, but also its properties are very versatile, so that different applications (housing, furniture, adhesives, advanced biomaterials, biochemicals etc.) are possible. Furthermore, forests provide also multidimensional, non-quantifiable ecological and social functions. Therefore, profit maximization based on economic rationale urgently needs to be supplemented by further indicators and objectives.

Likewise, the Seoul Forest Declaration[2] identified an urgent need for action and pointed out the most important steps for the future: the integration of different institutions, sectors and stakeholders fostering sustainable production and consumption as well as implementing circular bio-economy principles and the investment in forest respectively landscape restoration.

Sustainable production and consumption of wood promote forest conservation, enhance the value of forests and mitigates climate change. Building and living with wood respond to an increased demand for renewable materials and provides impetus for green recovery.[3]

In order to encourage the transformation to a holistic bioeconomy, policy has to provide the necessary framework conditions. Background knowledge and information for the development of a a long-term vision towards a Global Wood Policy Platform is generated by this report. It provides a synthesis of latest scientific innovations and knowledge in view of supporting a transition to an increased use of wood as a renewable, climate-neutral resource in circular and resilient economies, considering also possible trade-offs.

As “wood” can provide a huge variety of applications in the future we decided within the project team to focus on following two topics: “wood in construction” (in the building sector) and “wood fiber in the textile, packaging and construction sector”. Six senior and seven junior scientists

---

[1] Definition by Bernhard Kastner (2023), Centre for Bioeconomy (BOKU University)

[2] https://www.cepf-eu.org/news/seoul-forest-declaration-xv-world-forestry-congress

[3] Ministerial Call on Sustainable Wood (03.05.2022, at the XV World Forestry Congress) - https://www.fao.org/3/cc0247en/cc0247en.pdf

coming from different countries across the world (Austria, Bangladesh, Chile, Finland, Madagascar and Switzerland) were selected to contribute to this scientific report. Each of them provided their expertise highlighting “Best practices” (in terms of carbon-neutral bioeconomy), the “Transferability” respectively applicability in other countries (especially in Asia, Latin America, Africa) as well as “Key messages and Recommendations”.

CHAPTER 1:
WOOD IN CONSTRUCTION

Sustainable wood construction value chains in Finland – Best practices for innovative wood use

Henrik Heräjärvi, Anu Laakkonen, Joona Lampela, Mohammad Azarmi
University of Eastern Finland (Itä-Suomen yliopisto), School of Forest Sciences, Kuopio, Finland

Abstract

Production and use of materials for construction sector are responsible for catastrophic environmental impacts, which are expected to further increase due to population and wealth growth. Thus, even little steps towards construction practices with smaller environmental impacts may have a big national or global effect. While new buildings are needed anyway, the associated environmental impacts should at least be minimized. Wood, as a renewable solar energy empowered material, causes currently less environmental impact than the other major construction materials do. Wood is, therefore, an existing solution in reducing the environmental load of the construction sector. Wood is also a benchmark among building materials in the climate friendliness, thus speeding up the emission reductions in steel and concrete manufacturing. In Finland, approximately 90% of single-family houses, 70% of attached low-rise houses, 40% of schools and kindergartens, and 5% of multi-floor apartment buildings are nowadays built with wood as a load-bearing material. Broader application of engineered wood products has brought wood back in the larger buildings, while their construction was dominated by concrete and steel for decades. Finland has a broad scientific, educational, and business expertise related to using wood in construction value chains. We identified knowledge transfer and education export possibilities for the Finnish wood construction expertise in the Global South countries, to support their goals of increasing prosperity and well-being based on sustainable use of natural resources. Sufficient resources of certified timber enable viable forest-to-building supply chains with reasonable sized investments, thus contributing to local employment, improved living conditions, and broadening the sources of income. There are, however, societal, regulative, economic, and technical issues that must be accounted for prior to the transformative change in construction sector takes place in Global South countries.

1. Forest-based bioeconomy in Finland

1.1. Forests and their use

Finland has a long history of utilizing its forests and forest resources, mainly wood, in creating economic prosperity and wellbeing for the country. The forest sector, including forestry and forest industries, has been the backbone of the Finnish national economy for centuries. At its best in the late 1800s, forest products made up 80% of the export value from Finland, the current percentage being approximately 20. Recent developments in bioeconomy are again highlighting the importance of forests for Finland and its national economy. Accordingly, policies, strategies, and funding instruments that support the development of a bio-circular economy have been designed and deployed in Finland. For example, The National Forest Strategy 2035 (Ministry of Agriculture and Forestry, 2023) and the updated Finnish Bioeconomy Strategy (Finnish Government, 2022) guide the use of forests and forest resources. In these strategies forests are expected to continue generating economic prosperity and wellbeing for Finnish society and the economy while also offering ecological benefits as carbon sinks and biodiversity conservers. The strategies point out wood construction, and new wood-based textiles and packaging as important new developments in creating value and climate benefits, as they can substitute fossil-based, or energy or resource-intensive materials.

Approximately 77% of Finland's total area (land + water) is forest. The forestry land area (including productive forest land, poorly productive forest land, unproductive land, and forest roads, depots, etc.) in Finland is 26.3 million hectares, covering 86% of the land area. Forest land covers three-quarters of forestry land. Poorly productive forest land accounts for 10% and completely or nearly treeless unproductive land 12% of forestry land. Peatlands account for one-third and mineral soils for two-thirds of forestry land. Half of the peatlands were drained between the 1950s and 1980s, causing a significant increment in peatland forest growth. The annual increment of growing stock is approx. 103 million m^3 and annual roundwood removal varies between 60 and 90 million m^3. The main figures for growing stock volume and wood flows from Finnish forests in 2021 are illustrated in Figure 1. Annual increment has exceeded the removal every year since 1970, and the growing stock volume has simultaneously increased from approx. 1.5 to approx. 2.5 million m^3. Of the growing stock volume, 50% is Scots pine, 30% Norway spruce, and 20% deciduous species, mainly two birch species and aspen. Slightly over 50% of forestry land is owned by private people, and over 80% of all roundwood purchased by the forest industry comes from these forests (Karppinen *et al*., 2020). The rest are owned by the state (35%), companies (8%), and other institutions (6%), such as municipalities, parishes, and various associations. The average size of a privately owned forest property is 30 hectares. On average, 150 million tree seedlings are planted every year. There are approx. 600,000 private forest owners in Finland, and approx. 730,000 Finns (the total population in FIN is 5.5 million) get income from forests annually.

In Finland, 2.9 million hectares of forest land (including 1.7 million hectares of productive forest land and 1.2 million hectares of poorly productive forest land) are protected, comprising 13% of the forest land. Of this, forests in statutory protected areas covered 2.5 million, and in biodiversity conservation sites in commercial forests 0.5 million hectares. In addition to the protected forests, the rest over 20 million hectares of commercial forests are an important tool to protect biodiversity. The ecological values of each stand (and even the neighbouring stands) are evaluated before forest management practices such as thinning or final felling are allowed to take place. Untouched zones of 20–30 meters in minimum are left on shores of water areas, around springs, brooks, and other ecologically sensitive habitats. The biodiversity values have been considered systematically in managed forests for approximately 30 years, and the effects gradually become visible.

The forest sector is an important part of the Finnish national economy. For example, in 2021, the value added of the forest sector was 9.3 billion €, which comprised 4,3% of the total value added of the Finnish national economy. Nearly all forest industry products are exported, and thus the exports of the forest sector were 19% of Finland's total goods exports of which the pulp and paper industry accounts for 13% and the wood products industries 6%. The forest sector employs around 61,000 people, including employees and entrepreneurs. In addition, the forest sector is the most important bioeconomy sector accounting for over 30% of the total value added of the Finnish bioeconomy (Natural Resources Institute Finland, 2024). The forest bioeconomy, however, is more than just the forest sector. In addition, nature tourism, recreation, hunting, collection of non-wood forest products, and other forest services as well as energy and construction sectors are connected to the forest bioeconomy as they utilize forest and forest resources in their operations. For example, wood-based bioenergy, including forest chips, black liquor, and other industrial by-products and residues, is a significant source of energy accounting for around 30% of total energy consumption in Finland.

The wood products and pulp, paper, and paperboard industries use approximately 70 million m^3/a of wood in Finland. The wood-construction industries use approximately 40% of this wood and the pulp, paper, and paperboard industries use approximately 60%. The wood-based textiles and packaging industry both utilize the wood used by pulp industries. Sawlog harvesting volume has been relatively stable in Finland for the past 35 years, and the moderate year-to-year variations have been caused mainly by fluctuations in roundwood prices. The volume of harvested pulpwood, on the other hand, has increased considerably due to increased kraft pulp production and decreased and finally ceased import of pine and birch pulpwood from Russia. This can be seen also from the harvested species distribution that indicates increments in Scots pine and birch removals – both used in large volumes in kraft pulping.

More information on Finland's forests and bioeconomy can be found in the publicly available National Finnish Statistical Yearbook of Forestry (Finnish Statistical Yearbook of Forestry, 2023).

Best practices
Sustainable forest management practices and forest certification

Finnish forests are managed according to tens of different silvicultural regimes based on forest owner's preferences, site type, tree species, growing stock structure, biodiversity conservation needs, etc. The minimum levels of sustainable forest management and biodiversity conservation are set by forest and environment protection laws, still, the voluntary environmental protection practices go beyond the levels required by laws. For example, there are two voluntary protection programmes, METSO biodiversity, and Helmi habitat, through which forest owners can protect their forests. In addition, the commercial forests are managed according to the 'Best Practices for Sustainable Forest Management' which are published, regularly updated, and implemented via forest owner advising organizations. Approximately 90% of Finnish commercial forests are PEFC (Programme for the Endorsement of Forest Certification) certified and 10% FSC (Forest Stewardship Council) certified. Most FSC certified forests overlap with the PEFC certified ones, i.e., there are two certificates in the same forest. Thus, the total share of certified forests is not 100% but just a little more than 90% of the commercial forest area.

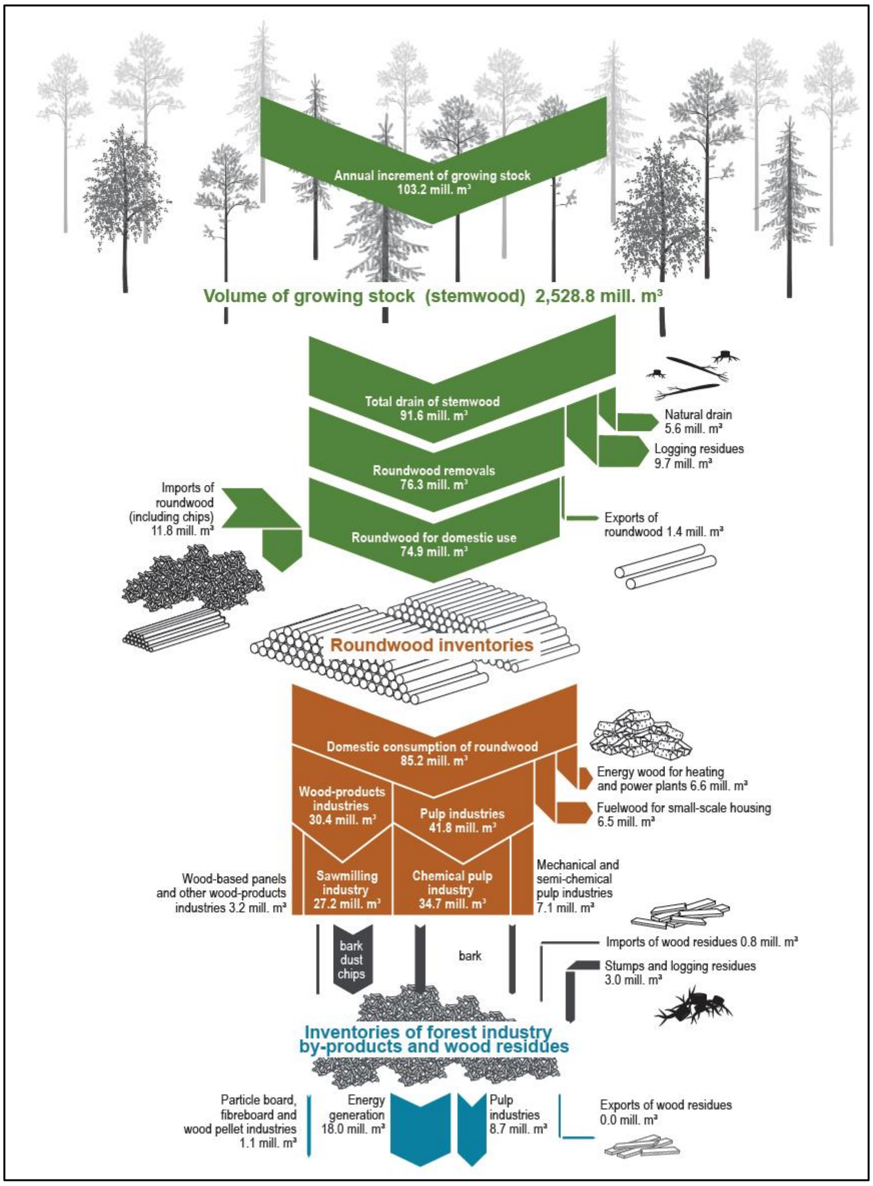


Figure 1: Wood flows in Finland in 2021. Source: Finnish Statistical Yearbook of Forestry (2023).

1.2. Policy support for forest products

The *EU's Biodiversity Strategy* (EC, 2021a) and the renewal of the *EU's Forest Strategy* (EC, 2013, renewed EC, 2021b) may have both short-term and long-term impacts on the availability and supply of wood-based materials. They may indirectly affect the substitution of fossil-based materials and products with wood-based materials and products, and the competitiveness of virgin raw materials versus recycled materials.

The National Forest Strategy 2035 (Ministry of Agriculture and Forestry, 2023) is a statutory forest programme, whose purpose is to guide Finnish forest policy. The vision of the National Forest Strategy 2035 is to gain growing wellbeing from forests and for forests, which is accomplished through three key projects aiming at increasing forest growth, carbon sequestration and timber output, improving biodiversity in commercial forests, and creating a competitive environment for a responsible forest sector that is capable of renewal. The updated *Finnish Bioeconomy Strategy* has a vision of 'Sustainably towards higher value added' and an aim to create economic growth and jobs with sustainable and highest possible value-added products and services (Finnish Government, 2022).

In both strategies, the use of wood in construction applications, textiles, and packaging value chains, is seen as important in fulfilling the aims of the strategies. The possibilities related to developing new technologies and business concepts around these new higher value-added wood-based products and applications are promoted in replacing fossil-based raw materials in the global textile, food, and beverage industries and their value chains. In addition, wooden buildings and wood-based construction materials serve as long-term, stable, and virtually indefinite carbon storages with significantly lower associated biotic and abiotic risks compared to forest carbon storages. Similarly, efficiently used wood-based materials replace fossil-based materials, causing significant substitution impacts by decreasing fossil carbon emissions. It is evident that the total above-ground wood-based carbon storage size, *i.e*., trees and harvested wood products (HWP), can be increased and maintained more by sustainable use of wood than without it.

Finnish forest and bioeconomy strategies consider collaboration and stakeholder perspectives as part of social sustainability and responsibility. Both strategies aim at increasing wellbeing and value added from forests through, *e.g*., rural development, providing job opportunities, and increasing the knowledge and competence of forest experts. In addition, the Finnish forest industry has made sustainability and responsibility commitments based on the United Nations' (UN) Sustainable Development Goals (The Finnish Forest Industries Federation, 2020).

The policy basis for the development of the use of wood in the built environment in Europe is written in the targets of the *EU Bioeconomy Strategy* (EC, 2012, updated 2018) and the *EU Action plan for the Circular Economy* (European Environment Agency, 2015). The *European Green Deal*, aiming as a flagship to lead to European Climate Law, was published in 2020 to make Europe climate neutral by 2050 (EC, 2019). This includes an ambitious revision of 2030 climate targets by a significant reduction of greenhouse gases. The Green Deal is expected to become the leading pan-European programme in the shift from the linear to the circular economy.

Best practices
National policy support for wood utilization

Finland has strong governmental, institutional, and policy support for using wood in both the manufacturing of chemical pulp fiber and packaging materials, such as different paperboard grades, and long lifecycle applications, such as wood-based construction value chains. Support for manufacturing wood-based fibres to be used in textile applications is increasing. Two governmental strategies are supporting and guiding wood use with sections related to using wood in construction applications, wood-based textiles, and the packaging sector. In addition, there are several other supporting initiatives fostered by ministries and other institutions.

2. Wood construction sector

2.1. Definition of wood construction

There are optional ways to define wood construction. Definitional country-to-country differences complicate the comparisons of statistical data, such as the number of ‘wooden’ houses built. One way to define wood construction is to concentrate on structural materials: if the load bearing structure of the building is made of wood, it can be called a wooden building. In this case, however, wood can represent only a minor share of all materials used in the building. Another way to define wood construction is to focus on buildings with wood as a dominant material, in which case the load bearing structures can be made of other materials such as steel or concrete, as well. In Finland, the statistics are based on the first option: a building is classified as a wooden one if its load carrying structures are made of wood.

2.2. Acceptability and policy support

The construction sector has huge economic, employment, and environmental impacts in the EU. Therefore, even small development steps improving the sector’s performance, for example replacing materials with higher emissions by use of wood, can result in great torque for the environmental performance of the entire construction sector in the bio-circular economy.

The European wood construction market is changing, driven by several sustainability-related market forces.

- Firstly, the sustainable development goals (decreasing the use of non-renewable materials, carbon footprint and handprint of the construction materials, energy efficiency requirements, etc.) guide the construction, land use, and climate actions towards increased use of wood as a construction material.

- Secondly, younger generations are increasingly aware of the environmental impacts of their consumption behavior. While their share of the whole consumption is still modest, one can expect radical changes to take place during the coming years and decades.

- Thirdly, wood construction materials, structural systems, and resource efficiency have developed tremendously during the last twenty years. This development enables a high degree of pre-fabrication that minimizes the on-site assembly time, high precision and standard quality caused by automatized component manufacture, 100% dry prefabrication-transportation-assembly chain, predictable high performance allowing demanding structural applications such as high-rise buildings, as well as innovative architectural designs not only in small buildings but also in large ones.

- Fourthly, resulting from all previous megatrends, the public attitude towards wood construction has turned positive, even trend-alike, while still some decades ago wood was often treated either as a material of low-income builders or lower quality buildings. Nowadays wooden buildings are marketed by arguments of environmental friendliness, good indoor air quality, architectural versatility, fire safety, and naturality of the material.

Based on several good and bad examples worldwide, forests thrive as long the precondition of value creation for forest owners is fulfilled: raw material produced is an investment that must have an economic value. The value is mostly created by wood product industries that buy the saw logs, use them in primary and further processing, and allocate the side streams to viable by-products. Since solid wood products are mostly consumed in construction value chains, the construction sector is an elemental contributor to the growing stock development. The net carbon balance of wood utilization suffers from a small share of long-lifecycle applications of harvested wood. Hence, wood use in construction applications, most of which represent a long lifecycle, improves the acceptability of wood utilization from the climate viewpoint.

According to the World Green Building Council, buildings and built environment are responsible for 39% of global human-derived climate effects. Furthermore, construction activities cover half of the exploitation of natural resources and produce 40% of waste globally. Therefore, even minor improvements in the sustainability of construction activities make a big environmental difference. Wood contributes to this development greatly, since it is the only renewable construction material available in industrial volumes, and features many other indisputable sustainability arguments, too. Recent research indicates that wooden interior materials have positive psycho-physiological effects on human well-being. Such findings may turn into powerful arguments for the wider use of wood in homes and offices.

At the EU level, construction & demolition and new bio-based products represent two of the five priority areas in the EU Action Plan for the Circular Economy (European Environment Agency, 2015). The transition towards a bio-circular economy is facilitated by conscious management and intelligent utilization of natural resources, which aims at boosting Europe's competitiveness, creating business opportunities and jobs, and increasing the overall sustainable growth and wellbeing of the European citizens. Shift from product-based to functional economy, in which functions of, for example, residential houses and public buildings are offered for the end-users, requires developed business models, as well as streamlining the regulatory framework. From the viewpoint of wood construction, the key initiatives operationalizing the European Green Deal are the *New European Industrial Strategy*, *Circular Economy Action Plan*, *Renovation Wave Strategy*, and new *Strategy for Sustainable Built Environment*, including *Construction Products Regulation* (Norton, 2021). *New European Bauhaus Initiative*, *Ecodesign Direction and Sustainable Products Initiative* and *European Framework for Life Cycle Analysis* (LCA) are proceeding (Kleinschmit, 2021; Norton, 2021).

Wood is acknowledged as a good construction material in the EU policy programmes and initiatives, but it must compete in products and their use on a functional and material-neutral basis, in the context of *Neutral Building Competition Policy and Construction Products Regulation* (Wall, 2020). Hence, functionality, assessed by energy efficiency, climate friendliness, recyclability, or some other feature, should be the main attribute instead of the material itself. Subsequently, there cannot be an EU policy promoting the use of wood over other materials, and even using the word promotion may be problematic. Increased wood use requires a function-based approach to policy-making at the EU and national levels, thus highlighting the aspects of the hybrid use of wood and other building materials.

The Regional Forest Programmes, prepared by Finnish Forest Centre (www.metsakeskus.fi/alueelliset-metsaohjelmat), feature a sub-chapter 'New wood-based products'. All 14 Finnish regions emphasize the role of wood construction as a tool to develop the forest-based value chains and livelihoods in the region, either as a main tool or among the most important ones. This reflects the high hopes set for wood construction by the forest sector, as well as its overall visibility throughout the country.

2.3. Sustainability

The key targets of the EU's Circular Economy Action Plan cover a sustainable products policy framework to promote the best materials and reuse/recycling options, legislative proposals for sustainable green claims with methods for Environmental Product Declarations (EPD) and Product Environmental Footprint (PEF), as well as a regulatory framework for certification of carbon storage and removals. Non-biocide-based durability improvement methods of wood products, *i.e.*, wood modification, represent high potential to reduce the environmental impacts of wood products exposed to water, soil, or weather exposure. To retain their environmental performance in the circular economy framework, the modification treatments should not compromise the recyclability of modified wood products in comparison to untreated or preservative impregnated wood products (Heräjärvi *et al*., 2020).

The EU's New Strategy for a Sustainable Built Environment will focus on reviewing Construction Products Regulation into more circular with climate change mitigation goals (Parenti, 2020). They may set requirements for recycled content in construction products and revision of material recovery targets from construction and demolition wastes. The LCA approach to buildings to set carbon reduction targets will be obvious and level(s) in public procurement and taxonomy will be defined. EPDs and PEFs are intended to benchmark the products and create single, weighted, and normalized scores to show the impacts of each lifecycle stage. Several EU member states prepare their national rules for the carbon footprint estimation of new buildings. In Finland, the Land Use and Building Act (1999) currently under renewal progress will make the carbon footprint calculation of new buildings mandatory since 1.1.2025.

The New European Bauhaus Initiative is a discussion forum and meeting point for the European construction-related sector to support the Green Deal, focusing on combining the interplay of sustainability, aesthetics, and affordability of construction (EC, 2021c). The idea is to enhance accessibility for and participation of the citizens in all steps of the construction chain and building development. Ecodesign Direction and Sustainable Products Initiative aims to shift from a product-based to a functional economy, in which functions of, for example, modern residential houses and public service buildings are offered for the end-users, requiring new advanced business models, as well as streamlining the regulatory framework (EC, 2021d).

Finland is pursuing towards carbon neutrality as the first EU member state by 2035. The Ministry of the Environment, which is the responsible Finnish authority for setting the building codes and regulations, published a roadmap for low-carbon construction in 2017. The aim is to add the low carbon criterion as a new technical requirement for buildings along with the renewal of the Land Use and Building Act. In terms of volumes, single-family house construction has traditionally been the clearly biggest wood user in the construction value chains.

It has been pointed out that considering the local stakeholder perspectives is important in political decision-making related to the bioeconomy (Mustalahti, 2018) as well as in promoting the use of wood in construction value chains (Leszczyszyn *et al*., 2022).

3. Finnish practices supporting sustainable wood construction value chains

3.1. Wood construction expertise in Finland

With its long history of wood as a construction and interior decoration material, Finland features considerable scientific, educational, and practical expertise related to using wood in construction value chains. Lately, multi-floor wooden buildings and engineered wood-products (particularly LVL and CLT) as well as modern, industrially produced, turn-key delivery log houses, have gained a lot of research and development interest, and the expertise has progressed accordingly.

Table 1 lists the key organizations in the research, development, funding, and promotion organizations of wood construction value chains in Finland. In addition to the listed ones, industries carry out their own private or public research, development, and innovation activities. Furthermore, associations and innovation clusters support and promote wood construction.

Table 1: Major wood construction value chain research, development, funding, and promotion organizations in Finland.

Organization	Website	Purpose and expertise related to wood construction
Science University		
Aalto University	www.aalto.fi	Architecture, wood science, textile chemistry and applications
Tampere University	www.tuni.fi	Architecture, structural design, energy efficiency
University of Eastern Finland	www.uef.fi	Wood science, forest management, climate effects, sustainability
University of Helsinki	www.helsinkin.fi	Forest products markets, wood science
University of Jyväskylä	www.jyu.fi	Wood chemistry and physics
University of Oulu	www.oulu.fi	Architecture
University of Applied Sciences (UAS)		
Karelia UAS	www.karelia.fi	Structural engineering, building information models
LAB UAS	www.lab.fi	Furniture and interior design and applications, performance testing
Metropolia UAS	www.metropolia.fi	Structural design
Oulu UAS	www.oamk.fi	Insulation materials development
South-Eastern Finland UAS	www.xamk.fi	Structural design, product performance
Turku UAS	www.turkuamk.fi	Acoustics testing, building physics
Government research organization		
Natural Resources Institute Finland (Luke)	www.luke.fi	Forest inventory and management, bio-circular economy
Finnish Environment Institute (Syke)	www.syke.fi	Carbon foot- and handprints, LCA, biodiversity, climate change
Other research organizations		
VTT Technical Research Centre of Finland	www.vtt.fi	Biomaterials, circularity, nanomaterials, packaging, textiles
European Forest Institute (EFI)	www.efi.int	Policy support, bioeconomy development
Funding organizations		
Research Council of Finland	www.aka.fi	Government agency funding scientific research and providing expertise in science and science policy
Business Finland	www.businessfinland.fi	Public-sector organization offering investment and innovation funding, as well as internationalization services
The European Regional Development Fund (ERDF)	https://ec.europa.eu/regional_policy/funding/erdf_en	Funding research and business to strengthen economic, social, and territorial cohesion in the European Union
The Finnish Climate Fund	https://www.ilmastorahasto.fi/en/	State-owned company investing in businesses combating climate change, boosting low-carbon industries and digitalization
Private foundations	www.tiedejatutkimus.fi	Supporting basic and applied research on natural resources
Industry and other associations		
Finnish Forest Industries Federation	www.metsateollisuus.fi/en/home	Ensuring competitive and innovative operating environment for forest industry production, employment, and investments
CLIC innovation	www.clicinnovation.fi	Open innovation cluster owned by companies and research organizations aiming to facilitate creation of breakthrough solutions in bioeconomy, circular economy, and energy systems
The Finnish Sawmills Association	www.sahateollisuus.com/en	Providing economic, statistical, and promotional member services
Federation of the Finnish Woodworking Industries	www.puutuoteteollisuus.fi/english	Initiates and supports policies promoting wood utilization in Finland
The Log House Industry Association	www.hirsikoti.fi	A joint organization for leading Finnish log house factories, which obey design and production regulations

International ThermoWood® Association	www.thermowood.fi	Aim is to enhance ThermoWood® products
Central Union of Agricultural Producers and Forest Owners (MTK)	www.mtk.fi/web/en	An organization representing farmers, forest owners and rural entrepreneurs in Finland
Finnish Forest Foundation	www.metsasaatio.fi/en	Promotes the acceptability of forestry, forest livelihoods and forest industries, as well as increased use of wood and wood-based products
Sustainable Forestry Association	www.kestavametsa.fi	Promotes sustainable forest management in Finland and develops the use of forest certification (PEFC).
Finnish Forest Association	www.smy.fi/en/front-page	Organization communicating about sustainable use of forests

3.2. Wood construction value chains

Sawn timber is the most important solid wood product produced in Finland, both in terms of volume and value. However, the engineered wood products (EWPs), such as glulam beams, plywood, laminated veneer lumber LVL, cross-laminated timber CLT, which are manufactured by gluing smaller pieces of wood together to form more uniform and free-dimensioned structural billets (e.g., Smulski 1997, Heräjärvi et al. 2003), are produced increasingly. Their unit value is, at least, double compared to sawn timber, which makes them attractive export products, as well.

Good mechanical performance combined with homogeneity, i.e., low property variance, allows structural designers to use lower safety margins with EWPs than solid wood products. Increasing the dimensions of EWP posts, beams, or wall elements over those of traditional timber frame structures enables managing higher design loads and, thus, building larger or higher buildings. While wood's compression and tensile strengths are at least tenfold in parallel-to-the-grain direction compared to the transverse direction, EWPs with longitudinal grain orientation (glulam, LVL) exhibit the highest attainable performance under compressive or tensile stresses in applications such as load bearing vertical structures of high-rise buildings. This is one of the critical issues in high-rise buildings made with wooden load carrying frame, as well as long-span structures, such as sports or concert halls.

The small-sized buildings in rural areas, such as single-family houses, summer cottages, garages, and storage buildings, are typically built and owned by private persons in Finland. In the case of all these building types, the structural design is often based on either traditional timber frame or construction logs (either solid or glued), which are very cost-competitive solutions in small and medium-sized buildings. EWPs have had an elemental role in the revolution of wood as a construction material for larger buildings, which are characteristic for urban areas. Hence, EWPs particularly serve the urban building activities and are an enabling technology for modern wood construction development in urban areas.

Prefabricated volume elements are nowadays commonly applied in multi-floor buildings. Unit weight (ca. 500 kg/m3) of wood is far lower than that of concrete (> 2,400 kg/m3) or steel (> 7,000 kg/m3). Therefore, wood is less expensive and more energy-efficient to transport, handle, and assemble. Low weight also enables building extra floors on top of old houses without compromising the load bearing capacity of existing structures. Low material weight enables a high degree of dry-condition industrial prefabrication because the light-weight elements can be transported to the building site by trucks. Logistics can be organized based on the just-in-time delivery schedule. In an ideal case, a crane lifts ready-to-live-in volume elements from the truck to their final assembly position within a matter of hours. Wooden volume elements have transformed a traditional construction site into an assembly site, which potentially reduces the on-site activity time by more than 50 percent, subsequently resulting in considerable financial savings to the developer. Prefabrication of construction elements is more typical for wooden houses than concrete ones because the truck load capacity and fragility of concrete limit the transportability of concrete elements. In addition, transportation and lifting of lighter weight wooden elements consume less energy and cause less emissions compared to heavier elements.

Houses and house elements are nowadays mostly built for the domestic market in Finland. According to Sipiläinen (2020), the value of wood house exports was 45 million € in 2019, mostly covered by log house exports. The total number of personnel working in the Finnish wood product and furniture manufacturing sectors was approximately 24,000 and the annual turnover was almost 9 billion € in 2018. Residential houses account for approximately 2/3 of the building stock in Finland, thus their building and renovation activities stand for great societal, political, economic, technical, and environmental importance. Timber frame and façade are already the predominant construction principles in single-family and linked houses as well as second homes. A wide range of educational and institutional service buildings indicate great potential in public sector wood construction.

The wood itself provides high-level material properties for timber construction as regards the three basic requirements: stiffness and strength, dimension and form stability, and resistance against weather loads. The harmful variation in the technical properties that is typical for natural materials, have been largely overcome by applying intensive sorting, but also engineering and physical and chemical modifications (e.g., Heräjärvi et al. 2020). The trends of remote working and decentralization, which have taken place because of COVID-19, appear to increase the rural demand for single-family houses and second homes, thus maybe turning the 60-year-long urbanization trend into partial ruralization. While these two building types are responsible for the great majority of wood product demand in Finland, one can predict a positive development in demand for wood products and building components as soon as the current recession in building activity will be passed.

Finland is among the largest producers of wood products in Europe. Wood products industries used ca. 30 million m3 of roundwood in 2021, divided roughly into 27 and 3 million m3 between sawmilling industries and wood-based panel industries, respectively (Finnish Statistical Yearbook of Forestry, 2023). Out of the sawlogs and plywood logs used, Norway spruce covered 14.5 million m3, Scots pine 11.6 million m3, and the two birch species 1.2 million m3. The production volume of sawn softwood was 11.9 million m3 in 2021. Plywood production reached 1.1 million m3. A quarter of the produced sawn goods and 16% of the plywood remained in Finland.

The new Building Act will come into force at the beginning of 2025 in Finland. This Act aims at reducing GHG emissions and promotes digitalization in construction. The Act is expected to facilitate the construction processes and improve the quality of the buildings, and contribute to the cascade use of materials, as well. The National Building Code of Finland will be amended accordingly by adding a declaration for building products and limitations on the carbon footprint of the buildings. Moreover, buildings should be designed to be more durable than in the past. Buildings should also meet adaptability, which accounts for the used or released materials, soil or rock removed from the site, and hazardous wastes produced during construction or demolition processes. (Parliament adopted acts that will reduce emissions from building and promote digitalisation (valtioneuvosto.fi)). Table 2 lists the major Finnish associations contributing to building regulation and business development.

Table 2: Industry associations contributing to building regulation development in Finland. The ministry responsible for building sector regulation is the Ministry of the Environment of Finland (www.ym.fi/en).

Organization	Activity /themes	Structure	Website
Finnish Forest Industries Federation	Competitive and innovative forest industries	62 member firms in pulp, paper, paperboard, packaging, and wood product sectors	www.metsateollisuus.fi
Federation of the Finnish Woodworking Industries	Promote wood production and use in Finland	20 member firms, 6 federation members representing 500 firms, 8 associated companies	www.puutuoteteollisuus.fi www.puuteollisuus.fi www.puusepanteollisuus.fi www.kestopuu.fi www.hirsikoti.fi www.thermowood.fi www.porrasvalmistajat.fi
The Finnish Sawmills Association	Economic, statistical, and promotional activities	30 member companies with a total share of ca. 50% of Finnish sawn timber production	www.sahateollisuus.com

Best practices
National regulations to ensure safety and efficiency of wooden buildings

Building regulations for wood-based production in Finland are imposed to ensure the safety and efficiency of wooden buildings, aiming to improve material neutrality and reduce the cost of construction. Three crucial building codes concern the following:

1. ***Fire safety*** *regulations in Finland were updated in 2011, 2018, and 2021. Recurring updates are justified due to the increasing use of wood in urban construction. For example, in two-story buildings, the wall surfaces can be without protective cladding, if the materials meet a specific fire behavior class. Such regulations can reduce the design process and promote wood-based construction while ensuring building safety.*
2. ***Energy efficiency*** *codes for buildings have been developed actively since the 1990s. The new building code for energy efficiency was published in 2012 (Code D3). It is a performance-driven regulation that necessitates an energy frame calculation to estimate the forecasted monthly ultimate energy use of buildings. The regulation covers criteria concerning thermal envelope standards and factors in energy consumption calculations, encompassing HVAC, hot water, lighting, heat recovery, and bio-climatic design. The code advocates efficiency of the dynamic aspects of buildings such as u-values and air tightness. (National Building Code of Finland 2012 – Section D3 on Energy Management in Buildings | Global Buildings Performance Network (gbpn.org))*
3. ***Building acoustics*** *guidelines were introduced already in the 1950s. The newest revision of acoustic regulations was published in 2017. For example, the room acoustics criteria have been revised and set for open-plan offices. Research concerning the financial benefits of using acoustic-efficient structures in the building vs. the cost of insufficient acoustic conditions in the work environment shows that the revised regulations are also economically justified. (New Finnish building acoustic regulation (dega-akustik.de))*

4. Transferability and applicability of wood construction value chains in the Global South countries

We identify several knowledge transfer and education export opportunities for applying Finnish wood construction expertise in the Global South. An important question is how to integrate these practices in the local regimes and ways of operating within the society so that they support sustainable and just transformation. A crucial thing for the Finnish and other experts is to understand the local conditions and culture related to utilizing natural resources. Mutual learning and collaboration with and between the local actors planning, organizing, and developing the value chains is essential. Finland has a strong confidence that it can contribute to the sustainable development of forest-based value chains in the Global South, thus facilitating national goals to increase the prosperity and wellbeing of the societies.

Since the beginning of the 20th century, Finland has had a national political consensus and institutions supporting the utilization of timber resources and the development of the forest sector. This tradition has continued with the introduction of forest-based bioeconomy. The 'Best Practices for Sustainable Forest Management', intended for the use of private forest owners, is a good example of this support. These guidelines, for example, emphasize the use of native tree species in the right fertility class sites and provide optional forest management practices for different forest compartments. Keeping in mind and respecting forest owners' goals and objectives in forest management enables responsible utilization of wood without compromising future crops.

Related to research, development, and innovation (RDI) activities, the Finnish forest cluster is a state-of-the-art example of the triple-helix collaboration between academia, government, and industrial actors. Finland also features a recent introduction of the concept of industrial ecosystems and bioproduct mills, in which collaboration in manufacturing and RDI is built into the system. Such a model could be considered in the Global South conditions, too.

Timber resource with sufficient quantity and quality is a foundation for wood construction value chains, equally to any wood-based value chains. Sufficient resources can secure the forest-to-building supply chains and enable industrial offerings to the market demand. Industries must meet customer orders while maintaining continuous and efficient production on a sustainable basis.

Raising global awareness of sustainability drives consumers looking for environmentally sound solutions. Globally, the construction sector is the greatest single user of natural resources, the greatest source of GHG emissions, and the greatest producer of waste. Wood products industries, yet small in volumetric comparison to concrete industries, can provide products with significantly smaller environmental effects. This is an exceptional opportunity for the construction sector to reduce its huge environmental impact just by starting to apply the already existing technologies and materials. If there is access to a sufficiently large supply of sustainably managed renewable raw materials and sufficient financing for modern technologies, wood construction offers a great opportunity to improve local employment and living conditions and broaden the sources of income.

Simultaneously, poorly developed supply chains or issues regarding legality or sustainability are a clear barrier to wood construction, operational efficiency, and market development. Poor infrastructure and management bring about increased costs of wood material production and insufficient and delayed provision. Political and societal instability, such as regulatory, trade, and economic issues may expose the wood-based value chain development under threat. These profoundly impact the attractiveness of respective countries for investors, businesses, supply chain functions, and markets. Remedies for such issues can be the implementation of managerial practices, such as risk management strategies.

Table 3 presents a SWOT data that was collected for this report among the experts at the University of Eastern Finland. The role of societal questions (bullet points with red font) is emphasized in all SWOT categories. This highlights the fact that social sustainability issues are extremely relevant in value chains based on timber utilization in Global South countries. There are various questions related to, *e.g.*, land ownership structure, supply chain legality, ethics and just transformation, cultural factors, and political instability that relate to overseas investments and funding opportunities. Furthermore, technical questions such as wood durability in tropical or temperate conditions and fire regulations must be carefully considered. Wood enables, however, a major transformative change in the entire construction sector, if the local policies support it.

Table 3: SWOT table for wood construction value chains in Global South countries from the Finnish perspective. Green font stands for environmental, red for societal, and blue for economic issues.

Strengths Wood use has a low environmental load in comparison to concrete and steel. Substitute for fossil-based or fossil-energy-intensive materials. Timber from plantations => Almost completely certified wood. Excellent earthquake safety of wood due to low weight and elasticity. Climate reasons to use wood are obvious and politically sound. Use of wood enhances resident's well-being. New wood-based value chains create jobs. Abundant, proper-quality, and local raw material supply. Economic growth supports new materials and solutions. Labor availability. Low technical threshold of processing and using of wood – possibility to apply appropriate technologies.	**Weaknesses** Problems in FLEGT (Forest Law Enforcement, Governance and Trade) control. The use of natural forests has a bad reputation. Lack of skilled labor for modern production. Regulatory barriers (e.g., fire safety). Prejudices: 'poor people live in wooden houses'. Insufficient public awareness on wood's sustainability. Pulp intended plantation species => Poor quality for wood products. Illegal logging / availability of legal timber. Slow growth of timber compared to agriculture crops => Slow Return on Investment. Technical and financial restrictions (expensive and skills-intensive modern processing machinery). Poor availability of proper timber, underdeveloped supply chains. Raw material competition by pulping sector. Fire safety, weathering, biodegradation, and termite resistance in tropical or temperate climate.
Opportunities Turning the built environment into a carbon sink. Decreasing the ecological footprint of the built environment. Consumers demand greener materials. International political support. Economic aid supporting SDGs in the Global South countries. Collaboration with Global North countries. Large unused areas for timber production. Regulations towards renewable and low-carbon construction. Cascade use of wood and wood wastes. Extra lightweight structures on top of existing urban buildings. Quicker building processes. Affordable industry establishment costs.	**Threats** Deforestation and illegal logging. Climate change-related issues, *e.g.*, insect or pathogen outbreaks. More land deployed to timber production => Biodiversity loss. Plantation wood turns into GHG source by, *e.g.*, political decision. Political and societal instability. Prejudices against wooden buildings remain (cultural reasons, technical misunderstandings). Forest ownership structure and indigenous people's rights are not accepted. Governmental restrictions to utilize forest resources. Poor technical skills & education. Alternative materials gain further technical, economic, or environmental benefit.

5. Key messages and Recommendations

1. The use of wood in construction value chains is a considerable **business and job creation** opportunity that is not conditional to huge investments in the Global South countries.
2. As a solar energy empowered construction material, wood is an instantly available opportunity to **improve the construction sector's environmental profile**.
3. As a global forerunner, **Finland can contribute to the evolution of sustainable wood construction expertise in Global South countries** through knowledge transfer, education, training, and business partnerships.
4. Questions related to **legality, transparency, equality, and sustainability of the supply chains and businesses cannot be overemphasized** anywhere in the World.

Production and use of materials for the construction sector are responsible for catastrophic environmental impacts, which are expected to further increase due to population and wealth growth. Therefore, even little steps towards construction practices with smaller environmental impacts may have a big national or global effect. Once new buildings are needed anyway, the associated environmental impacts should at least be minimized. Wood is generally understood to cause less environmental impact than other major construction materials, which is largely because the primary energy supply for wood is solar, whereas fossil fuels are the primary energy source for concrete, steel, and plastics. Wood has, however, limited global potential in construction. Global concrete production, for example, is volumetrically over 10 times larger than the production of wood products for construction applications. Hence, even with intensive forest management, it is not realistic to envision volumes of wood that could fully, or even mostly, replace concrete. Wood, however, offers an exemplar for the greening of the construction sector.

For achieving a just and environmentally sustainable bioeconomy for the World, there is a need for a global understanding of what is good and desirable related to utilizing natural resources. The perspectives of different stakeholders should be considered when creating wellbeing with natural ecosystems and the resources they provide. This calls for a systemic change in the current views and paradigms on how people and societies consume and how companies produce products and services.

References

EC (2012). *Innovating for Sustainable Growth - A Bioeconomy for Europe*. European Commission DG Research and Innovation: Luxembourg.

EC (2013). *A new EU Forest Strategy: for forests and the forest-based sector*. European Commission: Brussels.

EC (2018). *A sustainable bioeconomy for Europe: Strengthening the connection between economy, society and the environment: updated bioeconomy strategy*. European Commission DG Research and Innovation: Brussels. DOI: 10.2777/792130.

EC (2019). *Communication from the Commission The European Green Deal*. European Commission: Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1576150542719&uri=COM%3A2019%3A640%3AFIN.

EC (2021a). *EU Biodiversity Strategy for 2030 - Bringing nature back into our lives*. Publications Office of the European Union: Luxembourg. DOI: 10.2779/677548.

EC (2021b). *New EU Forest Strategy for 2030*. European Commission: Brussels.

EC (2021c). *New European Bauhaus - Sustainable, Beautiful, Together*. Available at: https://europa.eu/new-european-bauhaus/index_en

EC (2021d). *Sustainable Product Policy & Ecodesign*. Available at: https://ec.europa.eu/growth/industry/sustainability/product-policy-and-ecodesign_en

European Environment Agency. (2015). *Closing the loop - An EU action plan for the Circular Economy* COM/2015/0614. Policy brief. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614

Finnish Government (2022). *The Finnish Bioeconomy Strategy: Sustainably towards higher value added*. Finnish Government: Helsinki. pp. 51. ISBN: 978-952-383-579-5. http://urn.fi/URN:ISBN:978-952-383-579-5.

Finnish Statistical Yearbook of Forestry (2023). *Metsätilastollinen vuosikirja 2022*. (Eds.) E. Vaahtera, T. Niinistö, et al. Natural Resources Institute Finland. Helsinki. ISBN: 978-952-380-584-2. https://jukuri.luke.fi/handle/10024/553167.

Heräjärvi, H., Jouhiaho, A., Tammiruusu, V., Nuutinen, T., Väärä, T. & Verkasalo, E. (2003). Mänty- ja koivupienpuun käyttömahdollisuudet rakennepuutuotteissa (EWP)[*Possibilities to use small-diameter Scots pine and birch in engineered wood products*]. Publications of the Finnish Forest Research Institute, Nr. 890. 59 p. + App. (In Finnish)

Heräjärvi, H., Kunttu, J., Hurmekoski, E. & Hujala, T. (2020). *Outlook for modified wood use and regulations in circular economy*. Holzforschung 74(4): 334-343. https://doi.org/10.1515/hf-2019-0053

Karppinen, H., Hänninen, H. & Horne, P. (2020). *Suomalainen metsänomistaja 2020 [Finnish forest owner 2020]*. Luonnonvarakeskus. http://urn.fi/URN:ISBN:978-952-326-961-3.

Kleinschmit, A.N. (2021). *Wood construction related policy development in the EU.* WoodCircus Consortium meeting, 10th February, 2021. 5 p.

Land Use and Building Act. (1999). Ministry of the Environment. Finlex 132/1999. Available at: finlex.fi/fi/laki/smur/1999/19990132

Leszczyszyn, E., Heräjärvi, H., Verkasalo, E., Garcia-Jaca, J., Araya-Letelier, G., Lanvin, J.-D., Bidzińska, G., Augustyniak-Wysocka, D., Kies, U., Calvillo, A., Wahlström, M. & Kouyoumji, J.-L. (2022). *The Future of Wood Construction: Opportunities and Barriers Based on Surveys in Europe and Chile*. Sustainability, 14, 7, 4358, DOI: 10.3390/su14074358.

Ministry of Agriculture and Forestry (2023). *Kansallinen metsästrategia 2035 [The National Forest Strategy 2035]*. Ministry of Agriculture and Forestry: Helsinki. pp. 55. ISBN: 978-952-366-740-2. https://urn.fi/URN:ISBN:978-952-366-740-2.

