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Wood-Based Products in the Circular Bioeconomy: Status and Opportunities towards Environmental Sustainability

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Abstract: The circular bioeconomy offers solutions to curb the effects of climate change by focusing on the use of renewable, biological resources to produce food, energy, materials, and services. The substitution of fossil products by wood-based products can help avoid or reduce greenhouse gas emissions over the life cycle of products. However, it is important to understand the potential impacts of large-scale material substitution at the market level. This study aimed to assess the role of selected wood-based products in the circular bioeconomy, the possible changes in their markets, and investigate which elements could ensure the environmental sustainability of these products. The demand for graphic paper has declined over the last 15 years, while the demand for packaging has increased. Cross-laminated timber and man-made cellulosic fibres have seen their global consumption increase over the last decade. While there are benefits associated with the substitution of non-renewable materials by wood-based products, there is still limited understanding of the substitution effects at market-, country- and global level. Some factors enabling the further uptake of wood-based products include initiatives that stimulate technological change, incentives to produce or consume less fossil-based and more bio-based alternatives, and the promotion and marketing of wood-based products as viable alternatives to non-renewable materials.

Keywords: wood-based products; circular bioeconomy; market development; climate change impacts; environmental sustainability

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1. Introduction

Global economic growth has brought prosperity and wellbeing to people, but has also contributed to the overexploitation of natural resources [1], thereby putting its sustainability into question. The volume of natural resources extracted each year, such as biomass, fossil fuels, metal ores, and minerals, increased twelve-fold between 1900 and 2015 [2]. If this trend continues, global natural resource extraction is expected to more than double until 2050, resulting in a major increase in greenhouse gas (GHG) emissions and contradicting the need to significantly reduce emissions to achive global climate targets [3,4].

The concept of the circular bioeconomy has risen in importance in recent years as a means for tackling challenges such as the overreliance on non-renewable natural resources [5–8]. While initially the understanding of the bioeconomy focused on resource substitution and biotechnology [7,9], the concept has been broadened to encompass sustainability, services, and circularity aspects [10–13]. More recently, the bioeconomy has been defined as "the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors and enable a transformation to a sustainable economy" [14].

Forests and wood-based products are essential to the circular bioeconomy model. Forests are natural systems that provide multiple goods and ecosystem services, including raw materials, various non-wood forest products, climate regulation, carbon storage, and biodiversity, which constitute important contributions to the economy [15]. Wood and wood-based products can contribute to climate change mitigation through carbon storage in materials and by avoiding GHG emissions through material and energy substitution. Such substitution involves the use of wood instead of other materials (e.g., concrete, steel, plastics) to avoid or reduce emissions over the life cycle of products [16]. The forest-based sector has been developing new and innovative products that have potential for substituting fossil-based materials [10,17] in applications such as textile fibres, composites, chemicals, and packaging materials [18,19]. However, there are no comprehensive studies that synthesize information on market development and environmental impacts of wood-based products of different typologies.

Numerous studies have been conducted to quantify the substitution effects at product level (for overviews, see [16,20–22]); however, it is also important to understand the potential impact of large-scale material substitution at the market level [23]. Therefore, this study aimed to shed light on the role of wood-based products in a circular bioeconomy. Specifically, we tried to answer the following questions: (i) how have markets been developing for selected wood-based products?; (ii) how can these products contribute to climate change mitigation and to reduce environmental effects?; and (iii) what are the factors enabling the products' further uptake? This study contributes to the research topic by pointing out novel technologies and product developments, presenting alternatives to traditional products that could contribute to reducing the overreliance on non-renewable materials and synthesizing information on markets for the selected wood-based products.

2. Methodology

The forest-based sector is evolving and becoming more complex through diversified product assortments [18,24,25]. In this study, we defined the major wood processing industries as lumber, wood panels, and the pulp and paper industries. Considering the trends in woody biomass consumption and the expected changes in wood-based products markets [18,26,27], we focused on the following products from these industries: Cross-Laminated Timber (CLT), paper and paper products, and Man-Made Cellulosic Fibres (MMCF). The selected wood-based products should also have global importance, being manufactured and/or consumed in several global regions [28]. Because of the potential of biochemicals to substitute petrochemicals [29], we also included potential products from biorefineries. More specifically, we focused on biochemicals that were or that could be produced in biorefineries integrated with pulp mills, i.e., crude sulphate turpentine and derivatives from black liquor. The literature on selected wood-based products was compiled from the online databases Web of Science and JSTOR, as well as through Google-based searches for peer-reviewed scientific papers, scientific and market reports, and white papers, published in English.

