Research Article

Life Cycle Assessment (LCA) of Wood Flour and Pellets for Manufacturing Wood-Plastic Composites (WPCs)

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Abstract

This study is expanding the previous studies that were focused on the material properties and transportation costs of the two alternative feedstocks for manufacturing wood-plastic composites (WPCs): wood flour and pellets. Besides the material properties and cost analysis, life-cycle assessment (LCA) is equally important to assess the environmental impacts of these two alternative wood feedstocks to manufacture WPCs and gain the knowledge of influences from the manufacturing and transportation processes. The main goal of this study was to compare the environmental impacts from the production and transportation of wood flour and pellets utilized in WPC manufacture. The environmental impacts on air, water, soil and

human health, as well as the cumulated energy consumption for one tonne and one truckload of the two wood feedstocks were compared. The case-study was based on a commercial wood pellet manufacturer in the state of Maine (ME). The cradle-to-gate approach was considered including the processing of mill residues, manufacturing of the two feedstocks and transporting them to commercial WPC manufacturers. LCA analysis showed that transportation of both feedstocks had the highest impact on the environment as opposed to the inputs associated with production. The global warming potential (GWP) from one tonne production and shipment of wood flour was higher by 8% compared to the pellets. One tonne production and shipment of wood pellets appears more environmentally friendly. Normalization results of one truck load of wood flour (22 tonnes) and pellets (30 tonnes) showed similar environmental impacts. Based on this study, from an environmental perspective, it is inferred that besides use as bio-fuels, wood pellets could be a better alternative feedstock for the manufacture of WPCs.

Keywords

Wood flour; wood pellets; wood-plastic composites (WPCs); life-cycle assessment (LCA); cumulative energy demand (CED)

1. Introduction

Wood and wood-based products are among the most important resources for sustainability. In the United States, wood and wood-based fuels contributed to around 20% for the production and consumption of renewable energy sources in 2017 [1]. Renewable energy is prominent in the transportation, electricity, and heating sectors with greater demand for wood fuels [2]. By 2030, attributable to the higher demand, there is increasing concerns on the scarcity of wood [3, 4]. Thus, efficient utilization of forest resources is essential. Cascading principles drive the end-of-life (EoL) alternatives to prioritize alternative applications for wastes or waste management through prevention, re-use, recycling, recovery, and disposal. The circular economy is the other concept for the recycling and circulation of waste materials highlighted in the European Union (EU) [5, 6] as well as ProgRess in Germany [7] to minimize the use of virgin materials. EU has a target of recycling plastics and wood up to 50% and 25%, respectively by 2025 and up to 55% and 30% by 2030 [8].

Life-cycle assessment (LCA) quantifies the inputs (i.e., materials and energy) and outputs (i.e., waste gases, wastewater, and solids) of a product/system and evaluates environmental impacts from each life cycle stage [9-16]. LCA is a tool to measure sustainability. The impacts of "cradle-to-grave" or "cradle-to-cradle" ranging from acquisition of raw materials, processing, consumption, and transportation to final disposal of a product are analyzed [17]. Shifting among life cycle stages without hurdles, identifying major "hot spots" in the life cycle, and accounting the consequences to environment are the merits of LCA [18]. The International Organization for Standardization (ISO) 14040 [19] and ISO 14044 [20] are the major standards for this study. Results of LCA have greater implications for decision making [21], waste management [22], materials technologies [23], design and processing [24], and industrial ecology [25]. Similarly, the cumulative energy demand (CED)

method assesses the direct and indirect energy usage in all life cycle stages of a product. It analyzes the renewable energy (RE) and non-renewable energy (NRE) consumption.

Secondary processing of mill residues generated after wood products manufacturing has various applications with low carbon emissions and less impact on forests [26]. One of the promising applications of mill residues is for raw material production in manufacturing wood-plastic composites (WPCs). WPCs are bio-based composites with applications in building materials [27, 28], automotive interior parts [29], and other consumer products. WPCs efficiently utilize biomass compared to recovering it for energy purposes [30]. WPCs are more environmentally friendly compared to pure plastics but can be less environmentally friendly than natural wood. Composites from recycled plastics can have more environmental benefits than from virgin sources [31]. Additives used in WPCs [32] and petroleum-based polymers such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), etc. [18] can have deleterious effects on humans and their surroundings. Wood fiber reinforced polymers exhibit the most desirable performance over other natural fibers. While wood fiber fillers can increase the weight of automotive composites, they can still lead to sustainability [33]. The environmental impacts of pure PP products were found to be more severe than wood flour – PP composites [17].