Mustalahti, I. (2018). *The responsive bioeconomy: The need for inclusion of citizens and environmental capability in the forest based bioeconomy*. Journal of Cleaner Production, 172, 3781–3790, DOI: 10.1016/j.jclepro.2017.06.132.

Natural Resources Institute Finland (2024). *Bioeconomy in numbers*. Available at: https://www.luke.fi/en/statistics/indicators/bioeconomy-innumbers [Accessed on 8 March 2024].

Norton, A. 2021. *Policy Context: The Green Deal and The Wood Building Sector. Can building in wood contribute to delivering the Green Deal? - a regional and city perspective*. Webinar, October 8, 2020. ERIAFF Network, Helsinki EU Office, Småland-Blekinge-Halland (South Sweden). East & North Finland. 17 p.

Parenti, A. 2020. *From Construction 2020 to a new vision for a sustainable built environment.* European Commission. DG Internal Market, Industry, Entrepreneurship and SMEs. 12 p. Available at:
https://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupMeetingDoc&docid=35639

Sipiläinen, I. 2020. *An overview of industrial wood construction - wood elements*. Publications of the Ministry of Economic Affairs and Employment 2020: 16. 55 p. (In Finnish with English and Swedish abstract)

Smulski, S. (ed.). 1997. *Engineered Wood Products: A Guide for Specifiers, Designers, and Users*. PFS Research Foundation, Madison, Wisconsin. 294 p. + App.

The Finnish Forest Industries Federation (2020). *Vastuullisia valintoja kohti 2025 – Metsäteollisuuden vastuullisuussitoumusten väliraportti [Responsible Choices towards 2025 – Interim report on sustainability commitments in the forest industry]*. The Finnish Forest Industries Federation. https://global-uploads.webflow.com/5f44f62ce4d302179b465b3a/5fce1d1a39327f2786663602_MT-esite_Vastuullisuussitoumus_2020_final.pdf.

Wall, J. 2020. *Can building in wood contribute to delivering the Green Deal? – a regional and city perspective*. Final comments to the webinar. European Commission, DG Internal Market, Industry, Entrepreneurship and SMEs. October 8th, 2020. ERIAFF Network, Helsinki EU Office, Småland-Blekinge-Halland (South Sweden), East & North Finland. 9 p.

Innovative wood-hybrid elements and re-use concepts in wood construction - an Austrian case study

Daniela Groiß-Fuertner, Sabine Ober, Martin Riegler
Wood K plus - Competence Centre for Wood Composites and Wood Chemistry (Kompetenzzentrum Holz GmbH), Linz, Austria

Abstract

As a renewable raw material, wood offers great potential for reducing climate damaging carbon emissions in the atmosphere. This positive effect is further enhanced by the reuse and cascadic recycling of wood as a secondary raw material in the sense of a circular economy. Due to the development of sophisticated engineered wood products, wood is nowadays used in the construction of multi-storey buildings. By that, wood serves as alternative bio-based construction material that is substituting cement-based building elements, which are the third largest source of anthropogenic carbon emissions. This releases pressure from the environment and helps to tackle challenges in the course of human-induced climate change. For construction purposes, high wood qualities are required, which promotes sustainable forest management by addressing e.g. the current change in available wood species (e.g. towards hardwoods) due to global warming or decreasing deforestation.

As long as wood is used in a material phase, carbon is stored in buildings and is not released into the atmosphere. To maximize the carbon storage effect of wood, building solutions need to be developed that allow intelligent reuse concepts. In the building sector, wood can replace fossil-based construction materials in most applications. For some applications, a combination of materials (e.g. wood with concrete) is required to meet the required specifications in terms of statics or durability. Especially for such hybrid materials the detachability is essential for their afterlife usage. By these cascadic uses, down-cycling of wood products should be avoided as long as possible. Only at the very end of the material use phase, energetic use by combustion should take place. In this late stage of energy harvesting, solutions to capture carbon before it gets emitted into the atmosphere should be developed in future. It is crucial to catch up with using bio-based materials instead of fossil-based resources in the construction sector – there is still plenty room for improvement.

1. Wood use in Building Construction

1.1. Technical solutions and potentials of wood use in building construction

The use of wood in building construction played an important role in the development of human settlements, reaching back to early history around 10,000 BC. The Neolithic long house represents one of the first constructed timber frames dwelling, shaped in a long, rectangular way built by the first farmers in Europe already 5,000 to 6,000 BC with evidence in different regions (Castleden, 1987). In the classic modern era, wood was replaced by newly discovered, non-combustible materials like concrete and steel (Kaufmann et al., 2017). Technical innovations in the construction sector and increasing ecological awareness led to a new upswing for timber constructions in the new millennium. As renewable material, wood has a great potential to reduce climate-damaging carbon emissions in the atmosphere. Reuse and recycling of wood as a secondary raw material in the sense of a circular bioeconomy enhances the positive effect of wood. The fact that wood stores carbon as it grows is a decisive factor to substitute cement-based building elements in the construction industry, which is the third-largest contributor of anthropogenic carbon emissions (Andrew, 2018). Due to the use of wood in the construction of multi-storey buildings, the proportion of wooden buildings increased by 75 % in Austria between 1998 and 2013 (Teischinger et al., 2014), initiated by high prefabrication and adapted regulations (Ramage et al., 2017). A comparison of multi-storey building construction showed that the use of wood reduces CO2 emissions by 70 % compared to reinforced concrete (Chen et al., 2020). The ability of trees to absorb CO2 during biomass growth is defined as biogenic carbon (Stamford, 2020), this ability indicates that increased wood use in urban building leads to a carbon sink (Amiri et al., 2020). However, it must be considered that the storage effect lapses with the combustion and decomposition of biomass as the CO2 is released back to the atmosphere (Stamford, 2020). Having in mind these numerous advantages, this storage effect shows the necessity for further developing building systems specialized for their reusability in the sense of a sustainable circular construction industry.

The utilization of wood in the building sector can represent a key strategy for climate change mitigation and a future bioeconomy. Despite the positive effects of wood, the increasing demand for wood cannot be regarded as fully sustainable, if questions regarding viable forestry and a long-life circular utilization of the raw material is not met. Besides concerns due to CO2 emissions other adverse ecological effects and emissions must be considered. The increased utilization of wood from forests for example can negatively impact biodiversity (Chaudhary et al., 2016; Martin et al., 2015), whereas the establishment of plantations for wood production can lead to overexploitation of agricultural land and soil and contributes to land use competition. The role of policies and regulations regarding the use of wood from forests and land use change becomes a critical issue in the urgent need to mitigate climate change and preserve biodiversity. In addition to technical solutions for the construction of multi-storey wood buildings, there is a need to improve the regulatory framework and standardization for the construction industry, which is a complex and highly dynamic policy field (e.g. EU Green Deal) (Weiss et al., 2021). Achieving this demanding task requires action and networking between several public and economic actors (Hurmekoski et al., 2015; Lazarevic et al., 2020; Tykkä et al., 2010). The role of policies and regulations in shaping the forest sector has never been more critical, as the world grapples with the urgent need to combat climate change and preserve biodiversity. By fostering transparency, accountability, and collaboration among actors, effective governance frameworks are essential for a more equitable and sustainable pathway towards a bio-based future. This study aims to shed light on the complexity of regulating the use of wood and to identify opportunities as well as limitations and trade-offs for collective action to promote and advance the use of wood in the construction industry, as well as to identify examples of good practices and analyzing their potential for application at a global level.

2. Potentials, benefits and limitations of Wood Use in Building Construction

2.1. Technical solutions and potentials of wood use in building construction

Even though timber construction has a long tradition, concrete and steel construction has become the dominant standard in recent years due to expected advantages in durability, fire safety, costs and structural integrity (Crawford & Cadorel, 2017).
Benefits of Wood Construction

Best practices
Wooden multi-storey buildings

Wooden multi-storey buildings also known as timber high-rise buildings, are structures utilizing wood as primary construction material ranging from three to over twenty (or even more) floors above ground level. Efficient and optimized wood use can be achieved through the use of slim elements of engineered wood like cross-laminated timber (CLT), laminated veneer lumber (LVL), glued laminated timber (glulam), and structural timber framing systems. The optimized bonding of individual layers of wood enables strong, solid and durable structures that are suitable for multi-storey buildings. The constructions can withstand varying pressures and strains with a higher load-bearing capacity than solid wood compared in the same dimensions (Yadav & Kumar, 2022). Prefabrication of construction elements saves time and allows a quick assembly at the construction site. A diverse range of design concepts can be realized with multi-storey wood constructions, from traditional to contemporary styles. Integrated and well-planned design helps to keep costs low and enables architectural features.

The most important technical timber construction systems are timber frame construction, timber panel construction, skeleton construction, timber framework or log houses (Kolb, 2014). Nowadays wooden elements are highly prefabricated and produced in modular systems. Especially the invention of CLT has significantly contributed to the boom of using wood for construction in the recent years.

2.2. Benefits of Wood Construction

Environmental Benefits

Wood is widely recognized as a sustainable natural resource and building material with high expectations in terms of saving CO_2 and other emissions. Trees serve as carbon sink through the sequestration of carbon dioxide from the atmosphere through photosynthesis during their life stage in the forests. The concentration of carbon dioxide in the atmosphere has increased in recent decades due to human influence through industrial emissions, deforestation, fossil fuel combustion and changes in land use patterns. Hence, potentials for carbon sequestration and storage are searched for. Changes in atmospheric carbon dioxide levels cause a variety of effects, such as changes in the global climate or on the preservation of biodiversity. Forests indeed not only provide the ecosystem service of carbons sequestration but provide habitats for a diverse flora and fauna.

The storage effect of CO_2 in utilized wood remains until decay or combustion of wood. Today's construction industry is characterized by the use of fossil-based resources with a significant contribution to carbon emissions and the cause of human-driven climate change. Conventional building materials contributed with up to 10 % to the global greenhouse gases in 2020 (Mishra et al., 2022). Emissions can be saved in several life cycle stages of buildings (construction, use and disposal) through choosing wood as the main building material instead of reinforced concrete and structural steel and additionally, carbon is kept stored in the built-in wood (Kumar et al., 2024). This shows the importance of cascading and recycling in a circular loop of already utilized wood to preserve the carbon storage as long as possible. Even though wood is a renewable raw material, it is not infinitely available as land is a limited resource. Although the forest area in Europe is growing, from a global perspective there is a noticeable decline in the area covered by forests.

Considerable fossil-based emission savings can be achieved by substituting conventional materials with wood-based ones (Leskinen et al., 2018). Building with wood can reduce carbon emissions by 50 % over the lifetime of a property (Ximenes & Grant, 2013) with energy savings during processing (Ormondroyd et al., 2016). Efforts towards energy-efficient buildings to achieve low- and ultra-low-energy buildings cause the construction phase rather than the use phase of these buildings to have the highest influence on emissions (Chastas et al., 2016; Ibn-Mohammed et al., 2013). The potential for saving emissions through wood construction is up to 53 %, which means a saving of 106 Gt CO_2 equivalents, if 90 % of all new buildings are made from wood-based materials (Mishra et al., 2022). Wood buildings are perceived as an interesting and sustainable (Franzini et al., 2018; Gosselin et al., 2016) option with great technical performance and aesthetics (Gosselin et al., 2016). However, weak regulatory policies and high expected costs represent a barrier to wood construction (Franzini et al., 2018). Additionally, it needs to be mentioned that the use of wood for construction is not per se sustainable, instead the whole life cycle of wood construction needs to be considered. (Hesser et al., 2017; Osburg et al., 2016).

Besides these environmental benefits, there are numerous advantages associated with wood construction. Franzini et al., 2018 categorizes the benefits of multi-storey wood buildings in three main groups, including technology, lifestyle and economy (cf. **Fehler! Verweisquelle konnte nicht gefunden werden.**). Sustainability per se is seen as an overarching benefit for the social sphere.

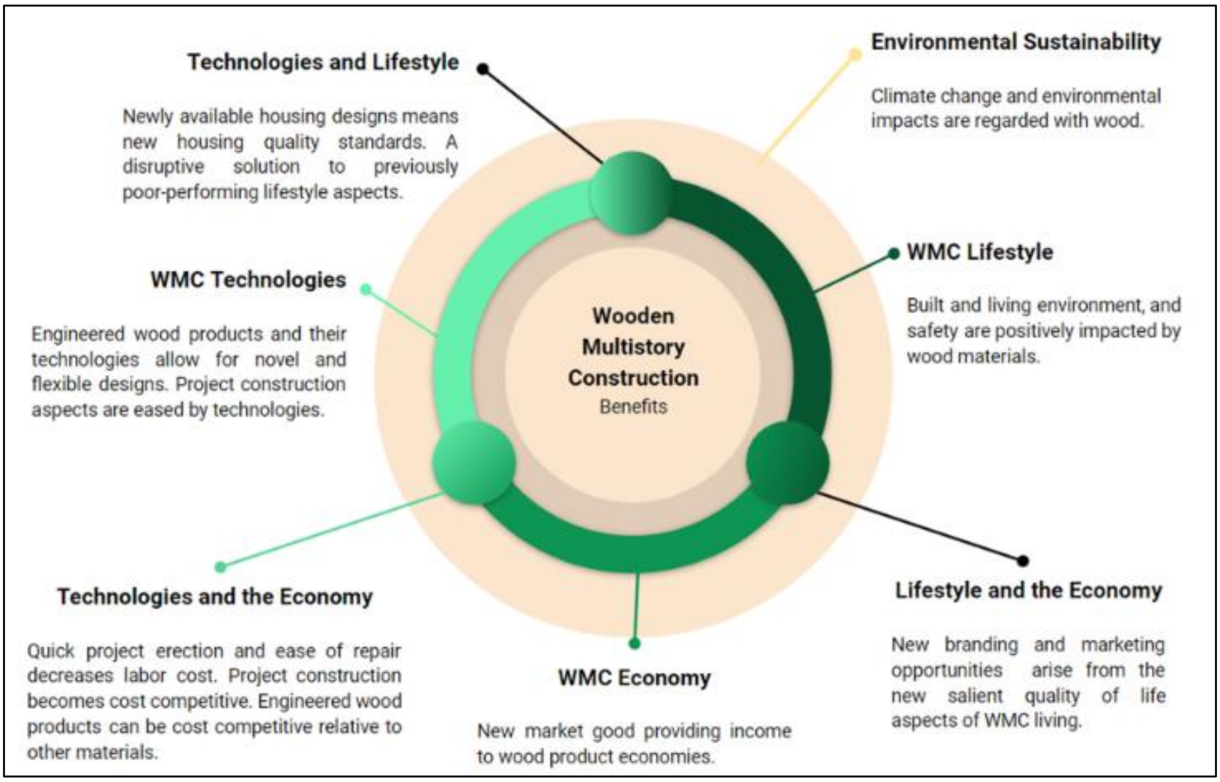


Figure 2: Linkages of benefits of multi-storey wood construction (©Franzini et al., 2018)

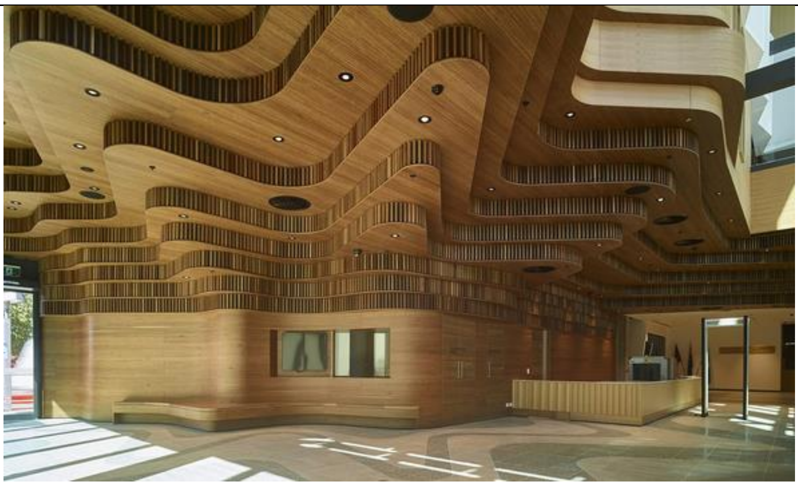
Social Benefits

Benefits for human health from spending time in forests are widely recognized and have been well-studied scientifically (Rowlinson, 2020). Wood can be beneficial to human health as indoor air quality is positively affected by lower levels of harmful volatile organic compounds (VOCs) compared to other building materials (Ikei et al., 2017; Mhuireach et al., 2021). A healthier indoor environment reduces the prevalence to respiratory issues and allergies as well as reducing blood pressure and psychological stress therefore promotes the overall human well-being.

These anticipated health benefits led to an own design principle called *"Biophilic Design"* that promotes restorative environmental design (RED), improving environmental performance by lowering impacts on the natural environment as well as the biophilic design approach which is intended to stimulate human contact with nature within the building (Kellert et al., 2013; Rowlinson, 2020). Kellert et al., 2013 describes six biophilic design elements and attributes, which are described in Table 4 and can be adopted also within wood buildings allowing a direct human-nature relationship (Rowlinson, 2020). Wooden buildings are commonly perceived as aesthetically appealing and exude a warm and authentic atmosphere with a timeless character. Local traditions, craftsmanship and the use of regional resources strengthens the communities, fosters engagement and secures local jobs, what strengthens the society.

Table 4: Six biophilic design elements and attributes with selected examples from wood construction

<table>
<tr><td>Environmental features:
Utilization of natural elements or materials</td><td>
Figure 3: Floating wooden house by Dornob (©Dornob.com)</td></tr>
</table>

Natural shapes and forms: Realization of shapes that imitate natural elements (e.g. botanical, animal, marine, etc.)	 *Figure 4: Peanut-shaped exhibition hall Landesgartenschau Schwäbisch-Gmünd, Stuttgart, Germany (robotic fabrication) by University of Stuttgart (©Institute of Computational Design's (ICD))*
Natural patterns and processes: Natural development and alteration of elements and materials over time	 *Figure 5: The „Bodnerhaus" is the oldest blockhouse in Austria, Carinthia built around 1470, located in the Freilichtmuseum Maria Saal with a typical dark wood-patina due to ageing (©kultur.net)*
Light and space: Natural color schemes are variable and create harmonious conditions	 *Figure 6: „Shepparton Law Court" in Victoria, Australia supports calmness through natural sunlight which imitates the canopies of a deciduous tree by architect Mark Wilde (©architectureanddesign.com.au)*

Place-based relationships: Orientation towards local conditions (e.g. historic, ecological, geographical, cultural, etc.)	 *Figure 7: Traditional construction interpreted in a contemporary way in the Chalet Village St. Martin, Lungau, Austria manufactured according to traditional craftmanship (©stmartinchalets.at)*
Evolved human-nature relationships: Reflection of nature in the built environment (e.g. order and complexity or security and protection)	 *Figure 8: The Fab Tree Hab - design of a living and breathing tree house from Mitchel Joachim, Javier Arbona and Lara Greden (MIT) (© terreform)*

Economic Benefits

Wood construction is often perceived to be more expensive than conventional buildings. However, this is mainly caused by the fact that buildings that have been planned in e.g. concrete are finally built in wood. Building with wood requires integrated planning from the very first beginning of the construction process. To prevent a biased bidding, concepts to include advisors for wood construction in an early design phase are discussed (Geier, 2018). This can save costs and make wooden constructions a cost-effective solution in the building sector. Furthermore, increased use of timber housing can drastically reduce construction times, as modular systems allow individual parts to be manufactured in a factory and delivered directly to the construction site, saving time and labor costs. Hurmekoski et al., 2015b emphasizes the importance of increasing competition within the sector and co-operation between wood product suppliers and the construction sector to successfully reduce the costs. In contrast to a widespread opinion, wood constructions are durable, long-lasting structures that can be dated back to the 15th century in the Austrian context. Wood-based buildings are often more flexible and allow easier renovation and adaptation than conventional built houses, what makes them a long-term investment.

2.3. Limitations and Trade-offs in Wood Construction

Stakeholder perceptions of wood in the construction sector are diverse. On the one hand, building with wood is seen as an interesting option that is more environmentally friendly, safe, aesthetically pleasant, and healthier – on the other side, costs are expected to be higher and that there are difficulties in availability. Concerns about fire safety and maintenance costs are probably the consequence of a lack of information regarding product characteristics and a lack of legislative support and strict regulations (Wallius et al., 2023).

Even though the focus in recent years has increasingly been on climate impacts, including carbon emissions into the atmosphere and the carbon storage potential of wood, there are many remaining uncertainties that need to be scientifically clarified. Key issues in relation to wood construction are sustainable wood sourcing and availability of wood, human health impacts and the storage of carbon over time as well as the emissions at the end of its service life. Life Cycle Assessment (LCA) studies are an essential support to gain knowledge about environmental impacts. Ideally this is done already during the planning and development phase to activate levers towards lowering emissions and eco-friendliness. However, it must be noted that LCA outcomes are strongly dependent on applied methods (Ouellet-Plamondon et al., 2023) and early-stage methods are hampered by limited availability of data (Hesser, 2015; Matthews et al., 2019). From a regulatory perspective, higher taxation rates on carbon emissions and fossil fuels push ahead competitiveness of wood construction (Sathre & Gustavsson, 2007).

From a technical point of view, it is vital to explore circular design principles and application potentials for constructed wood. The development of reuse- and recycle-able concepts is necessary for successful implementation of circular construction methods. Technical solutions are particularly important for reuse of elements after demounting (e.g. through detachable fasteners) and new products made from recycled wood materials (Passarelli, 2024; Tupenaite et al., 2023).

3. Best Practice: “SINK.CARBON” – Austrian Use Case in Wood Construction

Austria is widely recognized as a global leader in wood construction with regional traditions in craftmanship. Especially the Alpine regions are known for their commitment to wood-based building practices, combining traditional design elements and know-how with innovative technology and industrial development. Due to the rich forest cover of these regions an economic and cultural appreciation for wood as building material is given. As the global demand for sustainable solutions in the building sector is growing, Austria is well-positioned in the field of expertise and innovation, engineering as well as research and development in wood construction. Austrian companies are pioneering in the development of engineered wood products. Cross-laminated timber (CLT) was developed in the early 1990s in Austria and became an export product used in the wood construction industry worldwide nowadays. Wood and wood-based products represent a significant export factor for Austria and achieved a profit of 5.24 billion € compared to imports in 2022 (cf. Figure 9) (FHP Kooperationsplattform Forst Holz Papier, 2022). However, utilized wood is in Austria still mainly used in non-durable products or for energy generation. In 2011 only 25 % of the wood was processed as sawn timber into durable products such as buildings, windows, doors, or floors (Schwarzbauer et al., 2015).

Investments in research and development in the field of wood construction is a key strategy to further push forward the leading innovations and technology in building systems. Several collaborations between universities, industry and governmental institutions promote cutting-edge solutions in wood construction. A three-point action plan (Bundesministerium für Land- und Forstwirtschaft, 2023) was adopted by the Austrian government in 2023 which is intended to further strengthen wood construction, comprising the following points:

- Public buildings made from wood (utilization of renewable materials, thermal quality, and environmentally friendly heating)
- Promotion of wood construction (adaptation of building standards and legal framework conditions, promotion of funding instruments)
- Wood construction for multi-storey residential buildings (adaptation of housing subsidies).

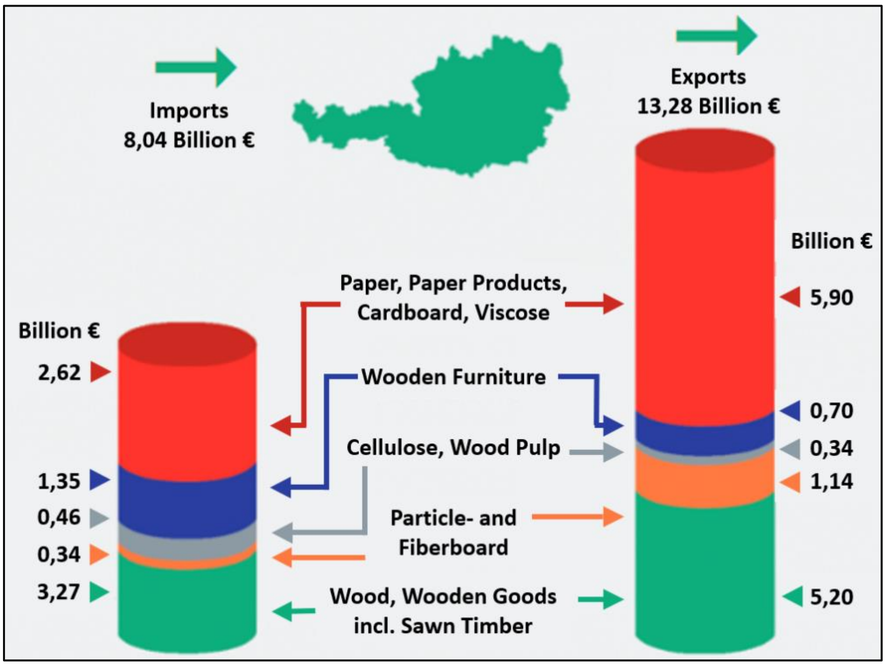


Figure 9: Export statistics of wood and wood-based products in Austria from 2022 (translated figure ©FHP Kooperationsplattform Forst Holz Papier, 2022)

Wood construction is deeply rooted in Austria's cultural heritage. Craftmanship and architecture are reflected in historic timber buildings. Traditional housing, especially in the Alpine region is steeped in timber construction traditions, which are incorporated again in today's innovative design principles and cutting-edge technologies. Nowadays the focus is primarily on sustainable and efficient construction techniques as well as environmental awareness that harmonizes with the natural and cultural landscape. Iconic structures, such as the HoHo Vienna designed by RLP Rüdiger Lainer + Partner, represents the world second tallest wooden skyscraper on 24 storeys, showcases the aesthetic versatility and structural integrity of modern timber construction (Hoffmann, 2017).

Figure 10: The HoHo Vienna (©TROX | DERFRITZ)

3.1. The research project SINK.CARBON

The Austrian research project SINK.CARBON aims at maximizing the material circularity of wood in multi-storey timber construction to act as a carbon sink and thus, as a central strategy for combating climate change to generate an important element for a future bioeconomy. The project is based on one of the fundamental cornerstones of the Austrian timber construction, to contribute to the sustainability of timber construction through research and development. This involves extending the material utilization of wood in buildings in order to maximise the use of resources ecologically and economically. The positive effect of the carbon sink is further enhanced by the reuse and recycling concept of wood as a secondary raw material.

Wood-hybrid components are reused in several life cycles before they are processed for the next recycling cycle (cf. Figure 11. The reuse of timber-hybrid construction elements in wooden buildings is already an integral part of the design phase of the elements or the construction system. Appropriate connectors between the individual construction elements need to be developed or adapted for this purpose in order to facilitate or simplify the detachability and dismantling of the elements. At each use stage, the aim is to maximise the degree of reusability before the respective building material is recycled and reprocessed. In the course of the project, several recycling cycles of the wood-hybrid construction elements are introduced:

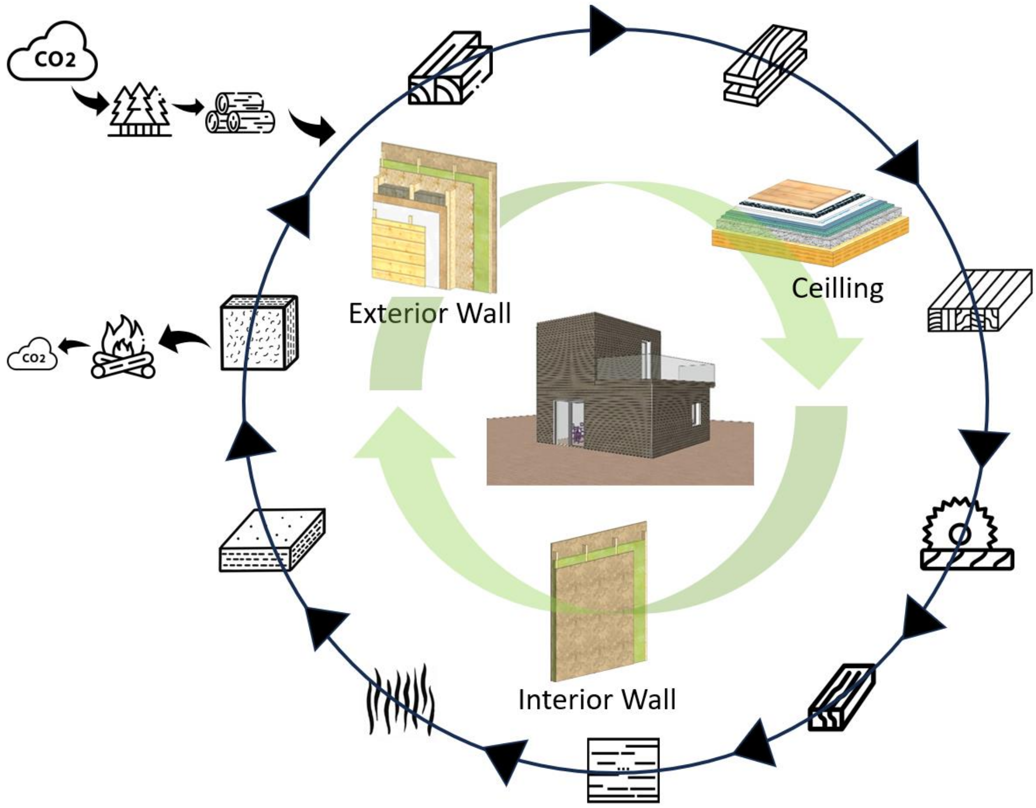


Figure 11: Circular use of wood-hybrid construction elements in SINK.CARBON (own illustration ©Wood K plus & Woschitz group ZT GmbH, Icons (flaticon, n.d.)

Currently, a large proportion of the wood produced during the dismantling of buildings is used for energy purposes instead of a further material use. This is due to a lack of reuse concepts and the poor separability of wood-hybrid elements. For instance, most ceilings are equipped with permanently connected floor structures. Until now, timber structures have mainly been optimized in terms of their technical properties. As a result, the wood used in buildings is currently connected to other building materials in a way that a separation into individual materials during dismantling after the use phase is difficult (Minehuber, 2017). Finally, the wood often ends up in the wood-based panel industry, is burned or even disposed.

From the total annual volume of waste wood in the EU (~52 million m³), on average only 32 % is reused as material, 37 % is used to generate energy and 31 % of waste wood is disposed of in landfills without energy recovery (Vis et al., 2016). There are several reasons why the recycling of waste wood is still on a low level. On the one hand, material use is in direct competition with energy generation from renewable raw materials and, on the other hand, the sorting and use of waste wood for recycling products is regulated and, as a very heterogeneous mixed assortment, challenging for further processing. Research for building material recycling often focus on concrete and its processing scenarios (Largo, 2016). Wood is considered a low priority here, which is why drastic downcycling is usually pursued rather than reuse. When building elements are dismantled, damage usually occurs that hinders direct reuse. However, a proper dismantling is essential for the use of timber-hybrid building elements, especially for multi-storey construction to exploit the strengths of the respective building materials (Mai Quang et al., 2018; Woschitz et al., 2021). Modern advances in engineering have expanded the use of wood beyond conventional framing to innovative applications such as cross-laminated timber, which has opened up new possibilities for wood in large-scale construction.

4. Transferability of wood construction concepts between countries with a focus on Asia and Latin America

To evaluate the transferability of wood construction concepts between countries, the current state of wood construction in the respective regions needs to be addressed. Here, some examples of using wood for construction in countries across Asia and Latin America are highlighted.

4.1. Asia

Cultural Heritage/Traditions/Design Excellence

The long-standing tradition of building, restoring, and maintaining structures using wooden joints is prevalent throughout Asia and continues to offer valuable lessons on hazard prevention today (Kelman et al., 2016). As an example, Japan has a strong and long tradition of wood construction (FCBA, 2022). As an example, the architectural heritage Kampung Laut Old Mosque (KLOM) in Malaysia is a perfect example on historic timber construction techniques (Sanusi Hassan & Syafik Ahmad Nawawi, 2014). The building elements reflect rich timber construction designs that consider local culture, spiritual perspectives, and climatic approaches, portraying the regional identity of the built environment. Indonesia has been using traditional timber building systems to construct seismic-resistant buildings (earthquake-resistant) (Kelman et al., 2016).

Current situation

Japan strongly depends on imports to meet its domestic demand and needs to focus on seismic issues as well as fire safety construction due to high probability of earthquakes (FCBA, 2022). The Green Building Masterplan of Singapore (SGBMP) has continuously evolved since 2005 with the BCA Green Mark program to promote sustainability in the construction industry (BCA, 2022). The goal is to make at least 80% of buildings in Singapore environmentally friendly by 2030. Initiatives such as the Super Low Energy (SLE) Building Program in 2018 and collaboration with the Singapore Green Building Council are increasing standards, creating incentives, and driving innovations to advance energy-efficient and sustainable development of the built environment. However, the majority of countries, except Japan, China and Korea lack in mandatory building codes for all sectors, as their implementation and enforcement are challenging (GlobalABC/IEA/UNEP, 2020). Some other countries have voluntary codes in place.

Lighthouse projects/techniques

The „Gaia Academic Building South“ at Nanyang Technical University (NTU) in Singapore is the largest timber construction in Asia (Lanz, 2023; Wiehag, 2024). The building was designed by Toyo Ito and constructed by the Austrian company WIEHAG, using 6,000 m³ glue laminated timber (GLT) (produced by WIEHAG in Austria) and 7,000 m³ cross laminated timber (CLT) (produced by Stora Enso in Austria) in modular timber frames. The building is certified as "Zero Energy Building".

The Mactan International Airport in Lapu-Lapu, Mactan Cebu, Philippines is the first international airport terminal in Asia partly built in wood (Rubner, 2023). It was designed in wood because of design, ecological and traditional reasons. The 4,500 m³ GLT were produced in Austria and the construction was carried out by Rubner according to European Standards.

A 17-storey wood-frame office tower is currently built in Nihonbashi, Tokio, Japan with a height of 70 m (Mitsui Fudosan and Takenaka Corporation, 2020). It should be finished by 2025. The hybrid structure uses CLT from domestic timber.

In Tokyo, the tallest wooden building on earth – the W350 (**Fehler! Verweisquelle konnte nicht gefunden werden.**) – is planned to be built by 2041, reaching 350 m (Hühn, 2019). The domestic timber should be provided by the building owner Somitomo Forestry.

Figure 12: Concept of the W350 wooden skyscraper to be built in Tokyo (©Sumitomo Forestry Co., Ltd.)

Statistical figures on timber construction / sustainability / forest management

Unlike in the other continents (Figure 13), forest areas in Africa and South America have declined from 1990 to 2020 (FAO, 2020). From 2010 to 2020, Asia experienced the largest increase in forest area (**Fehler! Verweisquelle konnte nicht gefunden werden.**), primarily in East Asia. China in particular, reported an annual net increase of 1.94 million hectares (FAO in statista, 2020). South and Southeast Asia experienced net forest losses from 1990 to 2020, offset by gains in India and Vietnam.

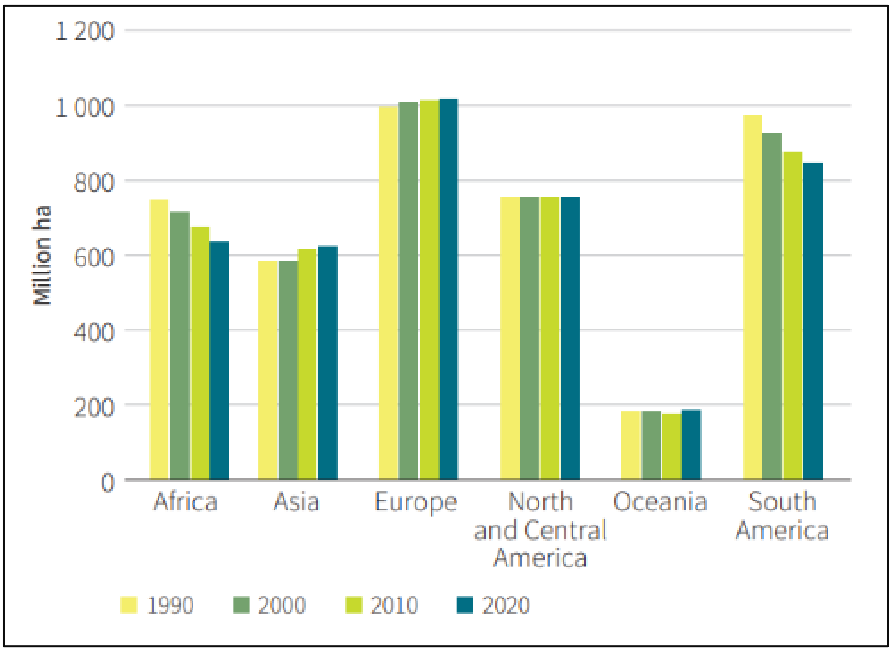


Figure 13: Forest area by continent (FAO, 2020)

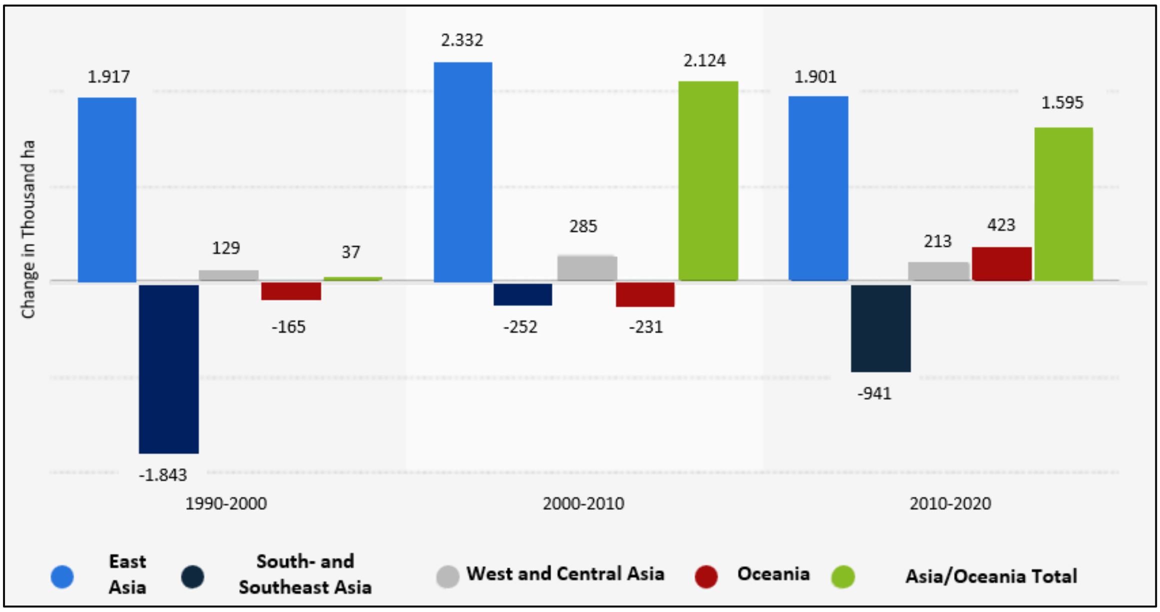


Figure 14: Change in forest area in Asia and Oceania from 1990 to 2020 in 1,000 ha (translated figure © FAO in statista, 2020)

In the Asia-Pacific region, forests cover approximately 25% of the land area (FAO, 2019). Deforestation and forest degradation pose threats to forests. Around one billion forest-dwelling people rely on forests for subsistence, shelter, and survival. Forests support millions of smallholders, communities, and industries, providing livelihoods, income, and employment. Reasons for deforestation include inadequate land governance, complexities in land ownership, rising population, urban sprawl, and land use competition with agriculture. FAO provides policy support for sustainable forest management, facilitating information exchange through the Asia-Pacific Forestry Commission (APFC) and establishing technical networks. Field projects are implemented and studies are carried out to raise awareness about the importance of forests for our climate. In 2023, the FSC-certified area in Asia-Pacific was 9 million hectares (FSC in statista, 2023). In Japan the share of new wooden structure buildings in construction was about 58.7 % in 2021 (MAFF & MLIT in statista, 2023).

4.2. Latin America

Cultural Heritage/Traditions/Design Excellence

Most of the Latin American countries don't use wood as a main construction material except Chile and Brazil, who are influenced by the European cultural heritage of colonization. Chile has a strong tradition of timber construction, particularly in the southern region (Araya et al., 2022). Wood was typically used for low-income or emergency housing. Therefore, the quality, design and technologies used under these conditions have commonly been of low quality (Araya et al., 2022). Exceptions can be found in certain settlements and regions. On the Chiloe Islands in Southern Chile, wood building techniques used for churches in the 18th and 19th century are known (Gutiérrez, 2011). Also, the historic centre of Valparaiso, Chile was built with wood cladding dated back to the 19th century (Gutiérrez, 2011).

Current situation

The number of wood buildings realised in Latin America is still low today. Even though wood construction is not being promoted in most Latin American countries, Uruguay is taking a step towards an upturn. A state-of-the-art cross-laminated timber (CLT) and glulam (GLT) plant, the largest in South America was newly built in Uruguay (Arboreal in Tacuarembó) (Araya et al., 2022).

Lighthouse projects/techniques

Two projects are currently in progress, which aspire to be the first wooden high-rise buildings in Latin America (Figure 15). Arboreal is promoting the first high-rise building in Uruguay, which should be completed by end of 2024. It will be the largest wooden building in Latin America, owing seven floors and a construction system emphasized for energy-efficiency and speed in construction. The building was designed in collaboration with Dovat Architects who are committed to promote timber construction in Uruguay (Uruguay XXI, 2024).

Alongside Uruguay, Tallwood architects planned the Tamango Project, which will be a 12-storey wood construction in Patagonia, Chile. The project should represent a shift towards greater sustainability by substituting concrete with wood and developing an efficient construction system including CLT and laminated veneer lumber (LVL) as well as glulam. The estimation or goal of the project is that it captures more CO_2 than emitted during construction and transport (Prieto, 2022).

Figure 15: Plans for the tallest wooden building in Uruguay (left) (Uruguay XXI, 2024) and the Tamango project in Chile (right) (©Tallwood)

Statistical figures on timber construction / sustainability / forest management

Statistics on timber construction in Latin America are rare, what is probably due to the fact that there is no tradition in timber construction. Focusing on South America, it was the region with the highest rate of forest loss globally between 1990 and 2010, with estimated 5.2 million hectares of net forest loss per year in the first decade of this century. The decline subsequently stabilized and South America moved into second place of the highest forest loss behind Africa. The figures show, that despite reforestation efforts, forest areas in South America continue to be endangered by massive deforestation and wildfires (FAO, 2020).

5. Key messages and Recommendations

5.1. Potentials

In the light of a more sustainable future and the global climate crisis, a transition from fossil-based driven technologies towards a bio-based economy is of vital interest. The use of wood for long-life products (such as buildings) can contribute to tackle these challenges, as wood has some advantages compared to fossil-based materials. E.g. a significantly lower amount of indicated CO_2 emissions is emitted through timber construction. Furthermore, the sequestration and storage effect of carbon dioxide over a long-term period avoids emissions, as the storage capacity exceeds the emissions generated during the production of materials and construction of the wooden buildings (Kumar et al., 2024; Mishra et al., 2022; Ormondroyd et al., 2016; Ximenes & Grant, 2013). This storage effect of wood is even increased by multiple cascading use phases, where wood is used as material in products. The cascadic use of wood needs generally to be favored over energetic uses of primary wood. To achieve these ambitions, emphasis should be given on product development, expanding production capacities and education to generate knowledge about wood in construction (Wallius et al., 2023).

Wood has technically the potential to substitute fossil resources in many applications. Life Cycle Assessment (LCA) methods are acknowledged as useful tools to gain important insights into technology implications. Especially ex-ante LCA provides the chance to assess potential future implications of emerging technologies which provides the opportunity to prevent or address adverse effects already in an early stage of development (Matthews et al., 2019; Roes & Patel, 2011). This is of particular interest as 80 % of environmental impacts are stipulated early on in the product development phase (McAloone & Bey, 2009).

5.2. Limitations

Having a look on the today's worldwide high consumption of energy and resources in diverse fields of application, it will not be possible to satisfy this demand just by using wood, as the availability of wood is limited due to sustainable forest management. However, innovative, cascadic and sustainable concepts established along the wood supply chain might be transferable to the processing industry of fossil-based resources.

Additionally, fossil-based materials cannot be substituted by wood in every possible application. Especially in contact to soil, it is rarely economically or ecologically reasonable to use wood instead of concrete, due to high efforts for protecting wood against microbiological decay.

Although the perception of stakeholders regarding wood in the construction sector is seen as an environmentally friendly or aesthetically pleasant option, wood buildings are perceived to be more expensive or not easily available. Concerns regarding fire safety and maintenance costs might be eased by improved regulations (Wallius et al., 2023). Higher costs for wood constructions are often caused by using original plans meant for building with conventional materials instead of considering the use of wood already in an early planning stage of buildings. Additionally, the economic competitiveness of wood in construction against conventional materials is expected to increase with higher taxation on carbon emissions (Sathre & Gustavsson, 2007).

5.3. Best practice and its transferability

Especially the development of innovative engineered wood products and sophisticated wood technological processes led to an increase of using wood for construction in Europe. One example is Cross Laminated Timber (CLT), which has become a well-known engineered wood product of global interest (Brandner et al., 2016). CLT consists of an orthogonal and laminar structure that allows its application as a full-size wall or floor element. In general, wood engineering has a long tradition in Austria and several world leading companies originate from this country. Using wood as an engineered building material is well incorporated in education and research.

Typically, integral planning is not that well established for building with conventional materials compared to building with wood. This is seen as advantageous for all stakeholders in the building process. As a consequence, the high degree of prefabrication enables the use of digital technologies such as robots (Ebner, 2021) or assistance systems (Bartuska et al., 2023). This already established digital transformation serves as solid basis for a prosperous future of building with wood.

Transferability to other countries and continents of incumbent technologies for a long-life utilization of wood in the building construction is dependent on a properly functioning and dense network of recycling and reprocessing facilities of used wood. Austria has a long tradition in wood buildings and other wood processing technologies and therefore, developed a network of recycling centers even outside urban structures. Additionally, the use of wood in the construction industry is particularly dependent on the overall availability of wood in the respective regions. Compliance with sustainable forest management must be ensured, as high emissions are associated with global trade and transport of timber and wooden products. Due to the small-scale forestry in Austria, transport distances to saw mills can be minimized within a radius of around 300 km (proHolz Steiermark, 2024). Sourcing local wood strengthens the rural areas and communities and allows consumers to be more aware of environmental and social conditions in the forestry practices. Avoiding deforestation of (primeval) forests with an important and rich biodiversity should be a key principle.