For the climate effects of wood-based products, we report on substitution factors, which describe the avoided emissions per unit of wood when producing a product from wood instead of a fossil-based or GHG-intensive material. For this purpose, we relied on a database of substitution factors compiled by Leskinen et al. [21], who conducted a systematic review of studies on substitution effects. Their review only included studies that provided original substitution factors, or that contained GHG emission data for a wood product and a functionally equivalent non-wood product that could be used to calculate substitution factors. We used this database and collected additional studies using the same data collection criteria and processing steps as done by Leskinen et al. [21].

3. Results

3.1. Cross-Laminated Timber

3.1.1. Market Development

Recently, a lot of research attention has been given to the development of mass timber buildings. This originated in Europe due to the impetus given to high-rise building construction, which was made possible due to the performant qualities of engineered wood products, such as CLT. This product has many advantages for construction systems, including their dimensional stability, possible large size of individual elements, and the installation speed at the construction site [30]. Good thermal and fire performance further add to the suitability of this material in construction [31].

Currently, there are 70 registered CLT manufacturing companies across the world [32]. The global annual production is still relatively small, estimated at 2.0–2.5 million cubic metres [33]. Germany, Austria, and Switzerland account for 70% of global output, followed by 14% for the remainder of the European Union (especially Italy and France), 12% for North America, and 4% for the rest of the world [33]. According to estimates, around 1.8 million cubic metres of CLT are produced each year in Europe, mostly for floors, roofs, and walls [34].

In North America, the current production capacity of CLT plants in the United States and Canada combined is estimated at 910 thousand cubic metres [28]. Unlike in Europe, 65–70% of CLT used in North America is used in industrial applications as access and crane rig mats and temporary pavement [28,32].

The production of CLT is also increasing in other global regions. At least two plants have started manufacturing CLT in Russia in 2021 [35,36]. One of the facilities has an estimated production capacity of 50 thousand cubic metres per year [36]. Japan currently produces around 30 thousand cubic metres of CLT per year. However, the Japanese government's CLT roadmap states that production should reach 500 thousand cubic meters by 2024 [37–39]. In Australia, production was launched in 2018, with a capacity of 60 thousand cubic metres [31]. In Brazil, the production of CLT has been slowly increasing since the early 2010s, being used mostly in single-family houses and low-rise commercial buildings [40,41]. Currently only two companies are producing CLT in the country, and their combined production capacity is over 100 thousand cubic metres per year [42].

3.1.2. Climate and Environmental Effects

While the body of literature of substitution effects by construction materials is quite large [21], few LCA studies exist for CLT used in construction. Available studies indicate a range in substitution factors of 0.16–1.95 kg C avoided emissions per kg C in products made with CLT (Figure 1; Table S1) [43–47]. This wide range can be explained by the specific product being considered, material being substituted, consideration of life cycle stage and assumptions on production technologies and end-of-life considerations (e.g., landfilling, incineration).

