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Review

Life Cycle Assessment of Forest-Based Products: A Review

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Abstract: Climate change, environmental degradation, and limited resources are motivations for sustainable forest management. Forests, the most abundant renewable resource on earth, used to make a wide variety of forest-based products for human consumption. To provide a scientific measure of a product's sustainability and environmental performance, the life cycle assessment (LCA) method is used. This article provides a comprehensive review of environmental performances of forest-based products including traditional building products, emerging (mass-timber) building products and nanomaterials using attributional LCA. Across the supply chain, the product manufacturing life-cycle stage tends to have the largest environmental impacts. However, forest management activities and logistics tend to have the greatest economic impact. In addition, environmental trade-offs exist when regulating emissions as indicated by the latest traditional wood building product LCAs. Interpretation of these LCA results can guide new product development using biomaterials, future (mass) building systems and policy-making on mitigating climate change. Key challenges include handling of uncertainties in the supply chain and complex interactions of environment, material conversion, resource use for product production and quantifying the emissions released.

Keywords: life cycle assessment; lumber; engineered wood products; mass timber; nanocellulose

1. Introduction

Globally, the use of raw materials (for the production of food, energy, and construction) has increased exponentially, especially since the nineteenth century [1,2]. The future prediction shows that demand for food, fuel and construction materials will grow because of the increasing global population and economic growth [1]. Moreover, climate change and resource depletion pose a serious threat to planet including human civilization. Buildings and construction account for more than 35% of global final energy use and nearly 40% of energy-related CO_2 emissions [3]. Resources from forests provide renewable construction materials (especially for buildings), pulp and paper, energy, bioproducts and more. Forests sequestering carbon and wood products storing carbon have the greatest potential to mitigate climate change [4]. Combining carbon storage and carbon displaced from using forest-based construction materials, especially building construction, is one of the most efficient options to mitigate climate change [5–7]. Despite abundant availability of forest resources, it may be hard to fulfill the global demand for forest resources to produce needed construction materials, pulp and paper, energy and fuel without continuing practicing sustainable forest management [8,9]. Society sees forests now as a source of renewable and sustainable natural resources for building materials, fibers, biofuel, and other renewable materials to mitigate climate change while fulfilling society's increasing demands for economic well-being [10,11]. Optimal and judicious use of scarce resources is critical; therefore, the actual environmental and economic performances of different products and services coming from forest resources have to be considered. Forest-based products provide economic, environmental and societal benefits and these benefits need to be properly quantified using tools that can properly assess and compare the benefits of different products coming from forests. Life cycle assessment (LCA) is a scientific approach to analyze and quantify the environmental burdens associated with resource extraction, manufacturing, use and disposal of a product [12–14].

Forest-based products are derived from what is commonly called roundwood or trees felled in their natural state for industrial purposes. For this article, the term "roundwood" is considered the raw material to produce final products such as those discussed in more detail later, although there are many other products that can be produced. Forest harvesting generates roundwood that feeds both the wood products (i.e., lumber, wood-based panels, bridges, pallets, etc.) and the pulp and paper sectors. The remaining forest residues left after harvesting and the mill residues produced during roundwood processing can be used for fuels such as pellets and firewood and biomaterials such as nanocellulose. A comprehensive review of various categories of wood products can provide a holistic view of the current state of research, especially performances related to environmental impacts. The life cycle starts in the forests, which are either natural or planted. Natural regeneration occurring in a natural forest with no or little human activity. Unlike natural forests, which are the dominant type globally, planted forests are established through planting or intentional seeding of native or introduced species primarily for wood production [15]. Regardless of forest type, roundwood harvested from forests is transported to the production facility typically by logging trucks and stored on-site in yards until the logs are ready for processing. Wood quality and log size tend to determine the final product type. Industrial roundwood can be broken into several categories such as sawlogs and veneer logs, polewood, pulpwood, and fuelwood. Primary wood processing includes the sawing of sawlogs into slabs for lumber production, slicing of veneer logs into thin sheets of wood and converting pulpwood into wood chips or fiber through mechanical (grinding) and chemical means of pulp production. Lumber, once sawn, is typically finished by air- and/or forced-drying for dimensional stability and by planing for smoothness and proper sizing [16]. Lumber can be used as-is for building or processed into other products such as wood flooring and mass timber products for mass timber buildings. There are various traditional engineered wood products such as oriented strand board (OSB), medium-density fiberboard (MDF), high-density fiberboard (HDF), particles boards and so forth, can be manufactured from wood particles combined with synthetic resin or natural adhesive [17–19]. Wood pulp can be further processed into other products such as paper and nonstructural wood-based panels. Emerging wood products or mass-timber such as cross-laminated timber, glue-laminated timber and so forth, had been developed for the main structure construction of tall-wood buildings or high-rise buildings. The objective of this article was a comprehensive review of environmental performances of manufacturing forest-based products, including traditional building products, emerging building products (mass-timber) and nanomaterials using attributional LCA. First, the analysis methodology showing the connection between forest resources and forest products is discussed along with a review of databases used to collect LCA data. Second, the forest products industry is described for the U.S. compared with the global industry to better illustrate the magnitude of wood product markets and their importance to sustainable forest product production. Third, the LCA approach is detailed along with the research conducted on the selected forest-based products. Lastly, the impacts are discussed and conclusions are provided on the work performed so far with recommendations for future LCAs.

2. Review Methodology

Generally, roundwood is harvested to produce high-value products while forest residues (a byproduct of harvesting activity) are left to decay, burned or used to produce low-value energy products. Roundwood along with forest residues can be used to make multiple products (Figure 1). At every stage of the supply chain, roundwood is differentiated into specific product types based on value addition and the manufacturing process. Detailed descriptions of these products can be found in References [20–22]. This study separated forest-based products into four categories: (i) traditional wood building products (i.e., lumber, plywood, oriented strandboard (OSB), particleboard, glue-laminated timbers, laminated veneer lumber (LVL), etc.), (ii) emerging wood building products [cross-laminated timber (CLT), dowel-laminated timber (DLT), nail-laminated timber (NLT) and so forth, (iii) mass-timber (tall-wood) buildings and (iv) advanced biomaterials (nanomaterials or nanocellulose). In the last two decades, the focus of LCA has been on traditional wood building products, biofuels [23], bioenergy (heat and electricity) [24] and biochar from wood resources. There are many review articles that examined the LCA and techno-economic analysis of biofuels and bioenergy [23,24]; hence, these products along with paper products and pulpwood and biochar were considered outside the scope of this study.

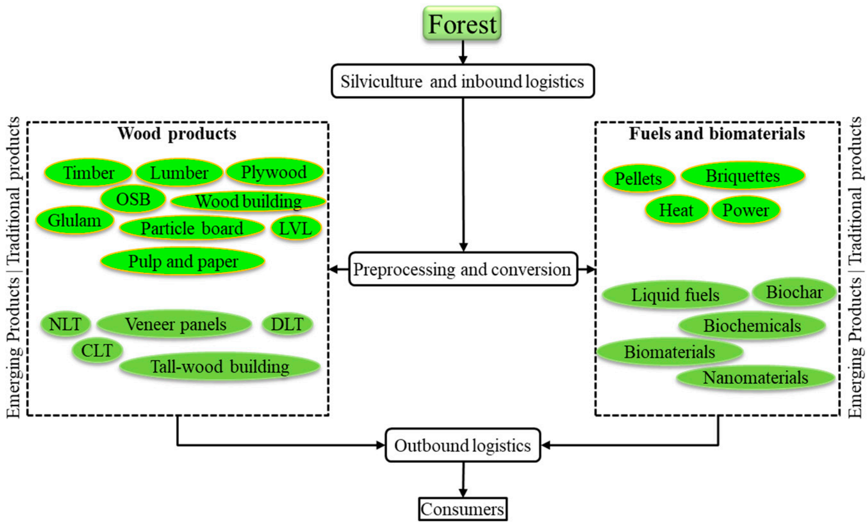

Figure 1. Supply chain of forest-based products. CLT: cross-laminated timber; DLT: dowel-laminated timber; NLT: nail-laminated timber; LVL: laminated veneer lumber, OSB: oriented strandboard.

A systematic approach was applied to ensure comprehensiveness and minimize bias in selecting literature relevant to the scope of this study—LCA of forest-based products. Appropriate keywords related to LCA were identified and combined into multilevel search strings including the names of forest-based products. The journal articles, conference papers and reports published between 2005 and 2019 were collected from databases such as Scopus, Web of Science and Google Scholar, which provide English language publications only. In addition, there are LCA studies not available to us for review including ones conducted by private entities or industry. The articles resulting from the complex search query in the database previously mentioned were further analyzed by reading title, abstract and the whole article (if necessary). The final database on the LCA study of forest-based products was categorized based on published year, related to specific product category, geography, authorship, and journals. Each article was read, data were collected related to the environmental impacts of each product and the article was then summarized. Throughout this article, the term "forest-based product" is used because it tends to consider products more generally than what falls under the term "wood product," which is categorized as traditional and emerging wood building products.

The descriptive analysis—published articles over time, articles on each wood products category, study regions, contributing authors and so forth—of published articles on life cycle assessment of wood products is presented in Figure 2. Figure 2a illustrates the number of articles published each year. The growth in the number of published articles is not consistent over time despite greater interest in the sustainable or low carbon footprint of construction materials in the last several years [25]. Among the wood products considered in this study, the LCA of traditional wood products was more than 80% of the total number of published articles (Figure 2b). In the United States, most traditional wood product LCAs have been developed under the Consortium for Research on Renewable Industrial Materials (CORRIM [www.corrim.org]) and were frequently published in special issues, which explains the high variability from year to year. The environmental impacts of any product are believed to be site- and region-specific and hence so is the applicability if results of an LCA study are influenced by inherent variabilities of the input data based on these locations. Figure 2c shows most LCA studies on forest-based products were specific to North America compared with other global regions including Europe. Despite the fact that South American is rich in forest resources (especially Brazil), there are only two LCA studies linked to that region, which is surprising.