Political Decisions and Regulation: For the protection of naturally grown forests and their biodiversity, planted forests can be promoted. Fast growing tree species can cover the demand for wood in a short time and store relevant amounts of carbon dioxide. Political decisions and strategies on the responsible consumption of natural wood resources should lead to combating land-use competition, focusing on sustainable forest management practices and defining end-user regulations (Ramage et al., 2017). An international perspective on forestry and forest plantation strategies is essential to meet global requirements. Successful recycling strategies need local regulatory frameworks, which are an essential step forward for increasing the recycling rate and reusability of wood. To promote the worldwide use of wood products in the construction sector, harmonized international standards are needed (Brandner et al., 2016).

5.4. Conclusion

Our overall conclusions and recommendations on the promotion of wood in the building sector comprise the following issues:

- Future research and knowledge generation should focus on integrated design in the planning phase of (wooden) buildings, digitalization (e.g. assistance systems) in wood construction as well as excellence in engineering. The early consideration of environmental, social and economic implications in the process of developing new technologies is essential for sustainable solutions.
- The utilization of wood for construction can only be promoted under the premise of using sustainable forest management. Wood products need to be designed in a way to maximize their reusability and to promote cascadic material utilization as well as circularity.
- Political decisions and regulations should comply with global requirements regarding the balance between wood utilization and protection of natural resources. On the other hand, local regulations are needed to push forward opportunities for recovering wood to be reused and recycled.

References

Amiri, A., Ottelin, J., Sorvari, J., & Junnila, S. (2020). Cities as carbon sinks—classification of wooden buildings. *Environmental Research Letters*, *15*(9), 094076. https://doi.org/10.1088/1748-9326/aba134

Andrew, R. M. (2018). Global CO2 emissions from cement production. *Earth System Science Data*, *10*(1), 195–217. https://doi.org/10.5194/essd-10-195-2018

Araya, R., Guillaumet, A., do Valle, Â., Duque, M. del P., Gonzalez, G., Cabrero, J. M., De León, E., Castro, F., Gutierrez, C., Negrão, J., Moya, L., & Guindos, P. (2022). Development of Sustainable Timber Construction in Ibero-America: State of the Art in the Region and Identification of Current International Gaps in the Construction Industry. *Sustainability*, *14*(3), 1170. https://doi.org/10.3390/su14031170

Bartuska, B., Teischinger, A., & Riegler, M. (2023). Effects of spatial augmented reality assistance on the efficiency of prefabricating timber frame walls. *Wood Material Science & Engineering*, *18*(3), 860–869. https://doi.org/10.1080/17480272.2022.2085528

BCA. (2022). *Green Building Masterplans*. Building and Construction Authority (BCA). https://www1.bca.gov.sg/buildsg/sustainability/green-building-masterplans#:~:text=The%20SGBMP%20aims%20to%20deliver,80%2D80%20in%202030%E2%80%9D.&text=The%20earlier%20editions%20of%20the,Singapore%27s%20buildings%20have%20been%20greened

Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): overview and development. *European Journal of Wood and Wood Products*, *74*(3), 331–351. https://doi.org/10.1007/s00107-015-0999-5

Bundesministerium für Land- und Forstwirtschaft, R. und W. (2023). *3-Punkte-Plan zur Stärkung des Holzbaus in Österreich*. https://info.bml.gv.at/themen/wald/wald-und-klima/staerkung-holzbau-oesterreich.html

Castleden, R. (1987). *The Stonehenge People. An Exploration of Life in Neolithic Britain 7400-2000BC*. Routledge & Kegan Paul.

Chastas, P., Theodosiou, T., & Bikas, D. (2016). Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. *Building and Environment*, *105*, 267–282. https://doi.org/10.1016/j.buildenv.2016.05.040

Chaudhary, A., Burivalova, Z., Koh, L. P., & Hellweg, S. (2016). Impact of Forest Management on Species Richness: Global Meta-Analysis and Economic Trade-Offs. *Scientific Reports*, *6*(1), 23954. https://doi.org/10.1038/srep23954

Chen, Z., Gu, H., Bergman, R., & Liang, S. (2020). Comparative Life-Cycle Assessment of a High-Rise Mass Timber Building with an Equivalent Reinforced Concrete Alternative Using the Athena Impact Estimator for Buildings. *Sustainability*, *12*(11), 4708. https://doi.org/10.3390/su12114708

Crawford, R. H., & Cadorel, X. (2017). A Framework for Assessing the Environmental Benefits of Mass Timber Construction. *Procedia Engineering*, *196*, 838–846. https://doi.org/10.1016/j.proeng.2017.08.015

Ebner, G. (2021, May 26). *100 Roboter fertigen 1000 Wohnungen im Monat. Oder: 1 Mio. m^2 Bruttogeschoßfläche pro Jahr*. Https://Www.Holzkurier.Com/Holzprodukte/2021/05/Importedcontent0.Html#.

FAO. (2019). *FAO's goal and role for sustainable forest management in Asia and the Pacific*.

FAO. (2020). *Global Forest Resources Assessment 2020*. FAO. https://doi.org/10.4060/ca9825en

FAO in statista. (2020). *Veränderung der Waldfläche in Asien und Ozeanien nach Regionen in den Jahren 1990 bis 2020 [Graph}*.

FCBA. (2022). *Woodrise: Overview of wood construction in Japan*. https://www.fcba.fr/en/ressources/woodrise-overview-of-wood-construction-in-japan/

FHP Kooperationsplattform Forst Holz Papier. (2022). *Export statistics of wood and wood-based products in Austria in 2022*. https://forstholzpapier.at/images/FHP-Exportfaktor_S%C3%A4ulenTabelle_2022.pdf

Franzini, F., Toivonen, R., & Toppinen, A. (2018). Why Not Wood? Benefits and Barriers of Wood as a Multistory Construction Material: Perceptions of Municipal Civil Servants from Finland. *Buildings*, *8*(11), 159. https://doi.org/10.3390/buildings8110159

FSC in statista. (2023). *Area of certified Forest Stewardship Council (FSC) worldwide as of December 2023, by region [graph]*. https://www.statista.com/statistics/807434/global-forest-stewardship-council-fsc-area-land-by-region/

Geier, S. (2018). Planen im Holzbau - ein Ländervergleich. *Zuschnitt. Zeitschrift Über Holz Als Werkstoff Und Werke in Holz. ProHolz Austria*, *70*.

GlobalABC/IEA/UNEP. (2020). *GlobalABC Regional Roadmap for Buildings and Construction in Asia: Towards A Zero-Emission, Efficient and Resilient Buildings and Construction Sector*.

Gosselin, A., Blanchet, P., Lehoux, N., & Cimon, Y. (2016). Main Motivations and Barriers for Using Wood in Multi-Story and Non-Residential Construction Projects. *BioResources*, *12*(1). https://doi.org/10.15376/biores.12.1.546-570

Gutiérrez, R. (2011). *The Urban Architectural Heritage of Latin America*. ICOMOS Conseil International Des Monuments et Des Sites. https://www.icomos.org/fr/116-english-categories/resources/publications/232-the-urban-architectural-heritage-of-latin-america

Hesser, F. (2015). Environmental advantage by choice: Ex-ante LCA for a new Kraft pulp fibre reinforced polypropylene composite in comparison to reference materials. *Composites Part B: Engineering*, *79*, 197–203. https://doi.org/10.1016/j.compositesb.2015.04.038

Hesser, F., Wohner, B., Meints, T., Stern, T., & Windsperger, A. (2017). Integration of LCA in R&D by applying the concept of payback period: case study of a modified multilayer wood parquet. *The International Journal of Life Cycle Assessment*, *22*(3), 307–316. https://doi.org/10.1007/s11367-016-1173-y

Hoffmann, R. (2017). *HoHo Wien®: From an idea about wood to the world's tallest wooden high-rise*.

Hühn, S. (2019). *Plyscraper W350: Das höchste geplante Holzhochhaus der Welt*. INGENIEUR.De. https://www.ingenieur.de/technik/fachbereiche/architektur/plyscraper-w350-das-hoechste-geplante-holzhochhaus-der-welt/

Hurmekoski, E., Jonsson, R., & Nord, T. (2015a). Context, drivers, and future potential for wood-frame multi-story construction in Europe. *Technological Forecasting and Social Change*, *99*, 181–196. https://doi.org/10.1016/j.techfore.2015.07.002

Hurmekoski, E., Jonsson, R., & Nord, T. (2015b). Context, drivers, and future potential for wood-frame multi-story construction in Europe. *Technological Forecasting and Social Change*, *99*, 181–196. https://doi.org/10.1016/j.techfore.2015.07.002

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings—A review of current trends. *Energy and Buildings*, *66*, 232–245. https://doi.org/10.1016/j.enbuild.2013.07.026

Ikei, H., Song, C., & Miyazaki, Y. (2017). Physiological effects of wood on humans: a review. *Journal of Wood Science*, *63*(1), 1–23. https://doi.org/10.1007/s10086-016-1597-9

Kaufmann, H., Krötsch, S., & Winter, S. (2017). *Atlas Mehrgeschossiger Wohnbau: Vol. DETAIL Atlas*. DETAIL.

Kellert, S. R., Heerwagen, J., & Mador, M. (2013). *Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life*.

Kelman, I., Gaillard, J. C., Lewis, J., & Mercer, J. (2016). Learning from the history of disaster vulnerability and resilience research and practice for climate change. *Natural Hazards*, *82*(S1), 129–143. https://doi.org/10.1007/s11069-016-2294-0

Kolb, J. (2014). *Holzbau mit System. Tragkonstruktion und Schichtaufbau der Bauteile*. Birkhäuser. Lignum.

Kumar, V., Lo Ricco, M., Bergman, R. D., Nepal, P., & Poudyal, N. C. (2024). Environmental impact assessment of mass timber, structural steel, and reinforced concrete buildings based on the 2021 international building code provisions. *Building and Environment*, *251*, 111195. https://doi.org/10.1016/j.buildenv.2024.111195

Lanz, K. (2023). *Vom Innviertel nach Singapur: Österreichbeteiligung am größten Holzbau Asiens*. https://www.holzbauaustria.at/news/2023/07/oesterreichbeteiligung-am-groessten-holzbau-asiens.html

Largo, A. (2016). *RE4 - Prefabricated elements from recycled materials to develop energy efficient buildings and minimize environmental impacts*.

Lazarevic, D., Kautto, P., & Antikainen, R. (2020). Finland's wood-frame multi-storey construction innovation system: Analysing motors of creative destruction. *Forest Policy and Economics*, *110*, 101861. https://doi.org/10.1016/j.forpol.2019.01.006

Leskinen, P., Cardellini, G., González-García, S., Hurmekoski, E., Sathre, R., Seppälä, J., Smyth, C., Stern, T., & Verkerk, P. J. (2018). *Substitution effects of wood-based products in climate change mitigation*.

MAFF, & MLIT in statista. (2023). *Share of wooden structure buildings in new dwelling construction starts Japan from 2015 to 2021 [graph]*. .https://www.statista.com/statistics/Klicken oder tippen Sie hier, um Text einzugeben.1345047/japan-housing-construction-starts-wooden-structure-buildings-share/

Mai Quang, K., Park, A., & Lee, K. (2018). Experimental and numerical performance of shear connections in CLT–concrete composite floor. *Materials and Structures*, *51*(4), 84. https://doi.org/10.1617/s11527-018-1202-3

Martin, P. A., Newton, A. C., Pfeifer, M., Khoo, M., & Bullock, J. M. (2015). Impacts of tropical selective logging on carbon storage and tree species richness: A meta-analysis. *Forest Ecology and Management*, *356*, 224–233. https://doi.org/10.1016/j.foreco.2015.07.010

Matthews, N. E., Stamford, L., & Shapira, P. (2019). Aligning sustainability assessment with responsible research and innovation: Towards a framework for Constructive Sustainability Assessment. *Sustainable Production and Consumption*, *20*, 58–73. https://doi.org/10.1016/j.spc.2019.05.002

McAloone, T. C., & Bey, N. (2009). *Environmental improvement through product development: A guide*.

Mhuireach, G. Á., Dietz, L., Griffiths, W., Horve, P. F., Laguerre, A., Northcutt, D., Vandegrift, R., Gall, E., & Van Den Wymelenberg, K. (2021). Differing effects of four building materials on viable bacterial communities and VOCs. *Developments in the Built Environment*, *7*, 100055. https://doi.org/10.1016/j.dibe.2021.100055

Minehuber, T. H. (2017). *Rückbau-, Wiederverwendungs- und Recyclingpotenziale eines Holzriegelfertigteilhauses*. FH Campus Wien.

Mishra, A., Humpenöder, F., Churkina, G., Reyer, C. P. O., Beier, F., Bodirsky, B. L., Schellnhuber, H. J., Lotze-Campen, H., & Popp, A. (2022). Land use change and carbon emissions of a transformation to timber cities. *Nature Communications*, *13*(1), 4889. https://doi.org/10.1038/s41467-022-32244-w

Ormondroyd, G. A., Spear, M. J., & Skinner, C. (2016). *The Opportunities and Challenges for Re-use and Recycling of Timber and Wood Products Within the Construction Sector* (pp. 45–103). https://doi.org/10.1007/978-981-10-0655-5_3

Osburg, V.-S., Appelhanz, S., Toporowski, W., & Schumann, M. (2016). An empirical investigation of wood product information valued by young consumers. *Journal of Cleaner Production*, *110*, 170–179. https://doi.org/10.1016/j.jclepro.2015.01.068

Ouellet-Plamondon, C. M., Ramseier, L., Balouktsi, M., Delem, L., Foliente, G., Francart, N., Garcia-Martinez, A., Hoxha, E., Lützkendorf, T., Nygaard Rasmussen, F., Peuportier, B., Butler, J., Birgisdottir, H., Dowdell, D., Dixit, M. K., Gomes, V., Gomes da Silva, M., Gómez de Cózar, J. C., Kjendseth Wiik, M., … Frischknecht, R. (2023). Carbon footprint assessment of a wood multi-residential building considering biogenic carbon. *Journal of Cleaner Production*, *404*, 136834. https://doi.org/10.1016/j.jclepro.2023.136834

Passarelli, R. N. (2024). Design for Disassembly and Reuse of Timber in Construction: Identification of Trends and Knowledge Gaps. In L. Braganca, M. Cvetkovska, R. Askar, & V. Ungureanu (Eds.), *Creating a Roadmap towards Circularity in the Built Environment* (pp. 57–67). Springer. https://doi.org/10.1007/978-3-031-45980-1_6

Prieto, C. (2022). *Latin America's First High-rise Building in Cross Laminated Timber is Built in Chilean Patagonia*. https://www.archdaily.com/992878/latin-americas-first-high-rise-building-in-cross-laminated-timber-is-built-in-chilean-patagonia

proHolz Steiermark. (2024, March 28). *Holz der Klimaschützer. Klimafreundliche Holzverarbeitung*. Https://Www.Proholz-Stmk.at/Rundumholz/Wissenswertes-Ueber-Holz/Holz-Der-Klimaschuetzer/.

Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., Allwood, J., Dupree, P., Linden, P. F., & Scherman, O. (2017). The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews*, *68*, 333–359. https://doi.org/10.1016/j.rser.2016.09.107

Roes, A. L., & Patel, M. K. (2011). Ex-ante environmental assessments of novel technologies – Improved caprolactam catalysis and hydrogen storage. *Journal of Cleaner Production*, *19*(14), 1659–1667. https://doi.org/10.1016/j.jclepro.2011.05.010

Rowlinson, D. (2020). *NZ Wood Design Guides. Social and Health Benefits of Timber Construction*.

Rubner. (2023). *Mactan International Airport: Erstes hölzernes Flughafenterminal in Asien*. https://www.rubner.com/de/referenzen/holzbau/mactan-international-airport/

Sanusi Hassan, A., & Syafik Ahmad Nawawi, M. (2014). Malay Architectural Heritage on Timber Construction Technique of the Traditional Kampung Laut Old Mosque, Malaysia. *Asian Social Science*, *10*(8). https://doi.org/10.5539/ass.v10n8p230

Sathre, R., & Gustavsson, L. (2007). Effects of energy and carbon taxes on building material competitiveness. *Energy and Buildings*, *39*(4), 488–494. https://doi.org/10.1016/j.enbuild.2006.09.005

Schwarzbauer, P., Braun, M., & Stern, T. (2015). *Klimaschutz durch den Aufbau eines Harvested Wood Product Pools: Von der Berechnung von THG-Emissionseinsparungen bis zur Steuerung der Speicherwirkung durch Harvested Wood Products*. https://www.bfw.gv.at/wp-content/cms_stamm/050/PDF/holzkette/BOKU_HolzKohlenstoffpool-end.pdf

Stamford, L. (2020). Life cycle sustainability assessment in the energy sector. In J. Ren, Aa. Scipioni, A. Manzardo, & H. Liang (Eds.), *Biofuels for a More Sustainable Future* (pp. 115–163). Elsevier. https://doi.org/10.1016/B978-0-12-815581-3.00005-1

Teischinger, A., Stingl, R., Berger, V., & Eder, A. (2014). *Holzbauanteil in Österreich*. https://www.proholz.at/wald-holz-klima/wie-viel-wird-in-oesterreich-mit-holz-gebaut

Tupenaite, L., Kanapeckiene, L., Naimaviciene, J., Kaklauskas, A., & Gecys, T. (2023). Timber Construction as a Solution to Climate Change: A Systematic Literature Review. *Buildings*, *13*(4), 976. https://doi.org/10.3390/buildings13040976

Tykkä, S., McCluskey, D., Nord, T., Ollonqvist, P., Hugosson, M., Roos, A., Ukrainski, K., Nyrud, A. Q., & Bajric, F. (2010). Development of timber framed firms in the construction sector — Is EU policy one source of their innovation? *Forest Policy and Economics*, *12*(3), 199–206. https://doi.org/10.1016/j.forpol.2009.10.003

Uruguay XXI. (2024). *Uruguay will have the tallest wooden building in Latin America*. https://www.uruguayxxi.gub.uy/en/news/article/uruguay-will-have-the-tallest-wooden-building-in-latin-america/

Vis, M., Mantau, U., Allen, B., Essel, R., & Reichenbach, J. (2016). *CASCADES, Study on the optimised cascading use of wood*.

Wallius, V., Kunttu, J., Leskinen, P., Van Brusselen, J., & Näyhä, A. (2023). Stakeholder perceptions of wood-based products in the built environment: a literature review. *European Journal of Wood and Wood Products*, *81*(2), 287–299. https://doi.org/10.1007/s00107-022-01905-4

Weiss, G., Hansen, E., Ludvig, A., Nybakk, E., & Toppinen, A. (2021). Innovation governance in the forest sector: Reviewing concepts, trends and gaps. *Forest Policy and Economics*, *130*, 102506. https://doi.org/10.1016/j.forpol.2021.102506

Wiehag. (2024). *Technische Universität von Nanyang*. https://www.wiehag.com/de/ntu-singapore/

Woschitz, R., Deix, K., Huber, C., & Kampitsch, T. (2021). Development of innovative wood-concrete composite floors in prefabricated construction method. *Bautechnik*, *98 (S1)*, 12–22.

Ximenes, F. A., & Grant, T. (2013). Quantifying the greenhouse benefits of the use of wood products in two popular house designs in Sydney, Australia. *The International Journal of Life Cycle Assessment*, *18*(4), 891–908. https://doi.org/10.1007/s11367-012-0533-5

Yadav, R., & Kumar, J. (2022). Engineered Wood Products as a Sustainable Construction Material: A Review. In *Engineered Wood Products for Construction*. IntechOpen. https://doi.org/10.5772/intechopen.99597

How can the use of wood in construction contribute to the development of a carbon neutral bioeconomy in Africa?

Tahiana Ramananantoandro, Andry Clarel Raobelina
University of Antananarivo, School of Agronomy (Laboratoire de Recherches Appliquées, Ecole Supérieure des Sciences Agronomiques), Department of Forestry and Environment, Antananarivo, Madagascar

Abstract

The construction sector is responsible for a significant share of global CO2 emissions and energy demand. Due to the expected demographic explosion in Africa in the coming years and the housing deficit, especially in cities, the adoption of low-energy and low-carbon practices throughout the construction life cycle is an urgent matter. Instead of relying on traditional materials such as concrete and steel, which contribute significantly to carbon emissions, this paper explores sustainable practices, emphasizing wood construction as a pivotal component of the emerging bioeconomy. Prefabricated mass timber construction, utilizing materials like Cross-Laminated Timber (CLT), offers eco-friendly benefits such as reduced waste, lighter weight, and lower carbon emissions. While three CLT industries have been identified in South and East Africa, their production is still at a relatively small scale. On the other hand, the bamboo, characterized by its rapid growth and versatile applications, emerges as a promising bio-sourced alternative. Engineered bamboo, integrated with steel and concrete, not only enhances durability but also aligns with the principles of the bioeconomy. Reclaimed wood use, considered within the context of a circular bioeconomy, gains prominence for its role in reducing carbon footprint. To ensure the widespread adoption of bio-based materials and practices, the paper suggests measures like reducing deforestation, promoting reforestation and agroforestry practices, enhancing bamboo farming, sustainable forest management, wood traceability and technological decentralization. Overcoming negative perceptions of bio-sourced materials, establishing regulations, and fostering research and development are crucial for successfully integrating wood construction into the bioeconomy across African countries. Moreover, promoting the use of raw materials produced locally is important to reduce carbon dioxide emissions associated with the energy expended during material transportation. Addressing these factors can transform the construction sector, aligning it with the principles of a sustainable and thriving bioeconomy while mitigating environmental impact.

1. Wood construction according to bioeconomy in Africa

According to the Global ABC report (2022), the construction sector accounts for 37% of worldwide CO2 emissions and 34% of global energy consumption. Given the expected demographic growth in Africa over the coming years, there would be a substantial increase in the demand for construction materials (OCDE, 2018). According to Statista (2023), the total population in Africa is expected to double by 2050, reaching nearly 2.5 billion. Indeed, by 2100, Africa is anticipated to undergo a substantial population explosion, constituting at least 25% of the world's population, in contrast to less than 10% in 1950. In consequence, it is expected that the African construction market will rise by 70,20% in the five coming years, from USD 55.60 billion (2023) to USD 71.20 billion (2028). This exhibits a Compound Annual Growth Rate (CAGR) of 5.07% (Mordor Intelligence, 2023).

However, a significant portion of households in Africa faces challenges in affording basic formal housing or accessing mortgage loans, resulting in many households residing in poorly constructed, slum-like housing. According to the United Nations (2022), 85% of the global population living in slums and informal settlements was concentrated in Eastern and South-Eastern Asia, Central and Southern Asia, and Sub-Saharan Africa in 2020. In the Sub-Saharan region, approximately 62% of the population dwells in slums (Amegah, 2021).

Furthermore, the construction sector in Africa is characterized by an accumulated housing deficit. Most African countries are within this housing crisis, such as Uganda, which experiences an annual housing backlog of 1.6 million units, Kenya of 2 million units, Tanzania of 3 million units, South Africa of 3 million units, and Nigeria of 17 million units. The continent needs 4 million housing units annually to address its housing requirements (Shelter Afrique, 2019). However, only a small portion of this quantity is being built annually, resulting in a significant housing deficit. Seventy percent of the African building stock projected for 2040 remains undeveloped (IEA, 2019).

The construction sector should therefore adopt eco-friendly actions and practices to meet this growing demand while reducing its environmental footprint. The strategy for decarbonizing the building sector should vary according to rural and urban areas in Africa as the type of materials used for construction differs significantly between these two environments. Unlike urban areas, the use of traditional bio-sourced materials, which are easily accessible and affordable, such as earth, bamboo, and wood, predominates in rural areas (Westerholm et al., 2023). The use of these traditional construction materials, which are produced locally, aligns with bioeconomy because they are characterized by the use of low technology, low carbon emissions, and high circularity (Westerholm et al., 2023). In Africa, the need to transition to the use of low-carbon construction materials to decarbonize the construction sector therefore primarily concerns urban areas, while in rural areas, it is suitable to adopt good construction practices to promote construction sustainability and durability. Urban buildings currently rely on high-carbon materials in Africa, typically cement and steel, the production of which results in significant greenhouse gas emissions corresponding to 0.93 kg of CO_2 for every kg of cement produced.

This report explores existing low-energy and low-carbon practices that are already implemented in Africa and assesses their potential transferability and adaptability to other African countries.

2. Best practices

2.1. Prefabricated mass timber construction

The adoption of prefabricated construction is emerging as an innovative and environmentally friendly strategy in the construction sector. Prefabricated construction involves a streamlined process wherein elements are manufactured and preassembled away from the construction site, before being transported on-site for final assembly (Chen et al., 2010). The utilization of mass timber in prefabricated construction, including materials such as Cross-Laminated Timber (CLT), panels (Younis and Dodoo, 2022), glued laminated beams, and glued laminated columns (Mofolasayo, 2022), presents numerous notable benefits for building decarbonization. The production of waste at both the manufacturing and construction sites is minimized due to precise off-site manufacturing process (Lehman, 2013). Moreover, CLT prefabricated constructions exhibit higher structural strength compared to concrete and steel, thanks to their lighter weight (Bahrami et al., 2021). This reduced weight results in lower carbon emissions associated with on-site material transportation and equipment usage. The use of CLT enables reductions in foundation dimensions or the construction of taller structures with the same types of foundations (Macnamara, 2020), thereby decreasing emissions related to foundation construction. Foundations typically contribute to 15.0% and 22.8% of the total environmental impact in terms of embodied energy and global warming potential (Ondavà et al., 2020). Research by Liang et al. (2020) suggests that substituting mass timber for concrete in similar buildings offers a bioeconomic approach, potentially reducing global warming by 18%. Furthermore, when forests are managed sustainably, the energy consumption in wood production is also lower compared to concrete or steel production (Younis and Dodoo, 2022). Regenerated forests then serve as carbon sinks, helping to offset emissions (Chazdon et al., 2016).

The adoption of prefabricated construction in Africa is still in its initial phases. Two companies are producing CLT-based prefabricated construction in Johannesburg and Cape Town (South Africa, Figure 16), and one company is in Tanzania (Tanzania report, 2022).

Figure 16: Example of CLT-based construction in South Africa (Source: TheWoodApp, 2023; Pinto, 2021)

Currently in the design phase, there are notable projects underway in Africa. Zanzibar is conceptualizing the construction of the world's tallest green building a 28-story apartment tower incorporating hybrid wood technology (Construction Insight Magazine, 2013). Named Burj Zanzibar, where "Burj" signifies tower in Arabic, this extraordinary structure is envisioned to soar to a height of 96 meters. Upon its completion, Burj Zanzibar is poised to secure the distinction of being the world's tallest wooden building and will stand as the pioneering skyscraper in Africa crafted with this cutting-edge technology (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

Figure 17: Burj Zanzibar - a pioneering project in Zanzibar featuring a hybrid-timber tower, slated for completion in 2028. (Source : Burj Zenzibar, 2023)

2.2. Using bamboo as construction material

Bamboo, with its genetic characteristics and physico-mechanical properties, can serve as a promising bio-sourced alternative material for wood in construction. Compared to wood, bamboo has a very fast growth rate, up to 1 meter per day (Chen et al., 2022). In contrast to many tree species with a harvesting interval of 10 to 50 years, bamboos reach maturity for use in construction between 3 and 6 years of growth (Desalegn et al., 2014). The short rotation and rapid biomass production of bamboo make it a highly renewable resource and a more effective carbon sink than wood. Bamboo can serve as an alternative to meet the growing demand for construction materials and contributes to reducing pressures on forests due to wood harvesting for construction. A life cycle assessment conducted by Zea Escamilla et al. (2018) comparing bamboo-based construction to brick and concrete construction reveals that bamboo buildings provide a carbon-negative advantage. Laleicke et al. (2015) also assessed the carbon emissions from bamboo cultivation to its utilization in scaffolding construction and found that bamboo has a significantly more favourable impact on emissions compared to the production and use of steel. Regarding the material behaviour in construction, bamboo has comparable mechanical properties to wood (UNCTAD, 2022), which makes it suitable for use in many construction applications. A growing trend these last years involves the utilization of engineered bamboo, a process that entails treating and processing bamboo to improve its durability and fire resistance. Furthermore, bamboo is being integrated with other materials like steel and concrete to form hybrid structures, capitalizing on its full potential. This fusion of traditional and modern construction methods offers increased design flexibility while upholding the sustainable attributes of bamboo.

For the African region, the level of utilization of bamboo is far lower than that of other continents. Studies on the utilization of bamboo in Africa have suggested that the resource is undervalued compared to wood products. Its applications are predominantly traditional, and there are only a few reported manufacturing firms (Endalamaw et al. 2013; Ingram and Tieguhong 2013, Ximping et al., 2018). Among African countries, Ghana, Ethiopia, and Uganda, which were supported by the International Bamboo and Rattan Organization (INBAR) are the most advanced African countries in terms of processing and utilization of bamboo (Figure 18). Uganda, since 2019, under the support of INBAR, is going to develop micro and Small and Medium-sized Enterprises producing bamboo-based construction material (MWE, INBAR, 2020). Huojin (2014) reported that there are four modern enterprises in Ethiopia engaged in the production of bamboo flooring, doors, and curtains. In both rural and urban areas across Ghana, bamboo culms serve various construction purposes (Figure 18) such as fencing, scaffolding, framing mud houses, providing support structures, crafting rafters and roof materials, securing thatch for roofing houses, and constructing livestock pens (Obiri and Oteng-Amoako, 2007). Additionally, Ghana produces and utilizes processed bamboo products such as bamboo plywood, ceiling panels, flooring, window blinds, doors, and furniture (Obiri and Oteng-Amoako, 2007). Moreover, simple and pragmatic technology was assessed in Ghana to add further value to bamboo throughout the fabrication of Cross Laminated panels from bamboo culms, whose structure is similar to that of wooden CLT. The Cross Laminated Bamboo (CLB) in Ghana, however, was tested for carving. The use of this technology for construction would be very promising in terms of reducing carbon emissions and mitigating climate change. Indeed, research comparing laminated bamboo and cross-laminated timber shows that CLB has four times higher carbon absorption than CLT, with significantly lower energy consumption, measuring 2.67 GJ/m^3 and 4.5 GJ/m^3 respectively (House of Bamboo, 2023).

Figure 18: Haduwa arts + culture institute in Ghana protected by dynamic bamboo canopy (Source: https://www.designboom.com/)

2.3. Using reclaimed wood throughout deconstruction

Reusing wood construction material is one of the end-of-cycle scenarios of a wood building (Bertino et al., 2021). Reutilizing wooden construction materials involves employing them once again for the same purpose they were originally designed for. The process begins with extracting the installed raw material, transporting it to storage, process eventually to the application of refurbishing product and transporting the final product to the construction site (Bergman et al. 2010). Literature on the benefits of building materials reuse shows that such a practice allows reducing carbon footprint, conserving resources, and extending landfills (Smith et al. 2001;

Ericksson et al. 2005; Heilmann and Winkler 2005; Thorneloe et al. 2007). Bergman et al. (2010) found that the energy required to manufacture 1 m^3 of framing lumber from unused wood materials, and the associated Global Warming Potential is roughly 11 times and three times higher than for the reclaimed lumber from a deconstruction site. Reusing building materials adheres to the circularity principle as it minimizes waste production and allows the reduction of CO2 emissions (Bertino et al., 2021).

The need for building reconstructions and renovation after the deconstruction of houses and ancient buildings at the end cycle life has increased the demand for reclaimed timber and building materials (Polaris Market Research, 2021). The global reclaimed lumber market is expected to grow at a CAGR of 4.5% from 2021 to 2028 according to the Polaris Market Research forecast analysis (2021). A significant portion of the reclaimed timber market is expected to be in the Middle East and Africa (Polaris Market Research, 2021). In the Africa region, there are a few reclaimed timber companies such as Ross Salvage, located in Cape Town, which produces second-hand and affordable building materials (Ross Salvage, 2023).

3. Transferability and applicability of the sustainable practices in other African countries

3.1. Forest conservation and management

Reducing deforestation in Africa

The forest in Africa constitutes 16% of the world's total forested area (FAO, 2020), with approximately 21.3% (636.639 million ha) of continent's land area covered by forests (Statistica, 2022). However, Africa had the highest annual rate of net forest loss in 2010–2020, evaluated at 3.9 million ha (FAO, 2020). This loss is primarily attributed to deforestation, predominantly driven by forest harvesting for fuelwood extraction (90%) and for construction purposes (<10%), a trend that has increased over time.

The use of wood is considered "carbon-neutral" only when procured through sustainable harvesting practices. In this context, "sustainable" implies that the quantity of wood extracted in a yearly harvest aligns with the forest's growth during that period. The underlying principle is that as long as the carbon stock in the forest remains stable, the process of harvesting wood does not introduce additional carbon into the atmosphere. Consequently, minimizing deforestation in Africa becomes paramount to maintaining this delicate ecological balance. By integrating sustainable harvesting practices and fostering responsible forestry management, African nations can not only contribute to global climate goals but also unlock the economic potential of their forest resources within the framework of a sustainable bioeconomy.

Need for reforestation to prevent wood crisis

Substituting traditional high-carbon construction materials such as concrete and steel with wood, especially in urban areas across Africa, requires a sustainable investment in increasing the availability and coverage of local forest resources. Data from Grieg-Gran et al. (2015) on the projection of the demand and supply of wood for energy and timber production in Africa show that the area designated of African planted forests, primarily harvested for timber production, remains considerably smaller compared to those allocated for protective and regulative purposes, as well as for wood energy production (Grieg-Gran et al., 2015). Nevertheless, the area of plantation forests in Africa has experienced an annual growth of 1.75% in recent years (FAO, 2010).

Africa possesses sufficient forest resources to sustain the population's wood needs, as the average amount of wood removed annually per ha from the forests stands at 0.35 m^3, which falls within the range for Annual Allowable Cut (ACC) on a sustained yield basis to fulfil the current domestic demand, even considering importation (Adler 1999). The exploitation and sustainable management of natural forests and African plantations for timber production purposes thus help in preserving the forest resources. However, there is a projected increase in industrial roundwood demand between 2030 and 2050 that may surpass the capacity of African forest production. Therefore, to meet the demand in 2030, it would be necessary to double the sustained yield level, while three or four times this level is needed to meet the demand in 2050 (Grieg-Gran et al., 2015). Consequently, implementing reforestation projects for timber production purposes becomes essential as a complementary sustainable solution to minimize the impact on forests while addressing the growing needs for wood materials and expanding the production capacity of the wood construction industry.

Furthermore, in addition to planted forests, tree planting within agroforestry systems is encouraged for its partial contribution to the wood supply for construction. This practice also serves as an effective mitigation measure against climate change, as biomass and soil act as carbon sinks (Nair et al., 2009). Agroforestry also helps alleviate pressures on forests associated with wood harvesting. Some West and Central African countries, such as the Ivory Coast, the Republic of Congo, and the Democratic Republic of Congo, are already practicing improved agroforestry, demonstrating the potential of this system as an additional source of wood production (Mallet et al., 2022).

Need for sustainable forest management

Reforestation initiatives must be supported by solid sustainable forest management tools and government support to better adopt the use of wood and prefabricated construction by the population. For this purpose, forest certification, which guarantees the sustainability of forest practices and the use of responsible harvesting practices, preventing deforestation, is important. However, among the continents, Africa has the lowest Programme for the Endorsement of Forest Certification (PEFC) certified forest area, with only 1.3 million hectares, corresponding to 2.02% of the total forest areas in Africa (PEFC, 2023). These forests are located in Gabon and several countries in South Africa, with 891,651 hectares and 396,831 hectares of certified forests, respectively. Regarding FSC certification, 15.53% of Africa's forest is certified by FSC in several countries spread across South Africa, East Africa, North Africa, and Central Africa (FSC, 2023). Encouraging forest managers to certify their forests is crucial to avoid deforestation due to wood logging for prefabricated construction manufacturing.

3.2. Sustainable utilization of resources

Bamboo farming and sustainable management of plantation

Regarding the availability of bamboo, the African region has minimal bamboo resources compared to other continents, whether in terms of species diversity or area coverage, and these resources are predominantly confined to tropical zones. The total bamboo area in Africa covers 2.8 million ha and constitutes 7.3% of the world's bamboo resources (FAO, 2007). They are especially distributed in East Africa, such as Tanzania, Kenya, Zambia, Ghana, Ethiopia, Uganda, Mozambique, and Madagascar (Ahmad et al., 2021). Most bamboo species growing in Africa belong to the *Bambusa* (21,7%), *Nastus* (10,41%), and *Dendrocalamus* genera (9,54%) (Bahru and Ding, 2021). Not all bamboo species are suitable for construction, but those found in the tropics, especially the genera *Bambusa* and *Dendrocalamus*, exhibit favourable mechanical properties for construction purposes (Guadua bamboo, 2023).

To promote the use of bamboo as a complementary and alternative to wood for construction in Africa, it's crucial to highlight the importance of prioritizing bamboo plantation projects by prioritizing local or exotic bamboo species with properties suitable for construction. Additionally, sustainable management of bamboo plantations is essential for production purposes, requiring the use of environmentally friendly and appropriate silvicultural techniques from bamboo planting to exploitation.

In Africa, very few bamboo plantations have obtained certification. Currently, the EcoPlanet Bamboo group in South Africa stands out as a leader, holding Forest Stewardship Council (FSC) certification. Covering an extensive 4,500 hectares of plantations (EcoPlanet Bamboo, 2023), EcoPlanet Bamboo's commitment to sustainable practices and certification emphasizes its dedication to environmental stewardship and responsible resource management.

Promotion of bamboo as a sustainable and low-carbon material

The persistence of traditional bamboo-based construction techniques in most African countries shows a lack of knowledge and skills in bamboo processing and treatment, despite bamboo having been used in construction for a long time on the continent. Providing training to farmers and bamboo users about plantation techniques, sustainable management practices, processing of bamboo, and low-carbon construction practices is therefore imperative. Encouraging African countries to join the International Bamboo and Rattan Organization (INBAR) is crucial for fostering collaboration with member nations, institutions, and international partners. This collaboration facilitates the exchange of knowledge, technology, and eco-friendly construction practices, which are essential for promoting the sustainable development of bamboo utilization in the construction sector and aiding in the formulation of relevant national policies for the utilization of these resources. For instance, Uganda has received INBAR support in developing its bamboo sector through a 10-year action plan (2019-2029). Currently, 20 African countries are INBAR members, with Ghana and Ethiopia leading in bamboo utilization. On the other hand, establishing inter-African country partnerships would facilitate the effective exchange of knowledge, skills, and resources. Ghana and Ethiopia, which are more advanced in the use of bamboo, could play a crucial role by sharing their expertise with other African countries. A well-structured public-private partnership can also play an essential role in financing the transfer of these technologies.

Identification and traceability of wood species for sustainable forest resource management

In the realm of sustainable forest resource management, the establishment of an identification and traceability system for wood is crucial. This system serves as a tool to bolster the sustainable management of forest resources along the wood exploitation and supply chain. The term "traceability" refers to the ability to follow a product through every stage of its production, processing, and distribution. The primary objective is to recognize and prevent the inclusion of unknown, unauthorized, and potentially illegal materials into supply chains (Godbout et al., 2018). Traceability systems typically involve collecting, transmitting, and archiving data on the physical harvest event, including location, date, time, species, volume, and harvesting entity identity; accumulating and retaining data on the transferred primary material's timing, location, method, and recipient; and storing and analysing data to identify discrepancies through reconciliation at subsequent supply chain stages. In Africa, various countries, including Cameroon, the Central African Republic, Gabon, Ghana, Liberia, and Madagascar have been actively or are currently engaged in implementing traceability systems for timber.

Identifying wood species and geographic origin in timber traffic is also crucial for sustainable forest management, legal compliance, and preventing illegal logging. It ensures adherence to regulations, helps monitor and manage timber resources sustainably, and contributes to biodiversity conservation. Accurate identification also supports quality control, market value determination, and traceability for certification programs, promoting responsible forestry practices and consumer confidence. Several tools have been developed in Africa. DNA fingerprints and stable isotopes were developed in Cameroon, Central African Republic, Democratic Republic of Congo, Republic of the Congo, Gabon, Ghana, and Kenya (Thünen Institute of Forest Genetics, 2015). Madagascar uses wood anatomy (and its automated computer vision-based technique), DNA fingerprints, and near-infrared spectroscopy to identify wood species listed in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) appendix. The current challenge involves enhancing the database and standardizing techniques (Dormontt et al., 2015), as well as the development of affordable and portable tools accessible to untrained stakeholders involved in forest resources management (Raobelina et al., 2023).

3.3. Advancements in technology and research

Research development in the field of wood and technology

Achieving the rational and sustainable utilization of forest resources stands as a significant challenge in the conservation of tropical forests. The Sustainable Forest Management Framework for Africa (2020-2030), jointly formulated by the African Union Commission and the African Forest Forum, highlights a key concern regarding the deficiency in wood processing industries. This deficiency is characterized by outdated machinery, diminishing the capacity for sustainable production, value addition, marketing, and trade.

Wood science emerges as a crucial player in this scenario. Understanding the wood properties and its variability is essential for selecting the appropriate species for various uses (furniture, indoor or outdoor uses in construction, etc.), ensuring sustainability in terms of both biological durability and strength. This informed approach seeks to establish a harmonious balance between available resources and their intended applications. For instance, in the construction sector, using a wood species that meets the desired use class ensures better durability and a longer life cycle for the structure. Additionally, knowing the properties of wood enables the identification of potential substitute wood species. These alternatives can be strategically exploited, helping to prevent the complete extinction of certain noble wood species that have historically been overlooked. Simultaneously, this approach supports the conservation of endangered species at risk due to logging activities.

Increasing the local capacity for timber processing is crucial to facilitate a broader utilization of timber in construction across Africa. This primarily includes optimizing logging and wood machining techniques, to improve material yield throughout the transformation value chain. Advancing expertise in the drying technique and elevating local kiln drying capacity are crucial for achieving the correct moisture content in wood. Augmenting preservation treatment capabilities is also vital to raise the wood's use class, thereby extending the lifespan of structures. This is particularly crucial in tropical countries where wood degradation organisms exhibit heightened virulence. Exploring the local sourcing of glues and wood preservatives in Africa holds significant promise, not only to reduce reliance on external suppliers but also to enhance the value of indigenous biological resources. A possibility is the extraction of extractives from durable wood, which can then be injected into less durable wood species, to extend the life of the latter (N'Guessan et al., 2023).

Promotion of the use of production of CLT-based prefabricated construction

Expanding the promotion of prefabricated construction in other African countries can be achieved initially by scaling up production to support existing local Cross-Laminated Timber (CLT) industries. The African production companies, located in Johannesburg, Cape Town, and Tanzania, produce CLT but still on a small scale. Therefore, most CLT-based prefabricated construction parts of buildings in Africa are imported from Europe (CPS, 2023). Promoting the use of CLT in other countries would consequently reduce imports and lower the price of CLT to meet the purchasing power of users. Moreover, using regionally sourced CLT prefabricated construction allows for a reduction in carbon emissions related to material transport from the production site to installation.

Technological decentralization

The lack of capacity and technology are major constraints on promoting the production of CLT-based prefabricated construction in other African countries. To address this issue, it is crucial to foster partnerships between established regional CLT producers, such as XLAM South Africa and CPS Zenzibar, and countries with abundant forest resources like Gabon, Seychelles, Guinea-Bissau, Congo, and Zambia (Atlasocio, 2019). It involves implementing effective capacity-building programs to transfer skills and enhance local production capabilities in CLT-based prefabricated construction. Furthermore, actively involving investors and promoting public-private partnerships is crucial for financial support for transferring CLT-related technologies.

3.4. Regulatory framework and perception

Improvement of the perception of biosourced construction material

One significant obstacle hindering the adoption of biosourced construction materials in Africa is the prevailing negative perception surrounding wood or bamboo-based construction. In South Africa, for example, wood remains underutilized, with less than 1% of urban buildings constructed using this material (Macnamara, 2020). There is a widespread belief that wood lacks the necessary properties for use in construction, especially when compared to conventional building materials like brick, concrete, and steel. Many households perceive wood as highly flammable, lacking in durability, and associate wooden houses with disadvantaged communities. There is a misconception that the construction and maintenance costs of wooden houses are higher, and building with wood contributes to deforestation (Macnamara, 2020). Social beliefs in South Africa tend to favour brick and mortar houses over wooden ones, as people are inclined towards what they are familiar with (Appiah-Kubi and Tekpetey, 2011).

Similarly, regarding bamboo construction, although bamboo has been utilized for construction in Africa for many years, unfavourable perceptions about this material persist. In Ghana, survey findings among different households show that the population associates bamboo houses with poverty and considers them as residences for the underprivileged (Akoto et al., 2017). Additionally, there is a misconception that bamboo constructions are not durable (Akoto et al., 2017). Traditional bamboo users often lack awareness, skills, and technology related to bamboo treatment methods that could substantially prolong the lifespan of bamboo constructions.

To enhance the perception of wood and bamboo as construction materials in Africa, an integrated strategy could involve awareness-raising campaigns targeting farmers, households, and other consumers in the construction value chain. These campaigns would highlight the environmental benefits, durability, and versatility of these bio-based construction materials. Additionally, leveraging successful pilot projects, such as the production of CLT-based prefabricated construction in South and East Africa would be instrumental in countering these negative perceptions and fostering greater acceptance of wood and bamboo in construction practices.

Development of appropriate regulations on mass timber and engineered bamboo construction

To enable the safe use of wood products on the African continent, governments must have the will to deepen standards and promulgate appropriate regulations to ensure robustness and product safety, especially related to fire resistance, height restrictions, and seismic construction requirements. South Africa is the pioneer in the development of CLT standards in Africa, under the South African National Standards (SANS) (Kurzinski et al., 2022). A CLT production standard (SANS 8892-2020) was developed in 2020 to support the CLT construction in South Africa to meet the performance requirements, especially regarding the strength and stiffness characteristics (South African Standards, 2020). Many other African countries still do not have their own CLT manufacturing standards. Drawing inspiration from South Africa's pioneering initiatives in CLT standardization, other African nations can leverage existing frameworks, adapt them to their specific needs, and promulgate regulations under their respective national standards bodies. Moreover, capacity-building programs and knowledge-sharing platforms can facilitate the dissemination of best practices and technical expertise to support the implementation of these regulations effectively. Similar circumstances are observed with engineered bamboo construction. There is a dearth of established classification systems that conform to building codes, especially in the realm of the structural use of engineered bamboo.