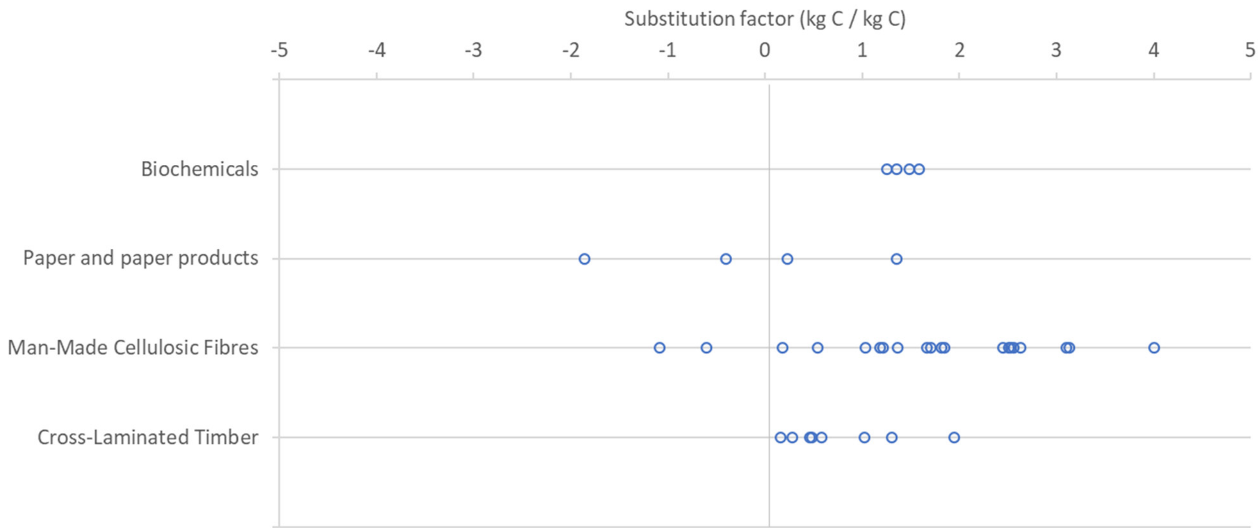

Figure 1. Overview of substitution factors reported in the literature for the selected product categories. See Table S1 (in Supplementary Materials) for details on the individual studies.

3.1.3. Development-Enabling Factors

Some countries and global regions have seen a stronger development of wood construction systems, most notably the Nordic countries, North America, Australia, Japan, and parts of southeast Asia [48]. In developing countries, wood is still largely seen as an old-fashioned construction material [49]. Consumer misconceptions, which are responsible for the perception of wood as a low-quality material with a reduced appeal due to maintenance requirements and outdated perceptions of durability and fire safety, or the association of it with deforestation, may hinder the widespread adoption of CLT [50]. Other constraints include the higher costs when using more modern construction systems, the lack of specialized labour, and the lack of specific legislation and standardization [50]. Regional differences in the appreciation of wood as a building material do exist, however, and are influenced by traditions and capacities in resource, industrial production and construction [51]. In most contexts, the industrial wood construction markets are still at a niche level [52]. Therefore, factors enabling the further uptake of CLT include supportive regulation and increasing consumer awareness.

3.2. Paper and Paper Products

3.2.1. Market Development

Graphic Paper

The pulp and paper industry produces many types of paper products and generates residues and by-products of economic importance (e.g., tall oil). Graphic paper has been seeing a shift in demand in the past 15 years [53]. The global graphic paper production increased steadily up until 2007, peaking at around 156 million tonnes. Since then, the global production has been strongly decreasing, reaching roughly 110 million tonnes in 2019 [54].

Significant regional differences exist, with on average 95% of the global graphic paper production (during 1961–2018) happening in Asia, Europe, and North America [54,55]. The global decline in graphic paper production and consumption is mostly visible in North America and Europe [56]. In Asia, the production of printing and writing paper has stabilized in the past few years, with a decline in newsprint production.

The linkage between rising graphic paper consumption and consumers' income growth appears no longer valid, as at high income levels further income growth is now associated with decreasing graphic paper production levels. The decline in graphic paper production and consumption is understood to be mostly due to the rise of digital media [55–59]. Projections show that as internet adoption is expected to continue to grow, global newsprint consumption could be 34–37 million tonnes lower and global printing and writing paper consumption 77–87 million tonnes lower by 2030, compared to 2012 production levels [30,60]. These estimates do not account for internet use. This corresponds to some 240 million cubic metres of roundwood equivalent that could become available for other purposes [61,62]. In terms of regional differences with regard to specific graphic paper types, in North America, newsprint production could be 78% lower in 2030 compared to the 2012 production level, 43–59% lower in Asia, and 49–58% lower in Europe [30,60]. For printing and writing paper, the production by 2030 could be reduced by 75–80% in North America, 17–31% in Asia, and 27–33% in Europe [30,60]. If the existing trends continue, there could be 460 million cubic metres less of the roundwood needed for all graphic paper production by 2050 compared to 2018 [63].