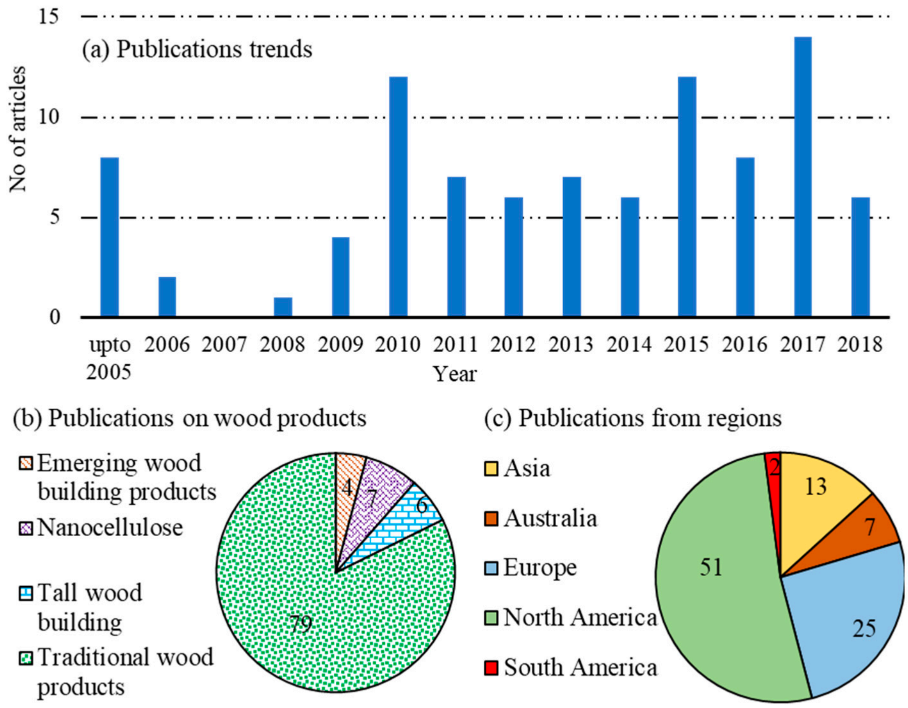

Figure 2. Descriptive analysis of published articles on forest-based products.

3. Forest Resources, Products and Markets: Status and Trends

3.1. Forest Resources in the United States and Globally

Forest resources are a key driver for many countries for forest product production including the United States. The United States is the 4th largest country in terms of land area (9.37×10^6 km^2) as well as the global forest area (8%). Russia, Canada, and Brazil are the three top countries with the most forested area, in that order. Despite the continuous loss of global forest area, the U.S. had gained 0.1% in forest land between 2010 and 2015 [26]. In 2012, U.S. forest land comprised 310 million hectares or 33% of the total land area [15,18]. Maintaining forests as forests (i.e., sustainable forest management) has been a critical component of the U.S. forest products industry to provide wood material for product production. Although substantial regional changes have occurred in the U.S. because of both agricultural and urban development, the total forest land area has been fairly stable for the last hundred years

Most U.S. forest land area is timberland (about 67% of the total forest), which is capable of producing at least 1.4 m^3 per hectare per year of industrial wood in a natural stand. While U.S. forest land area remains stable, the current forest inventory (volume) has increased by ~60% (Figure 3b) from 1963 because of higher growth (about 3%) and lower removal (about 1.5%) [27,28]. About 58% and 42% of total forest lands are owned by private and industrial landowners and the government (federal, state, county and city), respectively. The regional variations in the spreads of forest lands, ownership and forest growth and removal are wide and substantial. For example, the southern U.S. contains 31% of the total forest land in the U.S. and 87% of them are privately owned [29]. The largest amount of nonprivate forest is spread across the western states including Alaska and a large portion of that is reserved (i.e., not for utilization). Growth on timberland has increased consistently in the last two decades especially in the southern and northern regions of the U.S. [28]. Forests owned by the government are less productive than private forests, which provide more than 90% of the nation's wood and paper products [30]. Although the majority of forest harvesting/removal was from growing stocks (live trees of commercial species meeting specified standards of quality or vigor), there is a substantial portion of removals coming from nongrowing stocks (includes rough, rotten and dead trees). In 2017, the net growth and removal of growing stock were 0.71 and 0.37 billion m^3, respectively [27]. This highlights the continual accumulation of U.S. forest stocks. (Figure 3a).

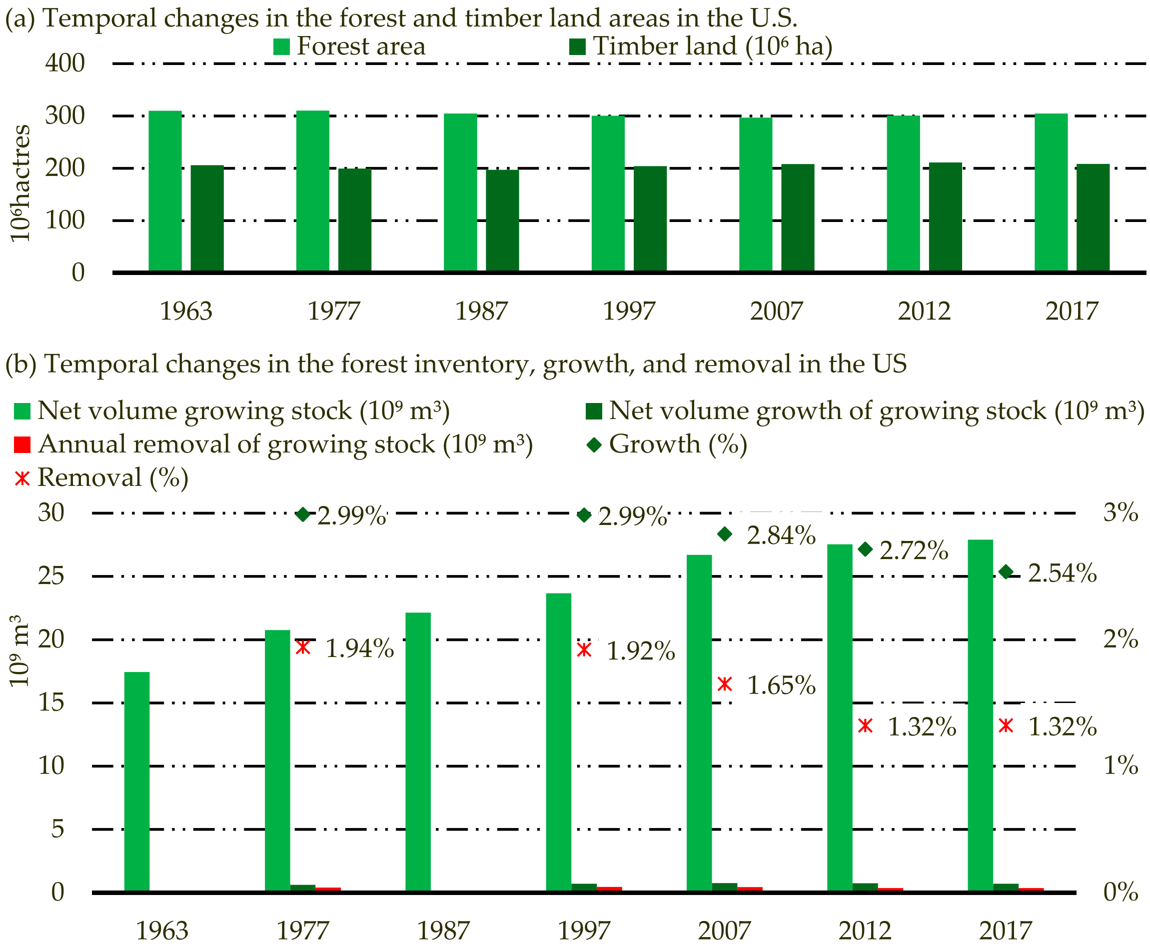

Figure 3. Trends of forest area, timberland, forest inventory, growth and removal in the U.S. (Source: [27]).

3.2. Wood Products Market Trends

Roundwood and wood fuel have been tracked globally by countries including the United States for decades to gauge usage of forest resources and available supply. The annual global total production of roundwood and wood fuel have been increasing since 1960 and in 2017, it reached 3.79 and 1.89 billion m^3, respectively, a ratio of about 2 to 1, roundwood to wood fuel. In 2017, U.S. annual production of roundwood and wood fuel reached 0.42 and 0.06 billion m^3, respectively (a ratio of 7 to 1, which is a much higher ratio).

The U.S. tends to produce far more roundwood than wood fuel. Several reasons exist for this. One, most U.S. housing is built from wood whereas fuel for cooking and heating and cooling of buildings is derived from fossil fuels, not wood fuel. As noted in Figure 4, the U.S. contributes substantial amounts to the world's annual wood products and wood fuel production, imports and exports. The U.S. exports large amounts of pulpwood and wood fuel products, primarily wood pellets, to other countries.

The feedstock source for wood pellets tends to come from mill residues produced during the processing of roundwood into other products, not from forest residues.

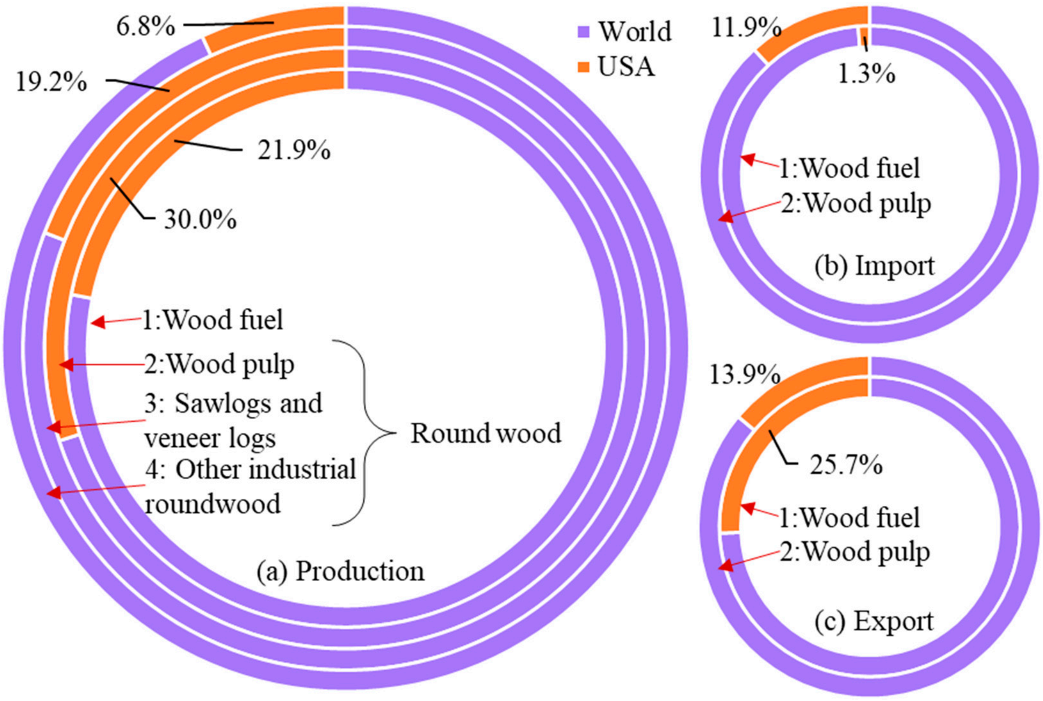

Figure 4. Global and U.S. contributions to the annual wood products and wood pellet production, import and export, annual average from 2000–2017 (Source: [31]).