Literature on comparative LCA of WPCs using various raw materials (wood, fiberglass, etc.) and based on the recyclability of the raw materials (virgin versus recycled) are available [34]. Sommerhuber et al. [35] and Vantsi & Karki [36] have suggested that WPCs made with recycled waste wood have lower environmental impacts compared to virgin wood. A similar case holds with the use of virgin versus recycled PP. Wood flour is commonly used in the commercial manufacture of WPCs and can be produced from mill residues. Pokhrel et al. [37] and Pokhrel et al. [38] have pointed out that besides wood flour, wood pellets can be an alternative wood feedstock to compound with plastics in WPC manufacture. Wood pellets (densified wood flour) were explored to reduce the shipping cost of raw materials over long distances. The authors focused on the material properties of the WPCs using wood flour and pellets separately in a PP matrix, both with and without additives. Pokhrel et al. [39] also discovered transportation of pellets with respect to wood flour, can be cost-effective by at least 25% in a truck and at least 69% in other transportation mediums having a higher weight limit.

This study is a companion analysis to understand the environmental effects during the production and transportation of wood flour versus pellets. Based on the material types, sizes, and management, there are several classifications of wood pellets [40]. Conversion of materials into pellets makes it convenient for collection, storage, and transportation. The global wood pellet market size in 2020 was US $5,324 million and is projected to be US $8,095.4 million by the end of 2026 [41]. Compared to 2019, the global production of pellets increased by 7% with the value of 19.3 million tonnes [42]. The highest market share is of wood pellets followed by plastic pellets [43, 44]. Kočí [45] mentioned that the weight of the pellets has a notable impact on the environmental performance of this product. LCA analysis on the manufacturing of wood pellets is abundant. However, an LCA study on wood flour manufacture is not available in the literature.

It is equally important to focus on the sustainability of the products besides the economic and material properties. Thus, this study aims to perform a comparative LCA and CED analysis in the production and transportation processes of the two feedstocks i.e., wood flour and pellets. This is a cradle-to-gate analysis considering one tonne and one truckload of the feedstocks as the functional units for two separate LCA studies to compare the environmental impacts and energy consumption.

The input variables considered during the analysis are based on a study region in Maine (ME), USA, and are taken from the actual wood mill visits. Accordingly, after modeling the input variables in SimaPro software, impact assessment (characterization) under the categories: ozone depletion, global warming, smog, acidification, eutrophication, carcinogenic, non-carcinogenic, respiratory effects, ecotoxicity, and fossil fuel depletion were applied for the equitable comparison. Normalization of the impact categories for one truck load of the feedstocks were compared. Similarly, from CED-LHV method, consumption of different renewable (biomass, water, and wind, solar, geothermal) and non-renewable (fossil, nuclear, and biomass) energy sources are compared.

2. Materials and Methods

2.1 Case Study

This study was carried out in the state of Maine (ME) in the Northeast (NE) region of the US. The state of Maine, being rich in forest resources has more than 100 sawmills and turning mills, which are the backbone of the state's economy [46]. The wood mills generate around 1.6 million tonnes of residues each year [47]. However, the closure of many paper mills, instability of biomass power plants and pellet mills, etc. have caused a great problem in the outlet of wood residues [48]. On the other hand, there is a wood-plastic composite (WPC) manufacturer in the state that currently sources its feedstock materials i.e., wood flour from out of state. With these compelling problems in a state full of resources, this study was motivated to find potential solutions to use these residues effectively and efficiently. Furthermore, this study can be a representative study for the NE region of the US.