4. Key messages and recommendations

Africa is experiencing rapid urbanization and population growth, driving an unprecedented demand for construction materials. However, the construction sector faces significant challenges, including a housing deficit, slum-like living conditions, and environmental concerns. The urgency to address these issues necessitates a shift toward the use of sustainable wood for a carbon-neutral bioeconomy. Implementing a bioeconomy-focused approach to sustainable practices in wood construction provides a viable pathway for meeting growing demand while lessening environmental impact. By embracing eco-friendly methods like prefabricated mass timber construction, bamboo utilization, and reclaimed wood, Africa can simultaneously tackle its housing crisis and contribute to global endeavours in reducing carbon emissions and conserving natural resources, fostering a bioeconomy that aligns economic growth with ecological sustainability. Despite challenges, Africa is already witnessing innovative solutions in sustainable wood construction. The Burj Zanzibar project, utilizing Cross-Laminated Timber (CLT), exemplifies how African nations are pioneering tall, green buildings. Additionally, countries like Ghana, Ethiopia, and Uganda are making strides in bamboo utilization, showcasing the potential for sustainable alternatives. Reclaimed wood through deconstruction contributes to a circular bioeconomy, reducing waste, conserving resources, and minimizing the carbon footprint associated with new construction materials. Several African countries, including South Africa, Kenya, Nigeria, and Morocco, are recognizing the benefits of using reclaimed wood, marking a positive trend toward circular construction practices.

Recommendations:

- Policy Frameworks for Sustainable Construction:

Governments across Africa should develop holistic policy frameworks that prioritize sustainable construction practices. This involves creating incentives for the utilization of eco-friendly materials, establishing guidelines for sustainable forestry management, and promoting the integration of circular economy principles within the construction industry.

- Promotion of Reclaimed Wood:

Governments should incentivize the use of reclaimed wood in construction projects. Additionally, policymakers should focus on developing policies and implementing incentives at promoting the reuse of wood in construction, such as tax incentives. Guidelines for deconstruction practices should be developed, and awareness campaigns should be launched to promote the environmental and economic benefits of using reclaimed wood.

- Scaling Up Production of Sustainable Construction Materials:

Promoting the use of regionally sourced materials, such as CLT, requires scaling up production and reducing reliance on imports. Governments should support local industries, provide incentives for sustainable practices, and foster an enabling environment for the growth of sustainable construction material production.

- Development of appropriate regulations and standards:

To ensure safety and product quality, it is imperative to promote the development and adoption of robust national regulations and standards for mass timber and bamboo construction. Building upon existing frameworks, governments should actively encourage the development and adoption of these standards. Moreover, supporting capacity-building programs and fostering knowledge-sharing platforms are essential steps to facilitate the effective implementation of these regulations and standards continent-wide.

- Capacity-Building and Technology Transfer:

Encouraging partnerships between established producers of sustainable construction materials and countries with abundant forest resources is essential. Capacity-building programs should be implemented to transfer skills, enhance local production capabilities, and promote technological decentralization. Public-private partnerships can play a significant role in financing the transfer of these technologies.

- Investment in Research and Development:

To enhance the utilization of wood resources, governments, NGOs, and international organizations should invest in research and development. This includes advancing wood science, optimizing processing techniques, and promoting the development of innovative wood-based materials that align with sustainable construction principles.

- Reforestation and certification:

Governments should actively promote the adoption of integrated approaches that blend reforestation efforts with agroforestry practices, while concurrently devising strategies to curb deforestation. Additionally, they should strengthen forest certification processes to ensure sustainable practices and responsible harvesting.

- Community Awareness Programs:

Changing negative perceptions about wood and bamboo construction materials is crucial. Governments, NGOs, and industry stakeholders should implement comprehensive community awareness programs highlighting the environmental benefits, durability, and versatility of these materials. Successful pilot projects, such as the Burj Zanzibar, should be leveraged to showcase the viability of sustainable construction practices.

- International Collaboration:

African nations should actively participate in international collaborations and organizations promoting sustainable construction practices. Joining initiatives like the International Bamboo and Rattan Organization (INBAR) can facilitate knowledge exchange, technology transfer, and collaboration among member nations.

In conclusion, promoting sustainable practices in wood construction requires cooperation between governments, industry players, and communities. By adopting the suggested recommendations, African countries can harness their abundant natural resources and drive the transition towards sustainable and low-carbon building practices. This not only fosters economic development and environmental stewardship but also addresses housing challenges and advances global sustainability goals.

References

Ahmad Z., Upadhyay A., Ding Y., Emamverdian A. and Shahzad A. (2021). *Bamboo : Origin, habitat, distributions and global perspective*. In : Ahmad Z., Ding Y. and Shahzad A. (eds) Biotechnological advances in bamboo. Springer. Singapore. pp. 1-31. ISBN 978-981-16-1309-8.

Akoto S.D., Obour R., Appiah M.A. and Frimpong A.P. (2017). *Bamboo use for the housing industry in Ghana : Urban Stakeholders' perception.* Journal of Energy and Natural Resource Management, 3, 85-91, https://doi.org/10.26796/jenrm.v3i3.93.

Alder D. (1999). *Some issues in the yield regulation of moist tropical forests*. Paper presented to a workshop on Humid and Semi-Humid Tropical Forest Yield Regulation With Minimal Data held at CATIE, Turrialba. Costa Rica 5th-9th July 1999.

Amegah A. K. (2021). *Slum decay in Sub-Saharan Africa*. Environemental epidemiology, 5, 3, e158, DOI:10.1097/EE9.0000000000000158.

Appiah-Kubi E. and Tekpetey S. (2011). *Wood for housing in Ghana : Why the low interest*? Proceedings of the Art and Joy of Wood conference, 19-22 October 2011, Bangalore, India.

Atlasocio (2019). *Classement des états d'Afriques par Superficie forestière, Classement des États d'Afrique par surface forestière (en % du territoire). Available at : Classement des États d'Afrique par surface forestière (en % du territoire)*. Available at : https://atlasocio.com/classements/geographie/forets/classement-etats-par-surface-forestiere-totale-afrique.php [Accessed on 10 December 2023].

Bahrami A. Vall A. and Khalaf A. (2021). *Comparison of cross-laminated timber and reinforced concrete floors with regard to lad-bearing properties*. Civil Engineering and Architecture, 9, 5, 1395-1408, DOI: 10.13189/cea.2021.090513

Bahru T. and Ding Y. (2021). *A review on bamboo Resource in the African Region : A call for special Focus and Action*. International Journal of Forestry Research, 2021, 1-23, https://doi.org/10.1155/2021/8835673.

Bergman R.D. and Gu. H. (2010). *Using reclaimed Lumber and Wood Flooring in Construction : Measuring Environmental Impact using Life-Cycle Inventory Analysis*. Proceedings of the International Convention of SWST and United Nations Economic Commission for Europe – Timber Committee, October 11 – 14, 2010, Geneva, Switzerland.

Bertino G., Kisser J., Zeilinger J., Langergraber G., Fischer T. and Osterreicher D. (2021). *Fundamentals of Building Deconstruction as a circular economy strategy for the reuse of construction materials*. Applied sciences, 11,3, 939, DOI:10.3390/app11030939.

Burj Zinzibar (2023), *The Burj Zenzibar.* Available at : https://burjzanzibar.com/ [Accessed on 15 November 2023].

Chazdon R.L., Broadbent E.N., Rozendaal D.M.A., Bongers F., Zambrano A.M.A., Aide T.M., Balvanera P., Becknell J.M., Boukili V., Brancalion P.H.S., Craven D., Almeida-Cortez J.S., Cabral G.A.L., de Jong B., Denslow J.S., Dent D.H., DeWalt S.J., Dupuy J.M., Durán S.M., Espírito-Santo M.M, Fandino M.C., César R.G., Hall J.S., Hernández-Stefanoni J.L., Jakovac C.C., Junqueira A.B., Kennard D., Letcher S.G., Lohbeck M., Martínez-Ramos M., Massoca P., Meave J.A., Mesquita R., Mora F., Muñoz R., Muscarella R., Nunes Y.R.F., Ochoa-Gaona S., Orihuela-Belmonte E., Peña-Claros M., Pérez-García E.A., Piotto D., Powers J.S., Rodríguez-Velazquez J., Romero-Pérez I.E., Ruíz J., Saldarriaga J.G., Sanchez-Azofeifa A., Schwartz N.B., Steininger M.K., Swenson N.G., Uriarte M., van Breugel M., van der Wal H., Veloso M.D.M., Vester H., Vieira I.C.G., Bentos T.V., Williamson G.B., and Poorter L. (2016). *Carbon sequestration potential of second-growth forest* *regeneration in the Latin American tropics*. Science Advances, 2, 5, e1501639, https://doi.org/10.1126/sciadv.1501639.

Chen M., Guo L., Ramakrishan M., Fei Z.J., Vinod K.K., Ding Y.L., Jiao C., Gao Z.P., Zha R.F., Wang C.Y., Gao Z.M., Yu F., Ren G. D. and Wei Q. (2022). *Rapid growth of Moso bamboo (Phyllostachys edulis) : cellular roadmaps, transcriptome dynamics and environmental factors*. The plant cell, 2022,34, 3577-3610, DOI: 10.1093/plcell/koac193.

Chen Y., Okudan G.E. and Riley D.R. (2010). *Decision support for construction method selection in concrete buildings : Prefabrication adoption and optimization*, Automation in construction, 19, 665-675, DOI:10.1016/j.autcon.2010.02.011.

Construction Insight Magazine (2013). *Burj Zanzibar to become Africa's tallest timber tower.* Available at : https://constructioninsightmagazine.com/burj-zanzibar-to-become-africas-tallest-timber-tower/ [Accessed on 22 December 2023].

CPS (2023). *Be the first to timber! Timber tower construction could begin in 2023/2024*. Available at : https://fumba.town/be-the-first-to-timbertimber-tower-construction-could-begin-2023-2024/ [Accessed on 11 December 2023].

Desalegn G. and Tadesse W. (2014). *Resource potential of bamboo, challenges and future directions towards sustainable management and utilization in Ethiopia*, Forest systems, 23, 2, 294-299, DOI:10.5424/fs/2014232-03431.

Dormontt E.E., Boner M., Braun B., Breulman G., Degen B., Espinoza E., Gardner S., Guillery P., Hermanson J.C., Koch G., Lee S.L., Kanashiro M., Rimbawanto A., Thomas D., Wiedenhoeft A.C., Yin Y., Zahnen J. and Lowe A.J. (2015). *Forensic timber identification: It's time to integrate disciplines to combat illegal logging*. Biological Conservation, 191, 790–798. https://doi.org/10.1016/j.biocon.2015.06.038.

Ecoplanet bamboo (2023). *Bamboo plantation in South Africa.* Available at : https://www.ecoplanetbamboo.com/south-africa-bamboo-plantations/ [Accessed on 23 December 2023].

Endalamaw T.B., Lindner A., and Pretzsch J. (2013). *Indicators and determinants of small-scale bamboo commercialization in Ethiopia*. Forests, 4, 710–729, https://doi.org/10.3390/f4030710.

Ericksson O., Carlsson R.M., Frostell B., Björklund A., Assefa G., Sundqvist J-O., Granath J., Baky A. and Thyselius L. (2005). *Municipal solid waste management from a system perspective*. Journal of Cleaner Production, 13, 241–252, https://doi.org/10.1016/j.jclepro.2004.02.018.

Escamilla E.Z., Habert G., Daza J.F.C., Archilla H.F., Fernández J.S.E. and Trujillo D. (2018). *Industrial or Traditional Bamboo Construction? Comparative Life Cycle Assessment (LCA) of Bamboo-Based Buildings*. Sustainability, 2018, 10, 9, 3096, https://doi.org/10.3390/su10093096.

FAO (2007). *World Bamboo Resources: A systematic Study Prepared in the Framework of the Global Forest Resources Assessment 2005*. Non-Wood Forest Products No. 18, Food and Agriculture Organization of the United Nations. Rome, Italy. pp. 73. ISBN 978-92-5-105781-0.

FAO (2010). *Global forest resources assessment 2010*. Food and Agriculture Organization of the United Nations, Rome. Available at : www.fao.org/forestry/fra2010 [Accessed on 20 December 2023].

FAO (2020). *Global forest resource assessment*, Available at : https://www.fao.org/3/ca9825en/ca9825en.pdf [Accessed on 05 December 2023].

FSC (2023). *Fact and Figures*. Available at : https://connect.fsc.org/impact/facts-figures/ [Accessed on 25 November 25 2023].

GlobalABC (2022). *Towards a zero-emissions, efficient and resilient building and construction sector*, UNEP, pp. 100.

Godbout J., Bomal C., Farr K., Williamson M., and Isabel N. (2018). *Genomic Tools for Traceability: Opportunities, Challenges and Perspectives for the Canadian Forestry Sector*. For. Chron, 94,1, 75–87. DOI:10.5558/tfc2018-010.

Grieg-Gran M., Bass S., Booker F. and Day M. (2015). *The role of forests in a green economy transformation in Africa.* pp. 65.ISBN : 978-92-807-3533-8.

Guadua bamboo (2023). *90 types of bamboo used for building and construction*. Available at : https://www.guaduabamboo.com/blog/types-of-bamboo-used-for-building#:~:text=The%20best%20bamboo%20species%20for,better%20structural%20and%20mechanical%20properties/ [Accessed on 09 December 2023].

Heilmann A. and Winkler J. (2005). *Influence of the source separation efficiency of recyclable materials on the environmental performance of municipal waste management systems*. Proceedings Sardinia 2005, Tenth International Waste Management and Landfill Symposium, S. Margherita di Pula, Cagliari, 3–7 October 2005.

House of bamboo (2023). *Cross Laminated Timber vs. Cross Laminated Bamboo : Which is better ?.* Available at : https://www.houseofbamboo.com.au/2023/01/09/cross-laminated-timber-vs-cross-laminated-bamboo-which-is-better/#:~:text=Cross%20Laminated%20Bamboo%20(CLB)%20is,greater%20negative%20carbon%20dioxide%20emissions [Accessed on 21 December 2021].

Huojin H. (2014). *Some proposals for developing the Ethiopian bamboo industry. in Suggestions for the Development of Agriculture and Forestry in Ethiopia*, pp. 50–54, China Agriculture Expertise Team in Ethiopia, Addis Ababa, Ethiopia.

Ingram V. and Tieguhong J.C. (2013). *Bars to jars: Bamboo value chains in Cameroon*. Ambio A journal of The Human Environment, 42, 3, 320–333, DOI:10.1007/s13280-012-0347-5.

International Energy Agency (2019). *Africa Energy Outlook 2019*. Paris: International Energy Agency. Available at: https:// www.iea.org/reports/africa-energy-outlook-2019 [Accessed: 20 November 2023].

Kurzinski S., Crovella P., Kremer P. (2022). *Overview of Cross-Laminated Timber (CLT) and Timber Structure Standards Across the World*. Mass Timber Construction Journal, 5, 1-13, DOI:10.55191/MTCJ.2022.1.

Laleicke P.F., Cimino-Hurt A., Gardner D., Sinha A. (2015). *Comparative carbon footprint analysis of bamboo and steel scaffolding*. Journal of Green Building, 2015,10, 114–126, DOI:10.3992/jgb.10.1.114

Lehman S. (2013). *Low carbon construction systems using prefabricated engineered solid wood panels for urban infill to significantly reduce greenhouse gas emissions*. Sustainable cities and Society, 6 ,2013, 57-67, DOI:10.1016/j.scs.2012.08.004.

Liang S., Gu H., Bergman R. and Kelley S. (2020). *Comparative life-cycle assessment of a mass timber building and concrete alternative*. Wood and Fiber science, 52,2, 217-229, DOI:10.22382/wfs-2020-019.

Locosselli G.M., Brienen R.J.W., Leite M.S. and Buckeridge M. (2020). *Global tree-ring analysis reveals a rapid decrease in tropical tree longevity with temperature.* PNAS, 117, 52, 33358 – 33364, https://doi.org/10.1073/pnas.2003873117.

Macnamara M. (2020). *Bin the negative perceptions about wood*. Timber iQ. Available at : https://www.timberiq.co.za/2020/10/02/ [Accessed 11 December 2023].

Mallet B., Pity B., Njoukam R. and Peltier R. (2022). *Do not forget that agroforestry can also provide wood, be it fuelwood or timber, for the benefit of populations! Examples in West and Central Africa.* 5th World Congress on Agroforestry – Transitioning to a Viable World, Quebec City, July 17-20, 2022.

Ministry of Water and Environment of Uganda (2020). *2019-2029 Uganda National Bamboo Strategy and Action Plan: National plans and policies*. INBAR. Available at : https://www.inbar.int/resources/inbar_publications/2019-2029-uganda-national-bamboo-strategy-and-action-plan/ [Accessed on 10 December 2023].

Mofolasayo A. (2021). *A comparison of life cycle impact of mass timber and concrete in building construction*. World Journal of Civil Engineering and Architecture, 2,449, 1-26, DOI: 10.31586/wjcea.2022.449.

Moror Intelligence (2023). *Construction industry in Africa size and share analysis – growth trends and forecasts (2023 – 2028).* Available at : https://www.mordorintelligence.com/industry-reports/africa-construction-market [Accessed on 23 December 2023].

Nair P.K.R., Kumar B.M. and Nair V.D. (2009). *Agroforestry as a strategy for carbon sequestration*. Journal of Plant Nutrition and Soil Science. 172, 1, 10-23. https://doi.org/10.1002/jpln.20080003.

N'Guessan J.L., Niamké B.F., Yao N.J.C. and Amusant N. (2023). Wood Extractives: Main Families, Functional Properties, Fields of Application and Interest of Wood Waste. Forest Products Journal, 73, 3, 194-208.

Obiri B.D. and Oteng-Amoako A. (2007). *Towards a sustainable development of the bamboo industry in Ghana*. Ghana Journal of Forestry, 21, 14–27, DOI: 10.4314/gjf.v20i1.50883.

OCDE (2018). *Global material resources outlook to 2060 : economic drivers and environmental consequences*. Available at : https://www.oecd.org/environment/waste/highlights-global-material-resources-outlook-to-2060.pdf [Accessed on 06 December 2023].

Ondavá M., Eštoková M. and Fabianová M. (2020). *Reducing the carbon footprint in the foundation structures of masonry family houses*. Journal of Civil Engineering, 15,2, 55-62, DOI: 10.1515/sspjce-2020-0018.

PEFC (2023). *Fact and Figures*. Available at : https://pefc.org/discover-pefc/facts-and-figures/ [Accessed on 27 November 2023].

Pinto A. (2021). *XLAM South Africa Design, manufactures Sustainable Cross-Laminated Timber*. Available at : https://www.autodesk.com/products/fusion-360/blog/xlam-south-africa-cross-laminated-timber/ [Accessed on 25 November 2023].

Polaris Market Research forecast analysis (2021). *Reclaimed Lumber Market Share, Size, Trends, Industry Analysis Report, By End-Use; By Application (Flooring, Paneling & Siding, Beams, Furniture, Others); By Region; Segment Forecast, 2021 – 2028.* Available at : https://www.polarismarketresearch.com/industry-analysis/reclaimed-lumber-market/ [Accessed on 22 December 2023].

Raobelina A.C., Chaix G., Razafimahatratra A.R., Rakotoniaina S.P. and Ramananantoandro T. (2023), *Use of a portable near infrared spectrometer for wood identification of four Dalbergia species from Madagascar*. *Wood and fiber science*, 55, 1, 4-17, DOI:10.22382/wfs-2023-03.

Ross Salvage (2023). *What we stock.* Available at: https://rosssalvage.co.za/ross-salvage-stock-products/ [Accessed on 23 December 2023].

Shelter Afrique (2019). *L'Afrique est confronté à une crise du logement*. Available at: https://content.shelterafrique.org/fr/wp-content/uploads/2020/08/Africa-is-facing-housing-crisis-FRENCH.pdf [Accessed on 12 December 2023].

Smith A., Brown, K., Ogilivie, S., Rushton K. and Bates J. (2001). *Waste management options and climate change, final report to the European commission*. Office for Official Publications of the European Communities : Luxembourg. pp. 234. ISBN 92-894-1733-1.

South African Standards (2020). *South African National Standard for performance-rated cross-laminated timber*. SABS standard division.

Statista (2022). *Forest area as a percentage of land area in Africa from 1990 to 2020.* Available at: https://www.statista.com/statistics/1286731/forest-area-as-a-percentage-of-land-area-in-africa/ [Accessed on 05 December 2023].

Statitsa (2023). *Forecast of the total population of Africa from 2020 to 2050*. Available at : https://www.statista.com/statistics/1224205/forecast-of-the-total-population-of-africa/ [Accessed on 23 December 2023].

Tanzania report (2022). *Affordable housing solutions; urban developer CPS applying to build the first CLT factory in Tanzania*. Available at: https://marcopolis.net/affordable-housing-solutions-urban-developer-cps-applying-to-build-the-first-clt-factory-in-tanzania.htm [Accessed on 04 December 2023].

TheWoodApp (2023). *Structural Engineering of Cross-Laminated Timber in South Africa*. Available at: https://thewoodapp.com/structural-engineering-of-cross-laminated-timber-in-south-africa/ [Accessed on 15 November 2023].

Thorneloe S.A., Weitz K.A. and Jambeck J. (2007). *Application of the US decision support tool for materials and waste management*. Waste Management, 27, 1006–1020, https://doi.org/10.1016/j.wasman.2007.02.024.

Thünen Institute of Forest Genetics (2015). *ITTO project PD 620/11 Rev.1 (M): Development and implementation of a species identification and timber tracking system with DNA fingerprints and isotopes in Africa*. Completion report: 01.02.2012-31.07.2015, pp 232.

UNCTAD (2022). *Commodities at a glance, special issue on bamboo*, N.15. pp. 88. ISBN 978-92-1-001321-5.

United Nations (2022). *Progress towards the Sustainable Development Goals.* Report of the Secretary-General, pp 25.

Westerholm N. (2023). *Unlocking the Potential of Local Circular Construction Materials in Urbanising Africa*. *Burkina Faso*. United Nations One Planet Sustainable Buildings and Construction Programme. pp. 111.

Ximping Y., Chenhao J., Xueying W., Zilong L. and Yucheng J. (2018). *Research on the applicability of Low tech bamboo architecture in new rural construction*. MATEC Web of conferences, 175, 04013, DOI:10.1051/matecconf/201817504013.

Younis A. and Dodoo A. (2022). *Cross-laminated timber for building construction : A life-cycle-assessment overview*. Journal of Building material Engineering, 52,2022, 104482, https://doi.org/10.1016/j.jobe.2022.104482.

Paving the way towards sustainable use of wood in construction - a governance-oriented and socio-economic approach in Switzerland

Sonja Geier, Pascal Wacker
Lucerne University of Applied Sciences and Arts, School of Engineering and Architecture, CC Typology & Planning in Architecture (CCTP), (Hochschule Luzern Technik & Architektur, Institut für Architektur IAR, CC Typologie & Planung in Architektur CCTP), Horw, Switzerland

Abstract

The utilization of wood as a sustainable resource has gained significant traction in various sectors like construction, the bioeconomy, and the energy industry, primarily due to its ecological advantages. Switzerland upholds one of the strictest forest laws and aims, amongst other objectives, at sustainable forest management and sustainable wood supply. However, the acknowledgment of wood's finite nature emphasizes the necessity for a prudent approach to its utilization.

Findings from three exemplary best practice examples in Switzerland illustrate the close link between the use of wood in construction, primary production and regional value chains and demonstrate the potential of wood in construction to adaptable building typologies that can extend the life cycle of building structures. The incorporation of wood in construction necessitates consideration of local value chain integration, stakeholder engagement, and forestry as primary sector.

The amalgamation of these diverse findings underscores the potential for vertical integration among decision-makers, planners, and stakeholders within the value chain, accompanied by participation and dialogue processes. The findings also emphasize the significance of governmental efforts in actively advocating for wood utilization within local civil society spheres.

Ultimately, an inclusive approach that engages stakeholders throughout the forest sector and wood value chain, alongside decision-makers, facilitates the delivery of ecosystem services and goods, creating benefits for the society comprehensively over time. Advancing sustainable practices in wood utilization supports the transition toward a carbon-neutral bioeconomy.

1. Introduction

1.1. Legal and political mandate

Switzerland upholds one of the most stringent forest conservation laws globally, ensuring the prevention of overexploitation and safeguarding the integrity of its forests. Article 77 of the Swiss Federal Constitution (BV 1999) shall ensure that forests are able to fulfill functions, such as protection against natural hazards, timber production, biodiversity, recreation, protection of drinking water, and filtering of air, etc. The Swiss Confederation lays down principles for the protection of the forest and promotes measures to conserve the forest. The Forest Act (ForA 1991) subsequently lays down the basic legal principles and framework conditions for the management and use of forests in Switzerland, as well as the tasks of the Confederation. The Forest Ordinance (ForA 1992) contains specific details and implementing provisions to put these principles into practice. The Vision 2023 of the Swiss Federal Council aims at sustainably managing forests, emphasizing multifunctionality and conservation of their area and distribution. (FOEN 2021, p.7).

The forest policy, drawn up by the Federal Office for the Environment FOEN, considers the relevant strategies of other policy areas such as spatial planning and land use, agriculture, energy policy and other environmental areas (climate, biodiversity/landscape, soil, water, natural hazards, air pollution control, chemicals, waste and resources/commodities, etc.). Forest policy is particularly relevant for the implementation of the 2030 Agenda in Switzerland: the goals 15.2 and 15.b are directly related to forests and other Sustainable Development Goals (SDGs 6, 7, 8, 12 and 13) are closely linked to them (FOEN 2021, p.8)

The Forest Act in Switzerland plays an important role in the conservation of forests, particularly the conservation of forest resources. There is a fundamental ban on deforestation (Art. 5 ForA 1991) and a ban on clear-cutting (Art. 22). The management principles focus on ensuring that the forest can fulfill its functions permanently and without restriction and that care must be taken at cantonal level to ensure that the wood supply is guaranteed, and that near-natural silviculture is pursued.

The Climate and Innovation Act, which was approved by voters in June 2023, stipulates that Switzerland must have net zero greenhouse gas emissions by 2050. It comes into force on 1.1.2025. The Climate and Innovation Act forms the framework for Switzerland's long-term climate policy and sets out the most important climate targets. The specific implementation will then take place in other laws, particularly the CO_2 Act. The forestry and timber industry has great potential to contribute to the Federal Council's 2050 net-zero climate target (DETEC 2023).

1.2. Political context regarding the demand side

A triangle of legal provisions is responsible for controlling the use of wood as a material and energy source on the demand side (Figure 19).

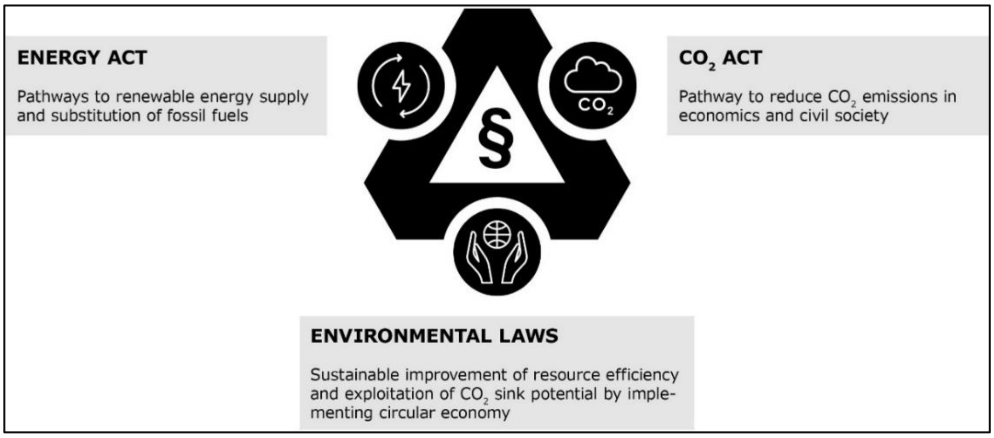


Figure 19: Triangle of political acts influencing the current demand side.

1.3. Economic framework

The forestry and timber industry accounts for 0.7 percent of Switzerland's gross domestic product. In Switzerland as a whole, just under 6,200 people are employed in the forestry industry and over 80,000 in the timber industry (BAFU 2022, p. 87).

Mobilization of wood[4] is a major issue in Switzerland. It is, beside other aspects, influenced by the ownership structure. The Swiss forests belong to around 250,000 different owners. Of these, 244,000 are private forest owners and almost 3,500 are public forest owners. The public - or more precisely "public-law" - forest owners include municipalities, cantons and the federal government, but also citizen communities and corporations. The average private ownership is only 1.5 hectares of forest, which corresponds to an area of around two football pitches. The proportion of private forest owners varies greatly from region to region and ranges from less than ~10 percent in the canton Valais to just under 80 percent in the canton Aargau (WaldSchweiz 2024). The motivation of forest owners to mobilize wood resources depends on market prices for wood and the wood harvesting costs depending on the specific locations. However, the mobilization of private forest owners is considerably costly, which is why the activities of forest associations (such as WaldSchweiz[5]) are largely concentrated on the large public forest owners.

1.4. Socio-political and socio-economic challenges

Figure 20 shows the challenges in achieving the climate protection targets as well as the socio-political and socio-economic challenges. These are:

An increasing demand for housing, especially affordable living spaces
Affordable housing is both a socio-political and a socio-economic challenge, as its availability and affordability have an impact on various aspects of social cohesion, economic development and individual quality of life. The solution to these challenges must therefore take into account both social and economic aspects.

Considering climate protection goals

[4] The term “mobilisation of wood” encompasses all organizational, advisory, and logistical activities aimed at increasing the amount of harvested timber.

[5] WaldSchweiz is the national association of forest owners and consists of 22 cantonal associations.

The challenge of affordable housing is under pressure to consider not only social and economic aspects, but also climate protection goals.

Achieving climate protection targets
To achieve global and national climate protection targets, a comprehensive transformation of the construction sector is required. Utilizing the substitution potential of wood and temporary carbon storage in wood-based materials is a first step. A transformation towards sustainable construction that respects planetary boundaries require more than just a material perspective.

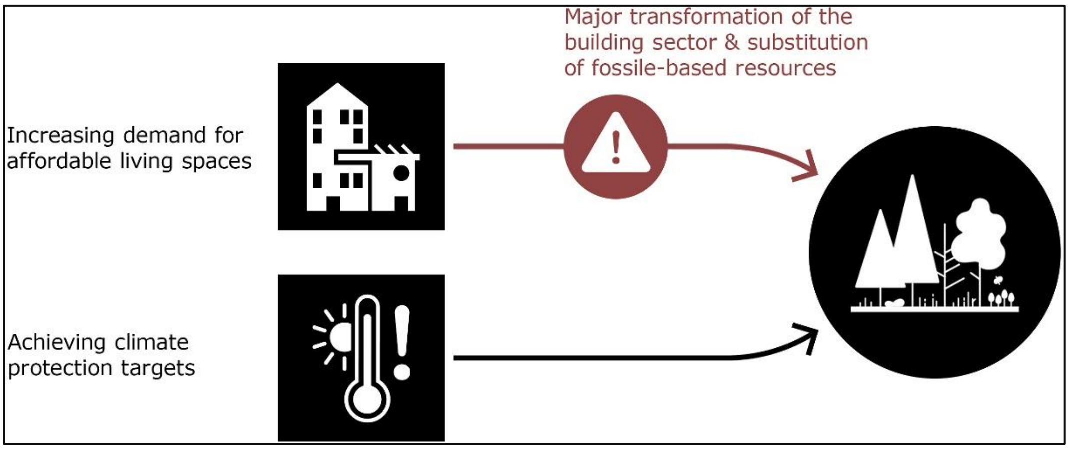


Figure 20: Socio-political challenge and climate protection targets. © CCTP

1.5. Need for action from the perspective of the forest and wood value system

In order to ensure that economic, protective and recreational functions of forests are safeguarded even under changing climate conditions, adaptation of forests is essential in many places. The rapid pace of climate change is overtaxing the natural adaptability of forests. This leads to consequential costs for securing ecosystem services.

Rising demands and conflicts of use (e.g. from leisure and recreation), increasing cases of damage due to storm damage and pests or diseases, volatile timber prices, rising costs (due to clearing damage, forest conversion, etc.) and weak points in the wood value chain (WSK) are putting increasing pressure on the economic concept of the forest. Forest owners and actors in forest planning are challenged, as shown in in Figure 21 (Geier et al. 2023, p.6).

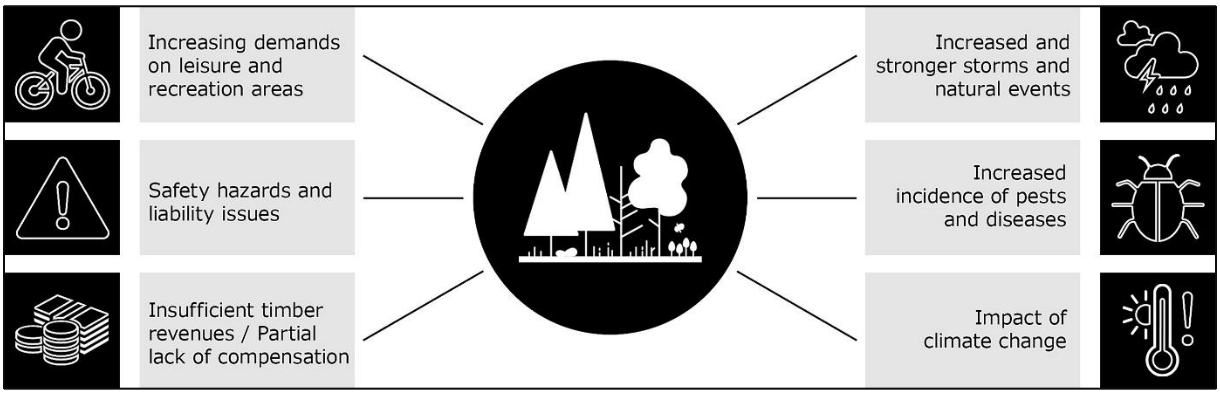


Figure 21: Multiple aspects challenge forests, forest owners and foresters. © CCTP based on Geier et al. 2023, p.6.

The forestry and timber industry are therefore facing major challenges, as forest management has financially largely covered by timber revenues. The volatile price situation on the raw materials market makes forestry planning and investments in the value chain more difficult. Decisions at the end of the value chain therefore affect the regional forest industry's ability to act to ensure the necessary forest conversion, forest services and the efficiency of the value chain in the long term. However, decision-makers and planners at the end of the value chain frequently exhibit limited awareness regarding the ramifications and consequences of their decisions.

As the demand for resources in construction increases, the issue of careful and sustainable use of resources is becoming ever more pressing. The circular economy is a starting point here. Although timber construction has great potential for the implementation of a circular economy, its implementation is under economic pressure: Dismantling is currently not economically feasible, competition with thermal recycling, handling of treated wood, etc. (Schuster and Geier 2023, p.100, 102). Closed material cycles in timber construction can only be realized if sustainable forest management can be assumed (Rosen 2021, p. 169). As sustainable forest management is under pressure due to rising costs and insufficient timber revenues, solutions need to be developed from a holistic perspective.

However, further influencing factors, such as necessary increase of entrepreneurial thinking in forestry companies will not be explained here, as this study focuses on the influence of the timber construction industry.

2. Methodology

The methodological approach is based on the analysis of best practices against the background of the national (Swiss) framework conditions and the identification of findings for transferability.

The first two best practices examples, the INNOwood project (Geier et al. 2023) and the Holzkreislauf Uri [Wood Circus Uri] initiative (Geier and Rupli 2023) were carried out based on a range of experiences in interdisciplinary projects and dialog processes[6]. The focus area of these two best practice examples is Central Switzerland. Central Switzerland consists of six cantons. These cantons represent three of the five forest zones in Switzerland (Figure 22): Central Plateau, Pre-Alps and Alps. This means that a wide range key characteristics of the primary production side (forest) can be covered.

The third best practice example, the development of the Modul17 (Keikut and Geier 2019), is not assigned to a specific region, but represents the demand side in the building construction sector, which is confronted with building in urban areas with increasing urbanization: building more densely and/or higher are requirements to deal with the increasing demand for living space.

[6] Geier et al. (2017). Holzbausanierung zwischen Ortsbildschutz und Energieeffizienz. Ein roter Faden für Bauherrschaften. Lignum (Ed.). Zürich. DOI: https://zenodo.org/records/10809018

Bodammer et al. (2018). Holzbausanierung und Erneuerbare Energien. Ein kooperatives Vorgehen am Beispiel eines Bergdorfes. In: Sturm, Ulrike und Lienhard, Melanie (ed). Kooperation Bau und Raum: Neue interdisziplinäre Wege in Forschung und Praxis. VDF Hochschulverlag. ETH Zürich. S. 148-163; ISBN 9783728139030.

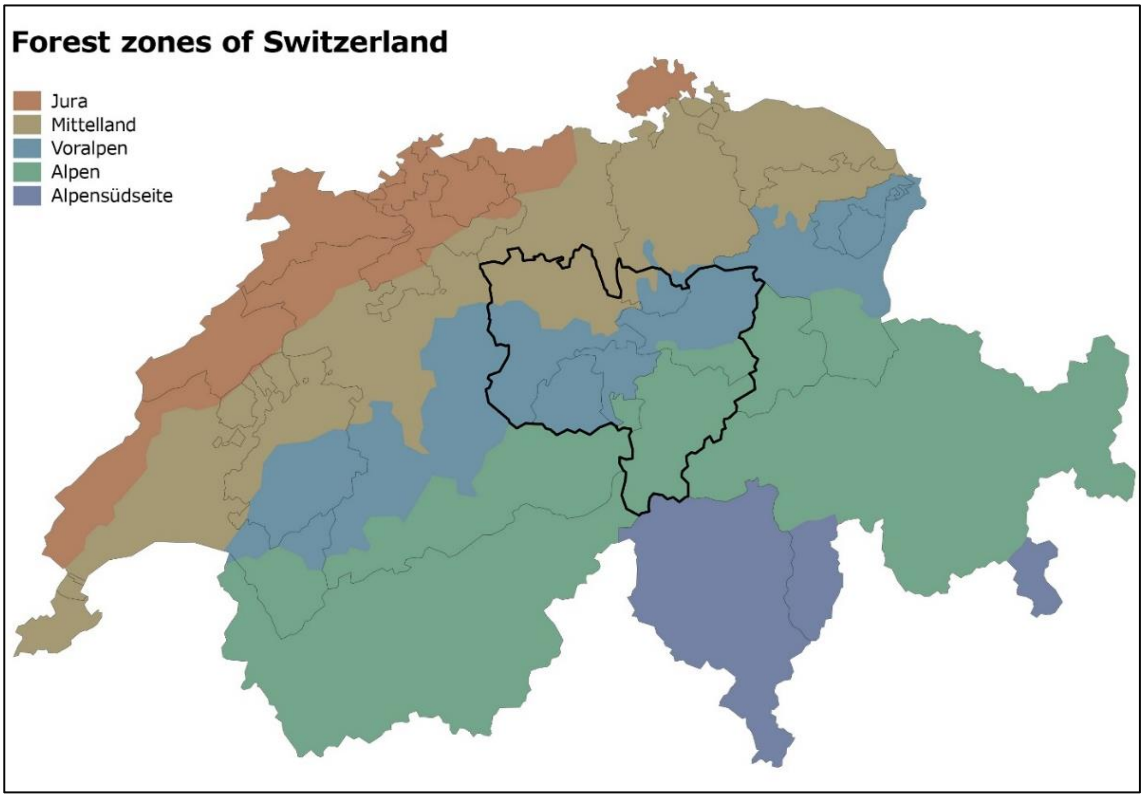


Figure 22: Forest zones in Switzerland and allocation of the six cantons of Central Switzerland. Source: BFS 2010, translated and adapted

3. Best Practice: INNOwood

3.1. Introduction

So far, system approaches of the forest-wood value chain (and thus also the understanding of it) have focused on the linear flow from the supply of the raw material wood through the products of the further sales stages to the finished building or supplied wood energy. The forest is only depicted as the "producer" and thus raw material supplier without further differentiation in terms of its forest services in a regional, ecological and climate policy context (Geier et al. 2023, p. 7). This leads to the marginalization of the decision at the end of the value chain as to whether local wood or wood from sustainable forest management is used for buildings.

The INNOwood project addressed this issue and aimed to raise awareness among decision-makers and the civil society at the end of the forest and timber value chain. The aim of the project was to identify connections and effects as well as interdependencies between forest management and the use of regional wood (impact network), to record them in a system map and to prepare the information for decision-makers and the population in a target group-oriented manner (Geier et al. 2023, p. 7-8).

3.2. Methodology

The methodological approach in the INNOwood project was based on three cornerstones:

- The integrative inter- and transdisciplinary approach to project work.

- The scientific-academic analysis of interrelationships by means of literature research, in workshops and based on case studies, and the development of a systemic impact structure.
- The development of target group-oriented (easily understandable) communication of the scientific-academic and abstract contents of topic dossiers and case study presentations in a website with an experiential character.

3.3. Results

The starting point for the development of the forest-wood impact structure was an inter- and transdisciplinary thematic mapping and the analysis of the case studies. The thematic map combines forest and wood topics and assigns actors to them. This thematic mapping reflects a generalized system approach. The analysis of the case studies identifies regional forms of dependencies and makes it possible to distinguish between generalizable and transferable aspects.

Ultimately, actors, processes and geographical allocation are interlinked in the impact structure. With their decisions, actions and processes, actors influence the timber industry and the financing of forest maintenance and conversion. This in turn has an impact on the forest, its functions and the services it provides for the civil society.

The impact structure encompasses ecological, economic, social, and environmental dimensions. Ecologically, it involves the interconnection of various plant and animal species. Economically, forestry and wood processing chains collaborate, while socially, forest workers, owners, communities, and industries rely on each other. Environmentally, considerations include climate adaptation and the effects of wood and forests on the environment. However, these dimensions are intertwined, with actors such as forest owners, municipalities, and businesses influencing each other. Fluctuations in the timber market, for example, affect forest owners' ability to maintain forests, impacting biodiversity. Forest owners decide on forest use, providing services like protection and recreation, benefiting communities. Local wood usage creates jobs and regional value, benefiting the entire area.

The impact network operates through linking various levels of consideration, with complex interdependencies affecting forest services for the population. Understanding these dependencies can ensure added value throughout the network. Regional wood usage is crucial, integrating forests into the local economic system and directly compensating for forest services. This supports forestry industry sustainability and regional forest management.
Figure 5 shows the graphical representation of the generalized impact structure forest-timber-society. The different benefits provided by donors and recipients are identified on the basis of impact structures in the specific case studies in INNOwood. The main questions were: Who benefits from services, who pays for services?

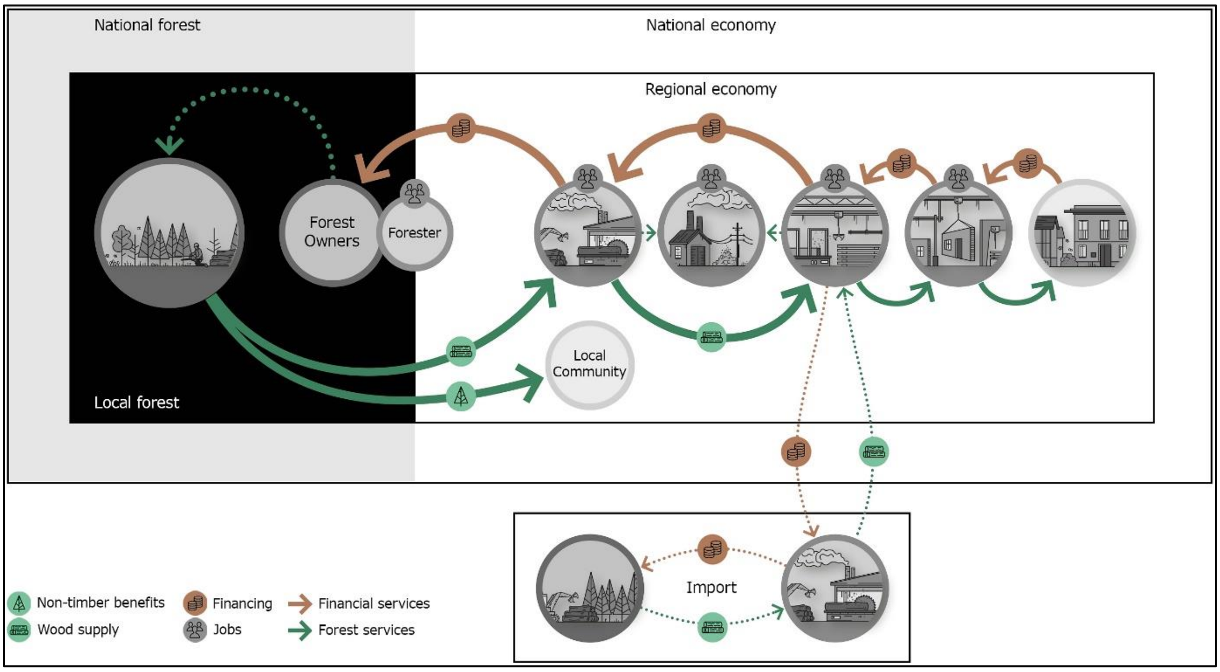


Figure 23: Impact network of the forest and the wood value system. Source: © INNOwood, scientifically adapted and translated.

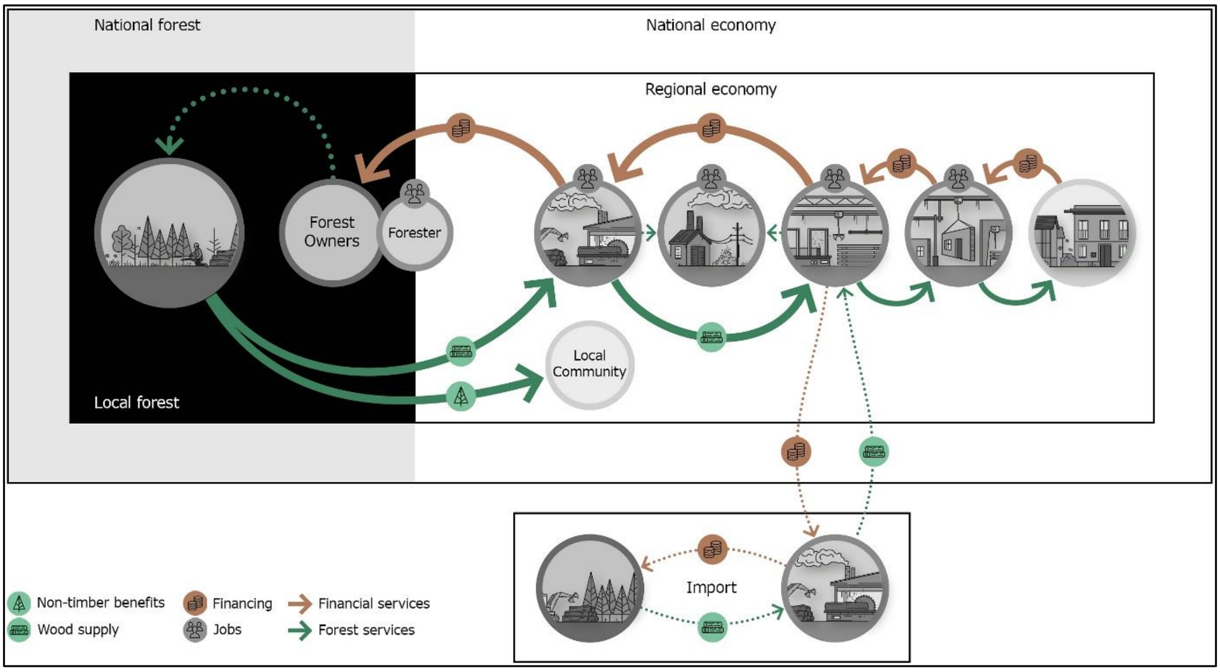


Figure 23 is structured in such a way that the forest and the actors are arranged as circles on an imaginary line. The services provided by the forest are shown 'below' this line are illustrated with green arrows. These services comprise the supply of raw materials and 'intangible' services such as recreational areas. Financial flows are shown 'above' this line with brown arrows. These include cash flows and revenues by selling the product “timber” at different stages. The dotted green arrow between the forest owners and the local forest indicates that they are the decisions and investments of the forest owner that lay the basis for the ecosystem services of the forest.