Globally, the forest products industry employed almost 10 million people in 2011 with products valued at more than $800 billion in 2014 [32]. In 2016, the U.S. forest sector exported goods valued at $30.6 billion with a direct and indirect contribution to the U.S. economy of $39.5 and $110.1 billion, respectively [33]. Wood product markets remain volatile and depend on the annual status of global and national economic activities such as growth and decline in the gross domestic product (GDP). The total production of roundwood and wood fuel in the U.S. had decreased after reaching a peak during late 1990 (Figure 5). In 1998, the U.S. share in the global production of wood products was 28% compared with 17% in 2013 [34]. The major causes for the overall wood consumption decline per capita post-1990 came from the digital revolution [34,35], increased paper recycling [34] and increased the productivity of the manufacturing process [35] along with a more general slowdown in the global economy from the Great Recession in 2008 [36]. However, the production of wood building products has increased since the Great Recession, especially from the growth of the housing sector in the U.S. [3]. As for wood fuel, since 2012, the U.S. production and export of wood pellets to European countries, especially the United Kingdom, has doubled to support the decarbonization policies for the European power sector [37]. Future solid wood demands depend strongly on economic activity including housing demand (especially in multifamily housing and nonresidential building), technological changes (e.g., use of engineered wood building products such as glulam beams, I-joists, LVL and mass timber products such as CLT, NLT, and DLT, etc.) and policies to mitigate climate change [34].

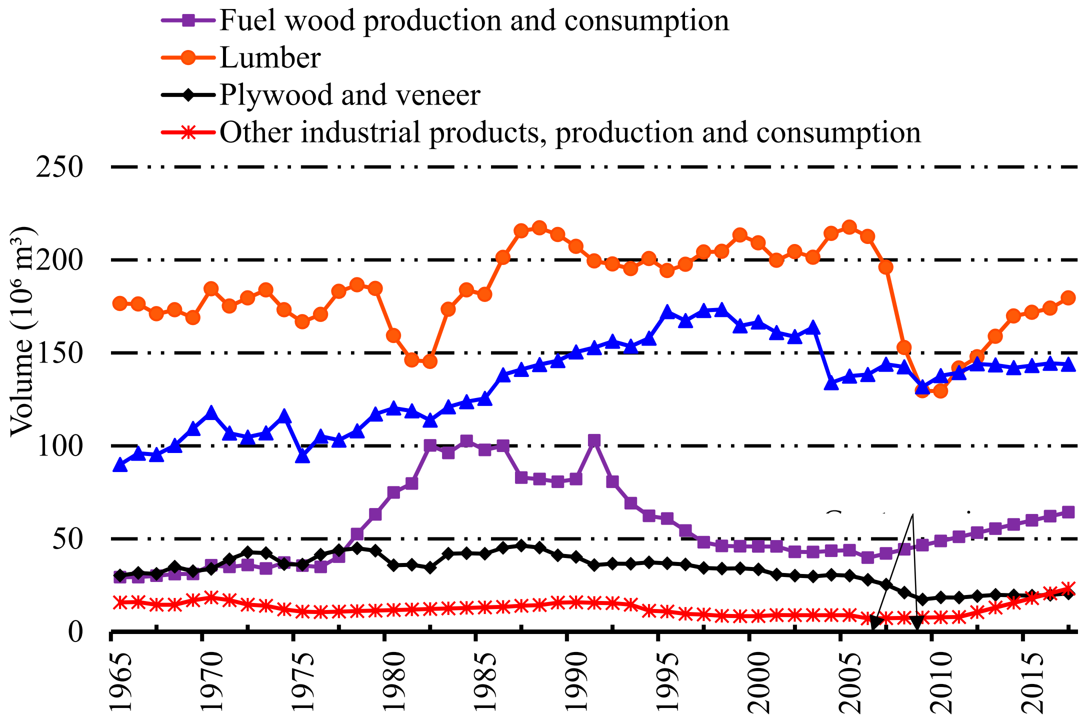

Figure 5. Wood products production trends in the U.S. (1965–2017) (source: [31]).

Post-Great Recession, both import and export values of wood products increased markedly, reaching about $27 billion (10.1% of the U.S. total economy) in 2017 [21]. Strong growth of the housing market in the U.S. after the 2008 recession is one of the main reasons for the increase in the growth of wood products production, especially lumber [36]. Between 2010 and 2030, a 15% growth of consumption in wood products is expected in European countries [22], especially for wood fuel (~35%), which may increase the export of wood products from the U.S. By 2030, paper and paperboard production may increase to 467 million tons with North America potentially contributing about 16% of total production. Global wood pulp production would reach 185 million tons by 2030 (31% would be from North America) [32]. Most of the wood products growth will come from Asian countries with nearly 50% of total global production in 2030. New residential construction and repair and remodeling are primary users of wood products in the U.S. [38]. Modest growth in the U.S. economy could lead to a 2% annual growth in softwood lumber consumption for several decades in the future, that is, between 2015 and 2070 (~100 million m^3 in 2014 to 150 ± 75 million m^3 by 2070) [39]. Woody biomass, especially forest residues, have been investigated and proposed as renewable resources to produce bioenergy to mitigate climate change. Therefore, a diversion of woody biomass to produce bioenergy from forest residues is expected to increase in the future [40]. Nepal et al. [41] estimated a 15% to 125% (56 to 64–125 million m^3) increase in the annual consumption of woody biomass between 2015 and 2050 and most of the increased wood consumption will be diverted from pulpwood. One caveat in current manufacturing practices is that pulpwood does not come from forest residues. The total timber production could reach from ~400 to 427–566 million m^3 from 2015 to 2050, respectively, based on the demand of bioenergy [41].

4. Life Cycle Assessment of Forest-Based Products

This section described what LCA is and discussed the LCAs evaluated for the four categories of forest-based product and building systems. This review covered the attributional (i.e., what is happening now) not the consequential (i.e., what if) LCA approach. Each individual system category was described before discussing the LCA studies found.

4.1. Approaches and Tools

LCA is the internationally accepted standard method for assessing the environmental impacts of products [13,14]. LCA estimates the environmental impacts of a product holistically, including the resources consumed and the emissions released. It can cover the life of a product from raw material extraction to the product production (conversion) stage (i.e., cradle-to-gate) or through distribution logistics, end-use and to its final disposal stage (i.e., cradle-to-grave) (Figure 6) [13,14,42].

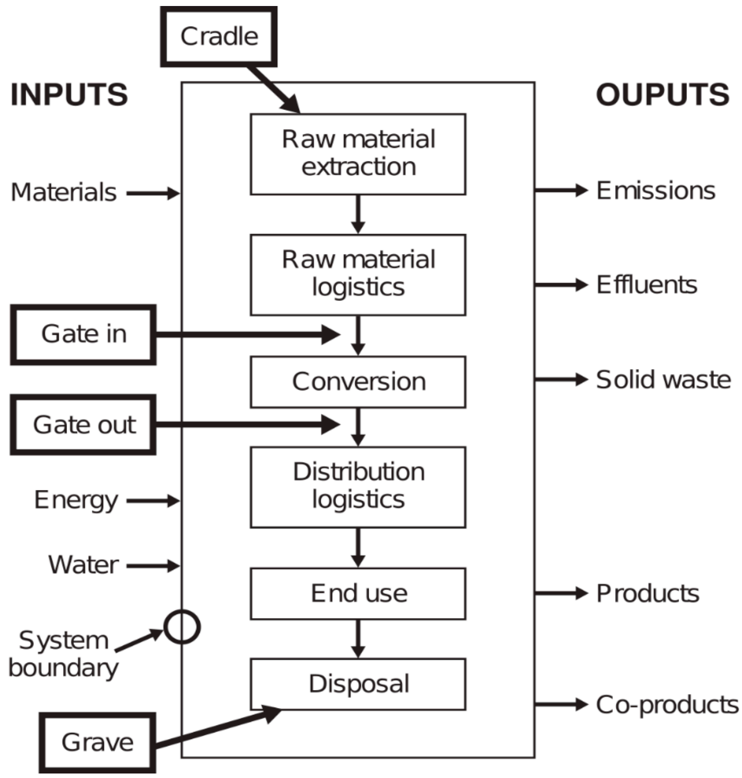

Figure 6. Whole life cycle from the regeneration of trees to the disposal of wood.

An LCA study comprises all stages (Figure 7) but life cycle inventory (LCI) studies do not include phase 3. The goal and scope describe the basis of the study and clarifies how and to whom, the results are communicated. An LCI tracks all the raw material and energy inputs and environmental outputs to manufacture a product, process or service on a per unit basis within diligently defined system boundaries. Many early LCA for U.S. wood products were simply attributional LCI studies and not LCA studies and therefore did not consist of the life cycle impact assessment (LCIA) stage. The LCIA phase aggregates the LCI flows to explore impacts for the following four areas: resource depletion, human health, social health, and ecosystems. Lastly, the interpretation phase is a systematic approach to sort, quantify, verify and evaluate the results of the LCI and/or the LCIA [13,14].

4.2. Forest-Based Products and Building Systems

The field of LCA has become increasingly active for documenting environmental performance. Initially, building products were evaluated in order to construct and populate whole building tools. As the green building movement grew over the last couple of decades, emerging wood building products were developed along with other forest-based products which used LCA in their product development. This section highlights the linkage of building product and building systems and the importance of providing LCA results on both, especially for newer mass timber building systems. Although there are several studies that show comparisons between building products such as Bergman et al. (2014), ideally, taking a building system approach to gauge the effectiveness of building with wood instead of other materials gives greater context on what building material to use from an environmental performance standpoint.