Packaging

Globally, traditional paper packaging formed 59% of total paper and paperboard production in 2018 [54]. Between 1961 and 2018, 94% of the global packaging production occurred in North America, Europe, and Asia, the latter accounting for 50% of the production. The overall market development of packaging is mainly driven by global population and income growth [18,64]. This has been connected to the continuously growing consumption of goods and the need to package them for transport and sale. Packaging material needs for e-commerce and take-away products also plays a role in the growth of packaging markets [18,64]. This is especially true in Asia, who is home to the majority of the world's population and where income levels are growing rapidly. Some uncertainty for future market development is posed by plastic packaging alternatives. On the one hand, plastic packaging reduction goals could benefit the demand for wood fibre packaging; on the other hand, the lightweight properties of some plastic packaging could favour plastic packaging for logistics reasons [30,64,65].

3.2.2. Climate and Environmental Impacts

There is a long tradition of recycling of paper products, particularly in developed countries. For instance, 67% of all paper and paperboard were recovered in the United States and Europe in 2018 [62], with some individual countries reaching recovery rates of up to 80% [66]. Even so, research has shown that recovery rates could still be improved upon by applying best practice collection methods [67]. Moreover, despite the large proportion of paper and paperboard recycling in some parts of the world, significant regional variations exist in the degrees to which various paper grades use recovered materials. Data collected in 2009 from 36 countries, representing over 70% of the world's paper and paperboard production, suggest that 18% of the feedstock for newsprint and 4% for printing and writing paper was composed of recovered materials [30,68]. More recent data, although not being fully comparable, indicate a trend of increasing recycling rates [69]. However, a point of caution is that recovered paper is traded globally due to profit incentives [70], which might be environmentally less sustainable compared to reprocessing it in the country of production [71].

Together with graphic paper, packaging materials have high recovery rates, particularly in developed countries [66]. Moreover, fibre length and stability properties in packaging materials like corrugated cardboard could withstand up to 25 recycling cycles, providing them high recyclability [72]. According to the same database from 36 countries, recovered paper contributed to 42% of the feedstock to case materials production, 6% to carton board production, and 13% to the production of other packaging [30,68]. Data from 2017 suggest rising recycling rates, even if the datasets cannot be fully compared [30,69].

Few studies exist that estimated substitution effects of paper products (Figure 1; Table S1) [73–76]. A study comparing the life cycle emissions of a printed magazine with an electronic tablet version indicated that the substitution factor may be positive (0.23 kg C/kg C) or negative (−0.40 kg C/kg C). Factors that influence this variation include the degree of use of the electronic device for other purposes, file size, and how many readers the printed edition and the tablet would have [75]. Another study considered a substitution factor of 0 kg C/kg C for graphic paper and 1.35 kg C/kg C for packaging board in Finland [74]. Contrastingly, a strong negative substitution effect (−1.86 kg C/kg C) has been observed for single use cardboard packaging box substituting reusable plastic crates, assuming that 82% of cardboard boxes were incinerated [76].

3.2.3. Development-Enabling Factors

The graphic paper and packaging industries are currently characterized by only incremental innovations, which usually contribute to cost savings. For example, new paper grades can offer similar or improved product properties as older grades but with enhanced cost-efficiency [77]. Likewise, packaging materials can be further developed by improving their barrier properties, thus making them more resistant to oil, for instance [78–80]. Similarly, advancements in production processes can lead to higher efficiency, thus generating energy savings [81]. However, there has arguably not been radical innovation in new product development, as exemplified in the case of corrugated cardboard, which is a very mature technology that has mainly seen incremental innovations since its inception [82]. Recent and more innovative product developments include thermoplastic cellulose, which is similar to plastic in its properties and can be refined into packaging films and bulk commodities [83]. Apart from continued investment in product development research, the growing markets may enable the further uptake of paper products, especially packaging.

