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RESEARCH ARTICLE

Forest Sector in a Sustainable and Circular Bioeconomy: Sustainability and Circularity of Forest-Based Value Chains

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ABSTRACT

This article analyses the existing and possible limitations to an increased circularity in forest-based value chains in the construction, furniture manufacturing, cellulose-based fibers, and plastics sectors. The analysis provides evidence that not all forest-based value chains can be circular in all circumstances. In some cases, the focus on circularity may cause environmental externalities, in other, it may not guarantee economic viability. Information analyzed comes desk research of existing scientific papers and previous reports. It was complemented by information from websites of organizations promoting circular economy and sustainability concepts. The analysis focuses on countries where these concepts are present in policy and research agendas, and consequently, are better documented in English scientific literature. In addition, opinion articles and discussions during the *International Conference on Cellulose Fibers* in Cologne, Germany, editions 2020, 2021 and 2022 served as a starting point for formulating original ideas and suggestions. The article concludes that to ensure sustainability of the forest-based value chains, continuous consideration, and coordination of circularity at all stages of the value chains are needed. In addition, the transition to a sustainable and circular bioeconomy needs to be enabled by the legislator and develop organically, based on the location of industries, proximity to available (waste) resources and the consumer preferences. These coordinated actions will require involvement and cooperation of different actors outside the existing sectoral silos towards a more cross-cutting value chains approach, at all levels. This will allow a progressive transition towards a comprehensive circular, bio-based system. Market forces will guide this process.

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1. Introduction

The existing economy model based on a 'take-make-consume-throw away' approach to resources management (European Commission, 2014) cannot sustain current lifestyles without growing environmental and economic risks. A progressive transition to a sustainable economic system, based on a coherent management of natural resources and a balanced consumption, is needed to increase the resilience of the global economy to the variety of economic, ecological and societal challenges, facing humanity today.

In this context, the mandate for a transition to a sustainable and circular, bioeconomy is getting stronger among political leaders and the society alike. Next to the societal and environmental benefits, the economic rationale for moving towards circular and sustainable approaches is strong, as it increases the resilience of value chains and secures the stability of supply. The transition is believed to provide a systemic shift that creates long-term opportunities, consolidating economic, environmental, and social goals.

The forest sector, situated in both the biological and the technical cycles of the circular economy, is well suited to play

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a significant role in a sustainable and circular, bioeconomy. Nevertheless, challenges to achieving an increased circularity of forest-based value chains are well present.

Most importantly, the transition towards a sustainable and circular bioeconomy generates an increasing demand for different forest-based products, in particular wood, while the regenerative capacities of forest ecosystems decrease systematically for the reasons related to climate change, the biodiversity loss, and the landscape degradation.

On the industry side, while the cascading use of the raw material is commonly applied in most of forest-based value chains, the end-of-life of wood-based products is rarely considered at the stage of primary processing. Consequently, the recovery of post-consumer waste, with a few exceptions, is not sufficiently reintegrated in the production processes. That represents an unused potential for the use of secondary raw materials.

Within this frame of reference, the forest sector, providing a renewable, biodegradable resource, has a potential to substantially contribute to the transition to a sustainable and circular, bioeconomy. Consequently, it is important to examine the sustainability and circularity of forest-based industries, their status, as well as the opportunities and the limitations resulting from such a transition.

This article analyses how the sustainability and circularity in the forest-based industries can be optimized in the context of growing demand for forest-based products and the decreasing level of regeneration of ecosystems. It aims to present a perspective on the conditions for increased circularity of forest-based value chains in support to the transition towards a sustainable and circular bioeconomy.

2. Materials and Methods

Evidence analyzed in this study comes mainly from scientific papers and reports. It was complemented by information from websites of organizations promoting circular and sustainability concepts. In addition, opinion articles and discussions during the *International Conference on Cellulose Fibres* in Cologne, Germany, editions 2020, 2021, 2022, served as a starting point for formulating original ideas and suggestions.

This paper also outlines international policy and practice promoting circularity and sustainability. It focuses on countries where these concepts are promoted in political agenda and research, and consequently are more extensively documented in English scientific literature (namely in the European region).

The results of this analysis can contribute to studies in the areas relevant to sustainable production and consumption, circular economy, bioeconomy, and forest-based industries.