2.2 Goals and Scope of the Study

As mentioned in the introduction section, this study is a companion analysis attempting to use wood pellets as an alternative feedstock in WPCs production. The goal of this study is to compare the potential environmental impacts of wood flour versus pellets during processing using the mill residues as well as shipping via a combination long-haul truck. The individual impact from the material inputs and processes for each feedstock on the environment is also presented. ISO 14040 [19] and ISO 14044 [20] were followed in this LCA analysis. The scope of this study is a "cradle-to-gate" comparative LCA analysis. The study covers the processes from acquiring the residues/raw materials (cradle) to the production of wood flour and wood pellets followed by the transportation of these feedstocks to the WPC manufacturers (gate). In addition to this, a comparative CED analysis is also carried out. The mill residues as byproducts to produce wood flour and pellets are not produced in the physical site of pellet plant. Thus, generation of mill residues, their transportation to the pellet plant, and utilization of the two feedstocks in WPCs manufacturing is outside the scope of this study. The target users of this study's output are researchers, practitioners, and the WPC industry. The LCA evaluation of wood flour and pellets can be used as an input for other comparative LCAs of WPCs manufacturing using different feedstocks. This is a case study based on the largest wood pellet producer and distributor in ME; the output of this study can be applied to the NE region of the US for representation. In the year 2020, 57% of the residues were green sawdust from sawmills and 43% from chips. For the chips, 71.0% and 73.4% were from sawmill operations for hardwood and softwood respectively. Pulpwood chipped offsite by the pellet plant was 29.0% and

26.6% for hardwoods and softwoods respectively [49]. An equal ratio of hardwood and softwood residues was used. However, performing the LCA analysis of WPC manufacturing using wood flour or pellets mixing with plastics and additives is beyond the scope of the study. One of the major reasons is because as of now, there is no commercial production of WPCs using wood pellets and only wood flour is utilized. Even so, LCA analysis of WPC manufacturing using these two different wood feedstocks is important for creating a more thorough understanding of the entire manufacturing process.

2.3 Life Cycle Assessment (LCA) Comparative Analysis

Besides production, the transportation process has a considerable negative impact on energy consumption [50] thus, we have included transportation of the wood feedstocks in this LCA boundary system to examine the associated impacts. The boundary system for the cradle-to-gate LCA includes three major stages, which are 1). acquiring raw materials with transportation to the manufacturing site, 2). the manufacturing of the products – wood flour and pellets [51], 3). transportation of the wood feedstocks to the WPC manufacturers. During the cradle-to-gate LCA analysis, the input and output datasets are convenient, concise, and appropriate as they are directly obtained from the manufacturers of the products [52, 53]. The four interrelated steps of LCA i.e., goal and scope, inventory analysis, impact assessment, and interpretation based on ISO standards 14040 and 14044 are explained in this study.

2.4 Functional Unit

The functional units can provide a reference in connecting the inputs and outputs to be normalized in the LCA as well as reflecting the goal and scope [19]. To compare the potential environmental impacts of the production and transportation of wood flour and wood pellets, we defined the two functional units for two comparative analyses, one as the one tonne of the feedstock products and the other as the one truckload of the feedstock products. One truckload can hold 22 tonnes of wood flour or 30 tonnes of pellets based on the vehicle weight limit and truck size in our study region. One tonne of the feedstock material is essential in the LCA study to maintain the uniformity of the inputs. One truckload is chosen because the weight of each wood feedstock a truck trailer can carry is different attributable to the bulk density of each material and the capacity limit of one truck trailer.