3.3. Man-Made Cellulosic Fibres

3.3.1. Market Development

The most common types of MMCF are viscose, cellulose acetate, lyocell, and viscose modal. Although bamboo, bast fibres, cotton linters and sugarcane bagasse are increasingly used as feedstock for MMCF, wood pulp is still the main cellulosic raw material [84]. The global textile fibre market is estimated to reach 146 million tonnes by 2030 [85], but the global production volume of all MMCF combined is much smaller, between 6.5–7 million tonnes during the period of 2017–2020 [85,86].

In Europe and in the Americas, the production of MMCF has been relatively consistent since the 1990s, while it has been growing in Asia since the early 2000s [86]. More specifically for viscose, the global production volume in 2019 was close to 6 million tonnes, with an estimated compound annual growth rate of 6.5%, from 2017 to 2022 [87]. The global viscose production volume decreased slightly in 2020, to 5.2 million tonnes, due to the COVID-19 pandemic [80]. In 2020, lyocell, the third most used MMCF, had a global market share of 4.3% of all MMCF with an approximate production volume of 0.3 million tonnes [85]. The compound annual growth rate for lyocell (between 2017–2022) is estimated at 15%, indicating that the production of lyocell will likely grow faster than other MMCF [87]. The high growth rate for MMCF will likely decrease in the future, as it would require large investments from the wood industry to maintain the high growth rate [88].

3.3.2. Climate and Environmental Impacts

In general, MMCF have lower environmental effects than cotton and synthetic fibres. This is due in part to the use of renewable energy during the production process, the reduced use of chemicals, reduced GHG emissions, and lower water consumption [89]. Based on existing studies, using wood to produce textile fibres may lead to a substitution effect of −1.09 to 4 kg C/kg C (Figure 1; Table S1) [73,74,89], thereby providing potentially the largest substitution benefits across all product types considered in this study. The large range is partly explained by the number of life cycle stages considered in the studies, but also the type of fibre, the assumed production technology and the resource base have a significant effect on the estimated substitution factors. For instance, an integrated mill that produces wood pulp and textile fibres using modern technology and factory biomass for process energy was associated with lower levels of GHG emissions when compared to conventional production technologies that uses market pulp as feedstock [89]. Furthermore, the use of residues from sawmills and small logs could favour the development of industrial constellations, where small logs and industrial side streams would be used as raw material for wood-based textile fibres [18,88,90,91]. Some pulp mills have been converting their facilities from kraft pulp production to dissolving pulp production [92,93]. This shift can be seen as an advantage, especially if mills have the flexibility to produce paper-grade pulp or textile-grade pulp based on market conditions [83,88].

The market share of recycled cellulosic fibres is still quite small, representing less than 1% of all MMCF in 2019 [87]. The recycling process is still under development and companies have been investing in technologies to use pre- and post-consumer textile fibres as feedstock. Although these recycling processes have been shown to be technically viable, it is still easier and less expensive to process virgin cellulosic pulp [94] and this could be a hindrance for the widespread implementation of these textile recycling technologies.

3.3.3. Development-Enabling Factors

Several policy instruments could potentially enable the development of the textile fibre market, especially for fibres with lower environmental effects. The new *Circular Economy Action Plan* [95] focuses on keeping the added value of product and materials in the economy for the longest possible period, thus ensuring less waste through better use of resources and better waste management. It considers the textile sector a priority, since the production and use of resources (such as land, water, materials and chemicals), the release of GHG, and the production of waste are not limited to a few countries, but occur and have an impact at the global level [95,96].

The EU Textile Strategy for sustainable textiles [97] aims to improve the European Union's competitiveness, sustainability and resilience of the textile sector while addressing its environmental and social effects. The initiative will guide international cooperation with the objective of improving the consumption and production patterns towards sustainability, including land and water use and the use of chemicals [97], which might stimulate the production and consumption of sustainable wood-based fibres as a result of the restrictions on the consumption of synthetic fibres.

Many textile and fashion companies are engaging in the circular economy with the objective of reducing the environmental impact of textile production and consumption. The motivation for the engagement lies with the companies' corporate social responsibility policies, securing future raw material supply and reducing the consumption of virgin raw materials by closing the loop in the processes, opportunities for making profit, creating 'green' jobs, and meeting consumer demands and expectations [96,98].