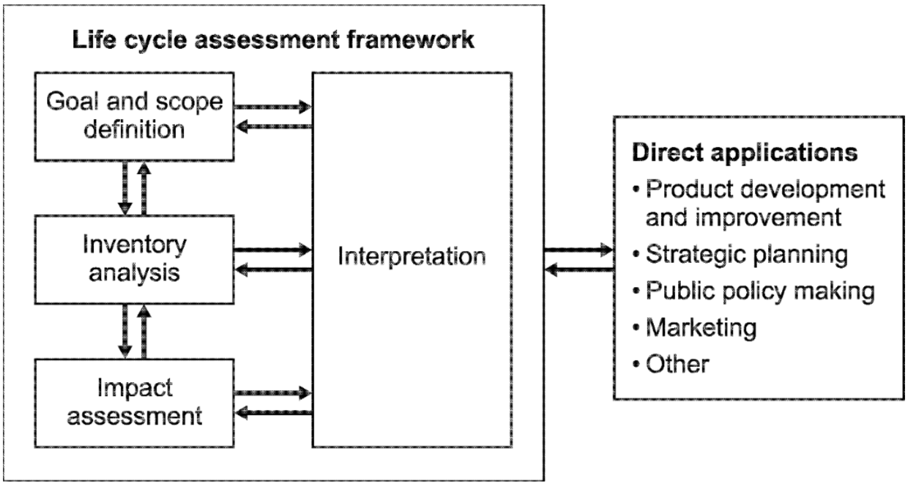

Figure 7. Life cycle assessment (LCA) stages (Source: [13]).

4.2.1. Traditional Wood Building Products

Traditional wood products have been used for centuries to build infrastructures such as buildings, ships, and bridges. This section focuses on forest-based products used in the building sector for both structural and nonstructural purposes. Although the word 'traditional' is used to describe this section, engineered as well as solid wood products are considered. Many countries including Scandinavian countries, Japan, Canada, and the United States have a long history of building with wood [43]. Wood products tend to have a lower environmental footprint, especially related to greenhouse gas (GHG) emissions, than other non-wood products [44–46].

Residential and commercial buildings consume about 40% of all energy used in the U.S. [47]. Although most energy is used during building occupation (i.e., after construction), there is increased awareness of decreasing the embodied energy, the amount of energy used in the production of building material, as part of the overall aim of lowering the environmental footprint of a building. This endeavor is becoming increasingly critical as buildings are being built to higher energy standards thus reducing their operating energy. Green construction practices have advanced markedly during the past 40 years in an effort to lower energy consumption, improve the total building performance and move toward more sustainable practices. In practice, green building began as a series of prescriptions that experts assumed were the most critical to moving construction toward sustainability goals. Green building certifications have now expanded to include LCA, which provides insight on how to improve energy and material efficiency throughout the material production and building construction and operation while lowering overall environmental impacts throughout the building's whole life cycle [41].

Classifying building materials that possess positive environmental attributes is one result of the increased attention given to green building practices. These practices may include using building materials with lower environmental impacts as well as reusing or reducing the use of building materials capable of doing the same function. The green building materials market is expected to reach nearly $240 billion globally in 2022 from $192 billion in 2016 [48]. In addition, building codes and standards such as the International Green Construction Code (IgCC) are implementing performance-based decision making based on scientific approaches including LCA [7]. There are many other green building certification systems in the United States, with the most recognized being Leadership in Energy and Environmental Design (LEED) along with ICC-700 National Green Building Standard, Green Globes, IgCC, California Green Construction Code (CalGreen) and ASHRAE 189.1 [49]. These green building certification systems are based on various parameters including building product LCA data as an objective scientific basis for showing the relative environmental benefit or "greenness," of projects built using these certification systems. This trend signifies a shift away from prescriptive-based to performance-based certification systems. In expectation of the adoption of such policies and their market implications, a number of industries have initiated efforts to develop LCA data for their products [50–53]. Furthermore, whole-building LCA tools, such as the Athena Impact Estimator for Buildings, are a necessary part of finding a building's environmental impact and are gradually becoming part of green building certification systems [54]. Developing metrics to measure sustainability is part of the green building process (Table 1).

Table 1. Peer-reviewed LCA studies on traditional wood building products.

Study	Location	System Boundary	Functional or Declared Unit with Output [a]	Impacts Methods	Allocation
[55]	China, Australia	Cradle-to-grave	1000 customer trips, carrying the same load	ReCiPe method	economic
[56]	Northeast/north central U.S.	Gate-to-gate	Declared unit, m^3	no, LCI only	mass
[57]	Northeast/north central U.S.	Gate-to-gate	Declared unit, m^3	no, LCI only	mass
[58]	Eastern U.S.	Gate-to-gate	declared unit, 1 m^3/ functional unit, 100 m^2	no, LCI only	mass
[59]	Southeast U.S.	Gate-to-gate	Declared unit, m^3	no, LCI only	mass
[60]	United States	Cradle-to-gate	Declared units, varied by product	Global warming impact only	mass
[44]	Northern California	Gate-to-gate	Declared unit, m^3	TRACI	mass and economic
[6]	North America	Cradle-to-gate	Functional unit, 1 m^2	TRACI	mass and economic
[61]	United States	Cradle-to-gate	Declared unit, km	TRACI	mass and economic
[62]	United States	Cradle-to-gate	Declared unit, m^3	TRACI	mass and economic

[a] Depends on the system boundary defined in the scope.

There is substantial literature on traditional wood building products (Tables 1 and 2). More than 100 articles were found. However, many (32) were not included in this study for various reasons including languages other than English and different wood product categories. In addition, there are numerous original U.S. LCI studies (no impact method categories reported) developed through CORRIM that eventually became CORRIM LCA reports to generate LCA-based ecolabels called environmental product declarations (EPDs) [63–65]. These wood building EPDs are helping to drive green building construction and are provided on a North American basis (i.e., combining U.S. and Canadian LCA data). All EPDs require periodic updating along with the underlying LCA data according to ISO 14025 [54]. Therefore, LCAs and EPDs for all wood-producing regions in North America are now in the process of being revised. Furthermore, many U.S. LCAs reported were found in both CORRIM reports and peer-reviewed journal articles. In this study, the journal articles took precedence (Table 2).

Table 2. LCA results of traditional wood building products from peer-reviewed journal articles.

Study	Products	Functional Units	Ozone Depletion (kg CFC-11 eq)	GW (kg CO_2 eq)	Smog (kg O_3 eq)	Acidification (kg SO_2 eq)	Eutrophication (kg N eq)	Respiratory Effects (kg $PM_{2.5}$ eq)	CED [Fossil Energy Only] (MJ)	Fossil Fuel Depletion (kg Oil eq)
[55]	Pallets	1000 customer trips		437–1558						131–520
[56]	Hardwood lumber	1 m^3 planed dry lumber		139 *					6408	
[59]	Hardwood lumber	1 m^3 of planed dry lumber		131 *					5860 [1981]	
[57]	Softwood lumber	1 m^3 planed dry lumber		65.1 *					3160 [783]	
[66]	Softwood lumber	1 m^3 planed dry lumber		72 *					3365 [1773]	
[67]	Softwood lumber	1 m^3 planed dry lumber		59					3434 [878]	
[44]	Redwood decking	1 m^3 of planed decking material	3.69×10^{-6}	57.4	6.61	0.534	0.0234	0.0365	1340 [1023]	
[68]	Solid wood flooring	1 m^2 of flooring (7.4 kg of dry wood)-40 years		0.424 *					49 [14]	
[69]	Wood flooring	1 m^2 of flooring (31.45 kg of dry wood)-50 years		−2.6		0.185			705 [424]	
[70]	Hardwood flooring New	1 m^3 flooring material (new)		240					7750 [3858]	
[70]	Hardwood flooring Recovered	1 m^3 flooring material (recovered)		175					859 [851]	
[58]	Prefinished engineered wood flooring	100 m^2 of prefinished engineered wood flooring		1050 *					23,000 [20,787]	
[70]	Softwood framing lumber-New	1 m^3 product		118					6440 [2430]	
[70]	Softwood framing lumber recovered	1 m^3 product		186					418 [413]	
[6]	Plywood	1 m^3 product		129					7232 [2222]	
[6]	Plywood	1 m^3 product		200					7737 [3339]	
[71]	Plywood	1 m^3 product		40 *					3140 [1590]	
[71]	Plywood	1 m^3 product		106 *					5060 [2770]	
[72]	Plywood	1 m^3 product		18,880		138			9,850,000	
[18]	Particleboard	1 m^3 product		392					10,865 [8245]	
[73]	Particleboard	1 m^3 product							3262 [837]	
[74]	Particleboard	1 m^3 product	7.0×10^{-6}	433		1.82			17,632 [4858]	
[19]	MDF	1 m^3 product		621					20,707 [12,058]	
[75]	MDF	1 m^3 product		834.4					5610	
[76]	MDF	1 m^3 product		897					17,901 [16,648]	
[77]	MDF	1 m^3 product							4035	
[6]	OSB	1 m^3 product	6.36×10^{-7}	207	28	2.11	0.10		7789 [3998]	

Table 2. *Cont.*

Study	Products	Functional Units	Ozone Depletion (kg CFC-11 eq)	GW (kg CO_2 eq)	Smog (kg O_3 eq)	Acidification (kg SO_2 eq)	Eutrophication (kg N eq)	Respiratory Effects (kg $PM_{2.5}$ eq)	CED [Fossil Energy Only] (MJ)	Fossil Fuel Depletion (kg Oil eq)
[78]	OSB	1 m^3 product		2693 *					3388	
[17]	OSB	1 m^3 product		294 *					3140 [1590]	
[76]	OSB	1 m^3 product		236					5569 [4845]	
[6]	Softwood plywood	1 m^3 product	$1.01–1.24 \times 10^{-7}$	129–200	20–22	1.5-2	0.05–0.06		2601–3865	
[6]	Cellulosic fiberboard	1 m^3 product	1.00×10^{-5}	302	214	8.4	0.44		5984 [5254]	
[6]	Hardboard	1 m^3 product	8.53×10^{-5}	772	772	26.6	2.13		27,594 [14,638]	
[79]	Hardboard	1 m^3 product	9.28×10^{-5}	350		3.84	0.686		6739	
[80]	Hardboard	1 m^3 product		347		3.93	0.849		6233	
[62]	I-joist	1 km	$1.78–8.65 \times 10^{-4}$	2100–2720	277–291	21–27	0.79–1.22		41,100–53,300	
[51]	Glulam	1 m^3 product		111–172					[3138–3291]	
[17]	Glulam	1 m^3 product		126 *–199 *					[3109–3900]	
[81]	Glulam	1 m^3 product		106					1560 [1260]	
[82]	Glulam	1 m^3 product		151–119	24–28	1.2–1.5	0.05–0.09		[1690–2097]	
[61]	LVL	1 m^3 LVL	$1.69–4.75 \times 10^{-7}$	218–339	31–36	2.3–3.3	0.08–0.12		[3740–5600]	

* LCI on fossil-CO_2 from fuel and heat used for the product. LVL: Laminated veneer lumber, OSB: Oriented strandboard, MDF: Medium-density fiberboard, Glulam: Glue-laminated lumber.

