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Cradle-to-Grave Life-Cycle Assessment of Cellulosic Fiberboard

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Abstract

According to the United Nations Environment Programme (UNEP), the construction and operation of buildings accounted for nearly 38% of total global energy-related CO_2 emissions in 2019. The construction sector has been striving to use more low-carbon footprint building products to mitigate climate change and enhance environmentally preferable purchasing. Over the last several decades, there has been substantial growth in engineered wood products for the construction industry. To assess these products used in construction for their environmental profile, lifecycle assessments (LCAs) are performed. This study performed an LCA to estimate environmental impacts (cradle-to-gate and gate-to-grave) of cellulosic fiberboard (CFB) per m^3 functional unit basis. The lifecycle inventory data developed were representative of CFB production in North America. Overall, the cradle-to-grave LCA results per m^3 of CFB were estimated at 305 kg CO_2 e global warming (GW), 19.3 kg O_3 e photochemical smog formation, 1.03 kg SO_2 e acidification, 0.33 kg N e eutrophication, and 415 MJ fossil-fuel depletion. Except for smog formation, most environmental impacts of CFB were from cradle-to-gate. For example, 71% and 29% of total GW impacts were from cradle-to-gate and gate-to-grave lifecycle stages, respectively. The sensitivity analysis showed that reducing transport distance, on-site electricity use, natural gas for drying, and starch additives in the manufacturing phase had the most influence. Around 353 kg CO_2 e/m^3 of CFB is stored as long-term carbon during CFB's life which is higher than the total cradle-to-grave greenhouse gases (CO_2 e) emissions. Thus, the net negative GW impact of CFB (-47 kg CO_2 e/m^3 of CFB) asserted its environmental advantages as an engineered wood panel construction material. Overall, the findings of the presented study would prove useful for improving the decision-making in the construction sector.

Keywords

Green buildings; engineered wood products; cellulosic fiberboard; environmental impacts; lifecycle assessment; environment product declarations

1. Introduction

The concerns over progressively increasing greenhouse gas (GHG) emissions and their negative impacts on the climate have reached the top priority of governments worldwide[1, 2]. The measures for climate change mitigation are now sought after in all major policy decisions; intended targets under sustainable development goals are an example of the highlighted interest of the world leaders [3]. The recently published sixth assessment report [4] of the Intergovernmental Panel on Climate Change (IPCC) has warned against the possibilities of catastrophic events if actions of great magnitude are not taken now. However, the report and many other researchers indicate the present time as an era of possibilities offered to mankind to minimize, delay, and even reduce climate impacts [4].

The above context attains high significance in the buildings and construction sector because of their energy-intensive operations and future growth [2]. According to the estimates of the UN global status report of 2020, the building operations and construction industry account for nearly 38% of CO_2 emissions associated with energy use [5]. Increasing awareness of climate change impacts has driven several research innovations and policy interventions globally. In addition, the introduction of Environmentally Preferred Purchasing (EPP) programs such as the USDA BioPreferred Program has stimulated the relative competitiveness in industrial sectors striving for greener alternatives [6]. The construction industry has emerged with a high potential to reduce fossil fuel energy use and resultant CO_2 emissions [1-3]. The wood industry has responded by assessing their building products for their carbon impacts [7-10]. With various engineering innovations, wood resources have been successfully used in developing products with affordability and enhanced performance [11, 12].

Generally, wood products are renewable and store carbon as well as a substitute for non-renewable and high-carbon (and energy) intensive construction materials like aluminum, concrete, and steel [13-15]. Although the storage of carbon in wood products is not permanent, reduced fossil energy use in their manufacturing, lower GHG emissions, and renewability make them critical for reducing environmental impacts of the building sector. During the logging operations, a substantial part of forest harvest (i.e., non-sawlog materials) can be of lower quality and usually discarded in the forest or used for low-value applications. Moreover, around half of the forest resources (i.e., sawlogs) are converted to dimensional lumber. The rest can be considered low-value by-products such as mill residue generally burned on-site to produce heat or power. However, these discarded forest resources can be engineered and produce engineered wood products (EWPs) with similar or improved properties for various building construction use. Further, the creation of EWPs using by-products of wood processing and building construction to achieve desired construction characteristics have contributed to the efficient utilization of forest resources [11, 12]. EWPs are designed to form larger and complex structural sections while reducing or removing the natural flaws and improving strength and harmonizing attributes. The significant growth of the EWP market in the last two decades highlights the implementation of EPP policy as the consumers are ultimately aimed at mitigating climate change by consuming sustainable products with low carbon impacts [7, 16, 17]. All these factors contributed to the advent of green building standards, rating systems, and green product certifications seeking mitigation of the climate change impacts of the construction industry [13, 18-20].

Cellulosic fiberboard (CFB), a member of the EWP family, is an appropriate choice for green building material to meet specific end-user requirements [21]. The boards are manufactured using cellulose fibers from renewable, recycled, and reused materials in the form of sawmill residues (wood chips, planer shavings, etc.) and construction waste. Using these woody materials, the extracted fibers are wet-processed and bonded by starch-based adhesives to form CFB panels [22]. The carbon within these panels remains stored during the life of the products, which corresponds to the life of the building. CFB panels are predominantly used in building constructions for roofing substrate, structural wall sheathing, sound-deadening board, and other specialty-use materials in North America [23]. Within North America, Canada and United States are the only producers of CFB. The CFB products of different types and categories are specified by the ASTM C208 (Standard Specification for Cellulosic Fiber Insulating Board) and/or CAN/ULC-S706 (Standard for Wood Fibre Insulating Boards for Buildings).

Given the progressive growth in the demands of the construction industry, the use of wood-based products is bound to expand in volume and diversity [17, 24, 25]. Although there is a widespread agreement on the environmental and economic benefits of EWPs [26], the use of fossil fuels and additives in manufacturing, transportations, and end-use of the wood products need to be accounted for [3, 8, 27, 28]. Thus, there is a need for lifecycle-based assessments to quantify the environmental impacts of EWPs [29]. Tools like life cycle assessment (LCA) are used for evaluating the environmental impacts of a product throughout its life [30, 31].

The objective of this study was to assess the cradle-to-grave environmental impacts of CFB produced in North America. The cradle-to-gate LCA covered lifecycle stages from the extraction of raw materials, transport of materials, and manufacturing of CFB using common industrial practices in North America. Depending on the woody material used in CFP manufacturing, extractions could be derived from forest operations or building construction. The gate-to-grave LCA model included CFB transportation, installation, use, and building demolition and disposal (i.e., landfilling) of CFB at the end-of-life (EoL). The study results and identified hotspots in the life cycle stages are intended to be useful for construction industry stakeholders and researchers aiming at reduction in environmental impacts of the construction sector.

2. Methodology

2.1 Goal and Scope Definition

The study's goal was to assess the cradle-to-grave environmental impacts of CFB panels manufactured in North America. The cradle-to-gate and gate-to-grave LCA models were developed separately. In 2019, there were four manufacturing facilities in North America producing 589,934 m^3 of uncoated CFB production of different types and categories of CFB of which two were surveyed using detailed questionnaires.

The study was conducted following the ISO standards 14040 and 14044 [30, 31] and product category rules (PCR) defined for Structural and Architectural Wood Products in North America [32, 33]. In addition to the environmental impacts, the PCR requires assessing additional indicators such as biogenic carbon flow and waste generation [32, 33]. For gate-to-grave LCA, the system was expanded to include the installation, use, and disposal phases. The intended audience for the LCA study involved the CFB manufacturers, the North American Fiberboard Association (NAFA), American Wood Council (AWC), Canadian Wood Council, building developers and owners, architects, and LCA practitioners in this area.