The grey square on the left side represents the national (Swiss) forest as a whole, the black square in the center of the grey square depicts the local forest as a specific forest in the region where the wood is used for a construction or other purposes.

Both squares (national and local forests) are connected with the rectangular areas of the 'Regional economy' and the 'National economy' system. This system approach illustrates how the use of regional wood financially supports the forest management and owners of the local and national forests. With this system in balance, revenues from local wood are able to largely cover forest management and the necessary forest adaptation to mitigate climate change effects. In addition,

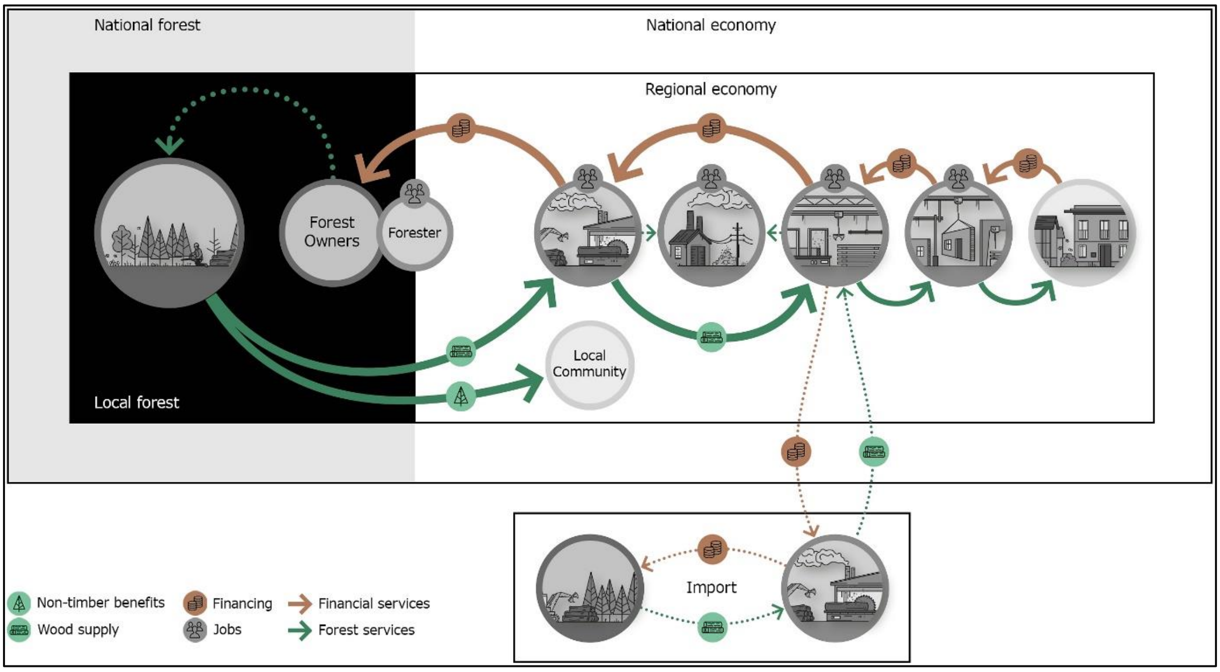


Figure 23 also shows that the use of imported timber does neither contribute to financially support the management of local forests nor to local value chains.

It has to be mentioned that some eco system services can also be provided to a greater or lesser extent independently of the utilization of local wood. These are, for example, the habitat for animals, the production of non-timber products or climate regulation and carbon storage. In many forests, protection against natural hazards, recreational use or the use of wood are of greater importance. Only a sustainable forest management is able to ensure these important eco system services for local communities and the society in general.

Overall, the system approach illustrates the interdependencies between the various actors and interests associated with forestry and the timber industry. A holistic view is important to ensure sustainable forest management and considers both environmental and socio-economic objectives.

The abstract character of the interdependencies hinders necessary awareness raising to clients, planners and civil society as they are most often laymen in terms of forestry. Therefore, the INNOwood project carried out communication tests with laymen and multipliers. The results of these tests were sobering, interviewees felt overwhelmed when it came to describing and naming individual dependencies. For this reason, a simplified effect structure was developed and connected to target-group oriented user stories of the local case studies. The individual aspects were shown with the help of pictures and explanatory text. A survey with simplified and target-group oriented approaches with a mixture of images, graphics and text and the fact that the texts are portioned and reduced to a few statements generally supported understanding.

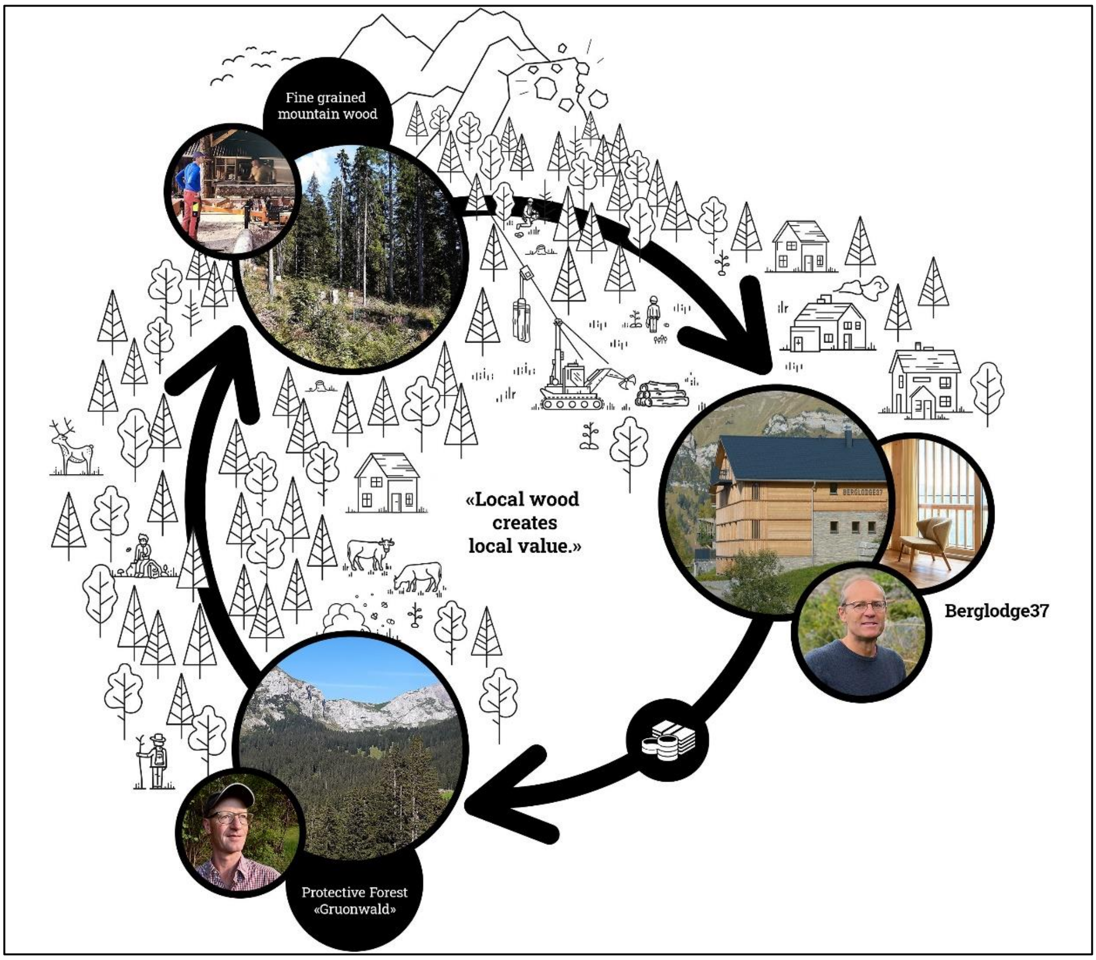


Figure 24: Simplified impact network illustrating interdependencies for laypeople. © INNOwood

The simplified impact network (Figure 24) illustrates the local forest, shows its primary forest functions and provides a key message at the center. The connection between the local forest and the relevant actors is shown in simplified form and provides the faces behind the roles. Actors are established as testimonials. The starting point for the simplified impact structure is the local forest, which fulfills forest services and forest functions. The path of the wood from its forest to the final use in a building construction is explained by the method of storytelling.

Finally, the value of the cognitions of INNOwood led to the launch of a new website, named www.waldnutzen.ch, on which six shining examples of buildings made of wood from local forests tell their stories as explained above. The stories of these shining examples are connected with relevant background information. Low-threshold access to information via a website and user guidance geared towards the desire to discover make abstract content accessible to laypeople and semi-experts.

3.4. Discussion

INNOwood is a best practice example that refers to the primary raw material source for the sustainable use of wood in construction. In future, the sustainable use of wood in construction must take into account resource-oriented use in a global but also in a local context. The demand side at the end of the value chain is able to influence by a pull-effect the supply chain. Informed decisions at the end of the value chain require ordering skills that respect the material and value loops that finally support sustainable forest management. Thus, clients and planners are responsible, but they are experts in the construction sector and are certainly rarely familiar with forest management issues and impacts across sectors. Awareness-raising for semi-experts and laypeople therefore plays an important role.

INNOwood aimed at the methodical processing on a systemic level and the concretization in the individual real case studies contributed to bringing together isolated, sectoral or functional structures and presenting abstract relationships in an operationalizable way. The key to success was the interdisciplinary composition of the project organization and a transdisciplinary approach to the topic. The research team was able to contribute a wide range of experience from previous research projects from their specialist areas. The joint analysis and development with practioners from planning, manufacturing and forestry grounded anchored theoretical system approaches with real-world experiences. The project's advisory group was deliberately designed to be diverse by including representatives from the forest and timber sectors as well as the WWF Switzerland (World Wide Fund For Nature). This composition made it possible to combine the perspective of the forest with its broad spectrum of forest functions and services and the perspective of the timber industry, which focuses on the entire process from the tree to the finished product and its (re)use. Through this integrative approach, the diverse dimensions and meanings of the forest and the economic processes of the timber industry could be brought into a mutually enriching relationship.

4. Best Practice: Holzkreislauf Uri [Wood Circus Uri]

The Holzkreislauf Uri initiative was launched in parallel with the INNOwood project in 2021 and still ongoing. While the INNOwood project has an integrative research and development character, the Holzkreislauf Uri aims to empower local actors to implement a political objective. The subsequent analysis is based on information from working papers elaborated during the scientific and methodological accompaniment of the initiative (Geier and Rupli 2023).

4.1. Introduction

The launch of the initiative of the Holzkreislauf Uri was based on several political drivers. Swiss cantons are challenged to contribute to achieving the Swiss Federal Council's net-zero greenhouse gas emissions by 2050. This requirement was adopted by the "Strategy and Government Program 2020-2024^{+}" that describes the specific legislative goals of the Canton of Uri for the period 2020-2024, which the Cantonal Government of Uri intends to implement in the years from 2025. Five focus areas define the framework for the concrete implementation of the vision and goals for the 2020-2024 legislative period.

In priority 3 "Climate-neutral, energy-efficient and secure Uri", the following objective is formulated in the lighthouse project "O. CO_2 removal from the atmosphere": "[...] Increase the use of wood from local forests and increase the use of local wood as a building material and energy source".

Two other political motions submitted to the Uri Corporation Council in 2021 and 2022 also aim to increase the use of wood from Uri by closing gaps in the cantonal processing chain and to do so on the basis of sustainable forest management:

- Motion "Establishment of a sawmill in the canton of Uri", submitted by Corporation Councillor Hermann Herger, Flüelen June 2021
- Postulate on the "Establishment of a commission to promote sustainable forest management" submitted by Corporation Councillor Peter Truttmann on March 17, 2022

As recognized in the INNOwood project, raising awareness of the use of regional wood is an essential contribution to maintaining the diverse forest services for the benefit of the people. The Korporation Uri [Corporation Uri][7], as the largest landowner in Uri, responsible to collaboratively and sustainably manage their own forest, aims to secure these services.

Based on the strategy and the government program 2020-2024+, with reference to the two political initiatives and the Korporation's Uri interest a broad-based implementation strategy was planned. To this end, the "Holzkreislauf Uri" project was launched by the cantonal forest office "Amt für Forst und Jagd" which is part of the Sicherheitsdirektion Uri [Security Directorate].

The overarching objective of the Holzkreislauf Uri is to fulfill the mandate from the government program. The aim is to develop and implement measures to remove CO_2 from the atmosphere. In addition, the forest and the forest and wood value chain in Uri have great potential to contribute to the Swiss Federal Council's net-zero targets. This development potential of the forestry and timber industry in Uri should be exploited. At the same time, the implementation of measures should strengthen the positioning of Uri as a residential, tourism and business location. Action should therefore be derived from the implementation of the government program together with the economy and the civil society.

4.2. Methodology

Since the government program is to be used to derive action from the economy and the civil society, the procedure was based on a participatory approach:

- Integrative approach: Involvement of the administrative and political levels, the corporation as the largest forest owner in the canton of Uri and committed representatives from the wood processing chain, the planning and education sector in the project team.

- Stepwise participatory development of the implementation strategy with a focus on the empowerment of regional stakeholders.

4.3. Results

An initial overview of the situation illustrates the challenges forest management has to face in the canton of Uri. For example, the figures of the wood harvest in 2022 show the low annual wood use compared to the other cantons in Central Switzerland (Figure 25).

[7] https://www.korporation.ch/

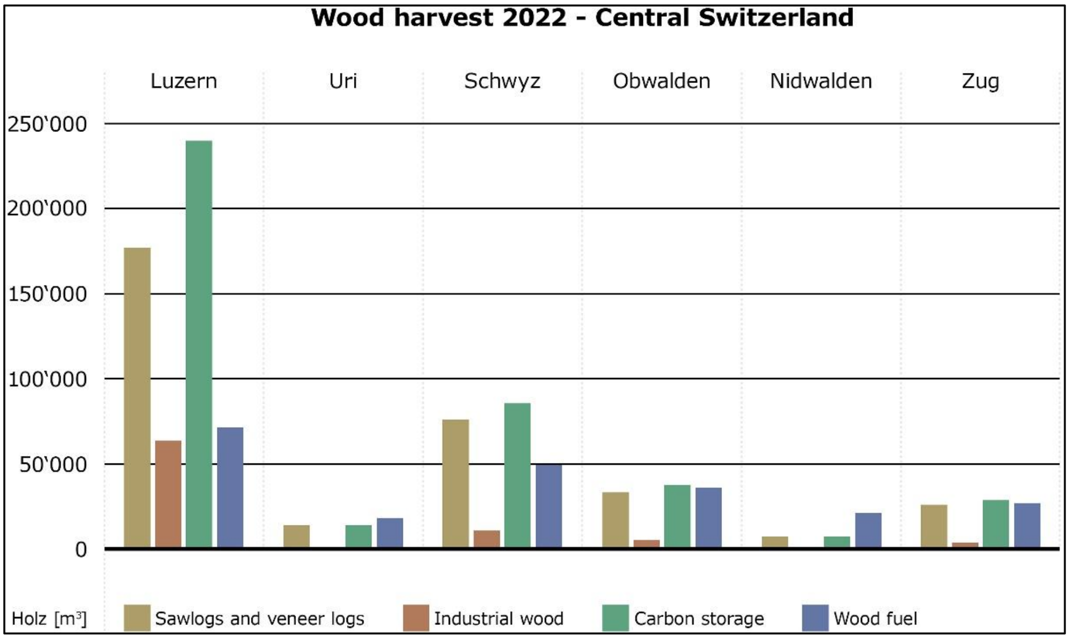


Figure 25: Wood harvest 2020 in the cantons of Central Switzerland.

The low amount of wood use is closely linked with the mobilization of local wood that is strongly influenced by the topography of the canton. 80 percent of the forest in Uri is situated above one thousand meters above sea level. The share of forest in the total area of the canton is only 19.5 percent. The Swiss average is about 31 percent. Due to the high share of areas (mountain landscape) above the tree line, the low overall proportion is put into perspective. However, the steep slopes result in a high proportion of protection forest of 57.30 percent. Nature and landscape conservation priority is at 37 percent, leaving only 5.35 percent of the area for traditional timber use.

Figure 26: Canton Uri, view on the valley of the river Reuss. Source: AdobeStock I AventuraSur

The identification of the existing situation in the value chain (Figure 27) showed on the one hand that there is no pull effect at the end of the value chain - the demand for local wood is lagging behind. Clients are not aware of the possibilities of using local wood, and architects are not familiar with suitable technologies and processes to integrate local wood with its specific properties into their planning. Both are unaware of the resulting benefits for local value creation and eco system services. This recognition was in line with the findings of the INNOwood project.

On the other hand, the fragmented cantonal wood processing chain, which cannot supply the necessary capacities or products even if there is a demand for wood from Uri.

The analysis of the status quo was discussed and confirmed with the administration as well as with forest representatives and players in the wood processing chain. Increased use of local wood in the future therefore requires know-how on the utilization of the range of local timber assortments, an establishment of communication structures between demand side and forestry sector to coordinate harvesting and targeted investments in the processing chain.

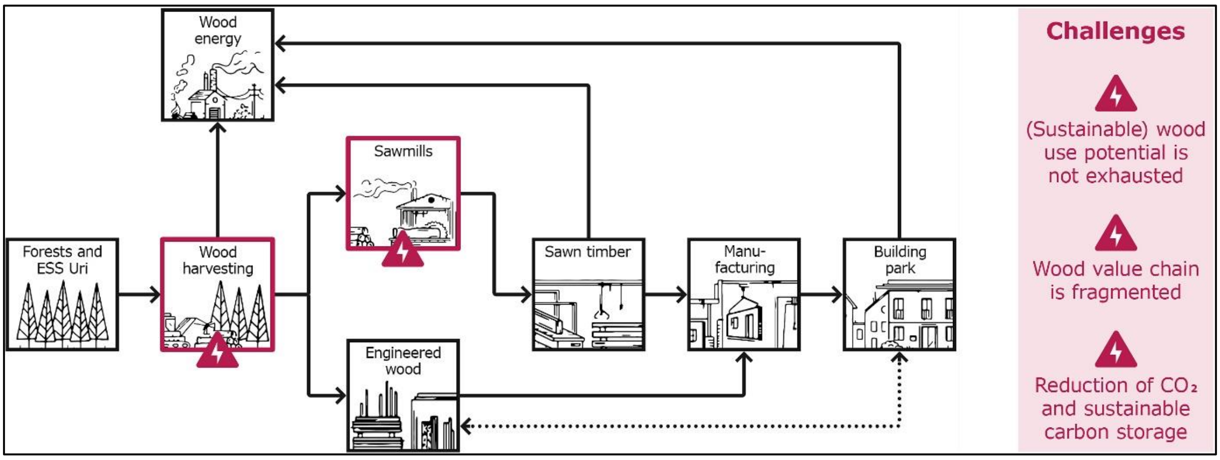


Figure 27: Analysis status quo wood value chain in the canton of Uri. © CCTP

For the implementation strategy, the mapping of the value chain was expanded to include possible options for action. In view of the need to use scarce resources sparingly, the concept of value creation cycles (instead of "chains") was coined. The systemic mapping (Figure 28) provided an overview of the entirety of value creation and material cycles and thus the necessary starting points for the implementation strategy and the allocation of specific measures. The measures marked in magenta in Figure 28 show necessary fields of actions. In a first step, it was identified on how these actions could be started (comments assigned to the specific fields in Figure 28). In parallel, two measures were prioritized: A cooperative approach to tackle the bottleneck “sawmill capacities” and “awareness raising” to achieve a pull effect in building construction. These two actions were further elaborated in working groups from administration and business.

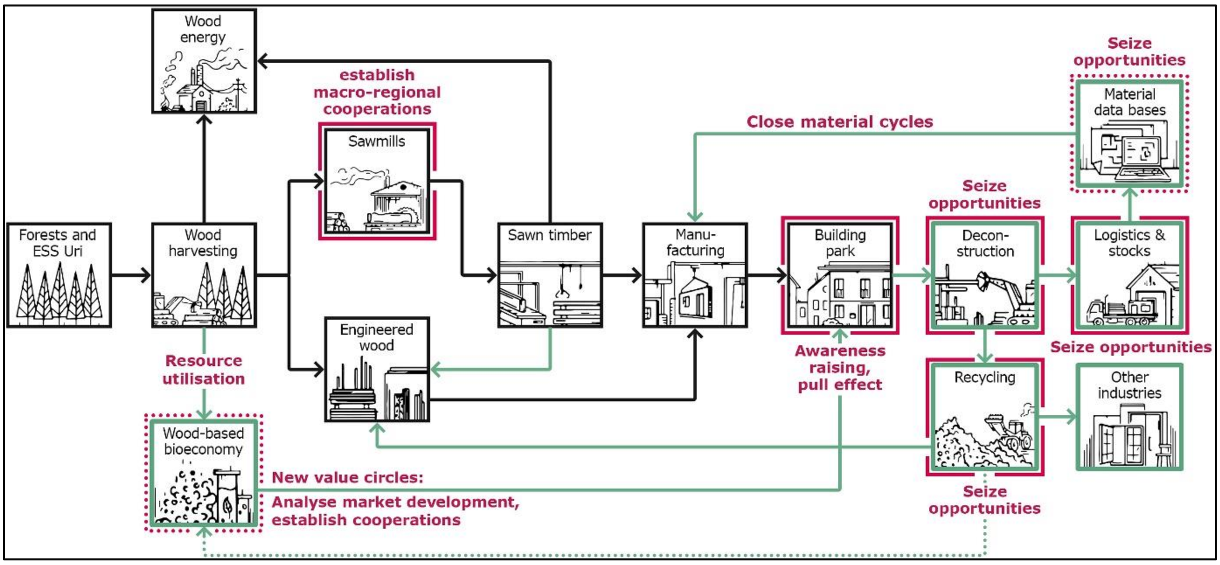


Figure 28: Development of a roadmap towards a new approach of value creation loops in the canton Uri. © CCTP

Transferring the initiative Holzkreislauf Uri into a long-term political framework for sustainable action is a task for the future that is currently being planned. The Holzkreislauf Uri can only be effective beyond the 2020-2024 period and beyond individual projects and pilot actions with an overarching framework for action.

In this field of action, it is important to develop the foundations and framework conditions for continuity:

- To define the values of the Canton of Uri.
- To ensure the framework conditions for the availability of wood as a resource in terms of the future wood requirements of all stakeholder groups.
- To draw up guidelines for the use of wood in public buildings and to implement showcase projects.
- To discuss the political framework conditions for the transformation from linear economic thinking to a circular economy with regard to the announced amendment to the Environmental Protection Act.
- To develop a roadmap for the wood-based bioeconomy.

The preparation of this framework for action is underway in the current project.

4.4. Discussion

The climate protection targets at national level with the Federal Council's net-zero target by 2050 were decisive for the initiation of the Holzkreislauf Uri. However, this would not have triggered any direct action at the level of the players in the forestry and timber industry in the canton of Uri. It was only the specification of the 2020-2024 government program and the link to the potential of the forestry and timber industry, which could generate a win-win situation, that provided the impetus for launching the initiative.

However, the real key to success was the dialogue-based approach and the alignment of the framework for action to the respective stakeholder level (politics-administration-business-education) and the active linking of these stakeholder levels with each other.

The support from Lucerne University of Applied Sciences and Arts made it possible to methodically develop the framework for action from a neutral position, to accompany the dialogue process methodically and professionally and to evaluate the interim results from an overarching perspective.

5. Best Practice: Modul 17

Technological developments in recent years have driven the realization of 6-8-storey residential and commercial buildings made of timber. With the liberalization of fire protection regulations in Switzerland in 2015, the height limit for timber buildings was lifted and became possible to build the same height as with other materials. The subsequent composition is based on the findings in the Innosuisse project "Timber Hybrid High-rise Building" (2017-2019) and the publication "Modul 17" (Keikut and Geier 2019).

5.1. Introduction

With increasing urbanization and the need to create living space, the pressure for urban densification is growing. However, the extent to which high-rise buildings can contribute to high-quality densification is controversial. From the perspective of timber construction, too, the question arises as to what role timber can play in this development.

This is where the project "Timber Hybrid High-rise Building" came in and investigated the characteristics of a new high-rise typology in timber hybrid construction and what contribution this typology can make to high-quality densification in urban areas.

5.2. Methodology

In an interdisciplinary collaboration with researchers and partners from planning and implementation practice, a new typology for high-rise buildings was developed based on the material properties and construction principles of wood and wood hybrid construction methods. These were examined at different height levels and evaluated in terms of their space efficiency, contribution to densification, cost-effectiveness, and structural implementation process. Finally, a proof-of-concept was carried out in a prototype test planning.

5.3. Results

The result of the project is a modular construction concept that utilizes the systemic approaches of timber construction as well as its construction principles and potential for urban redensification through high degrees of prefabrication while reducing disturbance for neighbours.

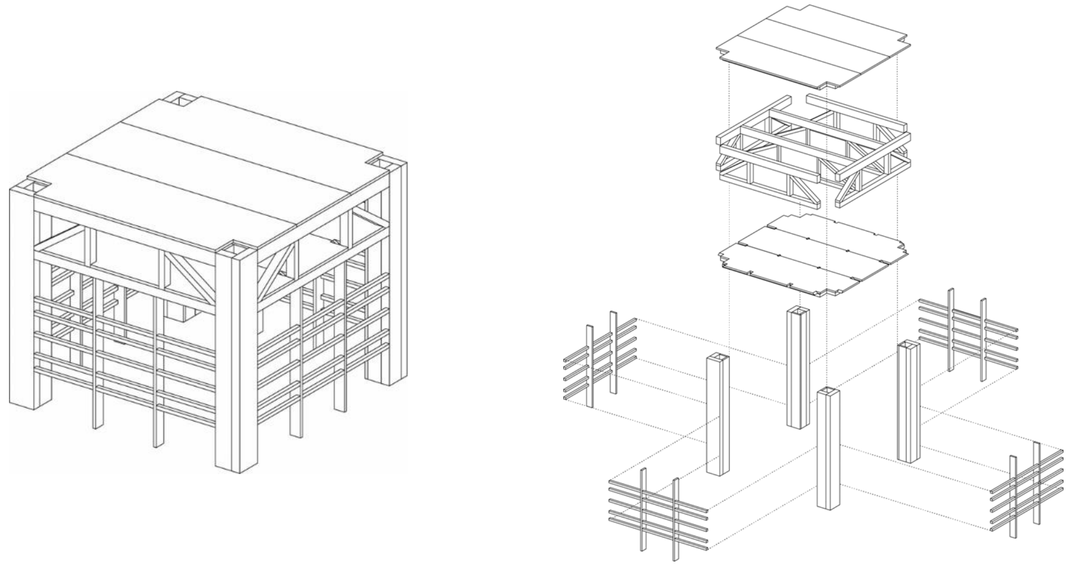


Figure 29: Modul17 – Axonometry. © CCTP

The basic module, the so-called "Modul17" (Figure 29), consists of almost 90 percent wood and, with a horizontal dimension of 17 by 17 meters - hence the name - and a height of around 14.5 meters, offers a high degree of flexibility in use both vertically and horizontally over the entire life cycle. This makes it maximally efficient, adaptable even in striking urban structures and also extremely flexible both horizontally and vertically.

Each individual module is held in the corners by four "mega columns", which transfer the vertical loads and conceal the building technology within a cavity. Directly under the ceiling of the module, a "mega ceiling" made of room-high truss girders transfers the vertical loads to the "mega columns".

This means that the entire floor plan is column-free and can be freely designed as "free space". The "mega ceiling" in wood-concrete composite construction separates the modules from one another and, together with reinforced concrete stairs outside the module, provides horizontal bracing. The modular system developed allows the Modul17 to be extended horizontally and stacked vertically. It therefore offers any number of possible combinations (Figure 30).

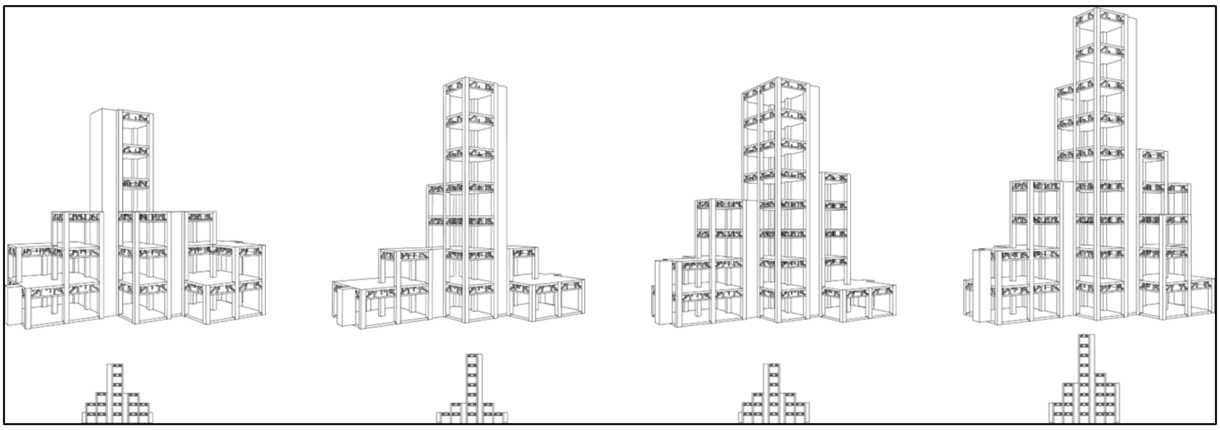


Figure 30: Combination possibilities Modul17. © CCTP

The share of timber in the load-bearing structure of Modul17 is around 87 percent, thus minimizing the consumption of grey energy. The wood used in each Modul17 absorbed 370,000 kg of CO_2 from the atmosphere. The degree of prefabrication enables a 50 percent shorter construction time compared to a realization with a lower degree of prefabrication.

Figure 31: “Cream-slices” in traditional high-rise-buildings. © CCTP

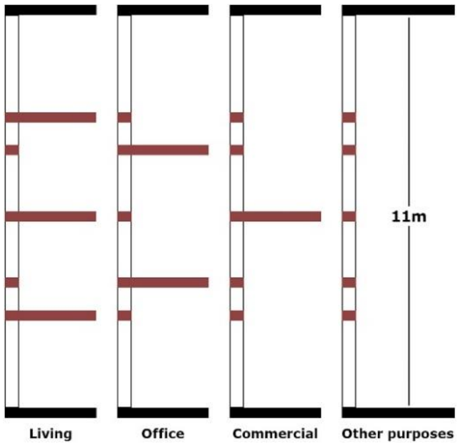


Figure 32: Modul17 vertical free space. © CCTP

The big advantage, however, is the vertical and horizontal flexibility. Instead of a stiffening core, the center of the module is left free (free space). Vertically, the usual principle of "cream slices" (Figure 31), which massively restrict flexibility of use due to fixed room heights, has been abandoned. The 11-metre-high free space area allows polyvalent uses with different scenarios, such as four residential floors, three commercial floors or an extra-high room for special uses (Figure 32). As each module forms an independent unit, it is easy to respond to the dynamics of use.

5.4. Discussion

The developments for Modul17 resulted from current questions about a difficult building typology and its role in urban development. The results provided a good insight into the role of a high-rise building and the possibilities and limitations of modular construction methods in the urban environment.

In view of the rapidly growing debate on resource conservation and the circular economy, the work and findings from the project make a valuable contribution. In the context of wood in construction, the Modul17 approach shows a strategic utilization of wood, leveraging its inherent strengths in conjunction with other materials in a judicious manner, rather than adhering dogmatically to a sole reliance on wood.

In addition, solutions are shown as to how the life cycle of a building can be extended through adaptable building structures. Utilizing the horizontal and vertical adaptation potential offers the individual user flexibility, design freedom and room for manoeuvre. From an urban planning perspective, dynamic building typologies are also an essential tool for minimally invasive solutions to necessary adaptation cycles while at the same time responding to the needs of users.

6. Conclusions

6.1. Local value creation loops

Both INNOwood and Holzkreislauf Uri succeed in triggering concern through regionality as well as the focus on regional lighthouses, resources and actors and thus derive impulses for action. The preservation and/or creation of jobs and regional value creation at a local level generate income and contribute to the quality of life and the preservation of cultural identity.

In a globally operating timber market, the focus on local resources has to be discussed. The vast offering of a global market is offset by limited local products and technologies. However, local supply chains can prove to be more resilient in the event of a crisis. On the other hand, self-sufficiency in the supply of resources can also lead to more effort and resource consumption than the development of supra-regional cooperation or supply chains. The fact that planners are not always aware of local availability was discussed in the Holzkreislauf Uri. First proposals on how to overcome this lack of know-how had been discussed but not yet realized.

In the long term, sustainable development will also require an appropriate balance to be struck with regard to local or global value creation loops, taking into account ecological, social and regional economic objectives.

6.2. Inter- and Transdisciplinary

In each of the three best practices, the adoption of an interdisciplinary and transdisciplinary methodology emerged as pivotal for success. In an increasingly interconnected environment, challenges cannot be tackled isolated and within the confines of a discipline. The increasing demand for living space cannot be viewed separated from climate protection targets. Neither can one afford to assign precedence to either objective, deeming one as inherently superior or more pressing than the other.
While disciplinary expertise serves as a fundamental prerequisite for addressing these challenges, a nuanced comprehension of complex issues necessitates transcending the temptation to oversimplify systems and compartmentalize concerns. Instead, fostering an understanding of system dynamics and cultivating iterative, interdisciplinary approaches to problem-solving becomes paramount.

6.3. Balance between regulation & participation

Another key is the interplay between the legal and political framework and the involvement of society through actors in a dialogical or participatory process.

In Switzerland and other countries, forest legislation regulates the fundamental values for the conservation and use of forests and their functions. Various regulations and policies then guide the strategic and operational implementation of these values. For the mobilization of wood resources for material and energy use, different legal bases must be applied at the end of the value chain.

In a dialogical process, as implemented in INNOwood, an environment is created in which all stakeholders are heard and solutions are sought together. The Holzkreislauf Uri has focused on dialogical, but also on a participatory process. In workshops and working groups, stakeholders were actively involved in shaping the implementation strategy and concrete measures.

Only committed players who push the boundaries of what is legally possible enable the implementation of lighthouse projects and, as a logical consequence, the establishment of new technologies and standards. Both projects emphasized the incorporation of stakeholders spanning various levels and societal segments. Notably, the pivotal factor contributing to their success was the integration within political agendas, exemplified by initiatives like the "Strategy and Government Program 2020-2024+" and the "Offensive Holz" in Lucerne, among others. Ultimately, this raises the question of how much legislation is necessary or is it enough to rely on voluntary, committed pioneers in order to achieve sustainable development in the construction sector in the long term?

Acemoglu & Robinson 2012[8] delineate that for sustainable development mechanism of pluralistic political institutions that allow wide sections of society to participate in governing the country are necessary to achieve prosperity, wealth and higher living standards on a long term. To master the balance between participation and ruling framework is thereby a key to success. This balance can be observed above all in the Holzkreislauf Uri. Without the legal requirements from the government program ("state"), which also brings together two subject areas (forestry and timber industry & climate policy), the process would not have been set into action. Nevertheless, the involvement of the relevant stakeholders ("society") is necessary in order to initiate implementation and to strive thereby for innovations.
A participatory process devoid of delineated structures governing role allocation and delineating the actionable competencies of participants would not have yielded the current outcome.

6.4. Target group-oriented awareness-raising at the end of the value chain

The INNOwood project refers to the primary sector (forest) in order to achieve a sustainable use of wood in the construction industry. The use of wood per se can only be considered sustainable in the context of sustainable forest management and the establishment of (local) value-added loops. The decisive factor here is to strengthen the (client's) ordering competence on the demand side at the end of the value chain. The Holzkreislauf Uri focusses on strengthening the local processing chain, among other things. At the same time, the project team is aware that strengthening also depends on the pull effect at the end of the value chain. With the increased demand, it is also possible to initiate the necessary investments in the processing chain. The INNOwood approach of not operating with purely factual, academic information, but rather using an emotional approach geared towards the discovery experience to appeal to laypeople and semi-experts has proven successful in the communication tests.

6.5. Wood in the construction sector

With the increasing demand for circularity, timber construction is pushing itself thanks to the ease of processing, advantages in logistics due to low weight and its traditional easy to be dismantled construction principles. Nevertheless, neither circular construction principles nor cascading use has yet been established in timber construction. Dismantling does not take place; during demolition, timber components are sent for thermal recycling.

[8] Why nations fail

The approach from Module17 breaks this vicious circle or at least drastically slows it down. Even if the typology was developed for the challenge typology of high-rise buildings, it can be transferred to others, less demanding building typologies. This new typology of adaptable building support structures enables the basic design structure of a building to be retained. The current dynamics in usage can be accommodated with minimal invasiveness in the horizontal, but now also in the vertical alignment. According to the implementation strategies for a sustainable circular economy by Geissdorfer et al. 2017, the "slow" aspect, i.e. extending the life cycle of products or buildings, comes to the fore here and the ability to dismantle the supporting structure becomes less important.

7. Recommendations

7.1. Integrated resource policy

Even if the legal framework for the mobilization of wood in the construction industry is based on different foundations, an integrative approach of the material (wood) with the primary sector (forest) is essential for the goal of a sustainable bioeconomy. Forest management and adaptation and their contributions to carbon neutrality depend on the integrative approach of actors in the forest sector, the wood value-chain, and the ordering competence at the end of the value chain. Finally, the society benefits from this integrated approach by the provision of ecosystem services and goods supported by the local forests. A sustainable integrated resource policy considers local and global value creation cycles depending on the specific framework conditions.

7.2. Interdisciplinary dialogue and participation processes

Both, dialogical processes and participation are important tools for promoting integrative decision-making. While emphasizing different aspects of stakeholder engagement they have to be used appropriately in the respective context. A distinction must be made between two levels for the objective of sustainable use of wood in construction:

- an interdisciplinary process in the development of new solutions (this also applies to planning processes)
- dialogical and participatory processes for the strategic and operational implementation of legal/political mandates

7.3. Awareness-raising

In order to promote the increased use of wood from local forests or from sustainable forestry in general in the construction industry, it is important to strengthen ordering competence on the demand side. Measures thereby include raising awareness of the benefits from the user's perspective in a target group-oriented manner. The benefits are not only related to the building, but also include the ecosystem services and goods of forest from which the wood is harvested.

An important aspect thereby is that the information is provided in a way that is appropriate for the target group. The findings from the best practices show that low-threshold access and the preparation of information with an experiential character are important.

Planners and architects also need to consider how information on regional availability can be prepared so that a balance can be struck between global and local value creation loops.

7.4. Enhancing adaptability of wood construction

Growing demand for residential and commercial space and increasing dynamics in the use of buildings require new building typologies that can accommodate this demand and these dynamics without undermining climate and resource policy objectives. The separation of load-bearing structure and fit-out has long been demanded as a system separation but has not yet been implemented in reality. In the future, solutions for the horizontal adaptability and vertical adaptability of structures must be realized. Module 17 shows how this can be achieved using the construction principles of timber construction.

8. Transferability

The situation in Switzerland exhibits a notable emphasis on the use of wood from local forests, which less prevalent in neighboring countries. Considering the imperatives of resilient supply chains and socio-economic effects, this focus on local resources can also be discussed in terms of constructions appropriate to material characteristics. The focus on the use of "wood from local forests" can also be linked to the use of wood from sustainable forestry in a broader sense.
The paper points out best practices which are transferable and applicable especially in the focus countries (especially Asia, Latin America, Africa) strengthening economic collaboration and investment opportunities with the private sector.

9. Key Messages

Forest management and adaptation and their contributions to carbon neutrality depend on the integrative approach of actors in the forest sector, the wood value-chain, and the decision-makers at the end of the value chain. Finally, the society benefits from this integrated approach by the provision of ecosystem services and goods.
The amalgamation of the findings of three different best practices underscores the potential for vertical integration among decision-makers, planners, and stakeholders within the value chain, accompanied by participation processes. The findings also emphasize the significance of governmental efforts in actively advocating for wood utilization within local civil society spheres. Ultimately, an inclusive approach that engages stakeholders throughout the forest sector and wood value chain, alongside decision-makers, facilitates the delivery of ecosystem services and goods, creating benefits for the society comprehensively over time.

References

Acemoglu D. and Robinson J.A. (2019). The Narrow Corridor: States, Societies and the Fate of Liberty. Penguin Books: London. ISBN 9780241314296.

Bundesamt für Umwelt BAFU (ed) (2022). *Jahrbuch Wald und Holz 2022.* Umwelt-Zustand Nr. 2225. Bern, CH.
https://www.bafu.admin.ch/bafu/de/home/themen/wald/publikationen-studien/publikationen/jahrbuch-wald-und-holz.html

BV (1999). *Federal Constitution of the Swiss Confederation of 18 April 1999* [Bundesverfassung der Schweizerischen Eidgenossenschaft vom 18. April 1999]. SR101.
https://www.fedlex.admin.ch/eli/oc/1999/404/de

Federal Department of Environment, Transport, Energy and Communications DETEC (2023). *Klimaschutz [Climate protection]*.
https://www.uvek.admin.ch/uvek/de/home/umwelt/klimaschutz.html; Retrieved 03.05.2024; 11:03

Federal Office for the Environment FOEN (ed) (2023). *2050 net-zero target.*
https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/emission-reduction/reduction-targets/2050-target.html; retrieved 03.05.2024; 10:49.

Federal Office for the Environment FOEN (ed) (2021). *Forest Policy: objectives and measures 2021–2024. For the sustainable management of forests in Switzerland*. Environmental Info no. 2119. Federal Office for the Environment. Bern, CH. p.8.
https://www.bafu.admin.ch/bafu/en/home/topics/forest/publications-studies/publications/forest-policy-objectives-and-measures-2021-2024.html;

ForA (1991). Forest Act on Forest of 4 October 1991 (Status as of 1 January 2022). [Waldgesetz, WaG]. SR 921.0. https://www.fedlex.admin.ch/eli/cc/1992/2521_2521_2521/en

ForO (1992). Ordinance on Forest of 30 November 1992 (Status as of 1 July 2021) [Waldverordnung, WaV]. SR 921.01. https://www.fedlex.admin.ch/eli/cc/1992/2538_2538_2538/en

Geier S.; Wacker P.; Witt S.; Hanisch Ch.; Gallati J.; Z'Rotz J. (2023). INNOwood. Innovative Betrachtung des Wirkungsgefüges Wald-Holz-Gesellschaft. [Innovative consideration of the forest-timber-society impact network]. Final Scientific Report, Federal Office for the Environment FOEN, Order number: 01.0101.PZ/0024/1E16D8856/2021.07

Geier S. and Rupli H. (2023). *Holzkreislauf Uri. Umsetzungsstrategie. [Wood Circus Uri. Implementation strategy].* Internal Report submitted to the government council decision. 28.03.2023.

Geissdoerfer M. et al. (2017). *The Circular Economy – A new sustainability paradigm?* Journal of Cleaner Production, 757–768, DOI: 10.1016/j.jclepro.2016.12.048

Keikut F. and Geier S. (2019). *Modul 17. Hochhaus in Holzhybridbauweise. [Timber hybrid highrise buiding]*. ETH Zürich: vdf-Verlag. ISBN 978-3-7281-3979-5.

Rosen A. (2021). Urban Mining Index: Entwicklung einer Systematik zur quantitativen Bewertung der Kreislaufkonsistenz von Baukonstruktionen in der Neubauplanung [Dissertation, Fraunhofer IRBVerlag; Bergische Universität Wuppertal]. GBV Gemeinsamer Bibliotheksverbund.

Schuster S. and Geier S. (2023). circularWOOD – Paradigmenwechsel für eine Kreislaufwirtschaft im Holzbau. [Paradigm shift towards circularity in timber construction]. German Federal Institute for Research on Building, Urban Affairs, and Spatial Development (BBSR). Online-Publication 15/2023. Bonn. ISSN 868 0097. https://doi.org/10.14459/2023md1725475

WaldSchweiz (2024). Waldeigentum [Woodland Ownership].
https://www.waldschweiz.ch/de/wissen/waldeigentum; Retrieved 03.05.2024; 11:42

Acknowledgement

The study leading to these results is based on three funded projects. The authors would like to thank the supporting organizations and actors of these research and development activities:

The INNOwood project (2021-23) was supported by the Swiss Forest and Wood Research Promotion Agency (WHFF-CH) with the participation of the Conference on Forests, Wildlife and Landscape (KWL) and the Federal Office for the Environment (FOEN), all cantonal forestry offices in Central Switzerland (LU, ZG, SZ, UR, NW, OW), the Lignum Holzwirtschaft Zentralschweiz LHZ, Pirmin Jung Schweiz AG, the Lucerne University of Applied Sciences and Arts via the participating competence centers' own funds and the interdisciplinary thematic cluster Space and Society (ITC RG).

The project Timber Hybrid Highrise Building (2017-19) was supported by Innosuisse, the Swiss Innovation Agency, partners from planning and timber manufacturing, Holzbau Schweiz, Lignum Schweiz and VKF.

The Holzkreislauf Uri initiative (2021-ongoing) is supported by the Canton of Uri, Korporation Uri, actors from industry, education, administration and forestry.

Key messages and recommendations for "Wood in construction"

Starting point:

According to the Global ABC report (2022)[9], the construction sector accounts for 37% of worldwide CO2 emissions and 34% of global energy consumption. Furthermore, construction activities utilize half of the world's natural resources and generate 40% of waste globally.

These negative effects are projected to escalate dramatically due to anticipated population growth in the future (especially in the Global South countries; e.g. in Africa the construction market is expected to rise by 70% in the next five years).