3.4. Biochemicals

3.4.1. Market Development

Crude Sulphate Turpentine

The pulp and paper industry generates residues and by-products that can be used in the manufacture of hundreds of products in the chemical, food and packaging industries, among others. In terms of production volume, one of the most important by-products of the kraft pulping of coniferous trees is the crude sulphate turpentine [99]. This biochemical compound is commonly used in fragrances, cleaning products, or as solvent for dyes and varnishes. The global annual production of crude sulphate turpentine is estimated to be around 350 thousand tonnes [99], being produced mostly in North America, followed by Europe and Russia [100].

Crude Tall Oil

Besides crude sulphate turpentine, the wood pulping process generates black liquor which can be used to produce crude tall oil (40–45%), lignin (35–45%), and other organic compounds (10–15%) [101]. In turn, the distillation of crude tall oil generates chemical compounds with applications in several industries, from biofuels to adhesives to pharmaceuticals. More specifically, crude tall oil yields the following chemicals: tall oil heads (10%), tall oil fatty acids (35%), distilled tall oil (5%), tall oil rosin (30%), and tall oil pitch (20%) [99,102,103].

The global production of crude tall oil is estimated at around 1.2 million tonnes per year [99]. The market for crude tall oil has always fluctuated and is still dependent on the price of their fossil-based counterparts. The supply of crude tall oil increased steadily from 2009 until 2018, with supply and demand in balance. According to estimates, after 2020 the demand would exceed the supply by 0.6%, which is attributed primarily to the increased demand of crude tall oil for biofuels [104]. Despite the interest from the industries and the possibility of increasing the fractionation, which is still around 80% of its current capacity [100], the production of crude tall oil is (and has historically been) limited by the resource availability [103].

Lignin

Among all chemical compounds issued from the pulping process, the one with arguably the largest potential for the industry is lignin. This compound has always been considered a low-value material due to its high level of impurities in the crude form [105]. Typically, it is used as fuel for energy within the industry [106,107], with less than 2% being used for materials [108]. Lignin, being a complex class of polymers, can potentially be used to produce value-added biofuels, biochemicals and materials, such as carbon fibres, polymer blends, phenols, and aromatic compounds (e.g., vanillin, toluene) [106,109–111].

Lignin can be obtained not only through the kraft pulping process, but also through sulphite pulping, soda pulping, and alternative processes such as organosolv pulping [108,110]. Combined, lignins have a potential market value of US$732 million, and it is estimated to reach US$913 million by 2025, with a 2.2% compound annual growth rate [112]. The global lignin production is estimated at around 1.2 million tonnes per year, comprised of 75–100 thousand tonnes of kraft, around 1 million tonnes of sulphite, and less than 8 thousand tonnes of sulphur-free lignins (including soda and organosolv) [106,108,112]. However, according to estimates, the potential global production of lignin is around 141 million tonnes per year (kraft lignin of 78 million tonnes, sulphite lignin of 3 million tonnes, soda lignin of 20 thousand tonnes, and other lignins of 60 million tonnes) [106].

3.4.2. Climate and Environmental Impacts

In general, biochemicals from crude tall oil have lower carbon and energy footprints than their counterparts, contributing positively to climate change mitigation [113,114]. Many biochemicals from the pulp industry can potentially substitute fossil-based chemicals, being not only functionally equivalent materials, but also providing environmental benefits. For example, one derivative from crude tall oil is bio-naphtha, which can be used in the production of biodiesel and bioplastics, replacing fossil-based naphtha [115]. Crude tall oil can also be used to produce bio-ethylene for bioplastics (e.g., polyethylene terephthalate and polyethylene furanoate) [115]. Bioplastics can also be produced with a mix of cellulose and lignin, with demonstrated lower environmental impacts compared to two conventional plastic films [116]. Despite the growing interest in biochemicals, limited estimates exist on the benefits provided by product substitution. For instance, Rüter et al. [73] estimated a substitution factor of 1.26 to 1.59 kg C/kg C for lignin-based polyol to produce adhesives instead of fossil-based phenol (Figure 1; Table S1).