2.2 Functional or Declared Unit

The role of the functional or declared unit in an LCA study is to provide a reference against which all environmental inputs and outputs needed to perform the functions of the CFB production system can be detailed. For the cradle-to-grave study, this study considered a functional unit of 1 m^3 of CFB used as an insulating board and disposed of in a landfill with methane capture.

2.3 Allocation

The manufacturing of wood-based products is often accompanied by multiple co-products. Therefore, the LCA study needs to allocate the environmental impacts to each product to reflect their relationship. The wood products PCR recommends a mass allocation approach for dividing the inputs-outputs between the main product (CFB in this study) and its co-products [30, 33]. All inputs and direct emissions were allocated based on their respective mass on their oven-dry (OD) basis.

2.4 System Boundary

The cradle-to-gate (A1-A3) system boundary of CFB manufacturing included all the processes up to CFB panels packaged (Figure 1). The output of the cradle-to-gate system includes 1 m^3 of CFB ready to be delivered to the end-user, environmental emissions, and solid waste. The co-products produced with CFB panels were not tracked once they left the system boundary [34, 35]. The PCR for wood building products allows that mass flows making less than 1% of the total mass flow in the system can be excluded, provided their environmental importance is negligible [33, 36]. However, this analysis included all energy and mass flow in and out of the system boundary including hazardous air pollutants (HAPs) specific to their wood product’s manufacturing process. The gate-to-grave (A4-C4) boundary included product transportation (A4), product installation (A5), product use (B1), waste transportation (C2), and waste disposal (C4).

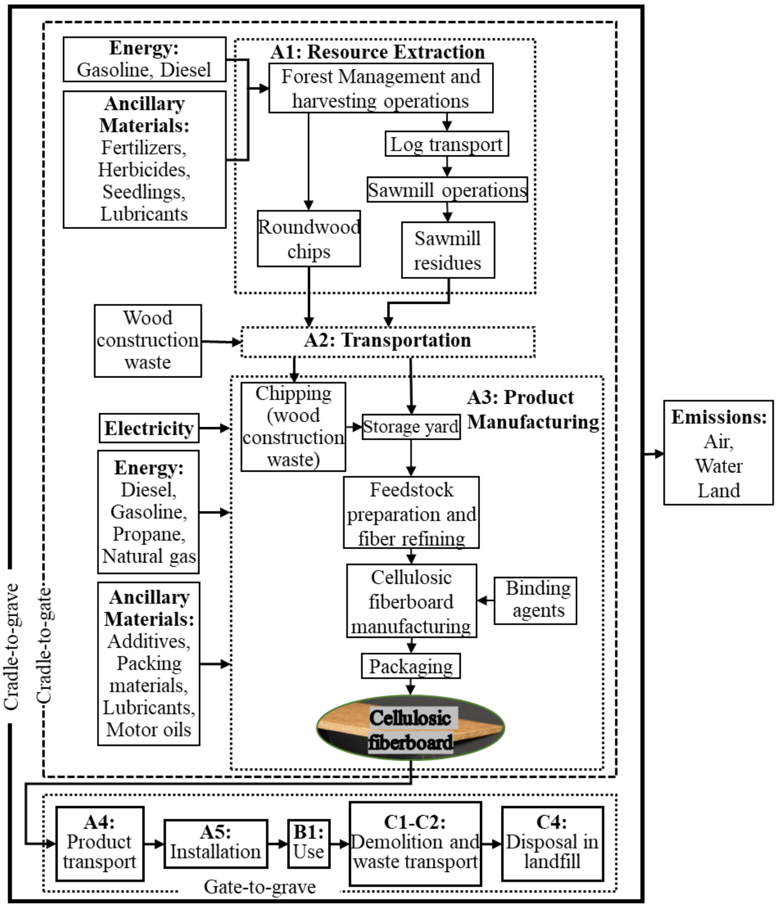

Figure 1 Cradle-to-grave system boundary for CFB manufacturing system.

2.5 Data Sources and Calculation Methods

This study collected data from North American CFB manufacturers. The two mills that responded to the surveys produced 355,264 m^3 in 2019, representing 60.2% of total production in North America. A total of four cellulosic fiberboard manufacturing facilities are present in North America (two mills each in Canada and the US). Two manufacturing facilities (one from Canada and one from the US) participated in this LCA study. A statistically significant sampling framework was needed to ensure valid results that can be generalized to the CFB industry. This study collected primary (source) data on CFB manufacturing using a questionnaire survey. Primary data are direct measured data such as annual production data along with the associated resources consumed such as electricity and fuels used to produce this production level. The surveyed data was provided in ft^2 (0.5-inch thickness) as well as on a mass (short ton) basis. It was normalized to a unit production basis of volume in m^3. A weighted average of input data (in SI units) was calculated to represent a composite of CFB production in North America while avoiding the representation of a specific mill. The primary data obtained from the surveys were weight-averaged using the formula shown in equation 1.

$$\bar{P}_w = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} x_i} \qquad (1)$$

Where $\bar{P}_w$ the weighted average of the values reported by the mills, P_i was the reported mill value, and x_i is the fraction of the mill's value to the total production of the surveyed mills for that specific value. The missing data were checked with facility personnel to confirm if it was a zero or a value not known. Such data were carefully noted, to avoid their averaging as zeros and were described as data not reported in surveys by the CFB manufacturing facilities. The use of outliers in the input data were decided by communicating with the mill staff and available literature. The background data on materials and energy used in CFB manufacturing were sourced from DATASMART [37] and Ecoinvent 3.6 database to assess off-site impacts such as electricity generation. SimaPro, version 9.1 [38] was used to track all materials and fuels. Secondary data were used for resource extractions, including forest management and harvesting. The inventory data for forest management and harvesting were obtained from previous studies on forest operations in the southeast (SE) United States [39, 40].

This LCA incorporated an appropriate diesel tractor-trailer and diesel locomotive lifecycle inventory (LCI) from the USLCI database in SimaPro based on transportation distances and mass of wood chips, mill residues, and construction waste for each mill location. Moisture content was considered and varied along the supply chain. Secondary data sources were used for raw material inputs, auxiliary materials and packaging, and transportation activities. Environmental emissions data were obtained from the surveyed CFB facilities as well as the relevant emissions data considered by the US Environmental Protection Agency [41].

2.6 Lifecycle Inventory (LCI) Analysis

This section describes the LCI data collection and compilation for the cradle-to-gate [A1-A3] system boundary. This includes the analysis of primary data collected from the surveyed mills.

2.6.1 Resource Extraction (A1)

The different feedstocks used to produce 1 m³ cellulosic fiberboard in North America are shown in Table 1. Roundwood chips represent the largest fraction of total feedstock followed by sawmill chips and wood construction waste. Details on each feedstock are described below.

Table 1 Wood feedstock inputs (types and source) in cellulosic fiberboard production.

Wood residue type	**Region**	**Oven-dry (OD) kg/m³**	**Percent contributions**
Roundwood chips, softwood, green	United States, southeast	128.24	53.73%
Sawmill chips, softwood, green	United States, southeast	41.62	17.44%
Wood construction waste	Canada	68.84	28.84%
TOTAL (weighted average)		238.70	100%

For roundwood chips, CFB mills procure roundwood chips from logs that include the upstream impacts of establishment, growth, and harvest of trees in the US southeast (SE) region. Table 2 provides the detailed fuel used for their resource extraction, including forest management, harvest, and chipping of roundwood [39, 40].