3. Results and Discussion

3.1. Circular Approaches: Why They Make Sense?

Every year, humanity consumes more natural resources than there are available to allow a sustainable regeneration of the planet. Despite the product innovation and value chain optimization efforts, levels of pollution and waste generation are going up. According to the *Global Resource Outlook 2019*, the global material extraction will double until 2060, the greenhouse gas emissions will increase by 43%, the area of agricultural land will increase by 20% and the pastureland by 25% while the area of forest ecosystems will diminish by 10% and of other natural habitats by 20% (IRP, 2019). In the absence of urgent and concerted action, these unsustainable patterns in use of natural resources will continue to create pressures on the environment.

Decoupling the economic growth from the increasing demand for natural resources, the biodiversity loss, the pollution, and from waste generation, is key to putting in place a regenerative growth model, which will allow to reduce environmental footprint on the planet. In that sense, the concept of the circular economy, which aims to reduce waste by keeping products and materials in the system as long as possible and to regenerate natural resources systems (Ellen MacArthur Foundation, 2017a) can contribute to reducing environmental pressures. It can also provide cost savings, thus increase the competitiveness of the economy.

Some of the circular approaches, such as recycling, redistribution and sharing have already been functioning with the support of specific policy measures, but not yet in a systematic and coordinated way. Many circular economy strategies have been under development in cities, regions, and countries in the last couple of years, mainly in Europe. At the global level, it is a relatively new concept and its benefits have yet to be assessed, however there is a clear business case in circular approaches since closed loop models have an impact on costs and thus increase profitability of individual companies.

In terms of policy development, supportive to the transition towards circular models, the *European Green Deal* (European Commission, 2019a) and the associated *Circular Economy Action Plan* (European Commission, 2020) likely constitute the most advanced, coordinated strategy addressing the implementation of the circular economy principles so far. These documents propose changes to production-consumption patterns that aim at improving the coherence along subsequent phases of value chains, at the inter-sectoral, economy-wide and regional (European) level.

3.2. Forest Sector in a Sustainable and Circular, Bioeconomy

Among the multiple forest ecosystem services, forests provide biodegradable natural resources, which have a capacity to restore themselves through natural regenerative processes. As the concepts of circularity and sustainability have been gaining attention, the interest in forest-based products, wood in particular, has been growing as well. This momentum is likely to continue in the upcoming years as forest-based industries provide alternatives to the use of some non-renewable, non-recyclable materials, such as concrete or plastics. If based on sustainably managed forests, forest sector has a potential to infinitely contribute to the transition to a circular, low-carbon economy.

New technologies, business models and consumption patterns are creating new opportunities allowing for forest-based products to make a greater contribution to other sectors, compared to an existing role of the forest sector as a timber provider, feeding into wood manufacturing, paper and pulp, and wood-energy sectors (UNECE/FAO, 2019). Major wood components -cellulose, hemicellulose, lignin and extractives- serve as the basis to produce innovative construction materials, chemicals, biofuels, heat and electricity, bioplastics, packaging, food and feed ingredients, textiles, and pharmaceutical components.

The key advantage of the forest sector in a sustainable and circular bioeconomy lies in the fact that it can provide not only a renewable but also a biodegradable resource, which can substitute for non-renewable resources and can be used for creation of a number of innovative, reusable and recyclable materials. These materials can feed into various value chains and prompt transformation towards sustainability in a number of strategic parts of the economy such as construction, manufacturing, energy production and trade.

3.3. Sustainability of Supply Amid an Increased Demand for Forest-Based Products

A sustainable, bioeconomy model, based on circular approaches increases the emphasis placed on the use of renewable materials, including forest resources, in a number of production processes. Opportunities for the forest sector resulting from the transition to a sustainable and circular bioeconomy will strongly depend on a sustainable management of forest resources, which will ensure sustainability of source on one hand but will also limit the availability of wood in the context of an increasing demand on goods and services from forests ecosystems.

And today forests face many pressures, resulting from consequences of climate change, form forest fires, insects' infestation, non-native species propagation and from land-use management decisions, which often promote an expansion of urban and agricultural areas. Consequently, an effective forest management for a sustainable and circular bioeconomy needs to combine objectives of deriving optimal benefits from forest products and ecosystem services with those of addressing the existing threats to forests.