On the contrary, the use of wood for buildings can contribute to tackle these challenges as the sequestration and storage effect of carbon dioxide over a long-term period avoids emissions and can be even increased by multiple cascading cycles.

The urgent transformation towards sustainability in the construction sector cannot be tackled solely by using wood, due to its limited availability. Therefore innovative, cascadic and sustainable concepts established along the wood supply chain are necessary and might be transferable to the processing industry of non-renewable resources (e.g. fossil-based and scarce material).

Additionally, a new challenging factor for the future forestry and timber industry has to be considered: climate change and the accompanying negative impacts (e.g. increased and stronger storms, incidence of pests and diseases, volatile timber prices, rising costs due to clearing damage etc.) call for adaptation in tree species and forest management and also challenge the wood processing industry.

Preventing deforestation with a special focus on forests with an important and rich biodiversity (especially for fuelwood extraction) and promotion of reforestation (with agroforestry practices) in areas with sparse forest resources has to be prioritized.

Here are some **recommendations how to reach this pathway and foster wood-based constructions**:

- **Holistic policy frameworks** prioritizing sustainable construction practices by creating incentives for the utilization of wood-based materials (e.g. carbon footprint calculation of new buildings mandatory in the amended "Land Use and Building Act" in Finland[10]), establishing guidelines for sustainable forest management (considering environmental and socio-economic objectives), and promoting the integration of circular economy principles within the construction industry considering legality, transparency, equality, and sustainability of the supply chains and businesses.

- Promoting the **use of regionally sourced materials** for reducing reliance on imports and minimizing carbon emissions related to material transport together with supporting local

[9] Global ABC (2022). *Towards a zero-emissions, efficient and resilient building and construction sector*, UNEP, pp. 100.

[10] https://valtioneuvosto.fi/en/-/1410903/parliament-adopted-acts-that-will-reduce-emissions-from-building-and-promote-digitalisation

industries, and fostering the growth of sustainable construction material production to strengthen the rural areas and communities (business and job creation, regional value, cultural identity).

- **Promotion of reclaimed wood** in construction projects by developing policies, implementing incentives and a dense network of recycling and reprocessing facilities together with appropriate guidelines for deconstruction practices and awareness campaigns to promote the environmental and economic benefits of using reclaimed wood (e.g. minimizing waste production, reduction of CO2 emissions).

- Strengthened consideration of an **integrated design** already in the planning phase of wooden buildings and **digitalization** in wood construction according to the principles of circular economy to guarantee a high percentage of reusability or at least recyclability (e.g. the "National Building Code" of Finland will be amended with a declaration for building products and limitations on the carbon footprint of the buildings with durable and adaptable design).

- Development of **appropriate regulations and standards**, as well as adaptation of existing frameworks for mass timber and bamboo construction supported by capacity-building programs and knowledge-sharing platforms to ensure the robustness and product safety, especially related to durability, fire resistance, height restrictions, and seismic construction requirements.

- Even if the legal framework for the mobilization of wood in the construction industry is based on different foundations, an integrative approach of the material (wood) with the primary sector (forest) is essential for the goal of a sustainable bioeconomy (**integrated resource policy**). Forest management and adaptation and their contributions to carbon neutrality depend on the integrative approach of actors in the forest sector, the wood value-chain, and the ordering competence at the end of the value chain. Finally, the society benefits from this integrated approach by the provision of ecosystem services and goods supported by the local forests. A sustainable integrated resource policy considers local and global value creation cycles depending on the specific framework conditions.

- **Capacity-building and technology transfer** by encouraging partnerships between producers recognized for their best practises in sustainable construction materials to transfer skills, enhance local production capabilities, and promote technological decentralization involving investors and public-private partnerships for financial support.

- **Investment in research and development** by governments, NGOs, industry and international organisations advancing wood science, optimizing processing techniques (e.g. material yield, drying technique, preservation treatment through local sustainable produced sources), and promoting the development of innovative wood-based materials (e.g. prefabricated, engineered wood products like CLT – Cross-Laminated Timber, CLB – Cross-Laminated Bamboo, module systems).

- Implementation of comprehensive **community awareness-raising programs** (targeting farmers, foresters, households, and other consumers) by governments, NGOs and industry stakeholders highlighting the environmental benefits, durability, versatility and viability (e.g. high-rise buildings) of wooden buildings through showcasing successful pilot projects.

- For promotion of greater use of **locally produced and sustainably harvested wood** in construction, it is crucial to **improve the knowledge of planners, builders and clients**. This requires raising awareness among these decision-makers at the end of the value chain of the commonly known benefits of timber buildings, but also of the added value of the ecosystem services provided by forests to educate local people and society in general. In addition, planners and builders need to weigh up information on regional availability in order to optimize the balance between global and local value cycles. For this awareness-raising, it is of utmost importance to tailor the information to the respective audience.

- Fostering and participation in **international collaborations and organisations** (e.g. INBAR – International Bamboo and Rattan Organisation, IUFRO) to facilitate knowledge exchange, technology transfer, and collaboration among member nations.

CHAPTER 2:
WOOD FIBRE IN TEXTILE, PACKAGING AND CONSTRUCTION

Expanding the use of wood fibers - applications of cellulose fibers and nanoparticles

Alex Berg, Felipe Guzman, Niels Müller
Unit for Technological Development, Concepcion University (Unidad de Desarrollo Tecnológico - UDT, Universidad de Concepción), Coronel, Chile

Abstract

Cellulose is the most abundant natural polymer in nature with multiple potential applications beyond traditional manufacture of paper, cardboard, and textile fibers. There is a strong trend, not only in Europe but worldwide, to replace synthetic materials with renewable alternatives such as cellulose fibers. In particular, nanocellulose fibers and particles have many new potential applications as nanomaterial in products that meet producer, consumer, and government requirements for more sustainable materials with a low-risk profile. These new applications can also contribute to improving wood utilization and recycling. Most applications require the separation of cellulose fibers and their modification, which presents important sustainability challenges related to energy and water consumption, environmental footprint, as well as product recycling alternatives. Examples of best practices are presented that highlight the use of wood macro- and nanoparticles in applications that are close to or already introduced in the market. Finally, some recommendations are offered from a Latin American perspective to promote cellulose (macro and nano) fiber applications in the context of a sustainable bioeconomy.

1. Introduction

Interest in new cellulose applications has increased enormously due to the abundance of cellulose, various public policies and citizen pressures that encourage the use of renewable materials and environmentally friendly products and processes. Wood, along with its components and materials derived from them, show significant promise for use in a variety of applications, such as construction, advanced biomaterials, and fine chemicals, among others. In fact, wood and especially cellulose fibers are considered fundamental resources for a sustainable and carbon-neutral bioeconomy (Goldhahn et al., 2021).

The properties of biodegradability, high strength, and low density that these raw materials display, make them a promising resource, with the potential to replace polluting and energy-intensive materials such as fossil plastics and steel. However, most applications require the separation of cellulose fibers and their modification, which presents important sustainability challenges related to energy and water consumption, environmental footprint, as well as product recycling alternatives.

For the use of cellulose fibers in mass applications, price, availability, and environmental footprint are decisive factors. On the contrary, for niche and high-value applications, specific functionalities are essential. Since the identification of application areas is a complex and demanding task, significant resources and efforts in research and development are required.

Over the last decade cellulose nanoparticles have shown great promise to expand the field of application of cellulosic materials. Nanocellulose can be obtained from wood, plants, or bacteria, relying on well-known, scalable, and efficient isolation techniques, including mechanical, chemical, and enzymatic treatments, or a combination of these. The source, the isolation technique, and subsequent chemical modifications influence the size, morphology, and other characteristics of nanocellulose and, consequently, their most attractive areas of application. The abundant hydroxyl functional groups on their surface, allow a wide range of functionalization via chemical reactions, typically used to introduce either charged or hydrophobic moieties, leading to the development of a variety of materials with tunable features.

Here we focus on the use of macro-, micro- and nanocellulose fibers for the development of new products in diverse applications, mainly construction and packaging, with examples in Latin America.

2. Wood fibers in construction

When analyzing interesting markets for value-added secondary products of wood, expanding the use of cellulose fibers beyond the range of traditional products (HDF, MDF and particleboard) and applications (construction, packaging, and furniture) is a promising idea, especially if fibers used are not only from wood but also from bark or agricultural byproducts.

For example, wood fiber insulation panels show attractive thermal and soundproofing properties not only with a low carbon footprint but also with additional health benefits, like humidity compensation and no release of respirable mineral fibers (Kirsch et al., 2018). A large emerging area of application is the use of lignocellulosic fibers in rigid and flexible foams. Wood foams can be a game-changer material for construction and packaging, and it is also a promising field for the use of other wood and related materials such as lignin, cellulose nanoparticles, and tannin, to address some of the shortcomings of these new materials. In addition, the use of lignocellulosic fibers in new products is a great opportunity to expand and optimize the material use of underused residues, such as bark and saw dust, contributing to efficient resource utilization.

Best practices:
Use of Eucalyptus bark fibers as thermal insulation in construction

Annually, a total of 12 million cubic meters of eucalyptus logs are harvested in Chile. If we consider that the logs arrive with a 7% mass of bark when debarked, we have an annual generation of over 400 thousand tons on a dry basis. This by-product, characterized by a low calorific value and challenging fibrous properties, is deemed undesirable especially for boiler feed. The technology developed involves a straightforward bark defibrillation process, subsequent processing using textile industry-standard technology, and the formation of a panel with two thermoplastic compounds. With material densities ranging from 50 to 150 kg/m^3, the resulting panels exhibit insulating properties comparable to or even superior to the mineral wool they are designed to replace. Mineral wool and expanded polystyrene products have a negative environmental footprint, mainly because they are not biodegradable, their recycling rates are very low, the energy requirement for production is high (in the case of mineral wool) and they release toxic gases in the event of combustion (in the case of expanded polystyrene).

The technology was licensed by AISLACOR Ltda. and first plant of the new insulating material with a production capacity of 4,000 m^3/year is under construction in Tomé, Chile, and will start operating in mid-2024.

3. Engineered wood products

Strategies aimed at enhancing the mechanical properties of wood to expand the scope of potential structural applications encompass Engineered wood products (EWP). EWP represent alternatives to conventional softwood dimensional lumber in markets where structural applications predominate, these include laminated veneer lumber (LVL), structural wood I-Beams, glued laminated timber (glulam), machine stress rated (MSR) lumber, finger jointed (FJ) lumber, and proprietary products such as parallel strand lumber (PSL) (Parallam™) and oriented strand lumber (OSL) (Timberstrand™). According to the United Nations, EWP manufacture and use is expanding globally. Glued laminated timbers are being employed worldwide, while structural wood I-beams and LVL are primarily a North American phenomenon and its presence is rapidly gaining popularity in Asian markets, making them promising applications for niche markets.

The general trend towards a greater use of wood panels and EWP in construction is also a major incentive to improve the sustainability and circularity of these products, in particular, the use of more eco-friendly and bio-based adhesives. In this regard, the use of wood based nanomaterials can be a sustainable and cost-effective approach to improve the adhesive systems used, decrease formaldehyde emissions and improve mechanical properties (Antov et al., 2023).

Best practices:
Extraction and use of pine bark polyphenols in adhesives and agricultural foams.

Pine bark contains high proportions of catechin-type polyphenols. A new extraction process makes it possible to extract these polyphenols in simple form and in low-capacity plants with a yield of up to 15%. Although there are multiple applications of the extract, the most important industrial applications to date are adhesives for wood and foams for hydroponic crops. In both cases, phenol formaldehyde-type resins will be replaced. Resinas del Bio Bío S.A. in Chile has licensed the technology and will begin the construction of the first pine bark extraction plant this year.

Best practices:
Woodflow Technology

Inspired by nature, the Chilean company Strong by Form creates lightweight structural solutions that are based on the sustainability of wood and the performance and productivity of advanced composites. The combination of digital design, structural optimization and robotic manufacturing makes it possible to produce structural wood-based composite parts. Use of additive manufacturing technology enables the placement of the wood particles to *produce a composite with the right density, fiber orientation and thickness for specific applications, with mechanical performance of unprecedented levels.*

Main applications include vehicle body parts, lightweight construction, freeform concrete formwork, and maritime and furniture structures. First industrial prototypes are being produced for a big German company.

4. Cellulose fibers in packaging

In the food processing industry, packaging is one of the main areas that reduces waste and improves product shelf life. In the case of food packaging, polypropylene (PP), polyethylene (PE) and other synthetic polymers are ubiquitous. However, due to its poor biodegradability, substitutes have been sought, with biodegradable polymers, such as polyhydroxyalkanoates, polylactic acid (PLA) and thermoplastic starch being alternatives. Unfortunately, their high price and inferior mechanical, rheological and barrier properties seriously limit their massive use.

On the contrary, very promising materials are cellulose macro, micro or nanofibers, which can be used as reinforcement in a biodegradable polymer matrix, reducing its cost and improving its performance, or preferably also as an alternative material to traditional plastics. Fiber thermoforming processes and cellulose based coatings as a barrier to water, lipids and oxygen are alternatives with a high application potential, with obvious environmental advantages. The above, because cellulose is a renewable resource and, compared to plastic materials, recycling cycles and the degradability in natural environments are much more effective.

Best practices:
Thermomoulded cellulose in food packaging

Replacement of both rigid and flexible plastic materials for food packaging. Along with the physical and mechanical properties required for each specific application, it is essential to endow the material with functional properties, such as water, lipid, and oxygen barrier. In this context, the virtuous combination of cellulose macro- and nanofibers in the material and coating can be a solution of high technological, economic, and environmental interest.

5. Cellulose nanoparticles

Lignocellulosic fibers are formed by semicrystalline microfibrils that reinforce an amorphous matrix formed mainly by hemicellulose and lignin. Nanocelluloses, whether crystalline or nanofibrillated, are mainly obtained through mechanical and/or chemical deconstruction (Dufresne, 2019).

The high surface area to volume ratio, high aspect ratio and mechanical properties of cellulosic nanomaterials make them suitable for a wide range of applications. In addition, the low density, low thermal expansion, and their readily chemical modified surface hydroxyl groups widens the spectrum of applications of cellulosic materials by filling the gap between molecular cellulose and individual wood fibers.

Table 5 presents a summary of the most well-known pretreatment methods to obtain nanocellulose. Some of these have only been tested at lab-scale, while others have already been tested on pilot or even industrial scale.

Table 5: Most prominent pretreatments to obtain nanocellulose from cellulose.

Technique	Classification	Function	Description	Benefits
Esterification	Non-covalent surface modification	• Pretratment for mechanical process • Hydrophobizatio n	Acetylation, modifying the hydroxyl groups present at the surface of the NFC through the esterification of nanocellulose with organic acids.	• Simple and reliable process. • May increase efficiency using catalysts and/or organic solvents. • Better compatibility and dispersion in hydrophobic matrix.
Silylation	Covalent surface modfication	• Improving dispersion in non-polar solvents and matrix. • Hydrophobization	Silylating the hydroxyl groups present at the surface of nanocellulose.	It leads to a desintegration of the crystalline regions
Urethanization	Covalent surface modfication	Hydrophobization	Reaction of isocyanate with hydroxyl groups on nanocellulose surfaces, generating urethane bonds.	• May use catalysts to improve efficiency. • Solvent reaction, may involve less solvent exchange steps than other methods to obtain the final products.
Amidation	Covalent surface modfication	Hydrophobization	Covalent attachment of amines on nanocellulose surface with carboxylic groups, isolated from oxidized biomass.	Reaction in aqueous solutions or DMF.
Grafting to-techniques	Polymer grafting	Improves dispersion, compatibility, and hydrophobicity.	Attachment of previously made polymer chains with reactive end groups onto the nanocellulose surface.	The properties of the polymer are easily tailorable.
Grafting from-techniques	Polymer grafting	• Improves mechanical properties and dispersion. • Provides new functionalities, such as conductivity.	Polymer is attached *in situ*, using the superficial hydroxyl groups as a starting point for ring opening polymerization.	Increased surface grafting density.

The pretreatment step aims to facilitate fiber degradation to the nanoscale, while maintaining its inherent properties (and often adding some new functionalities to the final product). It is commonly followed by a mechanical treatment, such as refining, high pressure homogenization, microfluidization and grinding, among others. These methods can be described as very energy demanding processes in which the modified cellulose is exposed to intense physical forces to reduce its size until a highly diluted suspension acquires a gel-like consistency.

The main applications of cellulose nanoparticles take advantage of their mechanical properties as reinforcement in polymers, their rheological, optical and barrier properties, as well as their network and template forming structures. Therefore, cellulosic nanomaterials show a great potential for applications in paper-based products, drilling fluids, as cement additive, adhesives, food coatings, in transparent flexible electronics, as well as in catalysis and biomedical applications such as drug delivery, tissue repair and medical implants (Moon et al., 2016).

The most appropriate application for the final product depends largely on the chemical modification applied during pretreatment. Despite the great versatility of nanocellulose, some of the applications may require long research and scale-up process to obtain volumes large enough for industrial production. Thus, many attractive applications with high potential and added value do not currently fit the criteria necessary for the implementation in a sustainable bioeconomy. We will therefore focus on reviewing two applications with high market potential for industrial consumption of nanocellulose in the coming years, and one that struggles due to policy and safety concerns despite its attractive qualities.

5.1. Nanocellulose in Wood Adhesives

Among several potential applications of nanocellulose, its usage in wood adhesives is highlighted due to its outstanding performance. Wood panels use synthetic adhesives such as phenol-formaldehyde and urea-formaldehyde and pressed at high temperatures. The use of nanocellulose as reinforcements in adhesives leads to an increased performance, providing the opportunity for reducing the amount of adhesive required to fulfill the industrial wood panel standards (Vineeth et al., 2019).

Best practices:
Production and application of acetylated cellulose nanofibers as a fortifying additive for urea formaldehyde adhesives.

The technology is based on generating cellulose nanofibers that can be homogeneously dispersed in a liquid matrix, free from agglomeration issues. This is achieved through a partial substitution of the hydroxyl groups of the cellulose chain. Consequently, even small quantities of the additive can result in a reduction in the adhesive dosage in the manufacture. The net result is that very low proportions of the additive allow lowering the dosage of the adhesive in the manufacture of particleboard and MDF by as much as 25%, with no adverse effects on the adhesive's rheological properties, the characteristics of the final boards, or the efficiency of the manufacturing process. In addition, the curing speed is increased, and formaldehyde emissions are reduced. The productive application of nanofibers in this application began at the end of 2023 by the company FINE Ltda.

5.2. Nanocellulose in Cosmetics

Nanocellulose, including nanocrystals, nanofibers, nanoyarns, and bacterial cellulose, have been integrated into skincare, cosmetics, and health monitoring products as green alternative biopolymer to replace synthetic polymers such as polyethylene, polyacrylamides, and nylon (Meftahi et al., 2022). Thickening agents, film formers, ultraviolet absorbents, antioxidants, sequestering agents, coloring agents, vitamins, pharmaceutical agents are the main components in many cosmetics and skincare formulations (Signicent, 2022). These are generally created by combining chemical compounds from synthetic or natural sources. New skincare, cosmetics, health monitoring products include natural biopolymers and bioactive compounds to meet the high demands for therapeutic and protective care products, which stimulate the skin functions such as healing, protection, immunity, and thermoregulation. On a productive level, nanocelluloses were incorporated initially only in cosmetics and skincare formulations as film-forming material to create a protective shield for the skin against harmful sunlight radiation. New skincare products based on nano-emulsion systems use nanocellulose thickeners and stabilizers, and they were also used as nanocarriers and delivery agents for active pharmaceutical ingredients. To date, the personal care industry is expected to become the second-fast growing sector for the nanocellulose market (Meftahi et al., 2022).

5.3. Nanocellulose in Packaging Industries

Nanocellulose has excellent potential to be incorporated into smart food packaging materials, due to its high physical, mechanical, as well as barrier properties to oxygen and water vapor; these are crucial qualities sought after in smart packaging development. Indeed, nanocellulose can be combined with active compounds to extend shelf life, improve product quality, and monitor the packaged product's actual condition (Perdani and Gunawan, 2021). In addition, nanocellulose can be combined with other materials through several ex-situ and in situ methods to improve the physical, mechanical, moisture, and gas barrier properties, as well as antimicrobial, antioxidant, and UV-blocking properties. Active ingredients can be added by making bio-composites, nanohybrids, impregnation dyes, and coatings. The active ingredients used also depend on the desired packaging properties. Active packaging can be done by adding absorbent compounds (such as oxygen absorbers, moisture absorbers) or emitting compounds such as antioxidants and antimicrobials according to the packaged product's needs (Xu et al., 2024). As for intelligent packaging, active ingredients must be added that can function as indicators such as pH indicators, temperature indicators, gas indicators, and even indicators of the presence of microorganisms (Perdani and Gunawan, 2021).

However, as a type of food packaging material, the security issues associated with nanocellulose composite films must be addressed. The safety assessment of food packaging materials mainly includes two aspects: migration and biotoxicity assessments (Xu et al., 2024). Packaging materials are in direct contact with food, so the composition of the raw material may migrate into the food. Undoubtedly, natural cellulose is innocuous, and its derivatives are usually considered to be safe. Moreover, micron-sized cellulose and its derivatives have already been adopted as fillers and thickeners in food processing and are generally regarded as safe for ingestion. However, nanocellulose is yet to be considered as safe or accepted as a food ingredient, since the extremely small size of nanocellulose means that there may be a risk that it could invade human organs and cells, interact with biological systems, and remain in the human body, threatening human health (Xu et al., 2024). Therefore, it is necessary to conduct further research to evaluate the safety of nanocellulose composite films, especially those adopted as edible films and fruit coatings. So, before the commercial use of nanocellulose for food packaging, further research on cytotoxicity is imperative to assure that there is no growth inhibition, cytolysis, or death in the cells of the body.

The value of the global nanocellulose market in 2023 was $474.8 million and growing demand is projected from the packaging, biomedical and electronics industries, mainly. Also, the increasing use of nanocellulose in the manufacture of paper products will boost sales. Consequently, the market is projected to rise at a CAGR of 19.1% from 2023 to 2033.

Regarding the characteristics of cellulose nanofibers, the production of chemically pre-oxidized cellulose through the TEMPO process is superior to conventionally purely mechanically produced nanocellulose (Arfelis et al., 2023). Also, a chemical functionalization of cellulose allows a less energy-intensive production process and a better homogeneous disintegration of the nanofibers into different matrices, both hydrophilic and hydrophobic.

The main nanocellulose manufacturers are in East Asia and North America, and Europe is one of the key consumer markets. In Latin America, cellulose nanofibers are produced in Brazil for papermaking and in Chile a plant for chemically modified cellulose nanofibers is being implemented for the fortification of thermoset and thermoplastic resins.

Recycled fibers and lignocellulosic agricultural residues, especially those that are non-seasonal and easily accessible throughout the year, are potentially more sustainable nanocellulose sources for large-scale applications than long virgin wood fibers demanded in traditional wood industries. The key steps in the process of producing nanocellulose from waste or recycled materials are largely unaffected, but will need to be tailored to the type of residue (Gröndahl et al., 2021).

Some shortcomings of cellulose nanoparticles are the high price of nanofibers due to high raw material cost and energy intensive manufacturing. In addition, the consistency of nanofiber products can be an issue and differ between manufacturers compared to nanocrystals. The recycling problem of composite plastic materials should also be mentioned which relies on separate recollection and separation of materials which is quite difficult.

6. Transferability and applicability in other countries

Latin America has abundant agricultural and forestry biomass, mainly by-products of agricultural and forestry activities, which can form the basis of a sustainable bioeconomy with a low environmental footprint. Encouraging examples exist in the region (see best practices) where fossil raw materials are being substituted by renewable resources, taking advantage of unique production or market conditions. These initiatives leverage factors such as resource abundance, technological synergies, and integrated production processes that will depend on local conditions, as well as local available resources affecting transferability from one region to other.

In general, first successful applications of nanocellulose fibers will be those targeting the production of expensive and relatively high demand products, such as the replacement of carbon fibers preferably from low-cost cellulosic raw materials (i.e., not microcrystalline cellulose, bleached pulp, or cotton). However, due to logistical constraints related to transportation, the most suitable products for each region should be defined locally. Eventually, the large-scale adoption of cellulose nanofibers in very diverse industries will only occur when current nanocellulose production processes are replaced by more environmentally friendly and much less energy-intensive processes.

New regulations and safety concerns can hinder transferability of nanocellulose-based products that come into direct contact with people, such as food packaging and biomedical applications. Nanomaterials, with nanosized dimensions and large surface area, have high reactivity and potential unknown effects on natural systems. As they can have a negative biological impact, their toxicological risks must be established. An accurate description of the product in terms of dimensions, chemistry and toxicity is also mandatory. Hence, potential end-users of nanocellulose also need to know how these materials may impact health and environment and, consequently, evaluate which regulations are potentially impacted. However, there has been a limited number of toxicological studies for nanocellulose-based products in comparison with other topics such as production, characterization, and applications. Although most of these toxicological studies found that nanocellulose-based products are safe and non-toxic, other researchers have demonstrated adverse health effects for certain biological systems (Stoudmann et al., 2020), which causes uncertainty regarding future regulations to assess potential health risks.

The global challenge of decarbonizing the economy requires new processes and products to replace fossil raw materials with renewable sources worldwide. Knowledge and technological solutions must be spread widely and geographically, changing the current paradigm of technology transfer from north to south. Collaboration among states, companies, and organizations globally is vital for progress.

7. Key messages and recommendations

Cellulose fibers and wood components show extensive potential for various applications, including mass applications like packaging and textiles, and for example as additive in adhesives and composites but potentially also in high-value niche applications in industries like chemicals, cosmetics, and pharmaceuticals.

The incorporation of wood fibers into different products does not mean that they are automatically preferable from a sustainability point of view. Also, the substitution effect of fossil alternatives can vary significantly because the impact of greener alternatives is highly dependent on local conditions.

Cellulose nanoparticles have many potential applications as nanomaterial in products that meet producer, consumer, and government requirements for more sustainable materials with a low-risk profile. However, sustainability must be assessed in detail especially for large scale applications as production of nanocellulose is energy intensive and chemical modifications are generally needed which can have impacts beyond the carbon footprint of the source material. Alternative fiber sources to virgin wood should be analyzed for production of functional materials with emphasis on residual and recycled materials.

The substitution of plastics in single-use applications, particularly in packaging, by cellulose macro, micro and nanofibers is of great interest in Latin America, since the region has very low rates of plastic recycling and waste-to-energy conversion of these materials is not widespread as in Europe. The encouragement of pilot and exhibition initiatives is imperative.

The enacting of extended producer responsibility regulations is spreading in Latin América, showing promising results. These regulations should be complemented with incentives for the adoption of innovative technologies that can facilitate the transformation of production practices and processes.

There is limited cooperation among Latin American countries and inadequate engagement with other global regions. This lack of interaction is observed in academia, businesses, and the public sector. It is crucial to encourage productive discussions and partnerships among various stakeholders globally.

We recommend a careful evaluation of the environmental impact of technological solutions aimed at introducing new products based on wood or its components to the market. At the same time, an evaluation of the social context is essential, particularly in Latin America.

The substitution of fossil raw materials for renewable resources must necessarily be linked to the design of circular products and processes, including both cascade production (in which one production takes over the by-products of others) and massive, simple, and effective recycling. Materials containing cellulose are generally more sustainable and preferable than alternatives based on fossil raw materials, but the high energy consumption and chemicals used in production and posttreatments demand more detailed life cycle assessments. The source of the raw material, the production process and recycling possibilities, especially in the case of composite materials, need careful analysis.

References

Antov P., Lee S.H., Lubis M.A.R., and Yadav S.M. (2023). *Potential of Nanomaterials in Bio-Based Wood Adhesives: An Overview*. In: Emerging Nanomaterials: Opportunities and Challenges in Forestry Sectors. (Eds.) H.R. Taghiyari, J.J. Morrell, and A. Husen. Springer International Publishing: Cham., pp. 25–63. DOI: 10.1007/978-3-031-17378-3_2. ISBN: 978-3-031-17378-3.

Arfelis S., Aguado R.J., Civancik D., Fullana-i-Palmer P., Pèlach M.À., Tarrés Q., and Delgado-Aguilar M. (2023). *Sustainability of cellulose micro-/nanofibers: A comparative life cycle assessment of pathway technologies*. Science of The Total Environment, 874, 162482, DOI: 10.1016/j.scitotenv.2023.162482.

Dufresne A. (2019). *Nanocellulose Processing Properties and Potential Applications*. Current Forestry Reports, 5, 2, 76–89, DOI: 10.1007/s40725-019-00088-1.

Goldhahn C., Cabane E., and Chanana M. (2021). *Sustainability in wood materials science: an opinion about current material development techniques and the end of lifetime perspectives*. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 379, 2206, 20200339, DOI: 10.1098/rsta.2020.0339.

Gröndahl J., Karisalmi K., and Vapaavuori J. (2021). *Micro- and nanocelluloses from non-wood waste sources; processes and use in industrial applications*. Soft Matter, 17, 43, 9842–9858, DOI: 10.1039/D1SM00958C.

Kirsch A., Ostendorf K., and Euring M. (2018). *Improvements in the production of wood fiber insulation boards using hot-air/hot-steam process*. European Journal of Wood and Wood Products, 76, 4, 1233–1240, DOI: 10.1007/s00107-018-1306-z.

Meftahi A., Samyn P., Geravand S.A., Khajavi R., Alibkhshi S., Bechelany M., and Barhoum A. (2022). *Nanocelluloses as skin biocompatible materials for skincare, cosmetics, and healthcare: Formulations, regulations, and emerging applications*. Carbohydrate Polymers, 278, 118956, DOI: 10.1016/j.carbpol.2021.118956.

Moon R.J., Schueneman G.T., and Simonsen J. (2016). *Overview of Cellulose Nanomaterials, Their Capabilities and Applications*. JOM, 68, 9, 2383–2394, DOI: 10.1007/s11837-016-2018-7.

Perdani C.G. and Gunawan S. (2021). *A short review: Nanocellulose for smart biodegradable packaging in the food industry*. IOP Conference Series: Earth and Environmental Science, 924, 1, 012032.

Signicent (2022). *Nanocellulose & Lignin in Cosmetics Report: How are natural ingredients transforming the cosmetic industry?*. Available at: https://signicent.com/nanocellulose-lignin-in-cosmetics-report-how-are-natural-ingredients-transforming-the-cosmetic-industry/ [Accessed on 29 April 2024].

Stoudmann N., Schmutz M., Hirsch C., Nowack B., and Som C. (2020). *Human hazard potential of nanocellulose: quantitative insights from the literature*. Nanotoxicology, 14, 9, 1241–1257, DOI: 10.1080/17435390.2020.1814440.

Vineeth S.K., Gadhave R.V., and Gadekar P.T. (2019). *Nanocellulose Applications in Wood Adhesives—Review*. Open Journal of Polymer Chemistry, 9, 4, 63–75, DOI: 10.4236/ojpchem.2019.94006.

Xu Y., Wu Z., Li A., Chen N., Rao J., and Zeng Q. (2024). *Nanocellulose Composite Films in Food Packaging Materials: A Review*. Polymers, 16, 3, 423, DOI: 10.3390/polym16030423.

Sustainable wood-based textile and packaging product value chains in Finland – Best practices for for innovative wood use

Henrik Heräjärvi, Anu Laakkonen, Joona Lampela, Mohammad Azarmi
University of Eastern Finland (Itä-Suomen yliopisto), School of Forest Sciences, Kuopio, Finland

Abstract

Wood-based textile and packaging products feature a great expected future demand. The global textiles sector searches for options for synthetic fibres that cause environmental challenges such as micro-plastics, and cotton that requires huge field areas and enormous amounts of irrigation water. Finland has a long history of research and development along the entire value chains of both sectors. New technically and environmentally feasible wood-based textile production processes – both dissolvent-based and non-dissolvent-based ones – are actively developed to substitute the traditional viscose process and synthetic fibres. Wood-based packaging (papers, paperboards, cardboards) is an established, export-driven business in Finland, with great further growth expectations. Wood-based textile and packaging value chains stand for interesting opportunities to the Global South countries, particularly to ones with large, unused, certified, and sustainably managed forest resources. Finland, with its state-of-the-art expertise of these value chains, can contribute to their development in Global South countries via education, various knowledge transfer approaches, providing technologies, or joint business models. The use of wood in textile and packaging products is a significant business opportunity, which is, however, conditional to a stable and sufficiently large supply of proper-quality raw materials and extensive investments in the Global South countries. Global markets of textiles and packaging products grow and miss producers of resource-efficiently produced goods. Despite existing global production, the expected demand for wood-based packaging materials opens space for new cost-competitive producers. Questions of legality, transparency, equality, and environmental soundness of the supply chains and businesses cannot be overemphasized.

1. Forest-based bioeconomy in Finland

See: Chapter “Sustainable wood construction value chains in Finland (p. 9) – Best practices for the Global South countries”

2. Finnish expertise related to wood-based textiles and packaging

The textile sector is one of the largest sectors worldwide, and one with the greatest environmental problems, too. The use of textile fibres exceeded one hundred million tons in the 2010s, and the market is expected to continue its increase unless the current fast fashion and overconsumption trends cannot be stopped (e.g., Lehto et al., 2023). Wood-based textile fibres represent less than 10% of the consumption, while cotton and oil-based synthetic fibres (polyester, polyamide, polyacrylate, etc.) cover the rest (e.g., Kataja and Kääriäinen, 2018).

Finland is strongly involved in developments that aim at environmentally sound biomass-based textile fibres. Finland features strong scientific and practical expertise related to the sustainable use of wood fibres in different fibre-based processes and product applications. Finland has been a global forerunner in chemical and mechanical pulping, as well as paper and paperboard production technologies, quality control system, and environmental impact reduction developments since the 1950s (selected major brands: Ahlstrom (www.ahlstrom.com), Andritz (www.andritz.com/pulp-and-paper-en/locations/andritz-oy), Valmet (www.valmet.com)). KCL Ltd. (www.kcl.fi), a Finnish industry-funded independent research company, has been the most acknowledged wood fibre research company in the world since the latter half of the 20th century.

The viscose process, which is based on further processing of dissolving wood or bamboo pulp, originates from the late 19th century, and aims at production of regenerated fibres for textile applications. Viscose has an equal molecular structure as cellulose, and it can be woven or knit into textiles for clothes or other end uses. Well-known product names for viscose-based fabrics include rayon, cupro, and Lyocell. Conventional viscose processes are based on treating regenerated cellulose with neurotoxic carbon disulfide, which makes them challenging in terms of work safety conditions and environmental risks. Stora Enso Ltd. produced dissolving pulp in one Finnish pulp mill until 2021, but no production has taken place in Finland after that. At least three pulp mills are, however, concentrating on dissolving pulp production in Europe currently. It is important to note that 'viscose' refers to the process, not the raw material used. Thus, for example, bamboo-based textiles are probably made with a viscose process, including its environmentally risky process steps.

Both in the case of textile and packaging value chains, one must bear in mind that raw material renewability or recyclability does not necessarily mean product biodegradability. Novel products of today should not turn into problems of tomorrow, which is the story of a 'super-material' of the 1960s, i.e., plastic. Furthermore, even the environmental sustainability of wood-based materials is neither self-evident nor necessarily superior to that of petroleum-based materials. Various industrial and non-profit associations and innovation clusters support and promote the utilization of pulp and its value-added derivatives.

Best practices

National support for the research, development, innovation (RDI) and education for novel wood-based textiles and packaging applications

Scientific and applied research on wood-based textiles and packaging applications is conducted in several academic universities, universities of applied sciences, and governmental or private research organizations in Finland. The development activities of packaging papers and paperboards, which are a major business in Finland, are mostly, yet not completely, performed by the large companies themselves. In the case of rapidly developing new textile processes, on the other hand, public or semi-public research and development, as well as private-public partnership projects are common approaches. Certain textile fibre technologies are developed by spin-off innovation companies of large forest industry corporations, such as Kuura® fibre by Metsä Spring Ltd, a spin-off of Metsä Group. Table 6 summarizes the expertise of different research, development, and education organizations in Finland in wood-based textile and packaging value chains.

Table 6 Research, development, and education organizations in wood-based textile and packaging value chains in Finland.

Organization	Website	Purpose and expertise related to wood-based textiles and packaging
Science university		
Aalto University	www.aalto.fi	**Pulping, biorefining, textile chemistry and applications**
University of Eastern Finland	www.uef.fi	**Wood science, wood chemistry, biorefining, forest resources**
University of Helsinki	www.helsinki.fi	**Forest products markets, wood science**
University of Jyväskylä	www.jyu.fi	**Wood chemistry and physics**
University of Oulu	www.oulu.fi	**Wood pulp chemistry**
Åbo University	www.abo.fi	**Wood pulp chemistry**
University of Applied Sciences		
Savonia UAS	www.savonia.fi	**Design**
South-Eastern Finland UAS	www.xamk.fi	**Design, textile manufacture**
LAB UAS	www.lab.fi	**Packaging, design**
Metropolia UAS	www.metropolia.fi	**Design, clothing**
Other research organization		
VTT Technical Research Centre of Finland	www.vtt.fi	**Biomaterial processes, packaging, textile applications**
Funding organizations		
Research Council of Finland	www.aka.fi	**Government agency** funding scientific research and providing expertise in science and science policy
Business Finland	www.businessfinland.fi	**Public-sector organization** offering investment and innovation funding, as well as internationalization services
The European Regional Development Fund (ERDF)	ec.europa.eu/regional_policy/funding/erdf_en	**Funding research and business to** strengthen economic, social, and territorial cohesion in the European Union
The Finnish Climate Fund	www.ilmastorahasto.fi/en/	State-owned company investing in businesses combating climate change, boosting low-carbon industries and digitalization
Private foundations	www.tiedejatutkimus.fi	Supporting basic and applied research on natural resources
Industry and other associations		
Finnish Forest Industries Federation	www.metsateollisuus.fi/en/home	Ensuring competitive and innovative operating environment for forest industry production, employment, and investments
CLIC innovation	www.clicinnovation.fi	Open innovation cluster owned by companies and research organizations aiming to facilitate creation of breakthrough solutions in bioeconomy, circular economy, and energy systems
The Finnish Packaging Association	www.pakkaus.com/?lang=en	Association promoting the general business environment of the packaging industries
Finnish Textile and Fashion		Association promoting Finnish textile and fashion industry and their member companies globally
Central Union of Agricultural Producers and Forest Owners (MTK)	www.mtk.fi/web/en	An organization representing farmers, forest owners and rural entrepreneurs in Finland
Finnish Forest Foundation	www.metsasaatio.fi/en	Promotes the acceptability of forestry, forest livelihoods and forest industries, as well as increased use of wood and wood-based products
Sustainable Forestry Association	www.kestavametsa.fi	Promotes sustainable forest management in Finland and develops the use of forest certification (PEFC)
Finnish Forest Association	www.smy.fi/en/front-page	Organization communicating about sustainable use of forests

3. Recent developments supporting sustainable wood-based textile value chains

Half a dozen novel wood-based textile technologies are under development in Finland (Table 7), whereas the production of conventional dissolving pulp ended in 2021. Some processes, such as Ioncell® and Kuura®, are based on application of ionic liquids in fibre dissolving, whereas Infinna® is based on the carbamate process and BioCelSol relies on enzymes. Spinnova® process does not dissolve the pulp at all. Each process represents different technology readiness levels from noncommercial laboratory production to pilot-scale commercial production. Some processes, such as the Spinnova® and Kuura®, are developed in cooperation with overseas companies.

Regeneration of cellulose from wood pulp towards textile fibres cost-efficiently and with desirable textile performance involves complex chemistry and environmental considerations. Ramping up the production from laboratory or demonstration scale to industrial scale involves different approaches regarding the process, environment, and cost-structure considerations in different processes.

Best practices
Ensuring the environmental sustainability of wood-based textile applications

The main idea in all modern, wood-based textile production processes is to produce textile fibres with significantly reduced environmental footprint (e.g., chemicals recovery rate) and risks compared to those associated with traditional viscose process or production of synthetic fibres. In comparison to synthetic fibres or fibres of agricultural origin, wood-based fibres are expected to feature a significantly better net GHG emission balance and lower water consumption per mass unit of fibres produced. Neither the net climate benefits (see, e.g., Hurmekoski et al. 2023) nor other environmental performance credentials of wood-based textile value chains are, however, not self-evident and must be verified by case sensitive life-cycle assessment.

Table 7: Textile production processes based on wood or other biomasses, representing different technology readiness levels in Finland.

Product, company, and website	**Raw material**	**Production method**	**Properties**	**Technology readiness**
Spinnova® Spinnova Plc spinnova.com	Primary: FSC certified eucalyptus pulp Secondary: Textile waste, agricultural waste, leather waste	Mechanically refined micro fibrillated cellulose (MFC) is transformed into spinnable suspension that is spun into filaments through air extrusion	Hand-feel comparable to cotton. Soft and breathable, modifiable, recyclable, and biodegradable. Suitable for, *e.g.*, clothing, home textiles, composites	Pilot scale Woodspin-factory running in Jyväskylä, FIN (co-owned by pulp producer Suzano Ltd). Industrial production in consideration. The factory's short-term goal is to test MFC and to optimize the production process.
Ioncell® Ioncell Ltd ioncell.fi	Wood pulp, textile waste, paper- and cardboard waste	Cellulose is dissolved in a non-toxic ionic liquid, which is then spun into filaments through an air-gap-spinning process. The ionic liquid is washed with water, and the resulting filament is pure regenerated cellulose.	Soft and natural feel, silky sheen, high tensile-strength even wet. Can be used either 100% or blended fabrics. Biodegradable and recyclable.	Ioncell Ltd is a spin-off company from Aalto Univ., aiming at commercializing the Ioncell® fibre. Developing industrial process in pilot factory in Espoo, FIN, and searches collaborators and funding.
Kuura® Metsä Spring Ltd / Metsä Group kuura.io	Primary: Undried paper pulp made of softwood	Undried paper pulp is dissolved in a novel ionic liquid.	Properties are similar to lyocell. Biodegradable and recyclable.	A 1000 t/a capacity pilot mill produces Kuura® fibre in Äänekoski, FIN. Examines possibilities to build an industrial-scale factory.

Norratex™ Nordic Bioproducts Group Ltd nordicbioproducts.fi	Primary: Wood pulp Secondary: Agricultural waste, textile waste	The process utilizes patented Aaltocell™- technology that produces microcrystalline cellulose through diluted acid hydrolysis (diluted sulphuric-acid). The process also produces sugars.	Norratex™ fibre properties are comparable to viscose and cotton to hand touch, it is easily dyeable.	NBG collaborated with CMPC, a pulp producer company to develop a textile fibre. MCC pilot plant in Lappeenranta, FIN, started production in 2023. NBG is looking for new collaborators.
Bio2™textile Fortum Plc Fortum.com	Primary: Fractionated straw pulp	Biomasses are fractionated with a formico® technology developed by Chempolis Ltd. The technology rapidly impregnates the biomass with bio solvent and separates cellulose, hemicellulose, and lignin into their own fractions. The material efficiency is up to 90%.	Bio2™textile- fibre feels comfortable and is comparable to cotton.	Fortum piloted the first straw-based clothes with Spinnova Plc in 2019. Bio2™textile collection was designed based on Infinited Fibre Ltd's technology in 2021. Fortum invests in Bio2X technology and biorefining globally. The first biorefinery was built in India.
Biocelsol VTT Technical Research Centre of Finland Ltd and Tampere University vtt.fi	Primary: Dissolving wood pulp Secondary: Paper pulp and waste textiles	Pulp is enzymatically pretreated and dissolved in a cold alkali liquid. The liquid is then spun utilizing wet spinning technique.	Biocelsol fibre is similar to viscose, high moisture absorption and good dyeability.	VTT is looking for partners to further develop Biocelsol-technologies.
Infinna™ Infinited Fibre Ltd infinitedfiber.com	Primary: Textile waste Secondary: Paper and paperboard waste, agricultural waste	Cellulose is activated with an alkaline solution and treated with urea into dissolvable cellulose carbamate. It is dried into a powder that is dissolved in alkaline liquid, filtered, and spun to filaments through a wet-spinning process, producing regenerated cellulose carbamate fibre.	Hand-feel similar with cotton. Easily dyable and usable in yarns and fabrics, pure or blended. Biodegradable and anti-microbial.	Infinited fibre Ltd plans to build its first factory in Kemi, FIN, with an estimated investment cost of €400 million.

4. Recent developments supporting sustainable wood-based packaging value chains

Paper is usually a single layer fibre product with a mass between 6 and 150 g/m2. Paperboards are thick fibre-based products with a mass of 125-600 g/m2, and often consist of several layers. Cardboards are, usually, glue-laminated products made of paper or paperboards, with a mass of over 400 g/m2.

Papers are mostly used in printed products (yet many exceptions, such as filter papers, tissue, and packaging papers, exist), whereas paperboards are used for packaging purposes, with some exceptions, too (e.g., Kärkkäinen, 2005). Including all quality features, such as square masses, structures, colours, opacities, strengths, etc., there are over 10,000 commercial paper, paperboard, or cardboard grades on the market. Depending on the product application and property requirements, the products can be made of agricultural fibres, used textiles, or wood fibres of virgin or recycled origin. Wood is globally the most common source of fibres in paper, paperboard, and cardboard products. On average, a single fibre serves seven product cycles until it does not qualify for products anymore, turns into effluent, and is washed away from the production line to the energy recovery.

Global demand for papers and paperboards started growing steadily in the 1960s (Kärkkäinen, 2005). Due to the 2000s decline in magazine, newspaper, and some other paper markets, in which

Finland used to serve its global customers and ca. 100 million consumers, Finnish printing paper factories have been one by one upgraded and transformed into packaging paperboard production. Unlike many paper grades, the global paperboard demand has been steadily increasing, and it is predicted to continue doing so. This development is explained by two megatrends. The first one is e-commerce which is based on packing and shipping single items – instead of large retail customer deliveries – from the manufacturer or retailer to the consumer (and often sent back, too). Independently of its material, the package is expected to offer technical protection to the product against moisture, hits, vibrations, sunlight, chemicals, etc. during its long logistics chain. On the other hand – being the second megatrend supporting paperboards in packaging – there is a need to decrease the environmental footprint of packages and product deliveries (renewability of raw materials, energy efficiency of production processes, weight of the package, etc.), which sets tremendous demands to the packaging materials (e.g., Leinonen et al., 2022). Furthermore, the appearance of the box or graphical paperboard product such as a postcard, including the box shape or print quality, may be a critical sales factor. Package appearance is further pronounced along with the transformation towards e-trade, i.e., from business-to-business to business-to-customer. Packages for foodstuff and drinks are regulated by the strictest demands concerning hygiene, liquid and air tightness, grease barriers, UV light transmission, and recyclability. Wood fibre-based products can effectively compete with non-renewable packages (mostly plastics) in most of these characteristics, and the global market for packaging paperboards is expected to continue its growth. Papers, paperboards, and cardboards are already used in thousands of packaging applications.