4.2.2. Emerging Wood Building Products

Innovative engineered wood building products (mass timber) are being developed to expand the use of traditional wood products, increase the efficiency of wood resource use and improve properties for specific applications. Advances in wood products design such as improved fire resistance and structural integrity help to promote the use of wood materials in taller wood buildings, expanding the application of wood beyond that for single-family houses. Today, the increased interest in green buildings has really pushed for the massive use of wood materials and more developments in the wood products sector [83]. Wood is preferred over nonwood structural products because of aesthetics, cost-effectiveness, environmental benefits and increasing sustainability interests [84]. The emerging wood building products can be used for mid- to high-rise wood building constructions because of structural capability and improved properties. Major emerging products from the forest products industries include CLT, NLT, massive veneer panels and DLT, which are designed to replace traditional concrete and steel structural materials in multistory buildings in which traditional wood building products cannot be used.

Traditional uses of wood in light-framed wood houses, engineered wood (I-joist or plywood, OSB, etc.) are mainly used as post and beams, along with dimensional lumber. The emerging structural wood products are mainly characterized by their use for floor, wall and roof structures. Among these products, CLT has been studied the most. The method to make CLT and similar perpendicular engineered wood products dates back to the early 20th century in the United States [85]. However, it was in Europe during the early 1990s where CLT started to be used commercially with its application as walls, floors, and roofs in residential and commercial buildings. During the past few decades, CLT has become widely accepted as a structural wood product alternative to concrete and steel, particularly in Europe [86]. It is a solid structural wood panel made of 3, 5, 7 or 9 layers of solid-sawn lumber or structural composite lumber glued together and oriented at right angles to one another [87,88]. Layers of kiln-dried lumber are typically glued with PUR (polyurethane), MUF (melamine-urea-formaldehyde-resin) or emulsion-polymer-isocyanate (EPI) resin. In addition to its advanced properties of greater rigidity and stability, CLT provides better fire resistance compared with traditional wood products, because it chars slowly [89–91] through its large mass. It also has good seismic performance resulting from its dimensional stability and rigidity [89,92–94]. This makes CLT a viable alternative to steel and concrete in the building industry.

Among the currently available emerging wood products, CLT manufacturing has been studied with LCA focused on investigating environmental impacts. Within the past five years, a limited number of studies evaluated the life cycle impacts associated with the CLT supply chain. CLT is a relatively new commercially produced product particularly in the United States and limited manufacturers are in the field. Therefore, North American CLT manufacturing data are limited [95–97]. Mass timber buildings constructed with CLT and glulam have also been investigated for environmental benefits using LCA tools [98–101], which is covered in the following mass timber building LCA section. The cradle-to-gate CLT product is typically composed of resource extraction, lumber (primary) manufacturing and CLT (secondary) manufacturing. The first stage, resource extraction, covers the forest operations from tree growth to logging and including transportation. The CLT manufacturing stage includes lumber preparation, adhesive application, layup assembly pressing, and panel finishing. The lumber preparation at the CLT manufacture includes lumber sorting, planing, drying and cutting to length. The lumber is also dried to 12% moisture content (MC) on a dry basis (db) to aid in the gluing process, which is lower than the drying level of commodity lumber (15% MC dry basis). The LCA studies used primary data collected through the surveys from the CLT manufacturing and also used secondary data from the literature for other stages [95–97].

The cradle-to-gate LCA studies showed that the CLT manufacturing stage contributed the most to the global warming impact compared with other traditional wood products [95–97]. Two studies were based on CLT production in the U.S. (Table 3). [97] investigated environmental impacts associated with CLT production in Oregon, U.S. Another U.S.-based study [96], performed a region-specific cradle-to-gate LCA for CLT with data representing technology available in the western part of Washington State. This study particularly investigated the effect of logistics, location of materials and their transportation and different wood species mix on the resulting life cycle impacts. Sensitivity analyses were performed by focusing on commercial softwood species in Washington State including Sitka spruce (*Picea sitchensis*), Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*). Wood species used and transportation had a notable effect on overall global warming (GW), where up to 14% reduction in GW can be achieved by reducing the transportation distances [96]. The study reported that up to a 29% decrease in GW impact can be achieved using a lighter species such as Sitka spruce compared with the baseline scenario (Douglas-fir and western hemlock mix). Another study investigated the effect of logistics, focusing on Japanese logistics [102]. That study revealed that, for shorter distances, ocean freight transportation resulted in lower GW impact compared with truck transportation. The scenario analysis showed that importing CLT from Austria resulted in a 20% increase in GW impact. In the analysis, 60% of the total GW impact was allocated to transportation.

Table 3. Peer-reviewed LCA studies on CLT production.

Study	Location	System Boundary	Declared Unit and Output	Impacts Methods	Allocation
[96]	Western Washington/U.S.	cradle-to-gate	1 m^3 of CLT	TRACI	Mass
[95]	Canada	cradle-to-gate	1 m^3 of CLT	TRACI, CED	Mass and economic
[102]	Japan	cradle-to-gate	1 m^3 of CLT	-	-
[97]	Oregon, U.S.	cradle-to-gate	1 m^3 of CLT	TRACI, CED	Mass and economic

Wood products processing results in various coproducts, which makes allocation necessary [103]. Mass allocation is commonly used in forest product LCAs, although recent studies began reporting results using both mass and economic allocation methods. For the CLT supply chain, the majority of the impact categories in the studies reported results for both economic and mass allocation showed a notable difference between the results [95,97].

Table 4 shows that the US-based studies reported higher GW impact compared with a Canadian study. This resulted from the higher GW impact of lumber and CLT manufacturing life cycle stages and was partially caused by electrical grid composition [95,97]. In addition, U.S. lumber production reported higher cumulative energy demand (CED) compared with the Canadian study. [71] noted that this may have been caused by lower resin use reported in Canadian CLT and the use of different wood species.

Table 4. LCA results per 1 m^3 of CLT from peer-reviewed journal articles.

Study	GW (kg CO_2 eq)	Eutrophication (kg N eq)	Acidification (kg SO_2 eq)	CED (MJ)	Smog (kg O_3 eq)
[96]	163–202	0.11–0.13	1.49–1.78		18.53–26.16
[95]	79.99	1.08×10^{-1}	41.98	1433	16.34
[102]	100–200				
[97]	158.67	30.9	0.09	4716	1.72

4.2.3. Mass Timber Buildings

For hundreds of years, wood buildings have been built with heavy timber construction although a small minority of the built environment especially in recent years. New advances in wood science and engineering for mass timber products and associated building systems are resulting in major changes in the built environment. These emerging mass timber products can replace heavy timbers and are designed for buildings with multiple stories. Structural elements of mass timber buildings are made from mass timber products such as CLT, DLT, NLT, and glulam. Glulam is a more traditional wood building product but its use in mass timber buildings is common in conjunction with CLT, DLT, and NLT. Other traditional wood building products can be utilized in these building systems as well but in much smaller quantities. The use of CLT as a building material started in Europe in the 1990s and in the last decade, many CLT mass timber buildings have been built worldwide because of its positive environmental benefits and potential local economic impacts [92,104]. There are sustainability assessment tools specifically designed for whole building LCA analysis. These include the Athena Impact Estimator for Buildings, Tally, BEES (Building for Environmental and Economic Sustainability) and BIRDS (Building Industry Reporting and Design for Sustainability) [54,105–107]. These tools include relevant material databases that can be used for whole building LCA analysis. Although LCA studies on CLT mass timber buildings are rare, as shown in Table 5, only the most relevant references with detailed building information and environmental impacts were included in this review.

Among these studies, all CLT buildings exhibited better environmental performance such as lower GW compared with their corresponding building alternatives, although different study periods and system boundaries were applied [98,101,108–111]. Except for the research conducted by Liu et al. [101], which used cradle-to-gate LCA, all others conducted cradle-to-grave LCAs to provide more information. System boundaries for building products and building systems are detailed in ISO 21930 [55] and EN 15978 [112], which comprise modules A1–A3 (production), A4–A5 (construction), B1–B7 (use), C1–C4 (end-of-life) and D (optional information beyond the system boundary). Module D points to the possible net benefits from reuse, recycling and any energy recovery outside the system boundaries and the effects are conducted through scenario analyses. Cradle-to-gate building LCAs cover modules A1–A3 while cradle-to-grave LCAs cover modules A1–A5, B1–B7 and C1–C4 with any exclusions noted. Only the research by Reference [108] includes module D for materials recycling, in which the total GW impact was reduced by 2% under the assumption of 40% wood materials recycling rate. However, this number might be too conservative compared with the 60% to 80% concrete and steel recycling rates. Currently, although module D is optional for LCA studies, it should be the point of interest for the forest products industry. Building LCA study periods range from 50 to 100 years to reflect stakeholders' expectations, in which the use stage (module B) usually causes the most environmental impacts [mainly because of the building's operating energy consumption (B6)]. For example, two studies from Athena Sustainable Materials Institute showed that the GW ratio (use stage versus total cradle-to-grave) was about 92% and 89% for a study period of 50 and 100 years, respectively [110,111]. However, as buildings become increasingly energy efficient, their embodied energy becomes more substantial. This trend will likely to continue for the built environment as green building practices become part of normal construction and business practices. The materials transportation (A4) usually is not a significant contributor to total environmental impacts. However, the use of local materials especially CLT should be encouraged to avoid the environmental burden. All CLT mass timber buildings in Table 5 used local CLT manufacturers except the study by Reference [108], which used European CLT and imported to Australia, which could significantly increase the environmental impacts, although the report did not show this information explicitly. It is expected that more LCA studies on mass timber buildings will come with the increasing interest in CLT and other mass timber use in the building industry sector. For both emerging mass timber products and building systems, there are areas of uncertainty. Being somewhat newer product and building systems, the actual versus expected service life effects the basis for selecting a functional unit for cradle-to-grave LCA analyses. Consequentially, a lower service life results in higher impacts for the system studied. Also, estimating end-of-life impacts is uncertain as well although there has been researched to quantify how wood and wood products are handled.