Beyond that, considerations of sustainability, need de facto, to take place at all stages of forest-based value chains, starting with the principles of sustainable forest management, following with an optimized cascading use of wood at every production stage, and concluding with the recovery of post-consumer wood at the end of value chains. In particular, circularity principles applied in forest-based industries will need to take into account an extended responsibility of producers for closing the loop with the post-consumer wood, which, whenever possible, should be reintroduced into the production cycle. In the linear economy model, the responsibility for production and waste creation are not interrelated, while it is at the beginning of the cycle (i.e., during the product design) not at the end, that waste can be most effectively eliminated.

3.4. Circularity of Forest-Based Value Chains

According to the Ellen MacArthur Foundation (2019)'s graphical illustration, two cycles underlie the circular economy: A biological cycle and a technical cycle (Ellen MacArthur Foundation, 2017b). Biological cycles are concerned with the management of renewable resources. Bio-based materials are designed to be restored into the natural systems and subsequently regenerated to provide renewable resources. On the other hand, technological cycles involve the management of finite resources in multiple economic cycles. This is achieved through reuse, repair, and remanufacturing of the materials and resources (CFI, 2020).

The forest sector is situated in both the biological and the technical cycle of the circular economy, as it is based on natural resources. That makes it well suited for a sustainable and circular bioeconomy. Consequently, forest-based resources need to be correctly managed and wherever possible the residue material returned to biological cycles from which they have been extracted to ensure the sustainability of the circular approach and avoid depletion of forest resources.

While considering opportunities that the circular economy creates for the forest-based industries, it is important to take into account how circularity principles such as designing out waste and pollution, keeping products and materials in use in value chains as long as possible, and regenerating natural resources systems (Ellen MacArthur Foundation, 2017a) are implemented within the sector itself.

Consequently, for the consideration of circularity aspects in the forest sector, two sorts of cycles, characteristic for all forest-based value chains can be proposed:

1) The forest biological cycle, which is at the base of forestry and involves cultivation and harvesting wood and non-timber-forest-products but also management of other resources such as water, soils, nutrients, and biodiversity to ensure preservation of forest ecosystems.

2) The forest industry technical cycle, which involves manufacturing of wood and non-wood-forest-products,

use and reuse of forest-based materials, and the recovery of post-consumer wood.

The first cycle is based on the natural cycle of forest growth and regeneration in which the dynamics of growth and regrowth create a symbiotic balance in ecosystems. This natural dynamic has been maintained and used over the years thanks to the forest inventory techniques. They constitute a main tool to managing the forests and shape their growth in combination with the optimization in the provision of forest services. Sustainable forest management aims at safeguarding ecosystem services to address societal demand, including through ensuring continuous provision of wood and other forest-based products.

The second cycle starts with a harvested tree that is taken away from the forest. Various industry practice shows how different parts of a tree can be used in a most efficient way to manufacture different products, starting from the highest to the lowest quality grade. In a typical tree, harvested for sawmilling, less than two-thirds is taken from the forest for processing, the remainder is usually left in the forest to decompose at the harvest site, providing organic material for forests soils and nourishing forest ecosystems. After sawmill processing, only 28% of the original tree becomes lumber and the remainder becomes other products (FAO, 1990).

Production side streams are used, reused and recycled to the maximum extent possible in a variety of value chains from more traditional, like wood-based panels or paper production, to more innovative, such as cellulose-based fibers and plastics production. Many value chains overlap at different stages through cascading use of by-products from one specific production process by other processes.

The European Confederation of Woodworking Industries (CEI-BOIS), the Confederation of European Paper Industries (CEPI), the Confederation of European Forest Owners (CEPF) and the European State Forest Association (EUSTAFOR) have developed an illustrative overview of 99 benefits of a tree which feed into value chains in 14 different industries (CEPF, n.d.).

Since a tree can be used in a number of different ways, many value chains overlap creating a complex system of dependencies: An industrial ecosystem. In the forest sector, there exist numerous industrial symbioses which enhance circular approaches. Value chains across different industries and different service providers promote cross-sectoral collaboration and support industrial clusters that share a mutual interest in resource efficiency, thus reducing an ecological footprint for each stage of production.

Good practice in resource efficiency in forest-based industries brings the forest sector closer to the principles of a sustainable and circular bioeconomy. Nonetheless, challenges in overall circularity of forest-based value chains are well present. They are often related to the limitations in sustainable sourcing of raw material and to unsustainable (linear) consumption of forest-based products.