Table 2 Fuel and electricity consumption per cubic meter of forest resource management (regeneration and thinning) and harvesting in the southeast United States [39, 40].

Processes	**Unit**	**Seedling, site prep, plant, pre-commercial thinning**	**Commercial thinning and final harvest**	**Chipping at roadside**	**Total**
Diesel and gasoline	L	0.52	2.93	1.14	4.59
Lubricants	L	0.009	0.05	0.02	0.079
Electricity	kWh	0.455	0		0.455

For sawmill chips, mill residues used in the production of CFB were sourced from sawmills that produce lumber located in the SE US region. For sawmills, the primary product was dimension lumber, but they produce a significant amount of mill residues (co-products). The mill residues can be in the form of bark, sawdust, wood chips, and hogged fuel. In this instance, CFB mills used wood chips.

For wood construction waste, it refers to wood waste generated during the construction of housing or infrastructure that can be separated from non-wood materials. The study considered no upstream impacts for wood construction waste as the final product such as lumber installed during construction carries the full environmental impacts [31].

2.6.2 Transportation (A2)

Table 3 shows the transport distance (one-way) for feedstocks and other inputs materials used in CFB manufacturing. The CFB feedstock (roundwood chips, sawmill chips, and wood construction waste) were transported in diesel-tractor trailers (trucks) from the source to the mill. Various ancillary materials and additives were used in the production of CFB, and these materials were also transported in trucks.

Table 3 Weighted average delivery distance for materials to cellulosic fiberboard mill, North America.

Input material	**Mode of transport**	**Weighted average transport distance (km)**
Feedstocks		
Roundwood chips, softwood, green	Truck	54.7
Sawmill chips, green	Truck	54.7
Wood construction waste	Truck	11.5
Non-feedstocks materials		
Additive: Starch	Truck	105.7
Additive: Alum	Truck	164.1
Additive: Wax	Truck	120.9
Additive: Carbon black	Truck	109.4

Additive: Clay	Truck	1860.0
Additive: FLOC (i.e., loose cellulose flakes)	Truck	742.8
Additive: Iron oxide	Truck	652.0

2.6.3 CFB Manufacturing (A3)

CFB is manufactured using feedstock such as sawmill residues (chips from primary log breakdown), wood construction waste from the building industry, and roundwood chips from chipping the stem of whole trees (pulp-grade logs). The feedstocks are broken down through wet process fiber manufacturing. A mechanical process with supplied heat converts wood raw material to fibers. Other materials like starch binders are added during manufacture to improve certain properties. CFB can be coated with asphalt, but it was excluded in this study [22]. The mass balance for CFB is shown in Table 4. The final product, uncoated CFB, has an average density of 239.5 kg/m³ (oven-dry), corresponding to 92% of main products and 8% of co-products. Figure 2 outlines the manufacturing of CFB [34, 35]. The operations are described below in brief.

Table 4 Mass balance of cellulosic fiberboard manufacturing per m^3, North America (unallocated).

	Inputs	
	Oven-dry mass (kg)	**Contribution (%)**
Feedstock		
Roundwood chips, green	128.24	49.27%
Sawmill chips, green	41.62	15.99%
Wood construction waste	68.84	26.44%
Total, feedstock	**238.70**	**91.70%**
Additives		
Starch	13.24	5.09%
Alum	1.25	0.48%
Wax	3.73	1.43%
Carbon black	1.02	0.39%
Clay	1.06	0.41%
FLOC (loose cellulosic flakes)	1.10	0.42%
Iron Oxide	0.21	0.08%
Total, additives	**21.61**	**8.30%**
Total, inputs	**260.31**	**100%**
	Outputs	
	Oven-dry mass (kg)	**Contribution (%)**
Products		
Cellulosic fiberboard	239.46	91.99%
Co-products		
Board trim (sawdust)	0.00	0.00%
Culled boards	2.48	0.95%

Pins and fines	11.11	4.27%
Other, not specified	7.26	2.79%
Total, co-products	**20.85**	**8.01%**
Total, outputs	**260.31**	**100%**

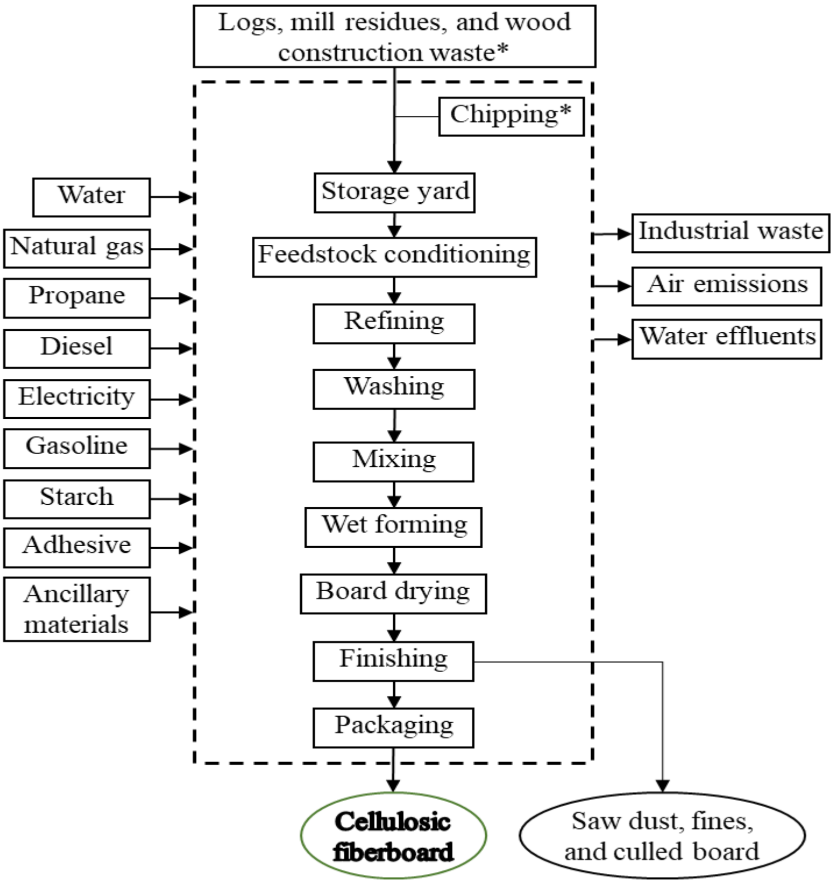

Figure 2 Process flow diagram of the manufacturing process of cellulosic fiberboard (adapted from [34, 35], *wood construction waste chipped in the plant.

Storage Yard. It is the first point of feedstock entry in the mill and provides a cushion for the mill's supply. The moisture content and weight of wood chips were determined before moving them to processing activities in the mill. The chips were moved using front-end loaders. Other mobile equipment was used to move all material inputs for further processing. Inputs at this step were feedstock, electricity, fuel, and lubricants. Outputs included feedstock transferred to the mills and air emissions such as particulate matter and CO_2 emissions (fossil-based).

Feedstock Conditioning. Homogeneity in the feedstock characteristics is vital for the mill, and hence conditioning is conducted. The homogenous feedstock was produced by chipping large chips into small pieces. This conditioning was also applied to feedstock from construction waste. Uniformity of wood chips was achieved by screening the oversized chips. Next, dirt and other foreign substances were removed by washing, and cleaned chips were kept in the storage bins. Steam digesters and steaming screws were used for conditioning the wood chips and other raw materials. Modeling inputs for this process were feedstock, water, steam, and electricity, and the outputs included cleaned chips and direct emissions.