2.5 Unit Processes and System Boundary

The unit processes and system boundary are shown in Figure 1. The plant manufactures premium quality wood pellets from a mixture of hardwoods and softwoods. The emissions from production and transportation of two wood feedstocks for the WPC are conveyed by dotted lines, which include generation of wood residues as byproducts from hardwood or softwood sawmill operation, manufacturing of the wood feedstocks and then transporting them to the manufacturing of WPCs manufacturers. The cumulative system boundary is shown within the solid line.
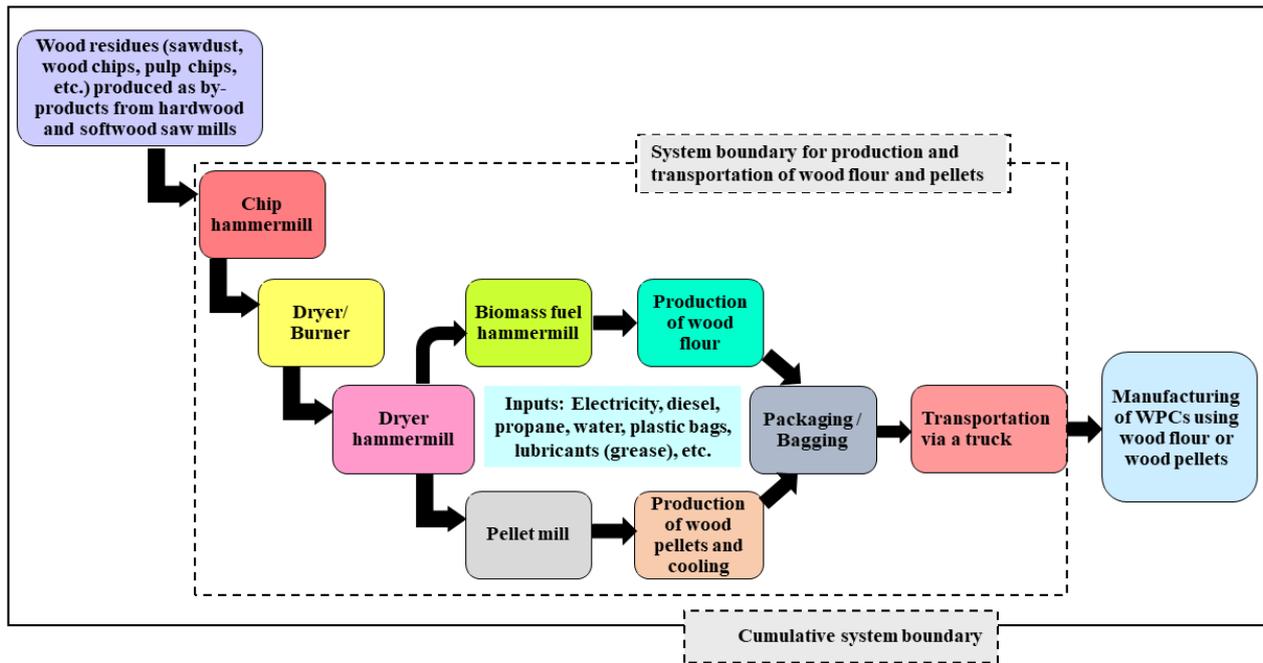
Figure 1 Unit processes and system boundary of the study.

a) Raw materials acquisition: The pellet mill used an equal proportion of hardwoods and softwoods residues acquired locally or from Canada, or the states in the New England region. The hardwoods used in the production consist primarily of maple and birch, with spruce-fir and hemlock as the primary softwoods. Cedar is excluded in pellet manufacture because of the considerable ash generation of the combusted product. Based on the average initial moisture content of 45-50% (wet basis) for residues by weight, two tonnes of residues are required to produce one tonne of pellets.

b) Chip hammer mill: Since most of the raw materials used were chips, the hammer mill for grinding the initial residues was termed as "chip hammer mill". There were five screens used in the chip hammermill with a screen size of 50.8-76.2 mm. The capacity of this machine was 372.8 kW.

c) Dryer/Burner: The ground materials from the chip hammermill were passed to the dryer or burner for the drying of residues. The average capacity of the dryer was 52,753 MJ which could dry the residues up to 7-10% of moisture content (wet basis). Less than one tonne of the residues (0.74 tonnes) was dried per hour. However, during winter, more heat energy is required for drying the freezing biomass. Propane is required for the burner in a dryer. 302.83 L of propane was consumed per day.

d) Dryer Hammermill: After drying, the residues are passed into the second hammermill termed as "dryer hammermill". The capacity of this machine was 372.8 kW. There were four screens used with one side being 7.9 mm and the other side being 9.5 mm for each. Rollers were also used to ensure sawdust passed through the finer screen size. The classification of the screened feedstock from the output of dryer hammermill based on 7.9 mm round holes is given below:

< 4 mm (5 mesh): 99.31%

< 3.25 mm (~6 mesh): 97.94%

< 2 mm (10 mesh): 83.16%

< 1 mm (18 mesh): 51.55%

< 0.1 mm (~140 mesh): 4.12%

e) Biomass fuel hammermill: This step is only for producing fine wood particles. In other words, what we have termed as "wood flour" in this study. In the manufacturing plant, the initial moisture content of the residues/biomass for the feed in this hammermill was slightly above 7% which didn't change much even after grinding in the hammermill. There were two screens used with the size being 1.6 mm. The machine capacity was 186.4 kW producing wood flour at the rate of 0.75 tonnes/hr. However, these obtained fine flour particles in the mills are not sold commercially that are reused in the biomass dryer for heating purposes.

f) Pelletizing: This step is only applicable for wood pellets, not flour. There were four pellet mills in the plant with the capacity of each 298.3 kW and a total of 1193.1 kW running through electric motors. The diameter of the die hole was 6.4 mm. On average, the temperature of the pellet mill was 93-99˚C and pressure of 207-483 MPa. No binding agent was used. Each pelletizer produces about 4.5 tonnes of pellets per hour. The moisture content of the pellets was 5-6% (wet basis).

g) Cooling: Once pelletized, the pellets are very hot and are required to cool to the ambient temperature. A 0.19 kW cooler motor was used to cool the pellets in about 20 minutes for bagging or storage.

h) Packaging/Bagging: Pellets were fed by conveyor to the bagging station where the packaging robots running on electricity could pack the pellets. PE bags were used for bagging. They are packed into 18.14 kg plastic bags and 50 bags of these were packed together by another outer plastic cover. Each full stack of 50 bagged pellets contains one tonne of pellets. Similarly, silos used by the customers who desire bulk pellets delivery don't require any plastic bags. The plant had silos of 68 tonnes, 113 tonnes, 408 tonnes, and 32,658 tonnes. In comparison, wood flour is packed in super sacks or bulk bags in industries or as pellets shipped in silos that don't require packaging. The plastic bags for packaging flour are made up of PP with on average an accommodating capacity of 1.3 m^3 volume and 0.45-4.81 tonnes of weight.

i) Transportation via truck: The study also includes the environmental impacts during transportation besides processing. Forklift trucks were used to transfer the bagged materials to the truck for distribution of materials to consumers. Usually, a truck-trailer or combination trucks are used to ship forest-based products in the study region. Combination type trucks with long haul distance transport these wood feedstocks. The weight limit of the truck trailer is 33 tonnes with volume ranging from 98-114 m^3. The calculation is based on one-way truck movement carrying the wood feedstock from the wood pellet mills to the consumers.

Throughout the manufacturing process, conveyors are used to transport the materials. Forklift, front-end loader, fire pumps, etc. use diesel for their operation. The mill has a biweekly shut down for cleaning, requiring 75.71 liters (L) of water each time. The water could be well water or the water stored in a fire hydrant (851717.7 L). Similarly, lubricants (oil/grease) per pellet machine were purchased in barrels. Each pellet mill requires 0.35 L of oil/grease per hour. So, four pellet machines require 4*0.35*24 = 33.6 L per day and loaders require 29.6 L of oil/grease every four months. Likewise, for commercial wood flour production classification of wood flour before bagging/packaging is performed which is missing in our case study. During the mill visit, data were collected for each component of the pelletization process. Data were sourced from the weekly statistics collected in the manufacturing process under assessment. The electrical energy consumption data were also extracted from the annual data recorded in the plant in 2020. The fine wood particles similar to the size of wood flour are produced by biomass fuel hammermills for the drying of biomass in the dryer. Thus, the initial steps for both wood flour and pellets production are

the same which are separated when the grindings of dryer hammermill are used in pellet mill for making pellets and in biomass fuel hammer mill for wood flour production. Similarly, variation in transportation occurs attributable to a greater difference in the bulk density of the two materials in a truck having weight and volume limits.