There are 16 paperboard factories owned by six different companies in Finland. The three biggest corporations in paperboard businesses are Metsä Board, Stora Enso, and Kotkamills. In total, 4.2 million tons of paperboards were produced in Finland in 2021, of which 4.1 million tons were exported (Finnish Statistical Yearbook of Forestry, 2023). This sets paperboards as the highest export value product category in Finland nowadays. Unlike earlier, there are no more 'bulk paperboards' or 'bulk cardboards' on the market. Paperboards are high-tech products with various functionalities and can even be equipped with smart technologies. Modern paperboard machines are large and expensive. The newest one, owned by Stora Enso Ltd. in Oulu, northern Finland, will start production in 2025. It is an old paper machine that is converted into consumer packaging paperboard production with an investment of approximately one billion euros.

Best practices
Sustaining the competitive advantage with novel packaging applications

Even though the wood-packaging industry is a well-established industrial sector in Finland, the sector is developing and there are major innovation activities in production processes, products, and related services (e.g., Leinonen et al., 2022). The scale of the innovations varies. Some are incremental processes or raw material innovations, such as replacing fossil-based raw materials in the barrier coatings. Some innovations are more radical new solutions with new technologies and partnerships. The companies behind the innovations represent mostly established forest sector companies, but also new start-ups have emerged.
Table 8 *presents recent developments related to wood-based packaging in Finland.*

Table 8: Recent developments in wood-based packaging production and products and technology readiness levels in Finland.

Company and website	Product	Material and production method	Properties	Technology readiness
Pyroll Pakkaukset Group Oy pyroll.com/en/solutions	Pyrollgreen-Solutions	Certified fibre. Produced on current paperboard machines.	Environmentally friendly, biodegradable barrier coatings, aluminium-free wrappers	Industrial production
MM Kotkamills kotkamills.com/products/consumer-boards	Absorbex® ISLA® ALASKA®	Certified virgin wood fibre. Water-based dispersion coated barrier boards. Produced on current paperboard machines.	Non-fluorinated. Easily recyclable. For different foods and non-foods.	Industrial production
Huhtamäki Oyj and Södra AB cooperation huhtamaki.com/en/fresh	Huhtamaki Fresh disposable food tray	Certified virgin wood pulp and a bio laminate layer. Produced on current paperboard machines.	Oven and microwave proof, recyclable and certified for home composting. Maintains rigid when heated. Natural aesthetics.	Industrial production
Walki Westpak, Fazer and UPM Speciality Papers cooperation walki.com	UPM Confidio™ UPM Confidio™ Pro	Certified wood-fibre. Produced on current paperboard machines.	A recyclable and heat-sealable barrier paper with moisture and grease resistance. One- or two-sided coated paper is suitable for all printing methods. A food-safe packaging designed for dry and frozen as well as greasy (Pro) foods.	Industrial production
Paptic Ltd paptic.com	Paptic® Paptic Tringa® Paptic Sterna® Paptic Apus®	FSC certified wood-based fibre. Produced on current paper machines with slight modifications.	Tough and tear-resistant, allowing the package to be reused many times. Moisture resistant, flexible, pleasant, and silent to handle. Can be printed using the same methods as with paper.	Industrial production
Sulapac Oy sulapac.com	Providing raw material for partnerships and factory as a service concept.	Bio-based and biodegradable biopolymers and sustainable fillers such as certified wood chips and other biomass side streams. Can use recycled materials. Produced with existing plastic processing machinery: injection molding, extrusion, 3D printing and thermoforming.	Bio-based and biodegradable. Mechanically and chemically recyclable. No microplastic or per- and polyfluoroalkyl substances (PFAS).	Industrial production
Woodly Ltd woodly.com	Technology firm, production of raw materials and products in partnerships. Woodly® granulate. Woodly 100 series Woodly 200 series	Certified wood with chemical components (bio-based carbon content 40-60%). Granulate is made by compounding (melt-mixing). Produced with existing plastic processing machinery: blown film and cast film extrusion lines and in injection molding.	Wood cellulose-based, carbon neutral, recyclable, renewable and transparent plastic. Clear, flexible, and easy-to-dye packaging for food, flowers, and textiles. Film with high gloss for laminating on cardboard packaging. Cups and containers for food and drink.	Industrial production
Jospak Oy jospak.com	Jospak® carton tray Jospak® technology	FSC certified wood-based fibre. Carton coated with a thin plastic film (85% less plastic compared to similar packaging solutions). Produced in Jospak factory with Jospak® technology.	Renewable, microwave oven-safe material. Brand and product information printed directly onto the tray. Easy recycling: plastic film can be removed from the cardboard and recycled separately. Octagonal Jospak®-tray with de-nesting feature ensures compatibility with the existing tray packaging processes.	Industrial production
Metsä Spring and Valmet cooperation www.muoto.io	Muoto™	Certified softwood, hardwood, and mechanical pulp. A single production process from wet pulp to the finished product.	Fit-for-purpose design, reusable and recyclable. Paperboard-like properties without plastic.	Demo plant
Fiberwood fiberwood.com/en	Plastic-free packaging protectors and cushions	Wood and natural fibres from textile industry by-products used in foam (water-air mix) technology.	Plastic-free, recyclable, and biodegradable packaging protectors and cushioning to replace styrofoam and bubble wrap.	Demo plant

5. Transferability and applicability of wood-based textile and packaging value chains in Global South countries

The wood-based textile and packaging value chains are an interesting opportunity in the Global South countries. Particularly, countries with large unused, certified, and sustainably managed forest resources should consider these lines of bioeconomy development, bearing in mind the foreseen growth in global demand for more sustainable textiles and renewable packaging. Finland has a long tradition and state-of-the-art expertise on these value chains and can contribute to their development in Global South countries via education, various knowledge transfer approaches, providing technologies, or joint business models. Potential Finnish contributions extend to all levels of research, development, education, training, and businesses along the value chains. We identified several knowledge transfer and education export opportunities for applying Finnish expertise related to wood-based textiles and packaging in the Global South.

One of the most important questions to address with these opportunities is to understand how these practices are integrated into the specific circumstances, i.e., local regimes, of each country and region. The ways of operating within society must be adapted so that they support sustainable and just transformation. Understanding the local regulative conditions and culture related to utilizing natural resources is a crucial asset for foreign experts. It is essential to foster mutual learning and collaboration with and between the local actors along planning, organizing, and developing the value chains. We are confident that the Finnish expert organizations can significantly contribute to the development of forest-based value chains in the Global South, thus facilitating individual societies’ goals to increase prosperity, sustainability, and wellbeing.

For more than hundred years Finland has had a national political consensus and institutions supporting the utilization of timber resources and development of the forest sector. This tradition has continued with the introduction of sustainable forest-based bioeconomy. Similar national support would undoubtedly facilitate the development of wood-based textile and packaging value chains in the Global South. A practical and widely applied example of such support in Finland is the ‘Best Practice Guidelines for Sustainable Forest Management’, intended for the use of private forest owners. These instructions, for example, emphasize the use of native tree species in the right fertility class sites, and provide guidance in choosing management practices for different forest compartments according to the various preferences (money, landscape, biodiversity, non-wood forest products, etc.) of the forest owner. Keeping in mind and respecting forest owners’ goals and objectives in forest management enables responsible utilization of wood without compromising future crops and possibilities.

Related to RDI activities, the Finnish forest cluster is an example of the triple-helix collaboration between academia, government, and industrial actors. Finland also features a recent introduction of the concept of industrial ecosystems and bioproduct mills, in which the collaboration in production and RDI is built into the system. This model has already been proven to be well-functioning with pulp-based biorefineries in Finland. Metsä Group’s bioproduct mill in Äänekoski has been running since 2017 and the industrial ecosystem around the mill has generated collaborations in, e.g., wood-based textiles (Kuura® fibre) and 3D fibre product for packaging (Muoto® product). Such a model could be considered in the Global South conditions, too, to increase the value added and boost collaborative RDI activities.

Table 9 presents SWOT data for wood-based textile value chains, collected for this report in a workshop among the experts at the University of Eastern Finland. Production of wood biomass and wood-based textiles have environmental strengths (indicated in green font) related to lower usage of, *e.g.*, water, pesticides, and other environmentally harmful chemicals. In addition, naturally decomposable wood-based textiles can be produced without increasing microplastic pollution. However, there are several economic weaknesses (indicated in blue font) related especially to production technologies and the availability of proper quality raw materials. Those need to be resolved before the production of wood-based textiles can turn into mainstream.

There are social (indicated in red font) opportunities that support the development of wood-based textile production and value chains. For example, sufficient policy support and market pull from the consumers, retailers and brands attract investments in improving production techniques, and offer an opportunity for reduction of production costs. Despite the possible technological developments in production technologies, the technical performance and features of other natural and artificial raw materials may outweigh wood-based textiles, *e.g.*, in features like mechanical strength or consumer preferences. These may appear as threats and decrease the competitiveness of wood-based textiles. Moreover, the loss of biodiversity caused by the expansion of land dedicated to wood-based raw material production is a serious threat. To mitigate this risk, it is essential to maintain reasonable relations between sustainable resource management and industrial growth to ensure the stability of the textile industry in these regions in the long run.

Table 9: SWOT table for wood-based textile value chains in Global South countries from Finnish perspective. Green font stands for environmental, red for societal, and blue for economic issues.

Strengths	**Weaknesses**
Wood biomass production is highly efficient in water consumption and pesticide use compared to agrobiomass feedstock (*e.g.*, cotton). Final products are biodegradable (less landfill waste) and do not break into microplastics. Production needs less harmful chemicals. Several techniques can separate and recycle cellulose and even upcycle materials. Substitute for fossil-, cotton- and animal-based textiles. Wood is less susceptible to disturbances compared to annual plant crops, allowing a stable raw material supply.	Environmental challenges in some techniques, *e.g.*, traditional viscose process. Non-existing textile recycling systems. Consumer preferences stick to traditional textiles. Few applicable industrial-level production technologies. Technical performance of other biomasses or synthetic fibres is better in terms of, *e.g.*, strength and abrasion resistance. Production costs: technology-intensive production, technologies are still developing. Energy-intensive production technologies. Availability of uniform fibre quality in large volumes. Competitiveness against other plant-based biomasses.
Opportunities	**Threats**
Environmental regulations improve the competitiveness of wood-based textiles. Global shortage of clean water causing a decrease in agrofibre production. Major brands and/or role models advertise wood-based textiles (luxury markets). Market pull (environmental awareness of consumers, retailers, and brands). International policy support. Collaboration and mutual learning via RDI with Global North. New jobs substitute current low-salary jobs. Production costs decrease along with industrial upscaling of novel techniques. Agricultural fields are prioritized for food production.	Plantation wood turns into GHG source by political decision. Biodiversity loss, if more land is used to timber production, resulting in image problems and consumer distrust. More competitive agrofibres via breeding. Single-use fashion continues supporting cheap, short-lifecycle products. Mainstream consumer awareness is still low. Slow development of technical or economic competitiveness of wood-based products. Availability of wood raw material: other plant-based biomasses are more accessible in large volumes. Confidence lack among investors results in reduced funding Fluctuations in roundwood prices.

Table 10 presents the SWOT data related to wood-based packaging value chains collected with experts at the University of Eastern Finland for this report. The environmental strengths (indicated in green font) of wood-based packaging are similar with wood-based textiles, as the raw materials of packaging products are recyclable and biodegradable, and act as substitutes for fossil-based materials and products. However, there are weaknesses related to the technical properties (indicated in blue font) of wood-based packaging, which can be considered as economic issues. For example, moisture sensitivity and extra barriers to protect food from oxygen and UV light are still better in products containing fossil-based plastics. In addition, there are still challenges related to the recyclability of the packaging materials, while fibres inevitably degrade in consecutive refining cycles.

The identified opportunities of the wood-based packaging value chains relate much to resolving the economic and technological weaknesses. Promoting the possible environmental and climate benefits of wood-based packaging materials can diminish societal and market obstacles. Similarly, constant development in packaging technologies and solutions brings opportunities. For example, there are unexploited material properties still to be discovered. Many of the opportunities lie in collaboration in RDI activities between Global North and South which can provide chances for technical and economic progress in the regions of the Global South.

Serious threats to the expansion of wood-based packaging are related to social (indicated in red font) and economic (indicated in blue font) issues. Major threats are the consumers' lack of willingness to replace current ways of packaging and the global political risks and unstable trade conditions. These political risks and market preferences may lead to progress in using non-renewable but recyclable packaging materials, especially if the climate and environmental impacts of fossil-based packaging are lower than the wood-based ones (shown, *e.g.*, through LCA or other environmental monitoring processes). These need to be resolved to strengthen the wood-based packaging value chains and remove the threats shadowing the expansion of the industry.

Table 10: SWOT table for wood-based packaging value chains in Global South countries from Finnish perspective. Green font stands for environmental, red for societal, and blue for economic issues.

Strengths Renewability, recyclability, and biodegradability of the raw material and the product. Substitute for fossil-based plastics and packaging materials. Fast-growing plantations are a CO_2 sink. Responses to consumers sustainability and eco-friendliness values. Hardwood fibres particularly applicable to liquid packaging paperboards. High food compatibility. Flexibility of design. Broad property range.	**Weaknesses** Limited number of recycling cycles due to degrading fibre properties. Bulkier than plastics. Production requires water. Consumer preferences stick in traditional packages (plastics and metals). Production is expensive due to high technology and expertise. Some properties (*e.g.*, moisture sensitivity) behind plastics. Extra barrier layers are needed for food packaging to have sufficient UV light and oxygen protection. Non-wood fibres may be more easily accessible than wood-based resources in some regions. Challenges in recycling logistics (costs, quality).
Opportunities Increasing climate and environmental benefits. Regulative support at national and international level. Collaboration and mutual learning in RDI with Global North countries in both technical and economic aspects. Hygiene and health can be improved in food packaging. Constant development of new packaging solutions. Unexploited material properties. Increasing demand for sustainable packaging. Good branding value (need to avoid greenwashing). Technological advances over traditional techniques.	**Threats** Plantation wood turns into GHG sources by political decisions. Biodiversity loss, if more land is shifted to timber production, results in image loss and consumer distrust. Inproper solutions for wastewater management in production processes. Political risks in global economy: large plantations and production units require stable politics and trade conditions. Consumers are unwilling to replace current ways of packaging. Plastics retain their advantages in for stored product quality. High investment costs of new manufacturing facilities. Progress in non-renewable but recyclable packaging materials. Net climate impact of fossil-based packaging turns to be lower than that of wood-based (*e.g.*, shown through LCA or similar method).

6. Key messages and recommendations

1. The use of wood in textile and packaging products is **a significant business opportunity**, which is, however, **conditional to a stable and sufficient supply of proper-quality raw materials and extensive investments** in the Global South countries.
2. Global **markets are growing and miss producers** of resource-efficiently produced wood-based textiles.
3. Despite existing global production, the **expected demand for wood-based packaging materials opens space for new cost-competitive producers**.
4. **Finland can contribute to the evolution of sustainable wood-based textiles and packaging expertise in Global South countries** by, e.g., knowledge transfer, education, training, and business partnerships.
5. Questions of **legality, transparency, equality, and sustainability of the supply chains and businesses cannot be overemphasized** anywhere in the World**.**

Production of cotton, for example, consumes over ten times more fresh water than production of wood for textile fibres. Therefore, wood-based textiles stand for a great and societally sustainable opportunity particularly in water-scarce regions, to substitute cotton and to utilize the fields for grain production or grazing. Thus, the regions can strengthen their position as players in sustainable wood-based textile and packaging markets and respond to the growing global demand. Investing in these sectors improves the countries' positions as global actors in sustainable wood-based textile and packaging industries, while positively affecting the environment by replacing synthetic materials with renewable natural ones. To achieve a just and environmentally sustainable bioeconomy, there is a demand for a holistic and participatory formulated understanding of the acceptability, desirability, and sustainability of exploiting natural resources.

The rapid increase of e-commerce has raised the demand for packaging products with a low environmental footprint. Increasing consumption has changed the materials use tremendously during just one generation, and overconsumption causes most of the environmental mega-problems such as climate change, biodiversity loss, and pollution. Material sustainability and transparency, as well as circularity and social responsibility, are, however, turning into predominant regimes. This, along with the greening of production processes of non-renewable materials, creates hope for a more sustainable future, in which renewable biomasses play an increasingly important role.

References

Finnish Statistical Yearbook of Forestry (2023). *Metsätilastollinen vuosikirja 2022*. (Eds.) E. Vaahtera, T. Niinistö, et al. Natural Resources Institute Finland: Helsinki. ISBN: 978-952-380-584-2. https://jukuri.luke.fi/handle/10024/553167.

Hurmekoski, E., Kunttu, J., Heinonen, T., Pukkala, T. & Peltola, H. (2023). *Does expanding wood use in construction and textile markets contribute to climate change mitigation?* Renewable and Sustainable Energy Reviews 174 (2023). https://doi.org/10.1016/j.rser.2023.113152

Kärkkäinen, M. (2005). *Maailman metsäteollisuus. [Forest industries of the World]*. Metsäkustannus Ltd. 355 p. (in Finnish)

Kataja, K. and Kääriäinen, P. (eds.). (2018). *Designing Cellulose for the Future: Design-Driven Value Chains in the World of Cellulose (DWoC) 2013-2018*. Final report of the DWoC project. https://cellulosefromfinland.fi/design-driven-value-chains-in-the-world-of-cellulose/

Leinonen, I., Kataja, K., Vares, S., Immonen, K., Räty, T., Viitala, E.-J., Verkasalo, E., Lähtinen, K., Hagner, M., Heräjärvi, H., Viitanen, J., Yadav, P. & Harlin, A. (2022). *Perinteistä muovia korvaavat materiaalit ja ratkaisut [Materials and solutions replacing conventional plastics]*. Natural Resources and Bioeconomy Studies 28/2022. Natural Resources Institute Finland. Helsinki. 104 p. (In Finnish) http://urn.fi/URN:ISBN:978-952-380-403-6

Lehto, M., Högel, H., Marttila, J., Miettinen, P., Hiidenhovi, J. & Heräjärvi, H. (2023). *Höyhenten ja poistotekstiilien jalostusarvon nosto ja uudet käyttökohteet [New products and added value for chicken feathers and recovered textile materials]*. Natural Resources and Bioeconomy Studies 17/2023. Natural Resources Institute Finland. Helsinki. 53 p. (In Finnish) http://urn.fi/URN:ISBN:978-952-380-626-9

Wood fiber- a sustainable resource for packaging and textile

M. Jahan Sarwar, Rahman Mostafizur
Pulp and Paper Research Division, BCSIR Laboratories Dhaka
Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhaka, Bangladesh

Abstract

Wood is a vital resource for the global economy and society by providing a wide range of products including packaging and textile. The global market shares of the packaging material and regenerated cellulose fiber (RCF) from the wood fiber account for approximately 33% and 6%, respectively. In 2022, the global paper-based packaging and RCF markets were worth US$416.5 billion and US$ 18.0 billion, and expected to reach US$ 503 billion and US$27.3 billion by 2028, respectively. China was the largest producer of paperboard and packaging paper in 2021 with the production of 80.6 million metric tons followed by United States with an output of nearly 51 million metric tons. The starting raw material for regenerated cellulose fiber (RCF) is dissolving pulp, which is mainly produced by prehydrolysis kraft process. The dissolved biomass in the dissolving pulp production process can be used for biochemicals and biomaterials in support of developing circular bioeconomy. Viscose is the most important RCF, with a market share of around 80% of all RCF and a production volume of around 5.8 million tons in 2021. But the process is environmentally damaging due to the usage of toxic carbon disulfide (CS_2). Considering environment point, lyocell - a generic subclass of rayon fibers is produced by dissolving in N-methylmorpholine oxide. To produce RCF in more environmental friendly manner, ionic liquid is introduced for cellulose dissolution. Corrugated board is one of the most important packaging materials developed from wood fiber. It is a flexible and economic, recyclable and easy for transportation of various goods. It can protect and preserves even the most fragile goods. Corrugated board can be recycled to a bleachable grade pulp. Nanocellulose derived from wood fiber has opened up new possibilities for biobased food packaging by replacing plastic based food packaging. In recent days, China is the key player in producing both textile and packaging materials from wood fiber.

1. Introduction

The world's economic growth has led to improved livelihood and welfare of people at the expense of natural resources excessively, raising concerns about its long-term sustainability. The circular bioeconomy is an economy governed by nature. Currently, circular bioeconomy has become an evolving awareness in national and international policy agendas. It works with sustainability, focuses on the increased utilization of renewable resources for energy, chemicals and materials, and recycling of these sustainable materials and products, consequently, the circular bioeconomy offers solutions to control the effects of climate change. The substitution of fossil products by wood-based products can help to reduce greenhouse gas emissions over the life cycle of products. The origin of greenhouse gas emissions is the burning of fossil fuels causes a threat to the environment and leads to global climate changes. The exploitation of wood, crop residues and organic wastes into chemicals and materials to replace non-renewable resources can establish bioeconomy in the society.

Wood has enjoyed extensive utilization for thousands of years in construction, furniture, interior decoration, and as a fuel source. Fundamentally, wood is a complex biological material having a porous structure. Chemically, wood is a composite of three biopolymers, composed of an interconnected network of cellulose, hemicelluloses and lignin with traces of extractives and minerals (Rowell, 2005).

Cellulose consists of ß-D-glucopyranose units linked via ß-(1, 4) glycosidic bonds, with glucose as the fundamental repeating unit. Two different terminal hydroxyl groups are found at each end of the cellulose chain. One end, the non-reducing end, contains an alcoholic hydroxyl group, and the other end, the reducing end, contains an aldehyde hydrate group (**Fehler! Verweisquelle konnte nicht gefunden werden.**). The cellulose chains consist of 5000 to 7500 glucose monomer units. However, the DP of cellulose from wood is around 10,000, which are arranged to form microfibrils and packed together as cellulose fibrils (O'SULLIVAN, 1997).

Hemicelluloses belong to the family of carbohydrates and represents normally 20-35% of the mass. Hemicelluloses are heterogeneous groups of biopolymers. Depending on the species, developmental stage, and tissue type, various subclasses of hemicellulose may be found, including glucuronoxylans, arabinoxylans, linear mannans, glucomannans, galactomannans, galactoglucomannans, β-glucans, and xyloglucans (Wyman et al. 2005). The hemicelluloses matrix strengthened the rigidity of the cellulose microfibril.
Figure 33 shows the structure of hemicellulose.

Lignin is a complex phenolic polymer form by the polymerization of three types of phenylpropane units, also referred to as monolignols namely- coniferyl, sinapyl, and *p*-coumaryl alcohol as shown in
Figure 33.

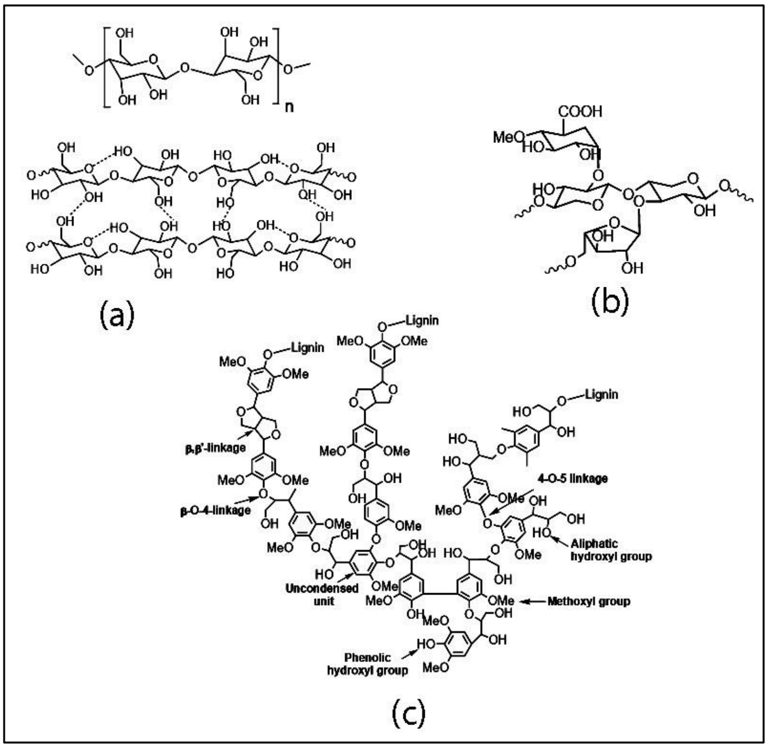


Figure 33: Structure of Cellulose (Dey et al., 2021) (a), Hemicellulose (Asif, 2009) (b), and Lignin (Ribeiro et al., 2019) (c)

In 1844, wood was grounded for the manufacture of pulp in Germany, and patented (Davis, 1886). The patent was used for the manufacture of newspaper. The mechanical pulp contains all the components of wood and thus is not suitable for white paper. The chemical wood pulps such as soda process was manufactured from wood in 1852 in England, and a patent was issued in the United States for the sulfite pulping process in 1867 (Britt, 2020). These pulps were high brightness, strength, and permanence, and could be used in writing and printing at that time. The produced pulps are being used in a wide range of application.

This report discusses the use of wood fiber in textiles and packaging, as well as how it can contribute to the development of a bio-economy.

2. Textile

The history of cellulose based cotton as textile fibers extends back 3000's BC of years, but the man-made fiber industry began with the first commercial production of rayon in 1910 (Fabric University). Regenerated cellulose fiber is a type of manufactured or man-made fiber that uses cellulose (mainly from wood or plant fibers) as a raw material for textile. It was the first man-made fiber applied in the textile and apparel industry in 1850s, and considered to replace silk, hence named as “artificial silk” (Woodings, 2001). The regenerated cellulose fiber was named as Rayon in 1924 by the U.S. Department of Commerce and various industrial associations. “Ray-” inferred fiber brightness and “-on” denoted the fibers cotton-like structure (Beda Ricklin, 2024).

The dissolving pulp is the starting raw material of regenerated cellulose fiber for textile. With the consideration of global warming, scientists and policymakers are trying to develop a biobased society. In this context, global production of dissolving pulp increased from 4.18 million MT in 2010 to 8.62 million MT in 2022 (Figure 34) (FAO, 2023). The increasing trend of dissolving pulp production is higher in Asia as compared to Europe and other regions. Due to the wide-ranging applications of dissolving pulp, especially in textiles, and increasing importance on environmental sustainability, it is being manufactured in significant quantities.

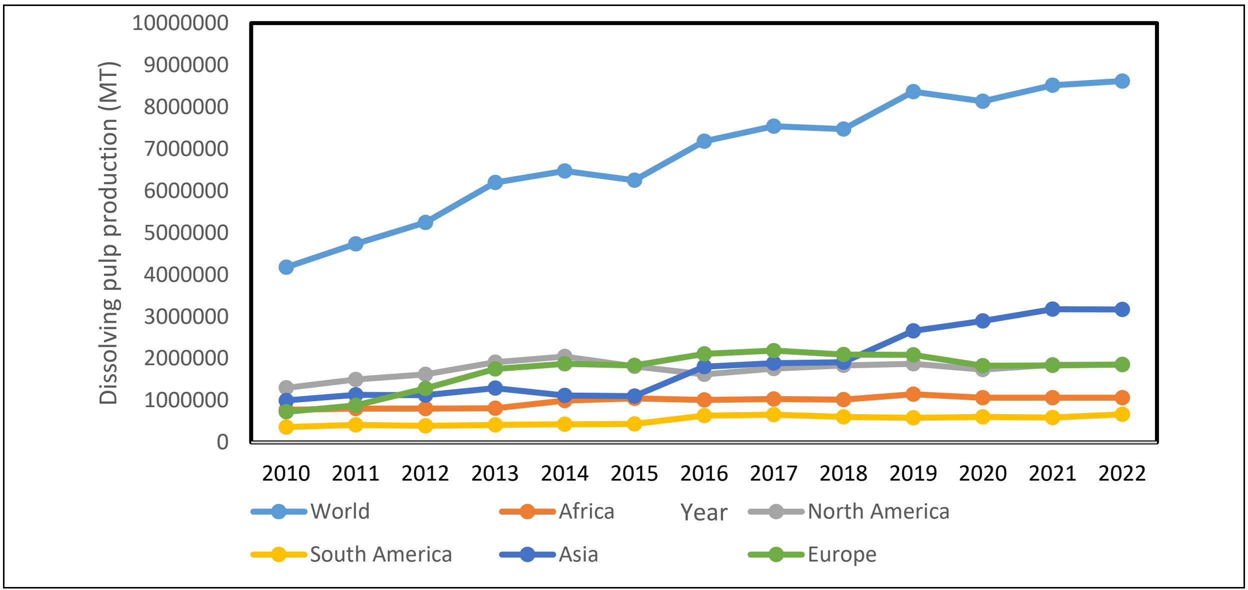


Figure 34: Production of dissolving pulp.

The dissolving pulp market on a global scale was valued at US$5,563.60 million in 2022 and is expected to surpass US$7,623.47 million by the end of 2032 (Factmr, 2023). In the 21st century, the global market of dissolving pulp has been growing rapidly due to a consistent growth of regenerated cellulose fiber productions, around 60% of the wood pulp and 65-70% of the regenerated cellulosic fiber was manufactured in China (Gøtterup, 2020). The key players of dissolving pulp producer in the world are Sappi, Aditya Birla, Rayonier, Bracell, Fortress Paper, etc. These top five manufacturers produce over 50% of the production share (Factmr, 2023). The largest application of dissolving pulp is Viscose, followed by Cellulose Acetate. Sappi- a big manufacturer produces 17% share of the dissolving pulp market in world with a capacity of 1.5 million tons per annum (Sappi Global, 2023).

Traditionally, cotton linter and woods are being used for dissolving pulp production. Wood (spruce, pine, beech and eucalyptus) occupies 85% of the total dissolving pulp production, while cotton linter occupies 10% (Chen et al., 2016; Sixta, 2006; Sixta et al., 2013). Most of the dissolving pulp mill uses hardwoods as raw materials. The Lenzing Group operates two pulp factories in Europe with regional wood supply. The Lenzing site in Austria uses mainly beech wood and small amounts of other hardwoods and spruce, whereas the Paskov plant in the Czech Republic utilizes mainly spruce (Lenzing Group, 2023). The state forests of Austria, Germany, Czech Republic, and Slovakia are also important wood sources for Lenzing's dissolving pulp sites and supply more than 20 percent of the wood procured; these countries have strong political commitments to the sustainable management of their forests.

Sappi for her Saiccor and Ngodwana dissolving pulp Mills uses eucalyptus (hardwood) from responsibly-managed plantations. Another Mills in North America Cloquet uses mixed northern hardwoods: aspen (65%) and maple (35%) (Sappi Global, 2023a).

A Brazilian dissolving pulp mills Klabin Bacell has researched with a team of expertise of the forestry, pulp production, research and sales personnel, to implement a program to speed up the development of Eucalyptus wood for dissolving pulp using tree breeding combined with advanced forest management techniques (Lima et al., 2003). The short and thick fibers of Eucalyptus provide high specific surface of the fiber material, leading to high affinity to polar solvents. The dissolving pulp of Klabin Bacell branded as Solucell, is resistance to chemical degradation, compared to other high purity grade pulps. *Solucell*™ is a patented material that produces an easily dissolvable yarn with enhanced characteristics and a low environmental impact. The products have superior reactivity, due to their morphological and chemical attributes. With Solucell it is possible to obtain a high yield in the viscose production and very good tenacity values. So, it can be seen that most of the company uses hardwoods as their raw material for the dissolving pulp production.

2.1. Regenerated cellulose fibers

The regenerated cellulose fiber (RCF) production process involves two essential steps: i) dissolution of the raw cellulose using either chemical or physical method, and ii) regeneration of cellulose through a spinning process (wet spinning, dry spinning, or dry-jet/ wet-spinning).
The global production of RCF in textile sector is only 7.2 million MT in 2021, while the polyester fiber stood at 60.5 million MT and the cotton fiber stood the second largest with around 24.7 million MT (Figure 35) (Statista, 2023a). The market value of RCF was US$ 18.0 billion in 2022, which projected to reach US$ 27.3 billion by 2027 (MarketsandMarkets, 2024). The main driving force of this increasing trend of RCF is fashionable fabrics. Based on the fiber production process, the regenerated cellulose fibers can be classified into i) viscose rayon, ii) lyocell fibers, iii) acetate and iv) Cupro rayon fiber. RCF contributes to approximately 6-7% of the worldwide textile market and is appreciated for its eco-friendly qualities and exceptional comfort.

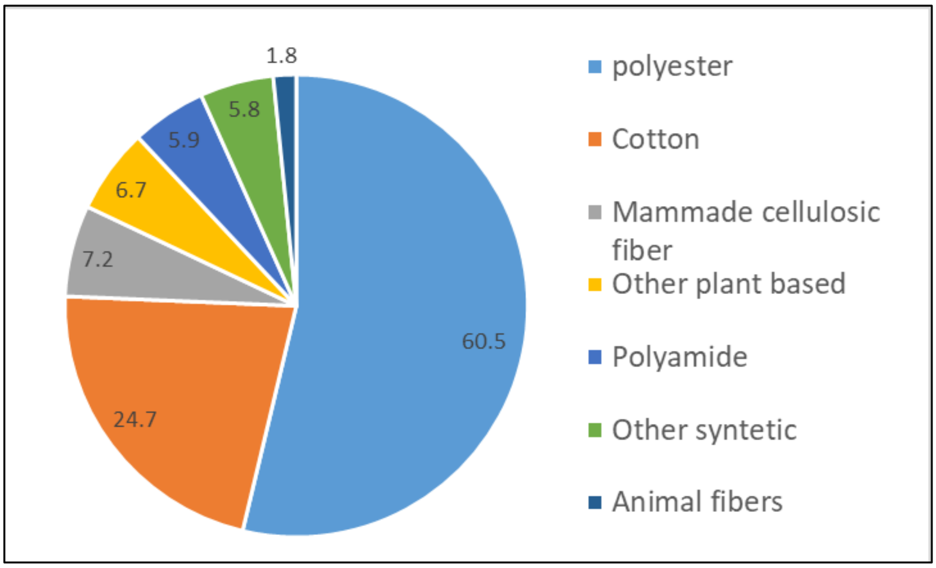


Figure 35: Worldwide textile fibers production by type in 2021 (million MT)

Viscose

Viscose is the most important RCF, with a market share of around 80% of all RCF and a production volume of around 5.8 million tonnes in 2021 (ÇEVEN and GÜNAYDIN, 2023). It is manufactured through a wet-spinning process, but environmentally damaging method due to the usage of toxic carbon disulfide (CS_2) (Gondhalekar et al., 2019). In 2018, China solely produced 65% of total global viscose fiber production. The Lenzing of Austria and Aditya Birla Group of India are the two leading producers of viscose fiber in the world (Yarnsand fibers, 2020).
Initially, the United States and the United Kingdom are the main manufacturer of rayon fiber, which has shifted to the Asian countries like India, China. Recently, Indonesia install a large rayon production facility. President of Indonesia, Joko Widodo, inaugurated Indonesia's largest integrated viscose rayon production facility 'The new Asia Pacific Rayon' with an annual production capacity of 240,000 tons in 2020 with the investment of US$1.1 billion (Renewable Carbon News, 2020).

The degradation of RCF is much higher than synthetic fibers. As for example, the degradation of polyester is only 4% after 250 days, while the degradation of rayon fiber is 60% and cotton fiber is 76% after same days (NCSU Bioproducts USDA Grant, 2019). Microplastic is a big concern nowadays. In every wash of polyester fabric in washing machine, generates 0.2% micro fibers, which goes to sea and hampers our marine life.

Cotton is a natural fiber, but RCF is advantageous over it because of its heavy reliance on farmland, use of huge pestiside and water, making it a less sustainable option for future textile production (Tausif et al., 2018).

Best practices:
Viscose rayon fiber from wood fiber

Only 6% regenerated cellulose is produced globally, on the other hand, over 60% textile fiber is produced from fossil fuel and 20% from cotton. Cotton requires ten times higher fertilizer and water, which is environment damaging. Although, the production process of viscose rayon fiber is not environmental friendly. Considering degradability of rayon fiber, it can be considered as best practice till to the commercial production of regenerated cellulose fiber in green methods.

Lyocell fibers

Lyocell fibers, a generic subclass of rayon fibers, are produced from cellulose dissolved in N-methylmorpholine oxide (NMMO). NMMO was discovered as a solvent which can directly dissolve cellulose pulp. Lyocell fiber is alternative type of regenerated cellulose fiber produce from wood pulp. The concept of lyocell fiber was generated from the environmental concern in viscose rayon fiber production process. In this method wood pulp is dissolved in organic solvent (NMMO) and dissolved cellulose is precipitated from an organic solution, where no substitution of the hydroxyl groups takes place and no chemical intermediates are formed like rayon fiber. First patent describes a process of dissolving cellulose in the NMMO solvent by Mcorsley (1981). China is the largest producer of lyocell fibers. Global lyocell fabric market was valued at US$ 1.1 Billion in 2021 in terms of revenue, exhibiting a compound annual growth rate (CAGR) of 6.9% during the forecast period (2022 to 2030). A largest producer of lyocell fibers in Asia is Boading Swan Fiber Co Ltd, China with a production capacity of 60000 ton/year (SwanFiber, 2023). Other Major players in the market are Lenzing A.G., Aditya Birla Group, AkzoNobel N.V., Smartfiber AG, Nien Foun Fiber Co., Ltd., Invista etc.

Best practices:
Lyocell fiber production

One of the best replacement options for rayon fiber is lyocell fiber production. The lyocell fiber concept was developed due to environmental concerns as the production process of viscose rayon fiber uses carbon disulfide. In the lyocell fiber production process, wood pulp is dissolved in an organic solvent (NMMO) and dissolved cellulose is precipitated from an organic solution, where no substitution of the hydroxyl groups takes place and no chemical intermediates are formed like rayon fiber. China is the largest producer of lyocell fibers. Global lyocell fabric market was valued at US$ 1.1 Billion in 2021 in terms of revenue.

Ionic liquid

To overcome the cellulose dissolution through derivatization using toxic chemical, a recent technology for cellulose dissolution involves ionic liquids (ILs), which is composed of organic cations or anions with melting point below 100°C. Considered as promising environment friendly solvents, ILs have received significant attention for their low vapor pressure, good chemical and thermal stability, non-flammability, and their easy reusability and recyclability. IL pretreatment generally occurs at moderate temperatures and ambient pressure.
Researchers from the Aalto University and the University of Helsinki have developed Ioncell technology. The Ioncell process consists of dissolution of cellulose in ionic liquid. In the dissolved state, cellulose can be transformed into beautiful, strong fibers using the dry-jet wet spinning technology. The only chemicals applied are the non-toxic ionic liquid and water. They are both re-circulated in the process in a closed loop (Ioncell, 2024).

Best practices:
Ioncell fiber production

One of the best options for cellulose based textile fiber using green technology is the dissolution of cellulose in ionic liquid without derivetization. A recent technology for cellulose dissolution involves ionic liquids (ILs) composed of organic cations or anions with melting point below 100°C. Researchers from Finland have developed this technology, which is called Ioncell technology. The Ioncell® process consists of the dissolution of cellulose in an ionic liquid. In the dissolved state, cellulose can be transformed into beautiful, strong fibers using the dry-jet wet spinning technology in a water bath. They are both re-circulated in the process in a closed loop.

Regenerated cellulose fiber from carboxymethylated cellulose

The cellulose is the most suitable and sustainable alternative to natural or synthetic polymer fibers in the textile industry. But increasing concerns about the environmental impact of rayon production are forced to find suitable alternatives method for textile fiber production. In addition to ionic liquid, carboxymethylation of cellulose (CMC) followed by dissolution in aqueous NaOH solution, and wet spinning in an acid coagulation bath was investigated by Islam et al. (2023). Spinning of CMC was possible when a carboxyl group content of at least 1.3 mmol/g cellulose.

This is an environmentally friendly approach over viscose process for the production of rayon. The process became difficult for filaments with carboxyl group content of 1.5–1.7 mmol/g cellulose. As shown in Table 11, the tenacity of the filaments obtained from the modified cellulose with a carboxyl group content of 1.3 mmol/g cellulose was 1.0 cN/dtex, which was higher than that of the filaments with carboxyl group contents of 1.5 mmol/g cellulose (tenacity 0.93 cN/dtex) and 1.7 mmol/g cellulose (tenacity 0.88 cN/dtex). The values of tenacity and water absorbency for filaments with 1.3 mmol/g cellulose were extremely promising for textile applications. Moradian et al. (2021) mildly etherified kraft and dissolving pulps to CMC, which were subsequently dissolved in alkaline solutions then cast, immersed in an acid bath, washed, and dried to form regenerated cellulose-based films, which do not dissolve in water. It was found that kraft pulp films were denser, stronger, more transparent and crystalline, had a smoother surface, and were more water absorbent than the dissolving pulp films due to their higher hemicellulose content. Islam et al. (2023) with functionalized amine carboxylated carbon nanotubes (CNT) and cross-linked with CMC. Incorporating 1 wt.% CNT by crosslinking resulted in filaments with increased mechanical strength (tenacity ~ 1.2 cN/dtex) and a lower water absorbency (water absorbency ~ 0.62 g water/g fiber). The fabricated cellulosic textile filaments also demonstrated antibacterial activity and UV protection capability due to incorporation of *afc*-CNT. This is a new concept for producing textile fiber from wood cellulose in an environmental friendly manner. This process can be alternative to viscose process, and help to increase wood fiber in textile sector in environmental friendly manner. Further research is needed for commercial production.

Table 11: Properties of regenerated cellulose fiber from CMC

- COOH mmol/g cellulose	Tenacity cN/dtex	Water absorbency g water/g filaments
1.3	1.0	0.54
1.5	0.93	1.08
1.7	0.88	1.89

Best practices:
Regenerated cellulose fiber for textile from carboxymethyl cellulose

Approximately 6% of the total textile fiber is produced from wood fiber, and 80% out of the 6% is viscose rayon fiber. But the problem with the viscose process of using carbon disulfide. To overcome the problem, a most recent technology has been developed of converting wood pulp into carboxymethylation followed by dissolution in alkali and regeneration in acid. The technology can be replaced in existing viscose rayon plant.

3. Packaging

The role of packaging is the safe delivery and transportation of products to prevent waste and loss, and a good package should ensure quality and safety of the product (Otto et al., 2021). However, a major disadvantage of packaging is that it adds to the world's environmental footprint because it is always discarded immediately after the product is used (Magnier and Schoormans, 2015).

The packaging materials include paper, wood, glass, metal, and various types of plastics. Paper, made from wood fibers, is the basis for the world's most widely used packaging materials. Paper as a packaging material is experiencing a revival, as consumers perceive it as a high-value and environmentally friendly material (Lindh et al., 2016). As shown in Figure 36, paperboard is the most used packaging material worldwide, accounting for approximately 33 percent of packaging material consumption. Types of paperboard packaging include cardboard, white paper and paperboard (Statista, 2023b). The use of non-renewable plastic materials in packaging sector is 44%, which needs to be replaced by wood fiber. In this context, more research and investment are needed to improve barrier properties of paper for packaging. Biobased materials such as nanocellulose, nano-chitosan, sodium alginate, polyvinyl alcohol etc. can be explored for improving food packaging.

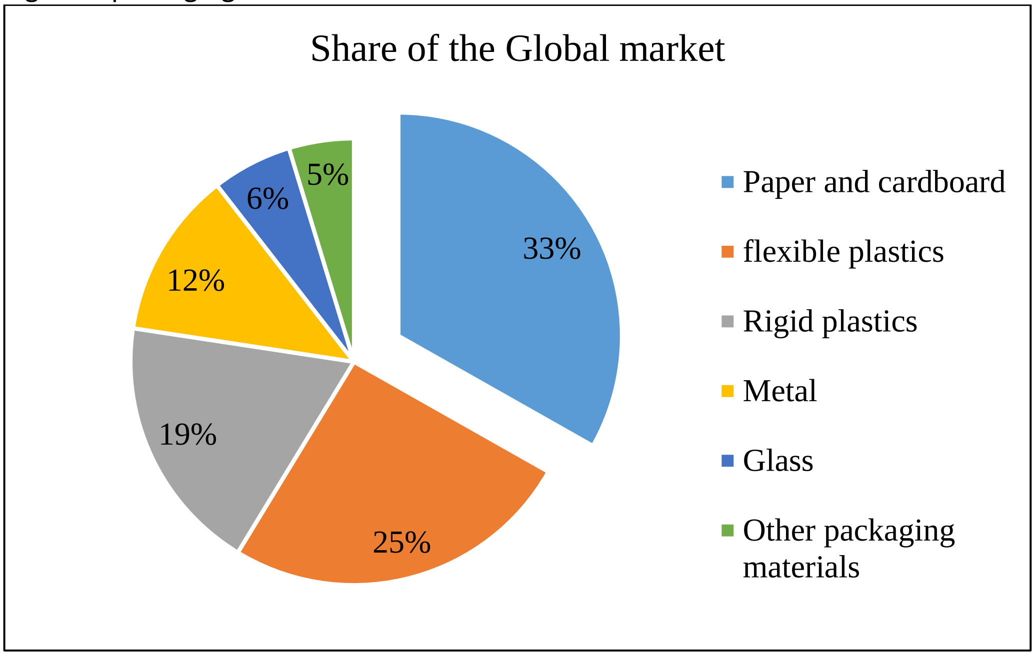


Figure 36: Contribution of different materials in packaging

The packaging paper demands is increasing because of increasing e-commerce, people's positive perception of packaged goods, concern for environmental sustainability as well as safety and intact the quality of the goods during transportation, people's attraction toward western lifestyle, urbanization. The percentage of packaged goods in the market is expected to increase as the demand for packaged goods increases. To reduce their environmental impact, companies are also increasingly turning to sustainable packaging solutions. Additionally, paperboard is one of the most environmentally friendly packaging materials, since it is made from renewable resources, can be recycled, and is lightweight, biodegradable, and compostable. As shown in Figure 37, the production of paper and paperboard in top 86 producing countries are increasing.