Pulping and Refining. The mechanical pulping of cleaned wood chips converted them into wood fibers. In the pulping process, chips were mechanically broken into fibers using rotating metal disks which was preceded by thermal softening of the pulp fibers. Refining is the segregation of fibers from the slurry of pulp and water. It is an energy-intensive process with 250-380 kWh average specific energy consumption per ton output [22]. Inputs in this process were cleaned chips, heat, and electricity. The outputs were pulp fiber and water vapor.

Washing. The dissolved solids produced along with pulp fibers were removed through the washing step. The washing of pulp fibers removes any remaining dirt and foreign materials. Inputs were mainly pulp fibers and water. Outputs were clean pulp fibers, wastewater, and solid wastes.

Mixing. The mixing of water and additives (alum, starch, and wax) into the pulp fibers initiate the bonding of the pulp fibers in stock chests making a pulp slurry for further processing. Lignin is a natural part of the wood which helps the additives in bonding the pulp fibers. No resins were used in the production of cellulosic fiberboard. Inputs included pulp fiber, water, additives, and outputs were additives and washed low-consistency pulp slurry.

Wet Forming. The slurry from the previous step having nearly 2% pulp fibers is sent to forming Fourdrinier machines, where it was metered onto a wire screen. The 2% solids consistency in the pulp slurry gives the highest bonding strength when producing cellulosic fiberboard [22, 42]. A fiber mat was produced with the gradual removal of the water from the slurry mix. Once the slurry attained around 25% solid consistency, the fiber mat was cut to length by high-pressure water jets. The wet formed mat was passed through continuous rollers removing additional water till it forms the board while considering shrinkage in the drying step. The collected water was recycled for use in mixing. Modeling inputs of this step included washed pulp slurry with additives, water, and electricity. The key outputs of the wet forming were a fiber mat, trimming residues, water, and steam.

Board Drying. The wet fiberboard produced was then passed through a drying process to reduce the moisture content. Board drying is a continuous process with intensive energy requirements. The fiber mats with 65-75% moisture content (dry basis) move along a conveyer belt into a heated enclosure (roller dryers) where the moisture content of the board gets reduced to nearly 4%. Overall, around two tonnes of water get removed per ton of the dry board. The operating temperature of the roller dryers was recorded as approximately 230°C (inlet temperature) and 160°C (outlet temperature). Inputs in this process were wet boards (fiber mat), electricity, and natural gas. The outputs include dry boards (untrimmed), steam, and air emissions.

Finishing. In the finishing step, trimming of dry fiberboard was carried out to meet the standard dimensions requirements. Inputs in this step were untrimmed dry boards and electricity. The outputs of the process were the final board product, board trimmings, and wood dust. The density of finished cellulosic fiberboard varied from 222-238 kg/m^3. The coating of the finished boards was not included in the study.

Packaging. The finished CFB product was packaged for transport. Inputs in the packaging step included the final product, electricity, and packaging material such as plastic wrapping, cardboard, and runners or wooden spacers. The runners made up the bulk of packaging materials, representing 93% of the total mass (Table 5). The plastic wrapping material, plastic strapping, and cardboard packaging made up 4%, 2%, and 1% of the remaining mass, respectively. Outputs include packaged uncoated CFB.

Table 5 Materials used in packaging and shipping per m³ cellulosic fiberboard, North America (unallocated).

Material	Value (kg/m³)
Wrapping material	0.107
PET Strapping	0.053
Cardboard packaging	0.027
Wooden spacers	2.544
Total	2.731

2.6.4 Heat, Electricity, and Fuel Inputs

The energy inputs required to produce CFB were primarily grid electricity and natural gas. Mainly, natural gas was used for heating refiners and roller dryers (Table 6). Electricity was used to power almost every piece of equipment within the mill, including conveyors, refiners, fan motors, hydraulic press motors, high-pressure water jets, rollers, and emission control systems. Regional variations in electricity use were considered during the development of the LCI. About 68% and 32% of total electricity for the reference flow in the LCI were from regional grids of Virginia, the U.S. and Quebec, Canada, respectively. This was based on the share of CFB production of mills located in these two regions considered in this study. Additionally, diesel fuel, liquid propane gas, and gasoline were used at the CFB facility to power transport equipment.

Table 6 Environmental inputs and outputs to produce 1 m³ of cellulosic fiberboard, North America (unallocated, gate-to-gate, weight-averaged).

Inputs	Value /m³	Outputs	Value /m³
Materials		***Product and co-products***	
Roundwood chips, green	128.24 OD kg	Cellulosic fiberboard	1m³ (239.5 OD kg)
Sawmill chips, green	41.62 OD kg	Culled boards	2.48 OD kg
Wood construction waste	68.84 OD kg	Pins and fines	11.11 OD kg
Starch, 100% solids	13.24 kg	Other, not specified	7.26 OD kg
Wax	3.73 kg	***On-site emissions to air***	
Clay	1.06 kg	VOC[3]	0.162 kg
Alum	1.25 kg	Acetaldehyde	0.00102 kg
Carbon black	1.02 kg	Acrolein	0.000344 kg
FLOC (loose cellulosic flakes)	1.1 kg	Limonene	0.0035 kg
Iron Oxide	0.21 kg	Particulates[4]	0.00765 kg
Water, municipal	514.91 L	Propanal	0.177 kg
On-site energy inputs		Sulfur dioxide	0.00562 kg
Electricity, at grid	186.46 kWh	Toluene	0.183 kg

Propane[1]	0.34 L	***On-site emissions to water***	
Natural gas[2]	39.27 m³	BOD[5]	0.321 kg
Diesel[1]	0.28 L	Oils, unspecified	0.003 kg
Gasoline[1]	0.02 L	Suspended solids	0.089 kg
Ancillary materials		***Waste to treatment***	
Hydraulic fluid	0.15 kg	Waste to an inert landfill	1.92 kg
Oils and grease	0.002 kg	Waste to recycling	0.082 kg
Lubricant and oil	0.087 kg		
Marking paint and ink	0.0001 kg		
Transportation to plant			
Woody feedstock	55.94 tkm		
Starch	3.78 tkm		
Wax	1.48 tkm		
Clay	5.79 tkm		
Alum	0.97 tkm		
Carbon Black	0.5 tkm		
FLOC (loose cellulosic flakes)	2.4 tkm		

[1] Combusted in industrial equipment, [2] Combusted in industrial, direct-fired, [3] Volatile organic matter; [4] Particulate <2.5 um and <10 um; [5] biochemical oxygen demand

2.6.5 Gate-to-gate Lifecycle Inventory

The gate-to-gate input and output flow associated with North American CFB production are summarized in Table 6. These flows were linked to the upstream unit processes for forestry operations, feedstock production, transportation, fuels, and electricity to calculate cradle-to-gate environmental impacts for CFB, which are shown later.

2.7 Gate-to-grave Model for CFB Products

A gate-to-grave model was created and analyzed for the same functional unit (1 m³ CFB). The assumptions made for gate-to-grave life stages were in consultation with the experts from NAFA. These were considered to represent an average CFB product. The assumptions made are briefly described in this section.

2.7.1 Cellulosic Fiberboard Transport (A4)

CFB is shipped from the manufacturing facilities to warehouses for distribution and then to the point of installation. In consultation with the experts from NAFA [43], transportation was assumed to be 80% by diesel-powered truck and 20% by train (to western Canada). The transport distance was taken as 500 miles between sawmill and warehouse. These values were based on the estimation of the production facilities to major consumer locations. Distance between warehouse and installation site was assumed to be 100 km. The weighted average transportation distance by truck was 386 km and 718 km by train. These transportation values are a source of uncertainty and are assessed later for their sensitivity to the overall environmental impacts.