3.4.3. Development-Enabling Factors

Technical challenges that hinder the development of the biochemicals industry are, e.g., preventing the degradation of certain chemical compounds at high temperatures, improving the complicated purification process associated with the large array of chemicals obtained during extraction, and ensuring the expected performance of biochemicals (especially when targeting the substitution of fossil-based chemicals) [106,109,110]. Other than technical feasibility and performance, these new products must be able to demonstrate economic and environmental benefits, being able to substitute materials that are more expensive or that have larger environmental impacts [106].

These constraints are being eased with the development of the bioeconomy and, consequently, the fostering of the innovation landscape [110]. Growing interest is being driven by the development of new technologies, the possibility to diversify the product portfolio of pulp and paper mills and biorefineries, the growing demand for biochemicals and bio-based materials, and the attractive potential market for lignin products [110]. The push for the decarbonization of the construction sector is also stimulating the development of lignin-based materials [117].

Although the annual production growth for kraft lignin is limited, its market is quite large [106]. Recent investments to increase the production yield and maintain the quality have been successful [118], evidenced by the increase by 150% of kraft lignin production during the period of 2014–2018 [119]. But the prospects are not equally positive for all biochemicals. The development of the sulphite lignin market is stunted due to the declining production of sulphite pulping and the probability of investments in lignosulfonates being quite low. Thus, new developments will likely be connected to organosolv lignin, since it is obtained with a higher chemical purity, in a less modified form, and is free of sulphur [117,120,121].

4. Discussion

In this study we analysed the market development of selected wood-based products, their climate and environmental impacts and factors enabling their uptake. For established product categories, data on market developments are available from international reports and databases (e.g., FAOSTAT, COMTRADE), such as in the case of paper products, including of region-specific market variations. However, the picture is less clear for several novel or emerging products, which are not yet recorded in statistical systems. For instance, CLT, MMCF and biochemicals from wood are considered promising products and categories [18,19,47], but data on production, consumption and trade are currently limited and often confidential, scattered and incomparable. The limited data availability also hampers the development of long-term projections of wood-based products manufacture, consumption, and trade [88,122], as well as the understanding of how wood-based products can contribute to climate change mitigation.

In terms of future markets for wood-based products and feedstock supply, the emergence of new wood-based materials and the role of investments that would increase sector diversification represent a source of uncertainty. Numerous new wood-based products are still in the experimental phase, and it is uncertain how product development will progress and how markets will respond to these innovations. What will enable or inhibit the emergence of new wood-based products is linked to investments both in capital and in research [123]. Hence, how investments will unfold can greatly affect the future role and development of wood-based products in the bioeconomy. The future demand for bioenergy and its increased substitution of other energy sources creates further uncertainty. These may pose a threat to the raw material requirements of traditional wood products [124]. For instance, forest bioenergy often uses residues and by-products from harvesting and sawmilling as feedstock. However, the pulp and paper industry uses the same sources as feedstock, and this industry is expected to grow significantly due to the rising popularity of e-commerce, which requires wrapping and packaging materials made of wood fibre [18].

Concerning the contribution of wood-based products to climate change mitigation, existing review studies report that wood products, on average, are associated with lower GHG emissions over their entire life cycle when compared to products made from non-renewable or GHG-intensive materials at the product level [16,20–22]. We compiled substitution factors reported in or derived from the literature for the four product categories included in our study. While we identified several studies for CLT and MMCF, we found very a few estimates for traditional products such as graphic paper and packaging. However, due to their large market volume, some of these products could have a significant impact on the overall substitution impact of industrial wood usage. Still, there are insufficient data to quantify the substitution impact of these product categories [21]. Similarly, few LCA studies are generally available for emerging products [125], and their substitution effects with regard to climate and other environmental impacts are not well understood. Importantly, substitution effects vary with the type of wood product under consideration, the type of non-wood product that it substitutes, manufacturing technologies and efficiency and the end-of-life management of wood and non-wood products, and generalizations are thus not straightforward. Moreover, most studies reporting on substitution effects focus on North America and few European countries [21,22], and substitution effects by wood products in many global regions are poorly understood despite their relative importance in the global wood markets. It is also important to note that allocating large quantities of wood to specific applications will likely increase competition for raw materials (and land) and may even lead to negative substitution effects when wood products can no longer be produced and are substituted by products made from other (non-renewable) materials [27].