Therefore, building on the Ellen MacArthur Foundation (2017a)'s principles of a circular economy, it is proposed that the circularity of forest-based value chains is analyzed throughout three respective stages, for a complete representation:

1) Sustainability of forest resources management (Ellen MacArthur: Ensuring regeneration of the ecosystems biological cycle).

2) Circularity of the forest industry technical cycle (Ellen MacArthur: Keeping the materials in the production cycles as long as possible through reuse and recycling).

3) Recovery and reuse of post-consumer wood (Ellen MacArthur: Reducing the pollution and the waste generation).

This approach will allow a more comprehensive consideration of the above-mentioned aspects of circularity in a view of a long-term sustainability of the sector. For instance, it is possible to increase the reuse of residual volumes of biomass from industrial processes to produce cellulose-based chemical compounds, creating additional gains in resources efficiency in the production processes. This reuse will allow to lower pressure on forests and residual volumes of biomass in forest ecosystems and may be more sustainable in a long term.

Another question related to the circularity of forest-based value chains is the reintegration of post-consumer wood into the production processes. It has been analyzed in the next section.

3.5. Management of Post-Consumer Wood: The Challenge of Closing the Loop

Post-consumer wood is the wood generated by the end-users of wood products that has fulfilled its intended purpose, including material returned from within the distribution chain (ISO, 2019) There are many challenges related to the management of post-consumer wood streams. First, there is no standard classification of post-consumer wood at the international level. Some countries have developed their own classifications (e.g., Germany) and apply them in trade with neighboring countries. However, no internationally recognized standard that would allow for identification and monitoring of different post-consumer wood quality, exists.

The recipients of wood waste streams, the wood panel industry and wood energy facilities, can take almost any quality of wood residues. A potential classification at the international level could unfold new outlets for valorization of upper quality of these residues -a positive development in the context of a circular economy- but it would create shortages in these two markets, which are currently competing for the raw material.

The second challenge related to the management of the post-consumer wood is the limited number of collection and sorting facilities. Paper recycling is an exception in this regard, as its recycling rates are high and economic viability is satisfactory in most areas. However, paper industry results cannot be simply replicated for the recycling of other wood-based residues. First, the sources of wood waste streams are various, contrary to paper which is mainly recovered within municipalities with easier-to-manage logistics. Second, sorting technologies are not widespread for most wood-based materials, contrary to sensor-based technologies for paper, which makes the recycling dependent on manual recycling. This labor-intensive technique incurs relatively high processing costs, an inconsistent end-product quality and health risks for people working at manual sorting facilities (e.g., exposure to microorganisms and dust).

The third challenge is related to the fact that post-consumer wood is a very low density and very low value product, leading to geographical limitations as regards the cost of transport and environmental sustainability of value chains.

In addition to the challenges related to the exiting post-consumer wood streams, innovative cellulose-based materials, such as textile fibers and plastics also come with new challenges for the recovery of their residues after use. These products are extremely diversified and their markets highly fragmented, consequently no coordinated system for their waste streams recovery exists. These new sectors are neither sufficiently structured yet in terms of quality standards nor organized in terms of industry representation to ensure the consistent approach to industrial symbiosis and circularity of their business models. Information about sustainability of cellulose-based fibers and plastics is often confusing, terms such as ‘recyclable’, ‘biodegradable’, ‘compostable’ are often used interchangeably, however they do not mean the same. Some of the products are biodegradable or compostable only in specific industrial conditions, which requires a development of a well-connected network of collection and sorting, not existent today.

All these challenges provide evidence that in practice not all forest-based value chains can be circular at any circumstances. In some cases, the focus on circularity may cause other externalities which do not guarantee sustainability in the long term (e.g., due to the impact of transport). The elimination of these externalities depends on a coordinated action at all stages of value chains including the extended producer’s responsibility, progress in eco-design, investment in collection infrastructure, availability of technologies supporting sorting process, geographical proximity of the waste stream users etc.

Finally, it is important to highlight that while the transition to a circular and sustainable economic system can be enabled by the legislator, it will need to develop organically based on the location of industries, proximity to available (waste) resources and the consumer preferences. Market forces will guide this process.