2.6 Life Cycle Inventory (LCI) of Material and Fuel Used

The questionnaires related to the consumption of resources/fuels/materials from each unit process in the system boundary were prepared before the study. Data were collected by an onsite visit of the wood mill. The plant manager and other associated technical staff were interviewed. We were able to get the data we required for the LCA in this study. Likewise, secondary data from the literature were also referred to for more understanding. The collected data from the mill visit represents the 2020-21 production and transportation data. The wood mill was from ME in the NE region of the US, which is the largest manufacturer of wood pellets in the state with an annual production capacity of 90,718-99,790 tonnes of pellets or 318-363 tonnes of pellets per day. The plant operates 24 hours and 7 days a week. The pellet mill is not co-located with other wood product manufacturers. The plant doesn't sell wood flour; only sells wood pellets as its commercial product. Likewise, input values for transportation are also based on the actual survey data in the study region.

Sawdust, wood chips, and pulp chips were the sources for the two feedstock products in this study. Most of these are residues from local wood mills in the New England region or Canada. Thus, hardwood and softwood sawdust at the sawmill (green), hardwood and softwood wood chips at sawmill (green), and pulp chips at the sawmill were chosen as the primary material inputs. The summary of other LCI data sources along with the ancillary materials and energy used in the mill along with the transportation of the products is presented in Table 1. SimaPro 9.2.0.2 (PRé Consultants 2016) software was used to model the two feedstocks' manufacturing and shipping processes and evaluate the various environmental impacts based on the input variables. The database of USLCI and US-EI 2.2 (DATASMART package) was chosen to source the LCI datasets since they are based on the US manufacturing and electricity data. The DATASMART package is included in the SimaPro software. Data were chosen focusing on the US or if possible Northeast region of the US to closely represent regional impacts. Based on the collected values of the input variables, the models were developed in simulating the technical system as well as calculating the mass and energy flows within the system boundary. Life Cycle Impact Analysis (LCIA) method calculates the environmental loads for each unit process concerning the defined functional unit.

Table 1 Input values of the LCA modeling for the production and transportation of one tonne of wood flour and pellets along with their LCI dataset chosen from the DATASMART in SimaPro.

LCI Dataset	Wood flour	Wood pellets
Input from nature (L)		
Water, well, US (USLCI)	0.02	0.02
Materials input (kg)		
Sawdust, hardwood, green, at sawmill, NE-NC/kg/RNA (USLCI)	285	285
Sawdust, softwood, green, at sawmill, NE-NC/kg/RNA (USLCI)	285	285
Wood chips, hardwood, green, at sawmill, NE-NC/kg/RNA (USLCI)	153	153
Wood chips, softwood, green, at sawmill NE-NC/kg/RNA (USLCI)	158	158
Pulp chips, at sawmill, US SE/kg/US (USLCI)	119	119
Fuel input (L)		
Diesel, at refinery/l/US (USLCI)	1.74	1.74
Liquefied petroleum gas, at refinery/l/US (USLCI)	0.89	0.89
Electricity input (kWh)		
Electricity, biomass, at power plant/US (USLCI)	111.46	129.49
Transport input (tkm)		
Transport, combination truck, long-haul, diesel powered, Northeast/tkm/RNA (USLCI)	371	371
Ancillary inputs (kg)		
Proxy_Oil and grease, at plant NREL/US U (US-EI 2.2)	0.0007	0.09
Polypropylene, resin, at plant, CTR/kg/RNA (USLCI)	10.28	0
Polyethylene, low density, resin, at plant, CTR/kg/RNA (USLCI)	0	3.16

2.7 Life Cycle Impact Assessment (LCIA) and Cumulative Energy Demand (CED) Methodology

The North American Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1, US-Canadian 2008 method built-in SimaPro software was used for the environmental assessment [54]. The TRACI method is focused on the US and prepared by the US Environmental Protection Agency. It is a midpoint-oriented method. Besides the environment-related impacts, impacts to human health were also examined in the assessment process. A total of 10 impact categories were reported from the TRACI method for both wood flour and pellets to compare in this study. These include ozone depletion (kg CFC-11-eq), global warming (kg CO_2-eq), smog (kg O_3-eq), acidification (kg SO_2-eq), eutrophication (kg N-eq), carcinogenic (CTUh), non-carcinogenic (CTUh), respiratory effects (kg PM2.5-eq), Ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus). Likewise, the total primary energy input was quantified based on the LCI profiles and