Table 5. Reference of LCA studies on CLT mass timber buildings.

Study	Location	Building Type	Floor Area (m^2)	CLT Usage (m^3) [a]	System Boundary	Study Period (Year)
[111]	Vancouver, BC, Canada	18-story dorm	15,120	2136	A to C (exclude B1, B5)	100
[98]	Amherst, MA, U.S.	4-story college	8129	2143	A to C (exclude B1, B5)	60
[110]	Prince George, BC, Canada	6-story mix-use	4820	1248	A to C (exclude B1, B5)	50
[108]	Melbourne, VIC, Australia	9-story mix-use	1755	1006	A to D (exclude B1-B5)	50
[109]	Quebec City, QB, Canada	4-story apartment	4060	1224	A to C (exclude B1-B3, B5)	60
[101]	Burnaby, BC, Canada	8-story office	14,232	4147	A1-A5	50

([a] includes glue-laminated timber).

4.2.4. Advanced Materials (Nanomaterials or Nanocellulose)

Nanomaterials and nanocellulose comprised of nanosized (1–100 nm) cellulosic fibrils or crystals are obtained generally from plants. This article covers only plant-derived nanomaterials. Nanocellulose is considered a novel advanced biomaterial but the global economic impacts of nanocellulose are projected to reach $600 billion by 2020, which is highly unlikely given the current commercial product output [10]. There are different types of nanomaterials produced from cellulose, which is the world's most abundant polymer. Cellulose makes up about 38% to 49% of dry wood with the remainder being made up of hemicellulose (15–26%) and lignin (18–35%), along with small amounts of extraneous materials.

Cellulose fibers in the wood cell wall create an amorphous matrix with lignin hemicellulose, proteins, and other organic substances. Cellulose nanomaterials are differentiated [25] as (i) nanostructured materials [cellulose microcrystal (CMC, width: 10–15 µm, L/D < 2) and cellulose microfibril (CMF, width: 10–100 nm, length: 0.5–50 µm)] and (ii) cellulose nanofiber [cellulose nanofibril (CNF, width: 5–30 nm, L/D > 50) and cellulose nanocrystal (CNC, width: 3–10 nm, L/D > 5)] based on the appearance and preparation method. CNFs can be extracted from plant cell walls either by mechanical shearing (such as grinding, cryo-crushing (mechanical fibrillation) and high-pressure homogenization) or thermal-mechanical (steam explosion, aqueous counter collision) or physio-chemical (high-temperature extrusion) or a combination of chemical pre-treatments followed by mechanical routes (hydrolysis—high-intensity ultrasonication, electrospinning, etc.). The production of CNCs is more complicated and involves multiple steps such as mechanical size reduction, purification, and bleaching of cellulose, chemical pre-treatment and mechanical/ ultrasound treatment. Acid hydrolysis can be used to produce CNCs without mechanical treatment but it degrades cellulose resulting in lower nanocellulose yield and poor thermal stability. To improve the thermal stability of CNCs, solid and gaseous acid hydrolysis has been used in place of liquid acids. Because nanocellulose is a newer forest-based product, investigating its production along the supply chain can provide insights into its environmental performance, influence which potential manufacturing process is chosen for commercial production and give insights into how to improve the product in future production.

The production of nanocellulose is a very energy-intensive process. Additionally, the aggregation of disintegrated fibers is very common during the process of defibrillation. Furthermore, noncellulosic components such as hemicellulose and lignin create a hindrance by blocking the cellulose from chemical intrusion [25,113]. Pre-treatment alters structural organization, crystallinity, and polymorphism of cellulose (frees the individual fibers), which is favorable in nanocellulose production, thus it can reduce the energy requirement by a factor of ten. Therefore, various chemical and mechanical pre-treatment methods had been proposed based on the input feedstocks such as pulping process, bleaching and alkali treatments, enzymatic treatment and oxidation (i.e., oxidation with 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) reagent) [114,115], carboxymethylation [115] and acetylation of the fibers [115]. Moreover, microwave-assisted pre-treatment, e-beam irradiation, chemical swelling, and extrusion pre-treatments have been proposed recently for use in the CNC production process [25]. As previously mentioned, using the LCA method now can be a critical driver.

There are only a handful of studies that used LCA to quantify the environmental impacts of nanocellulose. The cradle-to-gate LCA studies included raw material extraction, logistics, and manufacturing stages of products. The LCA studies of nanocellulose were performed using either primary data from lab-scale/pilot-scale experiments or from secondary data. The primary materials to produce nanocellulose were either from pulp or directly from woody biomass (Table 6). However, most studies consider pulp (kraft pulp or sulfite pulp) as feedstock to produce nanocellulose. Nanocellulose production from woody biomass requires a pulping process to dissolve lignin and hemicellulose [116,117].

Table 6. Peer-reviewed LCA studies on nanocellulose production.

Study	Study Locations	Pre-treatments Methods	Nanocellulose Extraction	Functional Unit with Output	Impacts Methods	Inputs
[114]	Europe	Enzymatic (endoglucanase) and chemical (TEMPO oxidation)	Mechanical (homogenization)	1 ton of NFC	ReCiPe + midpoint	Sulfite Pulp
[115]	North America	Chemical (TEMPO oxidation and chloroacetic acid etherification)	Mechanical (sonication + homogenization)	10 g of MFC	Eco-Indicator 99 + midpoint and endpoint	Kraft pulp
[116]	Japan	Mechanical-chemical (HCW only)	Mechanical (wet disk milling)	1 kg of CNF	-	Woody biomass
[118]	Europe	No pre-treatment and Enzymatic (endoglucanase)	Microfluidization and mechanical (homogenization)	1 kg of CNF	ReCiPe + midpoint	Sulfate and sulphite pulp
[119]	North America	Chemical (Acid hydrolysis)	Ultrafiltration	1 kg of CNC	TRACI + midpoint	Bleached kraft pulp
[120]	Japan	Mechanical-chemical (hot-compressed water)	Mechanical (wet disk milling)	1 kg of CNF	-	Woody biomass
[121]	South America	Chemical (Alkaline pre-treatment) and enzymatic (Novozymes-manufactured)	NA	10 g of CNS	-	Wood flour

CNF: Cellulosic nanofibrils, MFC: Microfibrils cellulose, NFC: Nanofibrils cellulose, CNS: Cellulosic nanostructures, TEMPO: 2,2,6,6-tetramethylpiperidine-1-oxyl radical, HCW: hot-compressed water.

Production of nanocellulose (without pre-treatment) is an energy-intensive process, where a large amount of electricity (~27 kWh/kg of nanocellulose) is consumed to break down the crystalline structure of cellulose and defibrillate individual fibers [113,122]. Without pre-treatment of pulp, microfibrillated cellulose (MFC) produced from kraft pulp or sulfite pulp requires about 12 to 70 and 27 kWh/kg of MFC, respectively [113]. Thermo-mechanical [116,117], chemical [115,118,119] and enzymatic [115,121] pre-treatments were proposed to pretreat the pulp/woody biomass to help free up the nanofibers and thus reduce the energy required in the process of nanocellulose extraction. The pre-treatment process (carboxymethylation and enzymatic) can drastically reduce the energy requirement of MFC production (0.5–1.5 kWh/kg of MFC) [113]. Hohenthal et al. [114] studied nanofibrillated cellulose (NFC) produced from sulfite pulp considering pre-treatments (enzymatic and chemical) and mechanical homogenization from two different geographic locations in Europe, France, and Finland, for its environmental life cycle impacts. Three pathways considered were (i) enzymatic (i.e., endoglucanase) pre-treatment of pulp and refined in a high-pressure homogenizer, (ii) TEMPO oxidation of pulp and refined in a high-pressure homogenizer and (iii) TEMPO oxidation of pulp and refined in a continuous high-energy Cavitron (ARDE Barinco, Inc., Carlstadt, NJ) disperser. Although enzymatic pretreated pulp required more than double the amount of electricity in a high-pressure homogenizer, its water usage was very low, yield of NFC was high (100%) and no chemicals were used. The requirement of electricity in the Cavitron disperser was about 25% compared with a high-pressure homogenizer. Tempo oxidation also requires chemicals such as 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO), NaBr, NaClO and NaOH and consumes a large amount of water to wash NFC (lower yield; ~71%), which negatively affects its environmental performance. Both midpoint and endpoint environmental impacts were measured considering a functional unit of 10 g of nanocellulose. GW impact varied from 750 to 3100 kgCO_2e/ton of NFC. The large range was caused by differences in the NFC production locations and concentration of NFC. For example, GW impact of NFC produced in France is half that of NFC produced in Finland because of the difference in the GHG emissions on a kWh basis for the individual country's electrical grid. This study also estimated other impact factors such as eutrophication, acidification and fossil fuel depletion (Table 7). Li et al. [115] performed a cradle-to-gate LCA study for the production of nanocellulose through four comparable chemical-mechanical methods in lab-scale (TEMPO oxidation followed by sonication or homogenization and chloroacetic etherification followed by sonication or homogenization) from kraft (chemical) pulp and impacts are estimated with the Eco-Indicator 99 impact assessment method. This study used similar inputs as Hohenthal et al. [114] for the TEMPO oxidation except for ethanol for quenching the reaction. The chemicals used in chloroacetic acid etherification were chloroacetic acid, NaOH, isopropanol and ethanol. The large differences in the LCA results between Hohenthal et al. [114] and Li et al. [115] (Table 7) were caused by the differences in the key variables such as type of chemical pulps (sulfite vs kraft) as feedstocks, processing time, concentration, number of passes and power consumption in the fibrillation step. Moreover, the use of ethanol for quenching the reaction and a large amount of electricity use during homogenization in Li et al. [115] had a large impact on the LCA results. Feedstocks from the various pulping methods can vary the LCIA results and thus additional investigation is required. Pulp production is an energy-intensive process with large environmental impacts. In the Japanese nanocellulose LCA, Sun et al. [116] and Moon et al. [117] evaluated CNF production from woody biomass considering combined wet disk milling and mild hot-compressed water (HCW) treatment. In the HCW treatment, the acetyl groups of hemicellulose and water itself act as acids, which dissolve both hemicellulose and lignin in woody biomass [123]. Sun et al. [116] assumed a CNF yield of about 80% to 92% of woody biomass and energy usage was much lower than other studies with no chemical inputs. The MiLCA, a Japanese LCA support system—supported by a database, the IDEA (Inventory Database Environmental Analysis) was developed by the National Institute of Advanced Industrial Science and Technology (AIST) and the Japan Environmental Management Association for Industry (JEMAI) [116]—to perform LCAs. GW impacts of CNF estimated by Sun et al. [116] and Moon et al. [117] were 1.2 to 3.7 and 5.7 to 7.6 kgCO_2e/kg of CNF, respectively, which were in the range of results produced by Hohenthal et al. [114]. Lower GW impact was possibly caused by the use of woody biomass in place of pulp, lower energy usage per production unit, absence of high-energy intensive feedstock chemicals and other inputs and the higher assumed CNF yield.