3.6. Understanding Limitations to an Increased Circularity in the Forest-Based Value Chains

Wood and other forest-based materials have an excellent potential to be an origin of circular value chains. Though benefits associated with the of use of forest-based products are known, much yet remains to be done, in the view of making forest-based value chains truly sustainable. That implies continuous implementation of sustainable forest management, development of long-term strategies for near-by sustainable wood supply, efficient processing of wood and its by-products as well as well-organized collection of and reuse of end-of-life wood residues.

The concept of a sustainable and circular bioeconomy is not yet widely familiar to forest-based industry actors. However, as they are familiar with the sustainable forest management and the optimized use of wood as raw material, the transition towards sustainable circular approaches should not be problematic, provided it is economically viable. Examples in the previous section demonstrate that the biggest effort will be needed in the collection and recycling of post-consumer wood streams with the view to developing complete circular value chains.

Recovery and reuse of raw materials have different meaning in different sectors. The most recycled materials such as steel, aluminum and glass, can be transformed into identical new products, and used again, often by the same sector.

In the forest-based industries, the meaning of recycling is different. Wood and derived wood products, recovered at different stages of production processes, do not constitute a homogenous raw material which can be recycled and reused in the same form. Paper, that can be recycled up to 4-7 times and transformed into new paper products, as well as some elements of wood construction, which can be reused in their original form are exceptions to this rule. Other woody resources are recovered according to the cascading use[1] of wood and they contribute to the creation of new products. Increased recovery and reuse of wood and of cellulose-based materials through cascading use has its merits in the context of transition to a sustainable and circular bioeconomy, but also its limitations. Some of the most characteristic forest-based value chains are reviewed in this section. This list is not exhaustive.

3.6.1. Construction

The construction sector uses wood in various forms and stages of processing for different applications. Sawn wood, in

[1]Cascading use is “The efficient utilization of resources by using residues and recycled materials for material use to extend total biomass availability within a given system” (European Commission, 2016).

the mainstream of use, has traditionally been used in single family buildings. With the emergence of the engineered wood products, such as glued-laminated timber (glulam) or cross-laminated timber (CLT), wood has been increasingly used in large-scale construction, including residential, office and public utility buildings. Related to this, a high degree of customization and application of wood for almost any building part, including load-bearing structures, is transforming the wood construction sector, and is contributing to the material efficiency (Verkerk et al., 2022). In addition, Cabral and Blanchet (2021) revealed that wood buildings account for 90% of single-family homes in Canada and the United States of America, 45-70% in parts of Europe, and 45% in Japan. In new constructions, the off-site wood construction technology, which involves a digitally precise design, fabrication, and assembly of new building elements at a location different than the installation site, offers the most promising optimization of value chains with a minimum waste, from the circular economy perspective. However, the highest potential in increasing circularity in the sector lies in utilization of construction and demolition wood from the renovation and the decommissioning of already standing buildings.

Wood is applied in different construction stages (e.g., foundation, structuring and building works) and in various parts of buildings (reinforcement of structure, windows, floors, etc.). Therefore, applying circularity approaches to construction value chains through innovative design, regular maintenance, adaptive reuse, refurbishment, repair, recovery, and recycling can help to recapture part of its value of the built environment, including wood buildings (Delphi Group, 2021). In this way, construction sites can contribute to a sustainable, circular economy by providing a source of secondary wood which can further be recycled through a cascading use.

Wood recovered from construction sites enters waste streams mainly when buildings are demolished. In individual construction sites these amounts are often marginal but could become substantial if gathered at the national or regional level. However, what makes the recovery feasible -the quality and the consistency of these streams- remains a challenge because:

1) Part of the wood is contaminated with non-wood materials (e.g., nails, paints, glues).
2) Wood is often mixed with other waste from construction and demolition (e.g., concrete, stones).
3) Irregular shapes and sizes of wood elements make the collection and the logistics complicated.
4) Construction and renovation projects are often long and involve number of actors at different stages, making the planning of waste recovery complicated.
5) High demand in wood energy and in wood panel industry, which can accept almost all qualities, does not encourage the development of other markets for higher qualities.

For these reasons, sorting and recovery of wood waste streams from construction remains challenging and economically not so interesting. In a long term, it is possible that technology innovation applied in wood sorting and new approaches to the optimization of collection strategies (WRAP, 2012) can improve the situation, however probably only a fraction of the recovered wood will be of good-enough quality to ensure further cascading use for increased circularity in this value chain.