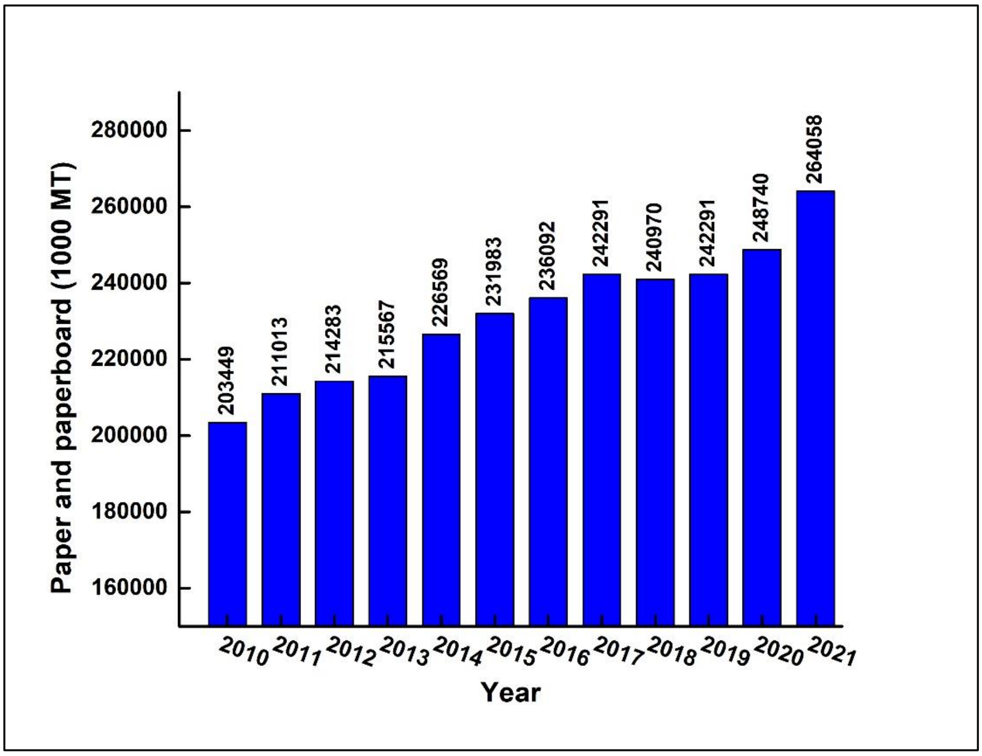


Figure 37: Production paper and paperboard worldwide from 2010-2021 (FAO, 2021)

All kinds of papers-bleached and unbleached are used for packaging. However, unbleached containerboard is the most consumed paper product worldwide. In 2021, containerboard represented approximately 46 percent of the global paper and paperboard demand (Figure 38). The packaging sector accounted for 56 percent of the global paper consumed in 2021. The amount of paper and paperboard consumed around the world in 2021 was 417 million tons. During the next decade, it is projected that the consumption of paper product will continue to increase to reach 476 million tons by 2032 (Statista, 2023c).

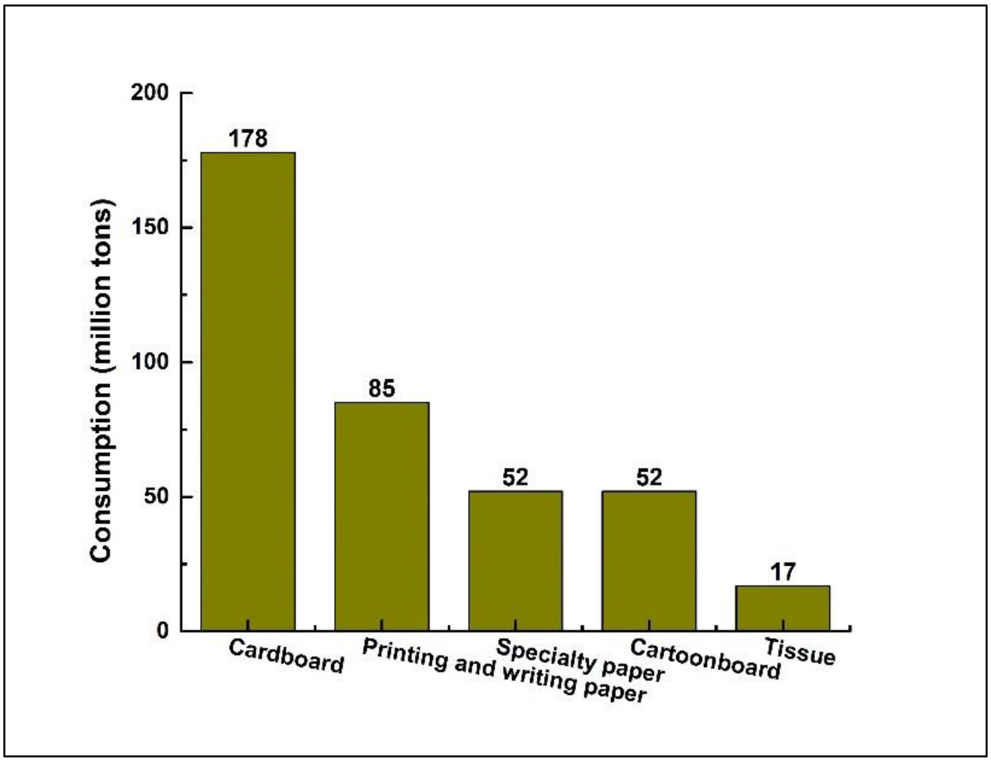


Figure 38: Global consumption of paper on the basis of type

3.1. Corrugated board packaging

Corrugated board packaging is a flexible and economical way to safeguard and transport various goods. More than 100 years have passed since corrugated boxes were first used for goods transportation. The corrugated box was accepted for freight transportation in 1903 after that its acceptance increased tremendously due to its lightweight, low cost, ease of assembly and disassembly, good sealing performance, certain cushioning and anti-vibration ability, easy recovery and waste treatment, and biodegradable (Meifen et al., 2004). In the EU about 75% of all goods on their journey from producer to customer are transported and protected using corrugated cardboard. It protects and preserves even the most fragile goods. Trade, both within Europe and beyond, could barely survive without it. It is also the greenest of all packaging materials, with a recycling rate of over 90% for cardboard and an average recycled content of 89% for corrugated cardboard. Global corrugated board revenues reached US$ 134.7 billion in 2022 and is projected to grow at a CAGR of 6.8% through 2030 (Grandviewresearch, 2024). The North American corrugated board packaging Market size is estimated at US$ 40.64 billion in 2023. It is expected to reach US$ 47.92 billion by 2028, with a CAGR of 3.35% during the forecast period (2023-2028). The market size reflects the demand and consumption of corrugated board for packaging (Mordorintelligence, 2024). However, the packaging market in Asia is expanding exponentially because of high economic and industrial production growth, growing e-commerce, environmental awareness in the region. The Asia-Pacific region represents the largest and fastest-growing corrugated packaging market in the world, accounting for 53.7% of total global production and shipment. China is the leader in the production and consumption of corrugated paperboard not only in the Asia-Pacific region but also in the world. In 2021, the demand for corrugated boards was approximately 55 million tons (Billerud, 2024).

Recycling of corrugated board

Post-use corrugated packaging material is commonly known as “cardboard", while it is typically referred to as OCC. Globally, policymakers are advocating for circular economy, which is largely dependent on recyclability. More than 35 million tons of OCC was recovered for recycling in 2021 (AF&PA, 2022). Repeatedly recycled fibers show less suitable property for papermaking mostly due to hornification and reduced fiber length. The physical strength is the prime requisite for linerboard and corrugating mediums.

Laivins and Scallan (Laivins and Scallan, 1993) hypothesized that the loss in swelling occurred because of an increase in the degree of crosslinking between cellulose microfibrils during drying. The level of fiber swelling is associated with the plasticization and conformability of the cell wall, which affect fiber bonding, and ultimately papermaking properties (Emerton, 1957). To improve the papermaking properties, the blending of virgin pulp, mechanical strength, refining, fiber fractionation and chemical treatment of recycled fiber were investigated (Krochak and Bjärestrand, 2022). The refining of the whole Korean OCC containing both long and short fiber fractions gave better strength (Kang et al., 2017). Refining of the long fiber fraction and remixing it with unrefined short fiber fraction also improved strength, but the improvement was less than the case of refining whole stock. Gurnagul (Gurnagul, 1995) improved fiber swelling of thermomechanical pulp (TMP) by adding sodium hydroxide during repulping, but had no significant fiber swelling of unbeaten kraft pulps (bleached or unbleached). Alkali treatment of OCC increased compression strength by 10.6%, liner board 20.4% and medium 11.3% (Freeland and Hrutfiord, 1994). Zanuttini et al. (2009) showed that the alkaline treatment reduced freeness and improved the papermaking properties, and also they found that the delignifying effect of alkali was enhanced by peroxide addition. Ozonation also used in improving strength properties of recycled fiber (Wistara and Young, 1999). The ozonization weakens the cell wall structure and makes it more elastic, presumably through the irreversible destruction of internal cross-links. The formation of additional acidic groups, as a result of the ozonization, was also thought to increase the swelling capacity of the pulps. Zanuttini et al. (2007) observed that ozonation of OCC pulp reduced kappa number and increased relative bonded area and strength properties of pulp sheets.

Nguyen and Simard (1996) produced bleached chemical pulp from OCC with 70% ISO brightness and 11 cp viscosity by alkaline peroxide delignification and/or bleaching. Prior to delignification, acid-washing of raw OCC pulp was done to reduce metal ion concentration. Danielewicz and Surma-Slusarska (2011) attempted to oxygen delignification of OCC pulps, and reached kappa number of approximately 30, further delignification was very slow. Researchers also delignified OCC by kraft pulping for bleaching and compared with the wood (birch and pine) delignification. These attempts showed that OCC pulps, when pulped together with wood, are delignified at a similar rate as that observed during separate delignification. Latibari (2012) investigated the alkaline sulfite pulping of OCC to produce bleachable pulp. After preliminary pulping and evaluation, pulp with a kappa number of 18.3 and brightness of 50.2%, which was produced applying 18% active alkali, sodium sulfite to sodium hydroxide ratio of 30:70, and pulping time and temperature of 120 minutes and 175 °C, respectively, having the yield of 64.0% (based on oven dry weight of washed OCC) and 72.7% (based on original weight of the OCC as received), respectively. Aguilar-Rivera (2021) delignified OCC in soda process, obtaining a pulp with significant physical–mechanical improvements in relation to the original material, such as tensile strength, tearing resistance, bursting strength and folding endurance. The OCC soda pulp was bleached by a sequence totally free of chlorinated compounds (TCF), obtaining bleached pulp with optical and mechanical properties comparable to virgin pulps of annual plants such as bagasse but with improved drainage properties and lower processing costs.

From the above discussion, it can be said that the corrugated board is recyclable and can return as a virgin pulp and even bleachable pulp, which is important in circular bioeconomy. In this context, more research is required to produce a good quality bleachable pulp from OCC. This concept is also important for forest deficient countries like Bangladesh, Pakistan, middle-east etc.

Best practice:
Packaging and bleachable grade pulps from OCC

Corrugated board packaging is a flexible and economical way to safeguard and transport various goods. The corrugated box was first approved for freight transportation in 1903. Since then, it has gained widespread acceptance due to its lightweight, low cost, easy assembly and disassembly, good sealing, cushioning and anti-vibration properties. Additionally, it is easy to dispose of and is biodegradable. Cardboard is the most environmentally friendly packaging material with over 90% recycling rate. The Asia-Pacific region is the world's largest and fastest-growing corrugated packaging production and shipment market. Post-use corrugated packaging material is known as old corrugated cardboard (OCC). A virgin-grade pulp is produced from OCC by adding sodium hydroxide during repulping. Bleached pulp is also produced from the OCC by alkaline peroxide delignification and bleaching.

3.2. Food packaging

The packaging of food can be made from a variety of materials, such as metal, plastic, glass, and paper. Paper is the second most common food packaging material after plastic. The global market of food packaging was US$ 357.06 billion in 2022 and is estimated to reach US$ 642.43 billion by 2032. During this time the market growth would be CAGR of 6.10%. Food packaging is expanding at a high growth rate because of the growing population, economic growth, and interest in Western lifestyles. Food industries prefer paper because it has an environmentally friendly tag attached to it (Khwaldia et al., 2010).

Smart packaging

Generally, packaging is used to protect a product from any kind of damage. However, the customer does not have access to product information before opening the package. Smart packaging brings the solution to this problem. Smart packaging is a sensor-based packaging that uses embedded technology to monitor product quality and freshness and display product shelf life. It also improves product and customer safety (Schaefer and Cheung, 2018). A packaging system with intelligent technology can provide the consumer with information on the quality and freshness of the product. The packaging can also be used to track the product's journey, allowing companies to monitor product quality and freshness. Smart packaging can also help companies to reduce the risk of fraud and counterfeit products. Due to its huge acceptance, the market size is expanding significantly every year. The global market for smart packaging systems was valued at US$35.92 billion in 2022 and expected US$37.68 billion by the end of 2023. It is anticipated that at the end of 2032, this market size will reach US$60.49 billion with a CAGR growth of 5.4% during the period of 2022 to 2032 (Figure 39) (Precedenceresearch, 2024). Globally, Asia Pacific is projected to be the most significant market for smart packaging in 2022 with 43% of the market revenue share, followed by North America and Europe. Smart packaging has grown in Asia Pacific as a result of population growth, economic growth, and government initiatives to make supply chains smarter and more seamless (Thebrainyinsights, 2024). The life cycle analysis (LCA) determines how a product, process, or service impacts the environment throughout its life cycle. In a smart packaging system, the environmental impacts as of packaging at each stage of its life cycle can be easier (Acosta-Alba et al., 2019). The benefits of paper-based packaging include its biodegradability, recycling, attractiveness, and reduced cost. Because smart packaging is growing faster, the contribution of paper and paper boards to the packaging market would be greater.

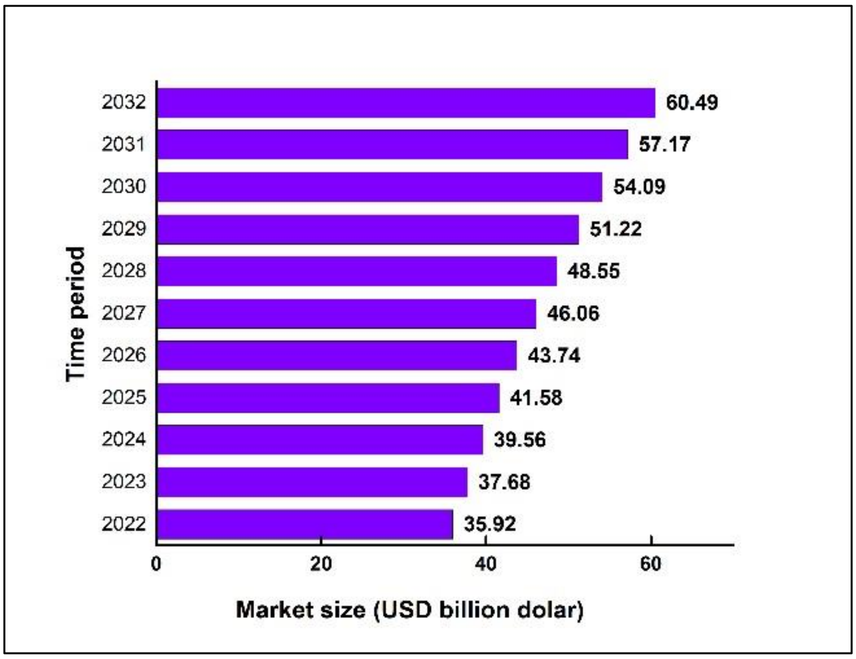


Figure 39: Global smart packaging market size

Best practice: Smart packaging

The environmental impact of packaging material is essential for a greener world. In a smart packaging system, it can be easier to assess the environmental impacts of packaging at each stage of its life cycle. The paper-based smart packaging has gained tremendous acceptance due to its biodegradability, recycling, attractiveness, and reduced cost. Because smart packaging is growing faster, the contribution of paper and paper boards to the packaging market would be more significant. Globally, Asia Pacific is projected to be the most significant market for smart packaging in 2022, with 43% of the market revenue share, followed by North America and Europe.

4. Transferability

From a long time, Europe and North America are rich in the production of textile fiber and packaging materials from wood fiber, and have a great potential to promote transfer of technology and knowledge to Africa, Asia and South America. To contribute to a successful bioeconomy, different links from raw material, production process, and finally to the recycling of the products are needed.

Research across world on RCF and packaging materials from wood fiber provides enormous potential for creativity and innovation. To exploit these vast innovations, technology transfer becomes pivotal. The bioeconomy, an emerging area where innovation is triggered by the combination of knowledge rooted in different disciplines. We focus here on textile and packaging sector.

4.1. Textile

The rayon fiber was produced initially in the United States and the United Kingdom, which has shifted to the Asian countries like India, China. As mentioned in earlier section that the market share of viscose of RCF is around 80% with a production volume of around 5.8 million tonnes in 2021 (ÇEVEN and GÜNAYDIN, 2023). China alone produced 65% of total global viscose fiber production in 2018. Indonesia has also a large rayon production facility.

But, the rayon production process is not environmental friendly, which put pressure to develop new technology for RCF. In this context, a patent describes a process of dissolving cellulose in the NMMO solvent by Mcorsley (1981), which is celled lyocell fiber. Boading Swan Fiber Co Ltd, China is the largest producer of lyocell fibers with a production capacity of 60000 ton/year (SwanFiber, 2023). Other Major players in the market are Lenzing A.G., Aditya Birla Group, AkzoNobel N.V., Smartfiber AG, Nien Foun Fiber Co., Ltd., Invista etc. Therefore, it is observed that the technology already has been shifted from the North America and Europe to the Asia.

European countries develop a new method of cellulose dissolution in ionic liquid method, which can be an alternative green method for RCF production (Ioncell, 2024).

With the concerns of the environmental impact of rayon production, MacGill university recently developed a new method of RCF production using softwood and hardwood pulps (Islam et al., 2021). The method comprises carboxymethylation of cellulose (CMC) followed by dissolution in aqueous NaOH solution, and wet spinning in an acid coagulation bath.

To implement the newly develop methods successfully, a series of workshops, meetings are needed among the scientists, politician and forest practitioners across the globe.

4.2. Packaging

The paperboard represents 33% and non-renewable plastic materials represent 44% in packaging sector. Substituting traditional high carbon packaging material with renewable paper, especially in food packaging, requires a sustainable investment in research and innovation.

The barrier properties are important in selecting food packaging material. Plastic packaging material has very high barrier properties, therefore, well-chosen in food packaging from a long time. On the other hand, paper is porous structure, so it is not suitable for food packaging to keep long life of the products. Already, many researches have been investigated to improve barrier properties of paper. Extensive research and development are required for improving barrier properties of paper in order to establish a sustainable society. The present knowledge of biobased packaging already have been discussed in earlier section. Across the globe, the best available technologies need to be shared through a series of workshops, conferences among the policy maker, scientists and foresters'. Policy dialogue need to be arranged in global forums.

5. Key messages and recommendations

The world has abundance wood resources which creates opportunities to establish a forest-based bioeconomy from a sustainable managed forest. It plays a crucial role in climate change mitigation, and economic growth through innovation. The production and use of packaging materials and wood-based textile fibers have been acknowledged as a promising area for carbon storage and greenhouse gas emission reductions as shown in Figure 40.

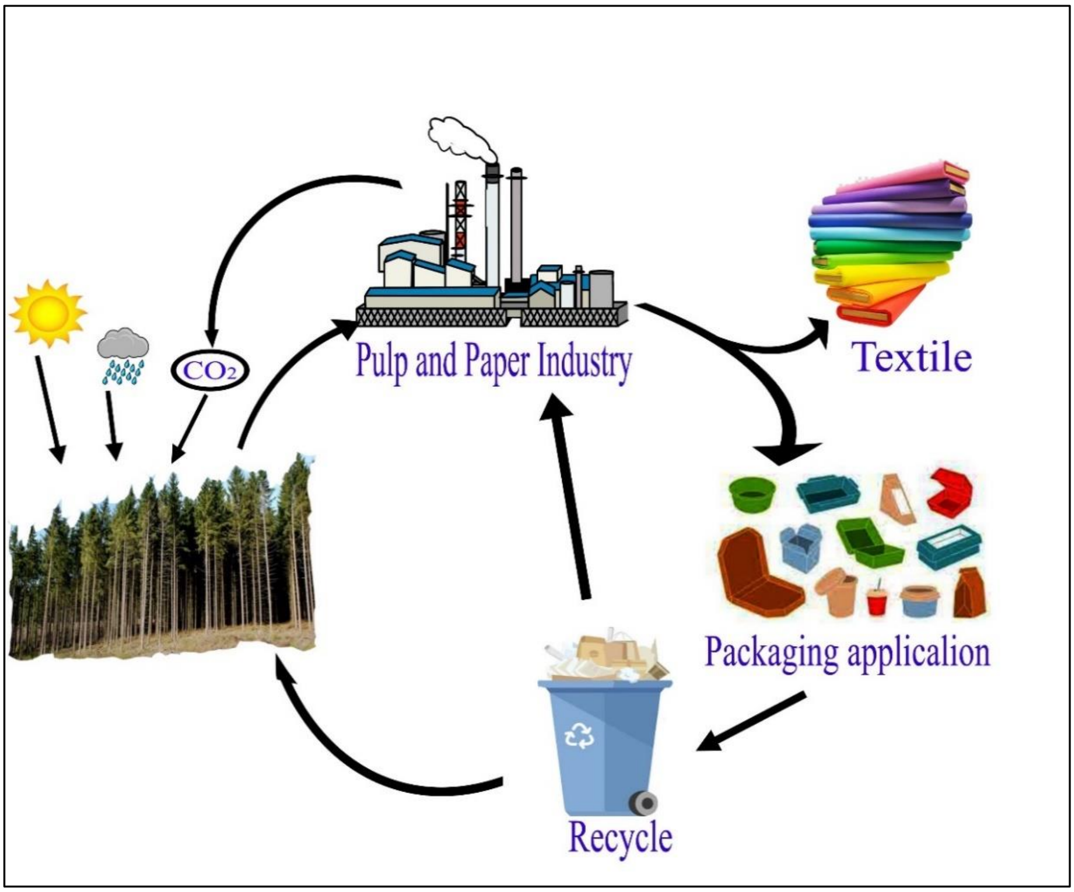


Figure 40: Circular Bioeconomy in textile and packaging sector

Only 6% of total textile fiber production is from wood fiber, while the polyester and polyamine fiber from non-renewable are above 50% and 5%, respectively. Microplastic is a big concern nowadays. In every wash of polyester fabric in washing machine, generates 0.2% micro fibers, which goes to water body and hampers our aquatic life. The degradation of polyester is only 4% after 250 days, while the degradation of rayon fiber is 60%. Cotton represented 24.7 million ton of textile fiber in 2021. It is a natural fiber, has become less popular because of its heavy reliance

on farmland, use of huge pestiside and water, making it a less sustainable option for future textile production.
The wood fiber use in textile sector need to be increased to develop a biobased society. Unfortunately, more than 80% of RCF out of 6% wood fibers in textile sector is produced from environmental damaging xynthation method, which involved carbon disulfide. In this context, the production of RCF from wood fiber must be increased in an environmental friendly manner. Policy maker should emphasize on alternative cellulose dissolution methods for RCF for **textile sector**. Therefore, policymaker should focus on

- Need investment in research for cellulose dissolution and regeneration processes for producing textile filament and film production.
- Need investment on commercial ionic liquid production for cellulose dissolution. Initiative needs to be taken to avoid harmful chemicals in textile fiber production, refurbishing the production process, and adopting circularity to minimize the generation of toxic wastewater.
- In addition to ionic liquid, RCF from carboxymethylated cellulose is a new emerging technology, so, more research is needed in this area.
- The demand for more eco-friendly options in the fashion sector is more apparent than ever. The textile industry can increase the use of wood-based fibers from sustainably managed forests, and reduce the environmental impact in this sector.

The paperboard is the one of the most used **packaging materials** worldwide, accounting for approximately 33 percent of packaging material consumption, while the use of non-renewable plastic materials in packaging sector is 44%. The largest amount of paper-based packaging material is cardboard, which accounts 178 million MT in 2021. Therefore, OCC pulping and bleaching is an important option to maintain a sustainability in this sector.

- So, more research and investment are important to get virgin like pulp from OCC, and increase wood fiber in packaging sector.
- More research and investment are needed to improve barrier properties of paper for packaging. Bio-based materials such as nanocellulose, nano-chitosan, sodium alginate etc. can be explored for improving food packaging.
- Policymakers should discourage the use of plastic materials and encourage bio-based packaging materials in order to establish bio-based society.

References

Acosta-Alba I., Chia E., and Andrieu N. (2019). The LCA4CSA framework: Using life cycle assessment to strengthen environmental sustainability analysis of climate smart agriculture options at farm and crop system levels. Agricultural Systems, 171, 155–170, DOI: 10.1016/j.agsy.2019.02.001.

AF&PA (2022). Unpacking the 2021 Paper Recycling Rate. Available at: https://www.afandpa.org/news/2022/unpacking-continuously-high-paper-recycling-rates [Accessed on 6 February 2024].

Aguilar-Rivera N. (2021). Emerging technology for sustainable production of bleached pulp from recovered cardboard. Clean Technologies and Environmental Policy, 23, 9, 2575–2588, DOI: 10.1007/s10098-021-02171-3.

Asif M. (2009). 2 - Sustainability of timber, wood and bamboo in construction. In: Sustainability of Construction Materials. (Ed.) J.M. Khatib. Woodhead Publishing, pp. 31–54. DOI: 10.1533/9781845695842.31. ISBN: 978-1-84569-349-7.

Beda Ricklin S.A. (2024). Viscose rayon - the oldest man made fiber - versatile fiber yarn. Beda Ricklin, Swicofil AG. Available at: https://old.swicofil.com/viscose.html [Accessed on 22 March 2024].

Billerud (2024). Billerud – world-class corrugated packaging solutions. Available at: https://www.billerud.com/products/packaging-materials/corrugated-materials [Accessed on 22 March 2024].

Britt K.W. (2020). Papermaking | Process, History, & Facts | Britannica. Available at: https://www.britannica.com/technology/papermaking [Accessed on 13 December 2023].

ÇEVEN E.K. and GÜNAYDIN G.K. (2023). Global Trends for Fibre Production and Marketing. International Conference on Trends in Advanced Research, 1, 255–262.

Chen C., Duan C., Li J., Liu Y., Ma X., Zheng L., Stavik J., and Ni Y. (2016). Cellulose (Dissolving Pulp) Manufacturing Processes and Properties: A Mini-Review. BioResources, 11, 2, 5553–5564.

Danielewicz D. and Surma-Slusarska B. (2011). Pulping and bleaching OCC. Part I: delignification. Appita: Technology, Innovation, Manufacturing, Environment, 64, 1, 62–65.

Davis C.T. (1886). The Manufacture of Paper: Being a Description of the Various Processes for the Fabrication, Coloring, and Finishing of Every Kind of Paper. H.C. Baird & Company. pp. 660.

Dey A.K., Dey A., Dey A.K., and Dey A. (2021). Selection of Optimal Processing Condition during Removal of Methylene Blue Dye Using Treated Betel Nut Fibre Implementing Desirability Based RSM Approach. In: Response Surface Methodology in Engineering Science. IntechOpen, DOI: 10.5772/intechopen.98428. ISBN: 978-1-83968-918-5.

Emerton H.W. (1957). Fundamentals of the beating process: the theory of the development in pulps of papermaking characteristics by mechanical treatment. British Paper and Board Industry Research Association.

Fabric University History of Textile Fibers. Available at: https://www.fabriclink.com/University/History.cfm [Accessed on 13 December 2023].

Factmr (2023). Dissolving Pulp Market Analysis. Available at: https://www.factmr.com/report/1614/dissolving-pulp-market [Accessed on 19 December 2023].

FAO (2021). Pulp and paper capacities, survey 2020–2025. FAO: Rome, Italy. pp. 218. DOI: 10.4060/cb7300t. ISBN: 978-92-5-135161-1. https://www.fao.org/documents/card/en?details=cb7300t/.

FAO (2023). FAO Statistical Yearbook 2023 - World Food and Agriculture - World | ReliefWeb. Available at: https://reliefweb.int/report/world/fao-statistical-yearbook-2023-world-food-and-agriculture [Accessed on 19 December 2023].

Freeland S.A. and Hrutfiord B. (1994). Caustic treatment of OCC for strength improvement during recycling. Tappi journal, 77, 4, 185–191.

Gondhalekar S.C., Pawar P.J., Dhumal S.S., and Thakre S.S. (2019). Mechanism of xanthation reaction in viscose process. Cellulose, 26, 3, 1595–1604, DOI: 10.1007/s10570-018-2213-5.

Gøtterup L. (2020). Regenerated Cellulosic Fibres: Viscose, Modal, Lyocell, Cupro, (Tri-)Acetate - Win-Win Textiles. Available at: https://win-win.info/sustainable-concepts/regenerated-cellulosic-fibres/ [Accessed on 13 December 2023].

Grandviewresearch (2024). Corrugated Board Market Size, Share & Growth Report, 2030. Available at: https://www.grandviewresearch.com/industry-analysis/corrugated-board-market [Accessed on 22 March 2024].

Gurnagul N. (1995). Sodium hydroxide addition during recycling: Effects on fiber swelling and sheet strength. Tappi Journal, 78, 12, 119–124.

Ioncell (2024). Ioncell. Available at: https://ioncell.fi/research/ [Accessed on 17 March 2024].

Islam Md.S., Alam M.N., and van de Ven Theo.G.M. (2021). Production of textile filaments from carboxymethylated cellulosic pulps. Cellulose, 28, 14, 9475–9488, DOI: 10.1007/s10570-021-04073-5.

Islam Md.S., Alam M.N., van de Ven T.G.M., Barbeau B., and Rahaman Md.S. (2023). Antibacterial and UV protection properties of textile filaments fabricated from kraft pulp-based carboxymethylated cellulose covalently cross-linked with carbon nanotubes. Polymer Bulletin, DOI: 10.1007/s00289-023-05044-5.

Kang T.Y., Youn H.J., and Lee H.L. (2017). Effects of Fractionation and Mechanical Treatments of Korean OCC on Paper Properties. Nordic Pulp & Paper Research Journal, 32, 1, 148–154, DOI: 10.3183/npprj-2017-32-01-p148-154.

Khwaldia K., Arab-Tehrany E., and Desobry S. (2010). Biopolymer Coatings on Paper Packaging Materials. Comprehensive Reviews in Food Science and Food Safety, 9, 1, 82–91, DOI: 10.1111/j.1541-4337.2009.00095.x.

Krochak P. and Bjärestrand A. (2022). Upgrading of recycled pulp quality by fractionation and selective refining. TAPPICon 2022,.

Laivins G.V. and Scallan A.M. (1993). The mechanism of hornification of wood pulps. Products of papermaking, 2, 1235.

Latibari A.J. (2012). Extended delignification of old corrugated container and totally chlorine free bleaching of the pulp. BioResources, 7, 2, 1740–1747.

Lenzing Group (2023). Lenzing's "Naturally positive" sustainability strategy. Available at: https://www.lenzing.com/?type=88245&tx_filedownloads_file%5bfileName%5d=fileadmin/content/PDF/04_Nachhaltigkeit/Broschueren/EN/focus-paper-wood-pulp-EN.pdf .

Lima A.F., Assis T.F., Martins M.A., Stumpf P., and Bacell K.C. (2003). Developing the eucalyptus wood quality for dissolving pulp using tree breeding. Available at: www.eucalyptus.com.br/artigos/outros/2003_Developing_Eucalyptus_dissolving_pulp. .

Lindh H., Olsson A., and Williams H. (2016). Consumer Perceptions of Food Packaging: Contributing to or Counteracting Environmentally Sustainable Development?: Consumer Perceptions of Food Packaging. Packaging Technology and Science, 29, 1, 3–23, DOI: 10.1002/pts.2184.

Magnier L. and Schoormans J. (2015). Consumer reactions to sustainable packaging: The interplay of visual appearance, verbal claim and environmental concern. Journal of Environmental Psychology, 44, 53–62, DOI: 10.1016/j.jenvp.2015.09.005.

MarketsandMarkets (2024). Regenerated Cellulose Market, Industry Size Growth Forecast, Global Trends Report, [Latest]. Available at: https://www.marketsandmarkets.com/Market-Reports/regenerated-cellulose-market-99265926.html [Accessed on 22 March 2024].

Mcorsley C. (1981). Process for shaped cellulose article prepared from solution containing cellulose dissolved in a tertiary amine N-oxide solvent (Patent No. US 4246332). New York, NY: Akzona Incorporated,.

Meifen G., Ninghong W., and Guorong W. (2004). History, Status and Development of corrugated box industry. Mechanical and electrical information, 5, 31–34.

Moradian M., Islam Md.S., and Van De Ven T.G.M. (2021). Insoluble Regenerated Cellulose Films Made from Mildly Carboxylated Dissolving and Kraft Pulps. Industrial & Engineering Chemistry Research, 60, 15, 5385–5393, DOI: 10.1021/acs.iecr.1c00485.

Mordorintelligence (2024). North America Corrugated Board Packaging Market Size & Share Analysis - Industry Research Report - Growth Trends. Available at: https://www.mordorintelligence.com/industry-reports/north-america-corrugated-board-packaging-market [Accessed on 22 March 2024].

NCSU Bioproducts USDA Grant (2019). Why are people talking about the Bioeconomy Part II - Dr. Venditti. Available at: https://www.youtube.com/watch?v=n1cR1bAugQM [Accessed on 22 March 2024].

Nguyen X.T. and Simard L. (1996). On the delignification of OCC with hydrogen peroxide.

O'SULLIVAN A.C. (1997). Cellulose: the structure slowly unravels. Cellulose, 4, 3, 173–207, DOI: 10.1023/A:1018431705579.

Otto S., Strenger M., Maier-Nöth A., and Schmid M. (2021). Food packaging and sustainability – Consumer perception vs. correlated scientific facts: A review. Journal of Cleaner Production, 298, 126733, DOI: 10.1016/j.jclepro.2021.126733.

Precedenceresearch (2024). Smart Packaging Market Size to Hit US$ 60.49 Billion by 2032. Available at: https://www.precedenceresearch.com/smart-packaging-market [Accessed on 22 March 2024].

Renewable Carbon News (2020). President of Indonesia Inaugurates Country's Largest Integrated Viscose Rayon Production Facility. Available at: https://renewable-carbon.eu/news/president-of-indonesia-inaugurates-countrys-largest-integrated-viscose-rayon-production-facility/ [Accessed on 13 December 2023].

Ribeiro R.A., Júnior S.V., Jameel H., Chang H.-M., Narron R., Jiang X., and Colodette J.L. (2019). Chemical Study of Kraft Lignin during Alkaline Delignification of E. urophylla x E. grandis Hybrid in Low and High Residual Effective Alkali. ACS Sustainable Chemistry & Engineering, 7, 12, 10274–10282, DOI: 10.1021/acssuschemeng.8b06635.

Rowell R.M. (2005). Handbook of Wood Chemistry and Wood Composites. CRC Press: Boca Raton. pp. 487. DOI: 10.1201/9780203492437. ISBN: 978-0-429-20900-0.

Sappi Global (2023). Dissolving pulp - sustainable fibre for a thriving world|. Available at: https://www.sappi.com/dissolving-pulp [Accessed on 13 December 2023].

Sappi Global (2023a). Dissolving pulp. Available at: https://www.sappi.com/dissolving-pulp-0 [Accessed on 22 March 2024].

Schaefer D. and Cheung W.M. (2018). Smart Packaging: Opportunities and Challenges. Procedia CIRP, 72, 1022–1027, DOI: 10.1016/j.procir.2018.03.240.

Sixta H. (2006). Handbook of Pulp, 2 Volume Set. John Wiley & Sons. pp. 1411. ISBN: 978-3-527-30999-3.

Sixta H., Iakovlev M., Testova L., Roselli A., Hummel M., Borrega M., van Heiningen A., Froschauer C., and Schottenberger H. (2013). Novel concepts of dissolving pulp production. Cellulose, 20, 4, 1547–1561, DOI: 10.1007/s10570-013-9943-1.

Statista (2023a). Global textile fiber production by type 2022. Available at: https://www.statista.com/statistics/1250690/global-textile-fiber-production-type/ [Accessed on 22 March 2024].

Statista (2023b). Global packaging market shares by material. Available at: https://www.statista.com/statistics/271601/packaging-materials-in-the-global-packaging-market/ [Accessed on 22 March 2024].

Statista (2023c). Global paper demand by type 2021. Available at: https://www.statista.com/statistics/1089092/global-paper-consumption-by-type/ [Accessed on 19 December 2023].

SwanFiber (2023). History_Baoding swan Fiber Co., Ltd. Available at: https://en.swanoricell.com/History1.html [Accessed on 13 December 2023].

Tausif M., Jabbar A., Naeem M.S., Basit A., Ahmad F., and Cassidy T. (2018). Cotton in the new millennium: advances, economics, perceptions and problems. Textile Progress, 50, 1, 1–66, DOI: 10.1080/00405167.2018.1528095.

Thebrainyinsights (2024). Smart Packaging Market Size, Growth & Trends Forecast 2032 | The Brainy Insights. Available at: https://www.thebrainyinsights.com/report/smart-packaging-market-13461 [Accessed on 22 March 2024].

Wistara N. and Young R.A. (1999). Properties and treatments of pulps from recycled paper. Part I. Physical and chemical properties of pulps. Cellulose, 6, 4, 291–324, DOI: 10.1023/A:1009221125962.

Woodings C. (2001). Regenerated Cellulose Fibres. Elsevier. pp. 349. ISBN: 978-1-85573-758-7.
Yarnsand fibers (2020). Where is rayon produced in the world? – YnFx. Available at: https://www.yarnsandfibers.com/textile-resources/regenerated-fibers/rayon/rayon-production-raw-materials/where-is-rayon-produced-in-the-world/ [Accessed on 13 December 2023].

Zanuttini M.A.M., Courchene C., Mcdonough T., and Mocchiutti P. (2007). Upgrading OCC and recycled liner pulps by medium-consistency ozone treatment. Tappi, 6, 2, 3–8.

Zanuttini M.A.M., Marzocchi V.A., and Mocchiutti P. (2009). Alkaline peroxide treatment for improving the papermaking properties of recycled unbleached softwood kraft pulps.

Key messages and recommendations for “Wood fibre in textile, packaging and construction”

Starting point:

Wood, along with its components and materials derived from them, show significant promise for use in a variety of applications, such as insulation panels, adhesives and wood composites in construction, advanced biomaterials, and biochemicals, among others. In fact, wood and especially cellulose fibers, hemicellulose and lignin are considered as fundamental resources for a sustainable and carbon-neutral bioeconomy.

The properties of biodegradability, high strength, and low density that these raw materials display, make them a promising resource, with the potential to replace scarce, polluting and energy-intensive materials such as fossil plastics and steel. However, most applications require the separation of cellulose fibers and their modification, which presents important sustainability challenges related to energy and water consumption, environmental footprint, as well as product recycling alternatives.

On the other hand, production of cotton, for example, consumes pesticides and over ten times more fresh water than production of wood for **textile fibers**. Dissolving pulp is used as raw material for regenerated cellulose fiber (RCF) for textile, which can be further processed in different fibers (viscose, lyocell, acetate, rayon). The global market has been growing rapidly (mainly in Asia) in the 21st century and is expected to increase further.

Paperboard (cardboard, white paper and paperboard) is used as **packaging** material worldwide for approximately 33%, whereas the contribution of non-renewable plastic materials encompasses 44%. The packaging paper demand is growing because of increasing e-commerce, people’s positive perception of packaged goods, concern for environmental sustainability as well as safety and intact quality of the goods during transport. The benefits of paper-based packaging include its biodegradability, recyclability, attractiveness, and reduced cost.

As both markets (textile, packaging) will further grow in the future, **recommendations** towards a circular, sustainable and carbon-neutral bioeconomy **in the textile, packaging and** (partially) **in construction** were developed:

- Use of wood in textile and packaging products is a significant **business opportunity**, which is, however, conditional to **stable and sufficient supply of proper-quality raw materials** and extensive **investments** (especially in the Global South countries). Reasonable relations between sustainable resource management and industrial growth have to be maintained.

- The incorporation of wood fibers into different products does not mean that they are automatically preferable from a sustainability point of view (e.g. production of nanocellulose is quite energy-intensive). Also, the **substitution effect** of fossil alternatives can vary significantly because the impact of greener alternatives is highly dependent on local conditions. **Alternative fiber sources** to virgin wood should be analyzed for production of functional materials with **emphasis on circularity by using residual and recycled materials**. The **evaluation of the environmental (e.g. LCA – life cycle assessment, CO2 foot print)** and **social** (ethical reviews) **impact** of technological solutions (including posttreatments) aimed at introducing new products based on wood and its components or composite materials to the market should be conducted.

- **Legal regulations** and comprehensive necessary frameworks such as quota for the **collection of used textiles and packaging materials** respectively **the reuse of textiles** should be conducted.

- Countries with a long tradition and state-of-the-art know-how on sustainable supply chains (e.g. Finland with regularly updated "Best Practices for Sustainable Forest Management" [11]) can contribute to the evolution of sustainable wood-based textiles and packaging expertise in Global South countries by, e.g., **knowledge transfer, education, training, and business partnerships.**

- **Research, development and innovation activities** should be supported as many unexploited material properties of wood have still to be discovered and some production processes need improvements (e.g. for cellulose dissolution and regeneration processes in the textile sector). **Collaboration** between and within Global North and South countries should be fostered amid academia, government, and industrial actors (e.g. knowledge exchange based on "Best practices"). It is crucial to encourage productive discussions and partnerships among various stakeholders globally towards a sustainable bioeconomy.

- **Awareness raising programmes** (for consumers, industries, designers, governments) to reduce cheap, short life-cycle and single-use fashion and packaging should be conducted. A holistic and participatory formulated understanding on acceptability, desirability, and sustainability of exploiting natural resources has to be promoted.

- **Legality, transparency, equality, and sustainability of the supply chains and businesses** are prerequisite. The ways of operating within the society must be adapted according to local regulative conditions, regimes and culture, so that a sustainable and just transformation can be supported.
- The substitution of fossil raw materials with renewable resources must be linked to the **design of circular products and processes**, including both cascade principles and massive, simple, and effective recycling.

- In addition to **virgin wood**, other renewable materials such as **non-wood and recycled paper** can be used for **dissolving pulp production in the textile process**. This production can be integrated into **forest biorefineries**. More research is needed to implement these innovations.

- As global markets are growing, producers of **resource-efficiently generated wood-based textiles** have to be extended and supported (e.g. investments to improve the production techniques and thus reducing production costs).

---

[11] https://metsanhoidonsuositukset.fi/en

- Further **research and investments** on the most **environmentally friendly methods in the textile processes** (e.g. **CMC** – carboxymethylation of cellulose instead of the xynthation method, **Ionic liquids** for cellulose dissolution instead of toxic chemicals) are necessary to avoid harmful chemicals in textile fiber production, refurbishing the production process, and adopting circularity to minimize the generation of toxic wastewater.

- Despite existing global production, expected increasing **demand of wood-based packaging materials** opens space for **new cost-competitive producers**. Policymakers should discourage and set up regulations to restrict the use of plastic materials and **encourage bio-based packaging materials**.

- More **research and investments** are important to improve the quality of virgin-like and even bleachable pulp from OCC (Old Corrugated Container), thus increasing wood fiber in the packaging sector and **circular bioeconomy**. This concept is especially important for forest deficient countries (like Bangladesh, Pakistan, Middle-East countries, etc.).

- More **research and investments** are needed to improve barrier properties of paper for **packaging** (e.g. for food). Bio-based materials such as **nanocellulose, nano-chitosan, sodium alginate etc.** can be explored for improving food packaging. Additionally, due to the unique (barrier and mechanical) properties of nanocellulose an incorporation of sensor-based technologies in **smart food packaging** (e.g. embedded traceability) is possible and facilitates the relevant LCA. Nevertheless, the effects on human health are not completely known and need further research.

CONCLUSIONS:
KEY MESSAGES AND RECOMMENDATIONS IN GENERAL

Derived from the expertise of all the scientists involved in the "Wood for Globe"-Project, the following key messages and recommendations were jointly developed, which refer to both topics ("Wood in construction" as well as "Wood fibre in textile, packaging and construction") and are aimed in particular at political decision-makers:

- **Sustainable wood policies** have to be implemented in every country. These are policy measures that, based on **sustainable forest management**, encourage and promote the supply, processing and use of wood in a sustainable and resource-efficient way and replace fossil fuel-based products and scarce non-renewable raw material.
- **Wood** is a diverse, versatile, durable, and biodegradable material with aesthetic appeal, high strength, reusability, and recyclability. It holds strong potential for **various applications**, such as in construction, packaging, food packing, textiles, biochemicals, and other sectors, optimizing the balance between local and global value cycles.
- An effective **balance between conserving and restoring valuable forests,** safeguarding biodiversity and sensitive ecosystems, and the **sustainable use of wood** for wood-based materials has to be found for every country. Reforestation (with agroforestry practices) in areas with sparse forest-resources should be promoted.
- As the substitution of non-renewable materials in different sectors cannot be tackled with wood alone due to limited resources a comprehensive **societal, consumption-minimized transformation** (especially in the Global North) is necessary. In this context **awareness raising programmes** are needed to promote a holistic understanding of the sustainability of exploiting natural resources.
- The **evaluation of the environmental** (LCA – life cycle assessment, CO2 footprint) and **social** respectively **socio-economic** (e.g. food security, fair salaries, local small and medium-sized enterprises, green jobs) **impacts** of new products and processes based on wood and its components or composite materials should be conducted. In this context **regionally sourced materials** should be preferred.
- Emphasis on **circularity, cascading principles and resource-efficiency** is needed. This requires already at the beginning of the process an appropriate **integrated design**. The traditional use of fuelwood in some countries should be therefore reconsidered and alternative renewable energy sources should be promoted.
- **Legal regulations** and comprehensive **policy frameworks** and **investments** are necessary to foster and implement sustainable forest management and innovative, circular, environment-friendly wood-based solutions. Additionally, **forest certification processes** to ensure sustainable practices and responsible harvesting should be further enhanced.

- **Education and training** have to be improved according to the new challenges towards a sustainable bioeconomy, especially in the Global South countries, to enhance local production capabilities, and promote technological decentralization involving investors and public-private partnerships for financial support.

- **Research, development and innovation activities** (e.g. unexploited material properties of wood, environmental impacts of the whole value chain, improving circularity) should be supported by governments, NGOs, industries and international organisations.

- **Collaboration, knowledge transfer and business partnerships** between and within Global North and South countries should be fostered involving academia, government, and industrial actors. Also, the participation in **international collaboration and organization platforms** should be strengthened.

- **Legality, transparency, equality, and sustainability of the supply chains and businesses** are prerequisite. The ways of operating within the society must be adapted according to local regulative conditions, regimes and culture, so that a sustainable and just transformation can be supported.

The **more detailed, specific key messages and recommendations** related to the both topics "Wood in construction" as well as "Wood fibre in textile, packaging and construction" can be found **in the respective chapters at the end of each scientific expertise**.