Table 7. LCA results from peer-reviewed journal articles per functional unit.

Study	Nanocellulose Production Routes	GW (kg CO_2 eq)	Eutrophication (kg N eq)	Acidification (kg SO_2 eq)	CED (MJ/kg NC)	Fossil Fuel Depletion (kg oil eq)	Water Usage (kg H_2O)
[114]	Enzymatic + hominization (homonizer)	1.2–3.1	0.015–0.016	0.045–0.008		0.30–0.75	50
	Chemical (TEMPO) + hominization (homonizer)	1.0–1.8	0.018–0.024	0.005–0.0065		0.25–0.5	158
	Chemical (TEMPO) + hominization (Cavitron disperser)	0.75–1.0	0.014–0.015	0.0045–0.005		0.20–0.25	120
[115]	TOHO (TEMPO oxidation + homogenization)	190				46.6	
	TOSO (TEMPO oxidation + sonication)	980				311.9	
	CEHO (chloroacetic acid etherification + homogenization)	360				116.6	
	CESO (chloroacetic acid etherification + sonication)	1160				382.2	
[116]	HCW + Wet milling	3.68					
	HCW + Wet milling	1.26					
[118]	No pre-treatment + homogenization	1.2		0.0069	240		130
	Enzymatic (endoglucanase) + Microfluidization	0.79		0.0078	1800		240
	Carboxymethylation pre-treatment + Microfluidization	99		0.18	87		1000

Table 7. *Cont.*

Study	Nanocellulose Production Routes	GW (kg CO_2 eq)	Eutrophication (kg N eq)	Acidification (kg SO_2 eq)	CED (MJ/kg NC)	Fossil Fuel Depletion (kg oil eq)	Water Usage (kg H_2O)
[119]	Chemical (Acid hydrolysis) + Ultrafiltration	29.64	0.05	0.54	992.7	20.8	
[120]	HCW + Wet milling	7.6					
[121]	Alkaline pre-treatment + enzymatic hydrolysis			20–60	5–350		

TEMPO: 2,2,6,6-tetramethylpiperidine-1-oxyl radical, TOHO: TEMPO-oxidation for chemical modification, homogenization for mechanical disintegration, TOSO: TEMPO-oxidation for chemical modification, sonication for mechanical disintegration, CEHO: chloroacetic acid etherification for chemical modification, homogenization for mechanical disintegration, CESO: chloroacetic acid etherification for chemical modification, sonication for mechanical disintegration; HCW: hot-compressed water.

Arvidsson et al. [118] performed an LCA of CNF production from four types of pulp considering no pre-treatment and enzymatic and chemical pre-treatments of pulp followed by microfluidization treatment for the extraction of CNF. That study provided a comprehensive and detailed analysis of all inventory used in the production of CNF including inbound logistics of all raw materials. The results (Table 7) suggested that the CNF production through either no pre-treatment or enzymatic pre-treatment routes have much lower environmental footprints than the chemical pre-treatment route, which consumes large amounts of solvents made from crude oil.

Gu et al. [119] studied the LCA of CNC produced from bleached kraft pulp through a pilot-scale production plant that used chemical pre-treatment (acid hydrolysis of pulp) followed by ultrafiltration of disintegrated treated pulp (50% CNC yield). The use of chemical (i.e., sodium hydroxide) and electricity had the largest impacts in all categories of environmental footprints of CNC. However, these impacts were much lower than other chemical routes to produce nanocellulose.

The environmental impacts of nanocellulose are lower than other nanomaterials [25,115,122]. Furthermore, adding nanocellulose to parent materials can improve their properties and requires less of the parent materials to achieve the same functionality. For example, the addition of nanocellulose in the raw material composition results in a reduction of 29% of raw material consumption for wet-laid nonwoven material [114]. Incorporating CNF to paper increased the recyclability of paper from 3 to 7 times, thus reducing the environmental impacts from paper production [124]. When nanocellulose was applied to wet-laid nonwoven, Hohenthal et al. [114] estimated a reduction in environmental footprints (~30% lower GW impacts) compared with reference product standard wet-laid nonwoven material. Similarly, Delgado-Aguilar et al. [124] performed the LCA of incorporating nanocellulose to paper to improve its physical properties and recyclability. In retrospect, nanocellulose production is in its infancy. Therefore, investigating the environmental performance offers a great deal of opportunity in forging the production process with the lowest life cycle environmental impacts while aiding commercial products such as paper products to improve their environmental performance.

5. Discussion

Forest-based products, especially building (construction) products are recognized as a renewable resource, having low environmental impact (i.e., low fossil fuel energy consumption, few pollutants released and stores biogenic carbon), material resource-efficient and aesthetically pleasing compared with competing materials such as steel, concrete, and plastic. Moreover, products made from forest resources can replace fuels, chemicals, and bioproducts that come from fossil resources. Looking at the diverse use of wood and its increasing market demand, it is essential and critical to know the life cycle impacts of products coming from wood to make decisions on the most environmentally sound and sustainable use of our forest resource. Providing accurate baseline LCA data for each forest-based product is part of sustainable practices to improve energy consumption and develop sound carbon sequestration policies.

5.1. System Boundaries

For LCA studies, system boundaries are crucial to identify relevant processes along a product's whole supply chain, quantify the input resources and output emissions and products outputs. Among three approaches (i.e., cradle-to-gate, gate-to-gate, cradle-to-grave), most studies followed the gate-to-gate approach in earlier studies because collecting primary data on traditional wood products is time-intensive and EPDs were not considered yet for green building certification systems, which require reporting LCIA results in a consistent framework [59]. In addition, LCI datasets were developed early on in the U.S. to upload into the U.S. LCI Database for use by other LCA practitioners and to populate whole-building LCA tools, not wood product EPDs [52,120,125]. Traditional wood building products (i.e., lumber, LVL, OSB, etc.) have been the most extensively studied products for their life cycle environmental impacts. There are many LCIAs and LCAs going from gate-to-gate and cradle-to-gate along with a few from cradle-to-grave. Environmental impacts generated from a unit supply chain operation/process are embodied within that product and it is transferred to another unit processing step until the product reaches the consumers and is disposed of or recycled after its end of life. It is this systemic approach that is the basis for the LCA methodology. There are few engineered wood products (e.g., I-joists) that are manufactured from other wood products (i.e., LVL, softwood lumber and OSB). Therefore, depending on the product production simplicity or its ability to be disaggregated into smaller unit processes, these gate-to-gate LCI studies had been performed using the black box technique (combining all sequential unit operations to a single operation for a product) to estimate the environmental impacts of a specific manufacturing process only (e.g., production of I-joists only). Initially, gate-to-gate LCI studies were prevalent in the U.S. because generating the individual life cycle stages were hugely data-intensive exercises and were new both to the researchers along with the wood product industry being studied. As one could expect, studies began to link life cycle stages along with the LCIA. All these earlier studies used mass allocation as their primary allocation with a few including an economic allocation to illustrate the potential difference and the need to set up a consistent protocol, which led to product category rules (PCRs) for creating wood building product EPDs along with the credits obtained in green building certification schemes [56]. Building product PCRs are constructed according to ISO standard 21,930 [65] and require a detailed process for eventual PCR publication and application [63].

The emerging mass timber LCA studies, which were focused on cradle-to-gate CLT production, mainly used mass allocation. Yet, studies that are conducted in accordance with the Product Category Rules (PCR) for North American Structural and Architectural Wood Products presented environmental impact results for both mass and economic allocation [126]. These LCAs are performed using cradle-to-gate system boundaries. Also, they did not consider carbon storage benefits of CLT and corresponding mass timber products and its effect on the global warming impact category. The LCA studies on advanced bioproducts, such as nanocellulose, followed the cradle to gate approach but were not covered under the previously mentioned PCR [95]. PCRs are typically developed for commercial products.

5.2. Functional Unit

The functional unit depends on the goal of the LCA study along with the final product-specific properties and its use. Functional units are used to represent the quantified performance of a product system to be used as the reference unit in a LCA study. Properties of a functional unit include quantity, service, and function (e.g., 1 m^2 of installed flooring lasting 50 years). LCA results of a system are referred to a functional unit and hence defining a functional unit is essential and crucial for an LCA study. Some LCA studies use a declared unit which corresponds to mass or volume of a given product. The declared unit is used instead of a functional unit when the exact function of the product at the building level is not stated or known or when the LCA does not cover a full life cycle. There are many declared units used in the LCA studies of U.S. wood products that are specific to the final products. Generally, unit volume (1 m^3) and mass (i.e., 1 oven-dry ton) of products were used for declared units depending on the location along the supply chain that the results were reported on. Traditional wood building product such as I-joists considered unit length (i.e., 1 km) as a declared unit. For both functional and declared units, both volume and surface area have to be considered. The conversion of mass to volume and vice versa for wood products is complicated because of variations in the product physical properties and various stand of measurements, especially in the U.S. However, the LCA studies in the U.S. for traditional wood building products provide in-depth information about the mass and volume conversion. There are few studies that compared environmental footprints of various wood products coming from the forest based on volume or mass. However, the volume and mass do not represent the function and use of the products. For example, the GW impacts of engineered wood flooring may be lower than solid strip hardwood flooring on a declared unit basis. But solid strip hardwood flooring lasts longer than engineered wood flooring and the environmental footprint of the former might be lower on a functional unit basis if both products are compared considering a more relevant reference unit such as floor area and length of use (i.e., square meter-year) as shown by Reference [48].