3.6.2. Furniture manufacturing

The furniture manufacturing sector is also accountable for a considerable consumption of wood. In the European Union (EU), it is estimated that 30% of the materials that go into furniture production is wood. Then again, more than two thirds of particleboard and about half of the medium density fibreboard (MDF) production are used in the furniture sector (European Commission, 2016). Consequently, the furniture manufacturing sector is one of the wood-based industries worth looking into for increased material efficiency and circularity in the value chains.

The efforts to improve circularity and resource efficiency in the sector are related to sustainable sourcing of raw material, which would ideally focus on either recycled wood or virgin wood obtained from sustainably managed forests (UNECE/FAO, 2022).

Besides sourcing the raw material in a sustainable manner on the producer's side, circular approaches in the furniture production, should be complemented with the 'avoid' principle on the consumer's side. In many countries, the growth of the furniture industry relies on shortening the replacement cycles by stimulating consumers to buy new furniture before their existing one is used. Product marketing is prompting consumers to buy new furniture for design and fashion reasons. As furniture purchases compete with other optional consumer spending, the demand for low-cost product segments have developed to address the increasing demand driven by a raising interest in interior design (ITC/ITTO, 2005). Improvement in this area requires concerted action of different actors beyond the industry (e.g., market regulators).

Next step in the circularity consideration is the decision on if and how to use wood so that it can be reused: The eco-design. This for instance includes standardized-modules design, which enable customers converting furniture items into alternative uses, the replacement of specific parts, and the addition of new elements.

Furthermore, reuse as well as repair, refurbishment and remanufacture services would allow further value recovery. However, whilst furniture recycling rates in the EU have improved thanks to the introduction of policy mechanisms such as the Landfill Directive (European Union, 1999), there is minimal activity in higher-value circular resource flows, with furniture remanufacturing accounting for less than 2% of the EU manufacturing turnover (EEB, 2017). The demand for second-hand furniture (reuse) is low. Also, creation of new loops through recycling of furniture wood is complex due to the content of composite products such as wood-based panels, limiting the possibilities of further cascading use. Consequently, in many countries, furniture residues receive no particular attention under waste management systems.

Overall, an effective strategy for an increased circularity in the furniture manufacturing sector would need to include:

1) Raising awareness about sustainable production and consumption patterns to decrease the demand for new, low-cost furniture.
2) Eco-design: Allowing disassembly and reassembly, repair or reuse of furniture modules for alternative uses as well as for separation of solid wood from fiberboards, metal, glass and plastic elements, for recycling.
3) Availability of spare and alternative parts, extending the durability and longevity of furniture elements, accompanied with guidance services on maintenance and repair in order to extend the product lifespan.
4) Extended producer responsibility and possible reverse logistics infrastructure to ensure furniture take-back, preventing landfill or incineration.
5) Increased material efficiency, including increased use of recycled sources in production of new furniture.

Currently, charity schemes and other social initiatives help improve the economics of furniture collection, however economies of scale are needed to make the reuse, the repair and refurbishment of furniture truly economically viable in order to drive more sustainable consumer behavior. As regards wood recovered from furniture, challenges related to its collection and sorting are similar to those in the construction sector.

3.6.3. Cellulose-based fibers

The textile industry, of which the cellulose-based fibers are part, is one of the biggest economic sectors, with complex, global value chains. Although cellulose-based fibers constitute only 6% of the global fibers market (Engelhardt, 2020), the demand for them has been steadily growing in the last two decades and is foreseen to continue to do so. This trend is related to the stagnating production of cotton (predicted cotton fibers market growth till 2025: 0.75%; polyester fibers: 3.75%; cellulose-based fibers: 4.75%) (Lansdell, 2020). Although the recovery in the sector after COVID-19 pandemic lags behind the general economic growth, textile industry remains a growth model and the growing awareness and new stimulus for sustainability will have a positive impact on the sector (Engelhardt, 2021). According to Claesson (2022), wood-based cellulose fibers will constitute 8% of the market in 2030.

Although more sustainable, because of the bio-based and biodegradable raw material, cellulose-based fibers value chains face the same circularity challenges as clothes produced from other fibers. For instance, the biodegradability of cellulose-based fibers should not justify the overproduction in the textile industry and the fast fashion model (personal notes, First International Conference on Cellulose Fibres, 2020). Therefore, because of limited sources distinguishing this segment of the market, most of information in this section is related to the garment industry production in general. Clothes production is even more prone to demand generated by fashion than in the furniture industry and it is a sector characterized by an enormous raw material footprint and waste generation. The fast fashion trend has been shaping the production and consumption patterns implying frequent purchase of products that only last one season and consequently lead to the concept of disposable clothing (UNECE, 2020).