2.7.2 Installation (A5) and Use of CFB (B1)

CFB is available in various dimensions depending on the user's requirements. For the installation of CFB into the building, this study considered a standard CFB panel of 1.22 m width, 2.44 m length, and 12.7 mm thickness. The estimated number of nails for each panel was 118 [44]. During installation, a 3% product scrap waste was assumed to account for the trimming and finishing losses at the installation site. The electricity used in panel installation was taken as 0.01 kWh/panel [45]. Service life of 75 years was considered in the study with no repair or maintenance inputs in the use phase.

2.7.3 End-of-life of CFB (C1-C4)

The end of life of a product typically includes four phases such as C1: demolition of infrastructure (i.e., buildings), C2: transport of waste from a demolition site to landfill, C3: waste processing, and C4: disposal. At the end of the building's service life, the building, including the CFB panels, were assumed to be demolished and disposed of in a local landfill site. Compared to the whole lifecycle, the impacts of C1 phase were negligible [46-48] and thus were not considered in this LCA. In this study, it was assumed that CFB waste was transported in trucks (C2) to a disposal site (landfill) which was 50 km from the demolition site [47]. In North America, landfill disposal (C4) has been considered a predominant way to discard wood products at the EoL [49, 50]. Processing of woody waste materials before landfilling is not a usual method; thus there were no impacts from the C3 stage. The biogenic methane and carbon dioxide emissions were estimated using the method considered in the U.S. Environmental Protection Agency Waste Reduction Model [51]. The estimated amount of emissions (i.e., landfill gas) generated due to anaerobic storage of CFB waste in landfills are provided in Table 7. During anaerobic decomposition, it was assumed that about 70% of landfill gas was considered captured and used for energy recovery to displace fossil fuel, i.e., natural gas, whereas the remaining 30% was captured and flared without energy recovery. Flaring tended to be used because of the cost to purchase and install generators, piping, and gas compression, treatment skid and auxiliary equipment for energy recovery.

Table 7 GHG emissions from cellulosic fiberboard landfilled with standard methane capture [51].

GHG Emissions	kg per OD kg wood
Methane, biogenic[1]	8.25E-03
Carbon dioxide, biogenic[1]	2.77E-02
Carbon dioxide, biogenic[2]	1.06E-01
Carbon dioxide, biogenic[3]	4.54E-02

[1]Released directly into the air. [2]Released after energy recovery (70%). [3]Released after flaring (30%) with no energy recovered.

This study assumed about 12% of wood decomposed in the landfill [51] and wood content in CFB products was taken as 92% with 50% carbon by weight (Table 4). About 353 kg CO_2e net long-term carbon storage was estimated for the cradle-to-grave life cycle of 1 m^3 of CFB (Table 8). This is the amount of carbon that remains stored in the landfill for at least 100 years.

Table 8 Carbon storage per m^3 of cellulosic fiberboard (CFB) in landfill.

Parameter	**Value (%)**
Carbon breakdown in landfill	12%
Carbon storage in landfill	88%
Wood content in CFB	92%
Carbon content in CFB	50%
Net long-term carbon storage (kg CO_2e)	353.45

2.8 Lifecycle Impact Assessment (LCIA)

The LCIA phase converts the LCI results into environmental impacts. SimaPro software (version 9.1) and the LCIA methods, namely The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1 [52], the Center of Environmental Science (CML) baseline, and cumulative energy demand (CED), were used to evaluate the magnitude and significance of the environmental impacts. This study estimated all impact indicators as recommended by the PCR of wood products and ISO 21930 [33, 36, 53, 54] were included in the analysis and were grouped into i) core mandatory impact indicators, ii) indicators describing primary resources use, and iii) indicators describing waste. The impact indicators were not additive or comparable as they have different units. Additionally, the LCIA results were relative representations, not predicting the impacts on category endpoints. The primary fuels used were grouped in non-renewable and renewable.

3. Results and Discussion

This section presents and discusses the cradle-to-grave environmental impacts of 1m^3 of CFB production in North American manufacturing facilities. Figure 3 shows the percent distribution of two LCA models (cradle-to-gate and gate-to-grave) in the overall cradle-to-grave impacts. The extension of the LCA model to include gate-to-grave life stages showed its significance in its percent share for the cradle-to-grave lifecycle impacts. Still, the share of the cradle-to-gate LCA results were higher in most impact categories except for smog formation discussed later. The environmental impact profile was generated using all environmental impact indicators required to develop an industry-average EPD for CFB.

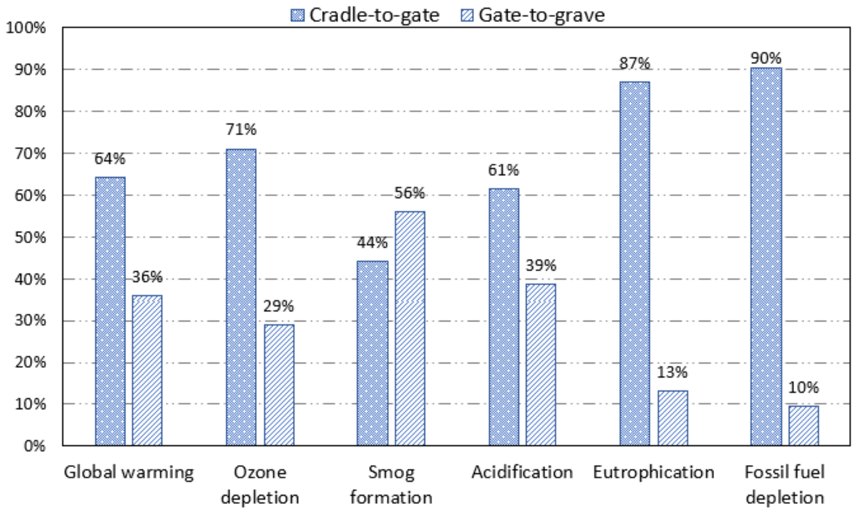

Figure 3 Percent share of lifecycle models in the overall environmental impacts of producing cellulosic fiberboard.

The overall results of the cradle-to-grave assessment are presented in Table 9. The impact indicators were grouped as per their requirements in developing EPDs for wood products. Certain impact indicators were only based on LCI results, such as water use, solid waste. Absolute values of the impact indicators and percentage contribution of the lifecycle stages are presented in Table 9. In Figure 4, a breakdown of the characterization results per lifecycle stage was made to identify the most important unit processes (hotspots) under different impact categories. The sub-sections below present and discuss the results of selected impact indicators.

Table 9 Summary of lifecycle environmental impacts per m³ of cellulosic fiberboard produced in North America (mass allocation).