5.3. Databases, Modeling Tool, Impact Assessment, and Impact Categories

LCAs have support mechanisms such as LCI databases. The U.S. LCI Database [127] was the most used LCI database but it is likely to be replaced or least augmented by the LCA Commons [128]. Similarly, ecoinvent and Gabi databases have been used extensively for LCA studies in Europe and Australia since they are embedded into the two most common LCA modeling software programs, SimaPro and Gabi. In addition, ecoinvent has been modified for specific countries including the United States (e.g., US Ecoinvent) to fill in missing data gaps. There are few studies from Asia and these studies either did not use any specific database or used ecoinvent with modifications. It is likely that some national databases are not used, are well known by LCA practitioners within the individual countries or the practitioners use what is available in current software programs.

SimaPro and Gabi are the two major software programs used to develop LCA models to generate LCI flows and estimate environmental impacts. These programs incorporate both the U.S. LCI Database and Ecoinvent databases. Environmental burdens of a process or product are estimated using a specific LCIA method, which contains a set impact category. Most initial LCA studies from CORRIM reported just the LCI and more recently the LCIA results for traditional wood building products. Generally, impact assessment tools used in the literature are specific to the goal of the study and study locations. Both midpoint and end-point environmental impacts were estimated in the reviewed LCA studies. Globally, the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI), CML, EcoIndicator and ReCiPe impact category methods are the most widely used tools to estimate the environmental impact categories. TRACI was developed specifically for the United States by the U.S. EPA [129]. The International Panel on Climate Change (IPCC) guidelines have been used by a few studies, when the GW impact estimation for a 100-year period is the main goal of the study [130]. There are many impact categories reported by LCA studies. However, GW is the most widely reported impact category from all LCA studies, irrespective of impact assessment tools, study locations and products. Carbon storage from wood products has been identified along with the associated carbon balance, especially in articles and reports from CORRIM. The carbon storage was often compared to the carbon emissions of product production to illustrate the magnitude of carbon storage which was especially striking for lumber products [41,53,54,56,63,64].

5.4. Allocation Approach

Allocation has been a critical issue for LCA in general and if an allocation is conducted in the LCA, the approach must be reported in the goal and scope [131,132]. The allocation of environmental burden is considered when a process produces several products or outputs (e.g., softwood lumber and redwood decking). Allocation is a separation of the environmental impacts according to the mass or revenue generated from the products and co-products produced and leaving from the system boundary.

Allocation is part of the attributional LCA approach. Mass and economic allocations are the two major approaches that have been used to allocate environmental burden to multiple products from a single process. However, most LCA studies, especially for traditional wood building products, have used mass allocation. The economic allocation may require stable prices of products for a consistent result, which has not occurred in the U.S. [103] reported on the pricing variability tied to economic allocation for wood-based panels. Thus, depending on the products studied, the LCIA results varied a little or a lot as shown by Reference [102] on wood panels. The current PCR for North American Structural and Architectural Wood Products [95] requires economic allocation to be used in LCA studies but the current PCR under revision will fall back to mass allocation partly because of the problem illustrated by Taylor et al. [103]. The ISO standards strongly recommend avoiding allocation, which can be achieved through system expansion but this is not necessarily a good approach for forest-based products.

5.5. Data availability and Quality

Data availability and quality of data are essential and critical for the LCA of any product. The data required for LCA of forest-based products, especially traditional wood building products are available in North America and Europe. For traditional wood building products, large amounts of LCA data exist for many products. In the U.S., for many years, CORRIM developed the LCI data for many forest-based products along the entire supply chain. CORRIM has been the data generator and data manager to maintain the highest data quality. Two ways have been used. (1) Each CORRIM LCA researcher was required to follow specified research guidelines developed by senior CORRIM members [133], which have undergone revisions to maintain its newness. These guidelines along with the PCR [95] overlap the standards provided by ISO. (2) Each LCA model and report were reviewed for consistency and accuracy internally as well as externally. Before 2018, the LCI data developed through CORRIM eventually ended up in the U.S. LCI Database [127], which went through another peer review before being posted online. As of 2019, forest-based LCA data will be uploaded into the LCA Commons hosted by the USDA NAL, which now hosts the U.S. LCI Database. The USDA National Agricultural Library and NREL are working to ensure the databases are backward compatible and that all forest-based LCI data submitted through CORRIM will continue to be available.

Emerging wood building products such as CLT have been around since the 1990s but they have not been heavily used in the building industry. The main obstacle has been the building codes, which prevented the use of wood mainly from concerns about fire resistance, in particular in multistory buildings (greater than eight stories), which would be mass timber buildings. If a building developer wanted to build with mass timber, he or she would need to acquire a variance, a lengthy and costly waiver process. However, this is changing because the International Code Council will allow for midrise buildings up to 18-stories constructed from mass timber in the 2021 revision of the International Building Codes. The states of Washington, Oregon, and Utah have already accepted these revisions in their building codes. A few EPD or LCI data for specific CLT manufacturing (mostly in Europe and Canada) are available. The U.S. is developing such data for a couple of new CLT manufacturers. Because of the relatively small number of producers, industry average data for CLT and other mass timber product LCI data are not available now except for glulam. Most cradle-to-gate CLT LCA studies used primary data collected through surveys for the core process of CLT manufacturing and used secondary data for the upstream and downstream processes. The major challenge in CLT and mass timber building LCA research is to obtain quality primary production or operational data from mass timber manufacturers or mass timber building contractors. Government support has helped in the collection of quality data. Continuous effort will be crucial to complete and reliable LCA studies of this emerging wood product and its application for the benefit of the world's environment.

LCI data for advanced bioproducts such as nanocellulose produced at the laboratory and pilot scale operations are available from Europe and North America. Unlike traditional wood and mass building products, the production of nanocellulose is limited to laboratory or pilot scale. With the expected rise in demand and maturity in commercial technology, the quality of LCI data for nanocellulose will improve.

5.6. Spatial and Temporal Variability

Spatial and temporal variability in forest management, yield, tree species, geography and so forth, may lead to distinctive LCA results. For traditional wood building products, LCA data exist on regional and temporal variability. For example, softwood lumber LCAs were conducted in four regions of the U.S. twice over roughly a 10-year period. This has not been duplicated elsewhere except for Canada which has worked closely with the U.S. on developing North American-wide wood product EPDs. The regional variabilities [51,66,78,134,135] in the LCA results are linked to variations in the tree species, harvesting methods, logistics options, transport distance, log handling, and processing, drying requirements and adopted technologies in producing wood products but the most significant variation was the power grid supplying electricity to the product production facilities and for the lower drying requirements. In addition, these variabilities tracked the changes in the industry including new regulations implemented along with increased efficiencies in wood product facilities. The present LCA studies for wood products are aggregate numbers and are specific to either to a continent, country or various regions or locations within a country. With a reduction in the scope of the study area size, that is, regional studies to high-resolution studies, LCA results can be accurate and precise.

6. Conclusions

This article provides a comprehensive and systematic literature review of LCA of forest-based products including traditional wood building products, emerging wood building products along with mass timber building systems and nanocellulose. The results show that most LCA studies were on traditional wood building products in North America, especially the U.S. This is expected considering the size of the U.S. forest sector along with its impact on the U.S. economy and the quantities of traditional wood building products going into the U.S. housing sector. A more current relevant driver for LCA studies on traditional wood building products is EPD development for green building schemes, which require recent underlying LCA data. This creates a scenario in which previous LCAs must be continually updated along with the PCRs used to frame the structure of the attributional LCAs.

Concerns about LCA shortcomings regarding spatial and temporal issues have been dealt with rigorously by traditional wood building products in the U.S. To handle the regional variations in the forest management, wood species, geography and so forth, the scope of the LCA studies for traditional wood building products were specific to various regions in the U.S. However, the basis for the reduction of the scope of the LCA studies to various regions was not explicitly given. The LCA studies for traditional wood products showed an improvement in the environmental impacts brought about by increased contributions of renewable energy and improvement in the manufacturing processes.

Unlike traditional wood building products, emerging wood building products and nanocellulose are in the beginning stage. Few LCA studies of emerging wood building products exist for CLT being used in mass timber buildings and there is no indication that other emerging mass timber product systems have been investigated for their environmental performance although they are being produced commercially in the U.S. and mass timber buildings are being constructed. The LCA studies on nanocellulose are available although only on a laboratory or pilot scale production, unlike the other forest-based products investigated in this article. Other forest-based products are produced commercially. However, LCA could potentially influence the type of nanocellulose production process chosen for future production. Given the various products included in this review, this shows that LCA can be used for different products for different reasons and thus highlights its widespread applicability and its ability to seek out the best science.

The purposes of conducting LCA research on forest-based products has been extended. Most early studies in the U.S. developed only LCIs to populate LCI databases and whole-building LCA tools, especially for traditional wood building products. LCIA results were included later when green building certification schemes became relevant, which further pushed the development of EPDs and whole-building LCA comparison tools. LCI data still need to be updated to create the LCIA results but LCIs are data-intensive. Therefore, other means of collecting primary data must be investigated such as utilizing current wood product industry surveys to collect the necessary data and its recency per ISO standards.

LCA is probably being underutilized for new product development and its potential to drive environmental policy. For nanocellulose, GW impact is the main impact estimated in the LCA studies reviewed in this article. However, LCA is more than just GW impact or often called the carbon footprint. Therefore, the LCA studies should focus on all segments of LCA including GW. The scope of LCA studies not only provides information on environmental impacts but it has been used as a tool for the design for environment concepts to compare the alternative design of a product and building systems that provide the lowest environmental footprints. Consequentially, LCA must be part of sustainable analysis and development policies. Therefore, LCA should continue to diversify toward social and economic dimensions of sustainability.

LCA studies can be strengthened. The uncertainties and variabilities of input data to LCA studies are inherent and those have significant impacts on the results. Although many LCA studies reviewed here performed scenario analysis and sensitivity analysis, they did not perform uncertainty analysis of input data on the results. Contribution analysis and uncertainty analysis such as Monte Carlo would strengthen LCAs in general and ought to be considered in any LCA conducted.

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