Existing studies that look into substitution effects mostly consider climate-related substitution effects. Wood and wood-based products can also have biodiversity and other environmental effects (e.g., eutrophication, acidification, photochemical oxidant formation and human toxicity) [126,127]. While reviews exist on the environmental impacts of wood products [125], our study did not come across any comprehensive analysis of the non-climate substitution effects of wood-based products. Wood products can have an impact on biodiversity through forest management [128], but this also applies to other materials obtained through fossil fuel extraction, for example [129]. Biodiversity is, however, still overlooked in LCA studies [130,131], and we are not aware of studies that estimated material substitution effects related to biodiversity for wood products. A systematic review of the existing LCA literature on bio-based materials found that bio-based products generally require less energy, but the production of bio-based materials might result in higher environmental impacts compared to their fossil- or mineral-based counterparts in the categories of eutrophication and stratospheric ozone depletion [132]. No conclusive results were found with regard to acidification and photochemical ozone formation.

Bio-based materials are generally seen as potential alternatives to reduce the reliance on fossil and GHG-intensive sources [47,133]. However, it is important to point out that bio-based materials are not outright environmentally sustainable, and that care must be taken during product development and manufacture to ensure sustainability throughout the product's entire life cycle. Attention should be given to product eco-design, where recyclability, biodegradability, and waste minimization at the end of life are cornerstones [19]. Another important aspect that should be taken into consideration is the source of raw material. As the extraction of raw materials has economic, social, and environmental implications, adopting climate-smart forest management is needed to meet the demand of a growing population while promoting biodiversity and other ecosystem services. Furthermore, possible ways to minimize environmental effects include changes in energy consumption behaviour, the promotion of renewable energy, improved sawmilling, proper wood waste management, use of less toxic chemicals, enhanced recycling, and the use of energy efficient and environment-friendly drying techniques and energy sources [134].

Finally, factors enabling the further uptake of wood products may include efforts or initiatives that stimulate technological change (or innovation) [123]. Other enabling factors include allowing (or restricting) certain economic activities, and facilitating holistic product design approaches by upgrading existing capacities of designers, architects, general education, and consumer awareness. Incentives to generate or use fewer fossil fuels and more bio-based alternatives, as well as investments in research and public-private partnerships, can increase substitution. Finally, consumer behaviour and preferences are key factors that may increase the consumption of wood-based products. Despite consumers likely being aware of options that are less harmful to the environment, promotion and marketing will still be required, as in any commercial setting, to guide them toward sustainable options. This could be done with the adoption of ecolabelling and by joining renowned certification schemes.

5. Conclusions

Forestry has long manufactured numerous products that are used in everyday life. Some of these products have undergone significant changes in recent years. At the same time, new materials and technologies are emerging that aim to add value to wood products, reduce the carbon and water footprint of products and processes, reduce pollution and waste generation, and improve circularity. Wood products are often, but not always, associated with lower GHG emissions throughout their life cycle compared to counterparts made from other materials. However, the available information on potential substitution benefits for many traditional and emerging wood-based products is limited. For a holistic understanding of the benefits of substitution with wood products, it is crucial to consider the impact on carbon sequestration in forest biomass and soils, carbon storage in wood products, as well as their permanence and potential leakage effects. Furthermore, allocating large amounts of wood to specific uses is likely to increase competition for raw materials and may even lead to negative substitution effects by which wood-based products are replaced by other (non-renewable) products. Finally, the consideration of possible substitution effects should be extended to other environmental effects. To strengthen the role that wood-based products can play in a circular bioeconomy, production (including eco-design), use, reuse and recycling of forest products and management of wood waste should be improved to reduce environmental impacts throughout the product life cycle. Raising awareness and bridging knowledge and implementation gaps in the global value chain of wood products is crucial to ensure the sustainability of a circular forest-based bioeconomy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11122131/s1, Table S1: Overview of substitution factors reported in the literature for selected product categories.

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