Impact category	LCIA Method	Cradle-to-grave (A1-C4)	Cradle-to-gate (A1-A3)	A1 (%)	A2 (%)	A3 (%)	Gate-to-grave (A4-C4)	A4 (%)	A5 (%)	B1 (%)	C1-C4 (%)
Core mandatory impact indicators											
Global warming (kg CO_2 e)	TRACI 2.1	305.74	196.11	2.72	3.44	93.84	109.63	38	19	0	43
Ozone layer depletion (kg CFC11e)	TRACI 2.1	1.00E-05	7.13E-06	1.38	0.17	98.46	2.92E-06	94	0	0	6
Acidification (kg SO_2 e)	TRACI 2.1	1.03	0.63	7.94	6.35	85.71	0.40	80	16	0	4
Eutrophication (kg N e)	TRACI 2.1	0.33	0.29	4.65	1.24	94.12	0.04	93	4	0	3
Smog formation (kg O_3 e)	TRACI 2.1	19.23	8.46	16.90	12.65	70.45	10.77	87	8	0	5
Abiotic depletion (MJ, NCV)	CML baseline	3013.77	2580.6	2.63	3.27	94.10	433.17	124	39	0	-63
Fossil fuel depletion (MJ Surplus)	TRAC 2.1	415.48	375.57	2.55	3.38	94.07	39.91	196	19	0	-116
Use of primary resources											
Renewable primary energy carrier used as energy (MJ, NCV)	CED	572.08	568.24	0.16	0.03	99.81	3.84	95	0	0	5
Renewable primary energy carrier used as material (MJ, NCV)	CED	4591.48	4591.48	100	0	0	0	0	0	0	0
Non-renewable primary energy carrier used as energy (MJ, NCV)	CED	3746.12	3281.8	2	3	95	464.32	633	0	0	-533
Total (MJ, NCV)	CED	8909.68	8441.52				468.16				
Consumption of freshwater resources (m³)	LCI indicator	1.38	1.38E+00	0.80	0.05	99.28	0	0	0	0	0

Indicators describing waste											
Hazardous waste disposed (kg)	LCI indicator	0.04	3.74E-02	1.78	0.28	97.86	0	0	0	0	0
Non-hazardous waste disposed (kg)	LCI indicator	93.11	93.11	0.53	0.71	98.76	0	0	0	0	0
Materials for recycling (kg)	LCI indicator	0.08	0.08	0	0	100	0	0	0	0	0
High-level radioactive waste, conditioned, to final repository (m^3)	LCI indicator	1.06E-07	1.06E-07	5.01	0	95.28	0	0	0	0	0
Intermediate- and low-level radioactive waste conditioned, to final repository (m^3)	LCI indicator	4.72E-06	4.72E-06	1.62	0.15	98.31	0	0	0	0	0

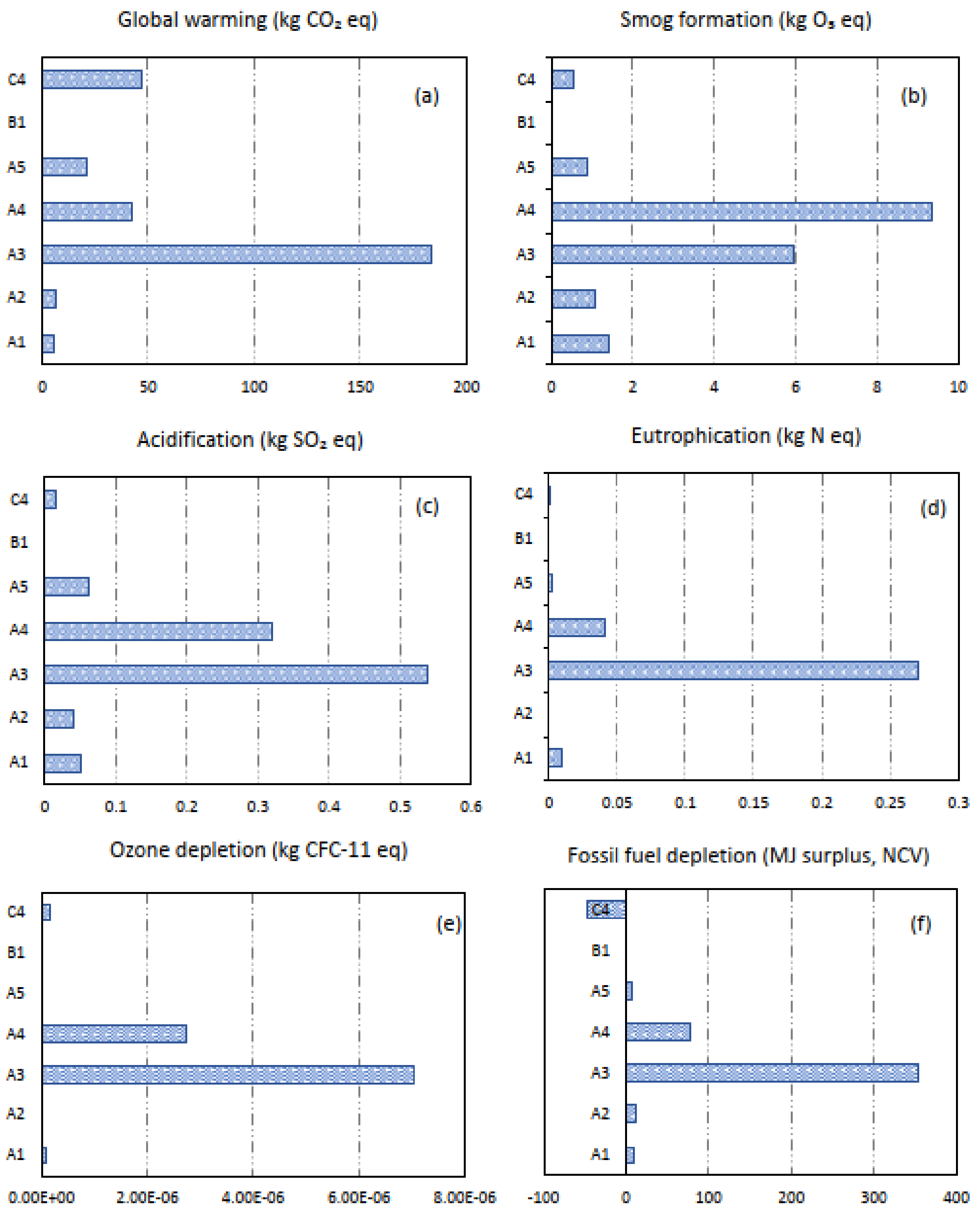

Figure 4 Characterization impacts of different lifecycle stages contributing to six major impact categories for production of cellulosic fiberboard.

3.1 Global Warming (GW)

Global warming (GW) has been the most assessed impact category for all wood products. It highlights the climate change impacts and mitigation potential of any product or technology. The cradle-to-grave GW impact of cellulosic fiberboard was 305 kg CO_2 e/m^3 with 64% share from cradle-to-gate lifecycle stages. About 36% contribution of gate-to-grave lifecycle stages in total GW impacts emphasized the importance of studying the full life cycle in such LCAs (Figure 3). Considering the entire life cycle of wood products (CFB in this study) would be crucial when assertions on their environmental preference need to be verified against conventional non-wood materials in construction. Figure 4a presents global warming impacts caused by different life cycle stages for

CFB. In the cradle-to-gate GW impacts (196 kg CO_2 e/m^3), the major contribution was from the product production stage, A3 (94%). This high contribution of A3 was mainly due to the fossil energy and additives inputs used in CFB production as shown in Table 6. Nevertheless, the value of GW impact of cradle-to-gate stages was significantly lower (34% less) than the previous LCA study on CFB by Puettmann et al. [40], which reported 295.5 kg CO_2 e/m^3. The possible reasons identified for this difference were: i) slightly lower material efficiency to produce CFB, which was 92% in the present study versus 96% in the previous study, so more environmental impacts assigned to co-products, ii) lower density of CFB (240 kg/m^3 in this study versus 254 kg/m^3 in the previous study), iii) improvement efficiencies in manufacturing technologies over the time and iv) reductions in high-impactful energy sources consumed in manufacturing. For example, in the previous studies by Puettmann et al. [40] and Bergman [34], 10% of on-site energy inputs were from coal which had higher environmental impacts.