Another specificity which impacts sustainability, and a possible circularity of the sector is the geographic extension of value chains at the global scale. Dissolving pulp is mainly produced China, East Asia and India, where most global textile production takes place. Ready-to-wear garments are then shipped to Europe and North America. This geographical fragmentation of value chains makes ‘closing of the loop’ with recovered materials practically impossible.

Instead, a system combining a reuse and cascading use of worn fabrics is in place. Secondhand clothes are often sorted and resold or redistributed by charities, while lower grade fabrics are used by other industries (e.g., for insulation material, wiping cloths, mattress stuffing). Still, 73% of materials used for clothing end up in landfills or are incinerated (Ellen MacArthur Foundation, 2017c).

Cellulose-based fibers from alternative feedstocks e.g., agriculture residues, municipal residues, textile recycling, etc. are key to an increased circularity of value chains. It is estimated that 50% of the current raw material supply can be replaced by these alternative sources (personal notes, First International Conference on Cellulose Fibres, 2020).

However, although the recent research (Cordeiro et al., 2022) shows that in the next five to ten years paper pulp, micro fibrillated cellulose and recycled textiles can technically become viable sustainable alternative stocks for textile production, they also have their practical limitations related to building of the logistics, and infrastructure for material recovery and the unreliable production cycles.

An optimal recovery of post-consumer residues is hindered not only by irregularity of stream flows, but also by the inconsistency in the quality of waste, the questions related to the sustainability of transport and the content of elastane: If it is higher than 7%, the chemical recycling cannot succeed. Also, the implementation of circular approaches in the sector will succeed only if the price of the waste streams remains low and their availability stable (personal notes, First International Conference on Cellulose Fibres, 2020).

Thus, the absolute sustainability imperative in this sector is to produce less.

While the development of technologies and infrastructure is already sufficient to allow recycling of cellulose-based fibers into new products, relevant regulations prompting change of production patterns (e.g., to eco-design allowing recycling, proximity of value chains), and new consumption models (e.g., including the extended producer responsibility and eliminating fast fashion) play a key role in facilitating the transition towards a more circular system. In addition, likewise in the management of the construction and furniture waste streams, the increased circularity of the cellulose-based fibers value chains will depend on the commercial viability of circular approaches.

3.6.4. Cellulose-based plastics

There are different types of plastics for different uses. In most cases, plastics are made from fossil fuels and only few types of them can be recycled. This creates major environmental challenges (CO_2 emissions, waste creation) and an increasing threat to the human health (related to micro- and nano-pollution of water and food).

Cellulose-based plastics are bioplastics manufactured using cellulose or derivatives of cellulose. They are manufactured using softwood as the dominant raw material. Regulations imposed on limitation in use of plastics have led to a surge in demand for bioplastics and thus for cellulose-based plastics. However, the development of bioplastics is still relatively slow due to a comparatively high cost of their production over the conventional plastics.

Cellulose-based plastics use a bio-based material for their making, however, in the view of a sustainable and circular bioeconomy, it is important to mention that not all of them spontaneously decompose into the natural environment. The decomposition depends on the chemical process of which they are a result. In most cases, biodegradable bioplastics will only break down in industrial composting facilities, with adapted temperature and atmosphere conditions.

Generally, bioplastics can be divided into the following categories:

1) Bio-based and non-biodegradable.
2) Bio-based and biodegradable.
3) Fossil-based and biodegradable (European Bioplastics, 2018).

Biodegradable and compostable bioplastics have been on the market for more than 25 years (European Commission, 2019b) however, there is still confusion about what they are, which raw materials have been used for their production, to what extent they are bio-based, and how to recycle them. In this context, it is difficult to estimate the market share of the cellulose-based plastics (which are only one type of bioplastics) and to analyze the circularity of their value chains. Yet, based on the evaluation of the bioplastics sector in general, the following assumptions on the existing gaps and solutions needed for their increased circularity can be made:

1) Extended producer responsibility schemes would drive product design towards collection, sorting and recycling or reuse of bioplastics by specific category.
2) Identification labels for specific bioplastics categories would facilitate collection and sorting for reprocessing or composting according to these categories.
3) Public (e.g., community collectors) and private (e.g., at retail points) recovery infrastructure would enable collection, sorting and recycling of different bioplastics according to each category.
4) Regulations, including on health and environmental safety aspects related to the use of bioplastics, would support the creation of after-use market and allow application of recycled bioplastics for different purposes, according to cascading use, e.g., food grade packaging materials, after reprocessing, could be recycled for industrial applications.
5) Development of industrial composting infrastructure would allow biodegradation of those bioplastics residues which cannot be reused or recycled.