In gate-to-grave GW impacts, the transport activities (A4) were major contributors (38%). Longer transport distances from the mill to the CFB installation site increased their share in the gate-to-grave GW impacts. Another hotspot was the landfill disposal (47 kg CO_2 e), contributing 43% to the gate-to-grave model and 15% to the cradle-to-grave GW impacts. Although wood tends to only partially be degraded in a landfill under anaerobic conditions, even the small amount of GHG emissions contribute to a higher GW impact when including the gate-to-grave stages in LCA. Around 2.15 kg CH_4 were estimated (Table 7) to release into the atmosphere from landfill disposal of 1m^3 CFB (239.5 kg OD wood). Though landfill disposal was considered a predominant choice, the magnitude of gate-to-grave impacts could change with the reuse of CFB after its service life into other products, including new EWPs or an enhanced disposal method of wood waste. Reuse could increase the carbon storage duration. However, only one active life was considered in this study. Regardless, the final carbon storage impact offsets all GHG emissions released from cradle-to-grave. The net long-term carbon storage during the lifespan of CFB was estimated to be 353 kg CO_2 e/m^3 (Table 8) which is higher than the total greenhouse gases (CO_2 e) emissions. Thus, the net negative GW impact of CFB (-47 kg CO_2 e/m^3) asserted its environmental advantages as an engineered wood panel construction material.

3.2 Smog Formation (SF)

The smog formation (SF) impact indicates the formation of photochemical oxidants during a product's life cycle. The SF characterization impacts for all life cycle stages are presented in Figure 4b. The SF impact of the CFB system evaluated in this study was 19.23 kg O_3 e/m^3. The share of cradle-to-gate and gate-to-grave stages was 44% and 56%, respectively (Figure 3). The cradle-to-gate SF impacts of the present study were 72% less than those reported in the previous study [40]. CFB manufacturing was the major hotspot in cradle-to-gate SF impacts, causing 70% of the impacts (5.96 kg O_3 e/m^3). Around 30% of the cradle-to-gate SF impacts were caused by resource extraction (A1) and transport of raw materials (A2) used to form fiberboard. The influence of change in the additive used in CFB production and feedstock transportation distances was further analyzed in the sensitivity analysis. In gate-to-grave stages, transportation (A4) contributed 87% of the SF impacts (9.33 kg O_3 e/m^3). Considering all cradle-to-grave life stages, the transportation of CFB manufacturing (A3) and CFB transportation (A4) accounted for 31% and 49% of SF impacts totaling 80% (Figure 4b). The major life cycle emissions causing SF impacts were noted as nitrogen oxides

(NO_x), hydrocarbons in transportation activities, and volatile organic compounds released from the fossil fuel combustion in CFB production and transportation.

3.3 Acidification (AC)

The acidification (AC) impact indicates the formation of acid rain during a product's life cycle. The AC characterization impacts for all life cycle stages are presented in Figure 4c. The acidification (AC) impact of the cradle-to-grave life stages of CFB was 1.03 kg SO_2 e/ m^3. The share of cradle-to-gate and gate-to-grave stages was 61%, and 39%, respectively (Figure 3). CFB manufacturing (A3) and CFB product transportation (A4) can be identified as the major hotspot of the AC impacts. CFB manufacturing [A3] generated 53% (0.54 kg SO_2 e/ m^3) of the total AC impacts and 86% of the cradle-to-gate AC impacts. Another lifecycle stage with a major role was transportation (A4), accounting for 31% (0.32 kg SO_2 e/ m^3) of total AC impacts and 80% of the gate-to-grave impacts. The CFB installation stage (A5) accounted for only 16% of gate-to-grave impacts and 6% of the total impacts. The main contributors to AC impacts are nitrogen oxides (NO_x) and sulfur dioxide (SO_2) emissions. The source of NO_x emissions was mainly the provision of energy for CFB manufacturing at the sawmill. The SO_2 emissions came from the combustion of fossil fuels for energy requirements at the mill and in the transportation processes.

3.4 Eutrophication (EU)

The eutrophication (EU) impact indicates the formation of eutrophication of water bodies during a product's life cycle. The EU characterization impacts for all life cycle stages are presented in Figure 4d. The cradle-to-grave EU impact of the CFB system was 0.33 kg N e/m^3. The share of cradle-to-gate and gate-to-grave stages was 87%, and 13%, respectively (Figure 3). The comparison of cradle-to-gate impacts showed the present study (0.29 kg N e/m^3) has substantially higher EU impacts than those of the previous study [40] 0.08 kg N e/m^3. However, the possible reason identified was only a difference in water use estimation methods. The major hotspot was CFB manufacturing with 93% contribution in the cradle-to-gate and 83% in cradle-to-grave EU impacts (Figure 4d). The water inputs and wastewater generated in CFB manufacturing were the major contributors. Per m^3 of CFB production, the load of 0.321 kg biological oxygen demand, 0.089 kg suspended solids, and 0.003 kg oils were discharged to water. The improvements in water use efficiency in fiberboard manufacturing processes could reduce the load of the nitrifying magnitude of wastewater released; however, it is still a challenge to be addressed. In addition, the NOx emissions from the provision of required energy in the CFB manufacturing also contributed to EU impacts. In the gate-to-grave EU impacts (0.04 kg N e/m^3), 93% of sources were mainly the CFB transportation stage (A4) involving the combustion of transportation fuels.

3.5 Ozone Depletion (OD)

The Ozone depletion (OD) impact indicates the loss or thinning of the ozone layer during a product's life cycle. The OD characterization impacts for all life cycle stages are presented in Figure 4e. The cradle-to-grave OD impact of the analyzed CFB system was 1.0E-05 kg CFC-11e/m^3. The share of cradle-to-gate and gate-to-grave stages was 79%, and 21%, respectively (Figure 3). The major hotspot in the CFB lifecycle was its manufacturing stage (Figure 4e). The OD impacts for the

CFB manufacturing corresponded to about 70% of the total and about 98% of the cradle-to-gate OD impacts. The use of various additives in the manufacturing stage was identified as the main cause of the high contribution of this life stage. Releases of air pollutants affecting ozone depletion were reported in a very small quantity in absolute values, but they have a high OD. Such inputs cannot be avoided in the manufacturing of wood products; however, the alternative with lower OD needs to be investigated in detail. The second major hotspot for OD impacts was CFB transportation (A4) stage which contributed around 94% of the gate-to-grave impacts and 27% to the total OD impacts (cradle-to-grave).