Many innovation and efficiency improvements promoted in bioplastic value chains have a potential to improve the circularity of the sector, however their implementation so far has been fragmented and uncoordinated to have an impact at scale on the entire sector. For instance, a variety of small-scale, local initiatives improving collection schemes have been introduced, however they are rarely coordinated at the national or regional level. Likewise, new sorting and reprocessing technologies have been developed, but they have not been implemented at a commercial scale yet.

Increased consumer awareness is also a key concern for the sector (UNECE/FAO, 2022). Independent certification and labelling schemes have emerged, but they rather focus on informing consumers on pragmatic features of the products, such as if the product is biodegradable or compostable, rather than the specification of their exact composition. That hinders public understanding and creates confusion about possible reuse and recycling of these bioplastics. In this context, increasing the after-use value of bioplastics, which would allow the economic viability of keeping the recovered materials in the system, remains a challenge.

4. Conclusion

The existing economy model based on a 'take-make-consume-throw away' approach cannot sustain current lifestyles without growing environmental and economic risks. Decoupling the economic growth from the increasing demand for natural resources can be achieved through a transition to a sustainable and circular bio economy approaches leading to a regenerative growth model, allowing to reduce environmental footprint on the planet.

The concept of a sustainable and circular, bioeconomy is relatively vague and leaves room for interpretation as regards related areas of economic activity. As demonstrated in previous sections, the circular efficiency of the forest-based value chains may concentrate at their various stages in different sectors. However, the design for the end-of-life valorization, aiming to reduce the amount of post-consumer wood, is key to all sectors.

All forest-based materials are bio-based, therefore in principle, all forest-based products can be naturally decomposed, if properly designed. They are also renewable. Wood, in particular, has a high value as a renewable material. Therefore, almost all of its production side-streams become raw materials for other streams, including the smallest off-cuts. This material efficiency, known in the forest-based industries for centuries, contributes to the sector's circularity.

In addition, in the context of the increasing demand for the forest-based products, the coordination between the biological cycle of forests and the technical cycle of forest-based industries will need to be strengthened to ensure the circularity along the value chains. For instance, when a tree is left in the forest, although it does not serve the economy, it serves ecosystems.

A successful transition towards a sustainable and circular bioeconomy requires breaking the silos of sectors and linking it with the objectives of the sustainable development and a low carbon economy. A sustainable and circular bioeconomy is in fact often seen not as a standalone objective, but as means to achieve the three dimensions of the sustainable development: Economic viability, environmental protection, and social equity. At the same time, it is perceived as means to reduce the catastrophic consequences of climate change through a shift from an economy which depends heavily on fossil fuels to a low carbon economy that relies more on biomass use as a natural carbon sink and a source of bioenergy.

So how a successful transition to a sustainable and circular bioeconomy can be enabled?

Transition efforts should focus on holistic approaches which extend beyond the creation of circular value chains with bio-based products. They should include the design of circular business models, supported by the design of circular services, and minimizing ecological and social costs. This can be done through the application of new technologies and organization methods (e.g., the production of off-site wood construction elements with minimum waste and assembly on the construction site) the product innovation (e.g., the development of biodegradable bioplastics which can degrade in the nature at the end of their life-cycle), but also through value chains optimization (e.g., inclusion of repair services). However, above all, a successful transition requires the design and implementation of:

- Enabling national strategies (economy-wide, cross-sectoral or sector targeted, e.g., promotion of wood construction),
- supporting policies (e.g., public procurement criteria giving priority to bio-based materials and products) and
- related funding.

These coordinated actions will require involvement and cooperation of different actors outside the existing sectoral silos towards a more cross-cutting value chains approach, at the macro and micro levels, to allow a progressive transition towards a global circular, bio-based system.

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Conflict of Interest

The author has no conflicts of interest to declare.

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