3.6 Fossil Fuel Depletion (FFD)

Fossil fuel depletion (FFD) tracks the unrecoverable energy loss when using fossil fuel during a products life cycle. The breakdown of FFD contribution by each lifecycle stage is shown in Figure 4(f). FU impact of the analyzed CFB system was 415 MJ/m^3 with 90% and 10% contribution from cradle-to-gate and gate-to-grave stages, respectively (Figure 3). In all life stages, the major hotspot having the most opportunities to improve in the future was the CFB manufacturing stage (A3). The CFB manufacturing accounted for 94% of the impacts in the cradle-to-gate model and 85% in cradle-to-grave LCA results. The comparison of primary energy (non-renewable) with results of a previous study [34, 40, 55]. This study showed a 32% lower energy use in the present study as compared to Puettmann et al. [40]. The reason for this difference was identified in energy sources, application of different heating values, and lower material efficiency in producing the final product, CFB affects the mass allocation. For on-site energy needs for CFB production, the previous study used coal, non-renewable fossil fuels for 10% of the total [34, 55]. In addition, this study applied lower heating values (LHV) of fuels to estimate primary energy, whereas the previous study used higher heating values (HHV). Also, a lower mass allocation to CFB products (92%) in the present study as compared to the previous studies (96%) contributed slightly. The provision of energy for CFB manufacturing at the sawmill was the main contributor to the higher FFD impact of the CFB manufacturing stage. A negative contribution was noticed in the gate-to-grave model results mainly due to the energy recovery in the landfill. In the disposal of CFB products, the generated landfill gas was considered captured for energy recovery that offset fossil fuel use (-46 MJ). Around 22% of FFD impacts in gate-to-grave stage were caused by all transportation processes (91 MJ), wherein 86% came only from CFB transportation (A4) from mill to the installation site.

3.7 Sensitivity Analysis

The sensitivity analysis was conducted to further evaluate the influence of most critical inputs. Percent change in impact categories with change in key LCI parameters [feedstock (log) transportation distances, electricity use, natural gas, and starch additive use] were studied for a 20% increase and decrease values (Figure 5). For log transport distance, a 20% change had a relatively small influence on the impacts, mainly SF impacts changing by 3%, followed by a 1% change in AC, GW, FFD, and AD indicators. The non-renewable primary resources as energy (NRPRE) showed a 0.5% change in absolute values. A 20% change in electricity inputs showed substantial improvement opportunities exist in most impact categories. The impact categories which showed significant change in absolute values were OD (11%), RPRE (11%), EU (10%), NRPRE (9.8%), AC (8%), and GW (7%). For natural gas inputs, 20% change was observed mainly on the FFD (11%), AD (10%), and GW (9%) indicators which highlight the need for using renewable fuels as a primary energy source. Similarly, a 20% variation in starch inputs was observed as an important improvement opportunity for impact indicators of RPRE, EU, and OD, with an absolute change in values by 9%, 6%, and 4%, respectively. Overall, the inputs used in CFB manufacturing and transport activities were the major contributor in almost all the impact categories.

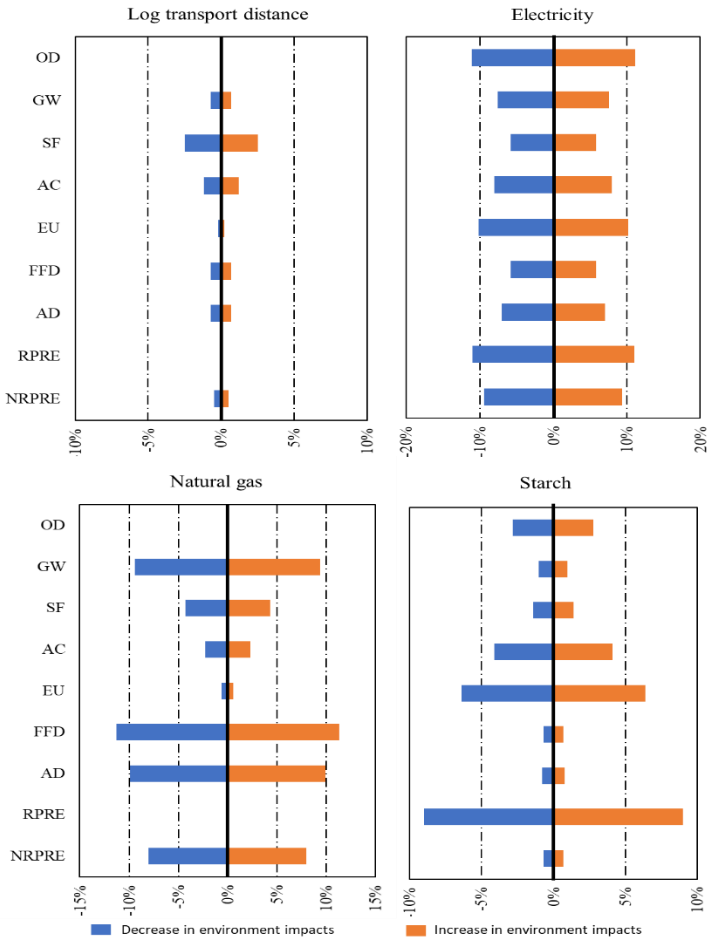

Figure 5 Influence of input parameters (variation of +20% and -20%) on LCA results per m³ cellulosic fiberboard. (OD–ozone depletion, GW–global warming, SF–smog formation, AC–acidification, EUP–eutrophication, FFD–fossil fuel depletion, AD: abiotic depletion, RPRE–renewable primary resources as energy, NRPRE–non-renewable primary resources as energy).

4. Limitations of the Study and Future Scope of Research

The present LCA study relied on data from manufacturers of CFB. There are only four manufacturing facilities that produce cellulosic fiberboard and cater to customers in North America. But only two of them participated in this study which limits rigorous statistical analysis of survey data. However, the weighted coefficient of variation values were included in the LCA used to develop the EPD [35]. There are multiple avenues of variations in the life cycle of CFB –including the location of manufacturer and procurement of forest resources, manufacturing process, logistics of inputs and outputs, and disposal of products at EoL– which may affect the LCA results. In assessing impacts, the present study does not report all the environmental impacts specific to the CFB manufacturing process. The aspects which were not covered in the study that would be useful for future investigations include human health impacts, land-use change, and biodiversity losses. Other limitations noted as scope for future research include reducing on-site water and energy inputs, change in transportation modal, and CFB waste disposal alternatives such as recovering CFB during deconstruction and reuse for new EWP production or bioenergy application to avoid fossil fuel usage. Unlike today in Canada and the United States, landfill disposal is not likely to be a predominant choice in a few decades, and greater utilization of landfill gas is likely.

5. Conclusions

This study offered a cradle-to-grave LCA for CFB representative of industrial practices in North America. Except for smog formation, the contribution of the cradle-to-gate lifecycle stage was substantially higher than the gate-to-grave stage in all impact categories. Overall, the cradle-to-grave global warming impact of CFB was 306 kg CO_2 e, and 64% of that was contributed by the cradle-to-gate stage. In the cradle-to-gate lifecycle stages, the contribution of the manufacturing stage of CFB was significant and consistent among all the core mandatory impact categories. The contribution of the gate-to-grave lifecycle stage was substantial in smog formation, acidification, and global warming impacts, with a share of 56%, 39%, and 36%, respectively. In gate-to-grave impacts, the disposal stage (i.e., landfill) of CFB was the most significant contributor to most of the environmental impact categories. The sensitivity analysis results showed that electricity, natural gas, and starch inputs used in manufacturing are the most sensitive inputs affecting the LCA results. Overall, CFB was found to be a carbon-negative (-47 kg CO_2 e/ m^3) construction material because it can store about 353 kg CO_2 e/m^3 of CFB more than that was released (~306 kg CO_2 e/ m^3) during the whole lifecycle of CFB. Overall, the findings of the presented study would prove useful for improving the decision-making in the construction sector.

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Author Contributions

K.S. and R.B. came up with the project and research idea; K.S. and R.B. designed the project and modeling approach; K.S. performed the modeling and analyzed the results; K.S., R.B, and P.K. reviewed the results. K.S., R.B, and P.K. developed the manuscript's structure and wrote the manuscript; all authors contributed to revising and editing the manuscript, and project administration and funding acquisition for the study was done by R.B.

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Competing Interests

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