using the Single-issue method – CED (version 1.00 in SimaPro). The method is based on lower heating values (LHV) for the primary energy resources. Both the characterization and normalization results were compared for one truckload of each wood feedstock and each impact category. Characterization results display the actual values of each impact having different units whereas normalization calculates the magnitude of each impact on the same scale relative to the reference for a more equitable comparison. For one truckload of the various wood feedstocks, normalization of impact categories relative to the reference in SimaPro [55] as well as the lower heating values (LHV) were performed to examine if the variation in environmental impacts is caused by weight alone or the other variables as well. The LHV of wood flour in our case study is 19,502 MJ/tonne and wood pellets is 19,538 MJ/tonne. Besides these factors, economic indicators could also be a basis for normalization but this is beyond the scope of the study.

2.8 Assumptions

a. There is no commercial production of wood flour in the studied wood mill as well as throughout the state of ME. The screen size used in the biomass fuel hammer mill was similar to the screen size used in wood flour production. Thus, grindings from the biomass fuel hammermill are comparable in sizing to wood flour, therefore were considered as "wood flour" for comparison with the wood pellets.

b. Wood flour is the major raw material in the manufacturing of WPCs commercially; there is no commercial application of wood pellets for WPCs manufacturing. However, as a follow-up to previous studies, we are assuming wood pellets can also be an alternative feedstock to WPCs.

c. All the unit operations in the pellet plant were single systems except the pellet mills which were four. Thus, the amount of electricity and other resources related to pellet mills is based on the average from the four pellet mills.

2.9 Limitations

The wood flour produced in this case study was not applied in WPCs manufacturing, instead was used as a feedstock for the biomass boiler/dryer. Thus, there are some limitations with the type of raw materials and processing steps as compared to the commercial wood flour production. Wood flour for manufacturing the WPCs is usually classified into different mesh/micron sizes after production by hammermill and before packaging or shipping. This case study has excluded the screening step because of the variation in the targeted end-use. Pulp chips are not typically chosen to make wood feedstock for manufacturing WPCs. However, the pellet mill in this study uses pulp chips as one of the residue types. Wood flour typically uses secondary residues that are already partially dried whereas pellet producers can use green as well as dried feedstocks. An additional drying process of the raw materials changes the LCA results in a large way [56]. Wood flour facilities are often co-located with the industries producing wood products that generate residues as their byproducts. Similarly, for large-scale production of WPCs, wood flour is never obtained in bags and for industrial wood pellets bags are also not used, but bags are commonly used for residential for ease of handling. Usually, pure hardwood or softwood species are used to make feedstocks for manufacturing WPCs. However, the pellet mill used a mixture of residues from hardwood and softwood species that need to be considered. These limitations can change the different impact categories of LCA as well as the consumption of energy sources and raw materials. Thus, future

studies focusing on LCA analysis on commercial wood flour production to supply to the manufacturers are highly recommended. Furthermore, for a comparative LCA study between the two feedstocks, it is suggested to survey the facility where wood flour production for supplying to WPC manufacturers is co-located with the wood pellets production. Ensuring similar sources of raw materials, equipment, electricity, fuels, and the manufacturing setting is important in the comparative LCA study.

3. Results and Discussion

3.1 Material Flows

The values of the input variables considered in this study are presented in Table 1. As described in the methodology section, the production of both wood flour and pellets are similar starting from the same raw materials to the operation in drying hammermill. The production processes separate when the ground material from the dryer hammermill goes to the biomass fuel hammermill to produce wood flour whereas it goes to the pellet mill to make wood pellets. The major inputs consumed in the production of wood pellets are the wood residues and electricity [57] which applies to our case study as well. A similar situation holds for the wood flour which was clearly explained in section 2.5.

All the input values for the two feedstocks are similar except the quantity of plastic bags, lubricants, and electricity. Wood flour is normally packaged/bagged using PP whereas for pellets PE is used. PE bags have better flexibility, tear-resistance, and durability applicable for heavier items compared to PP bags [58]. That is why wood pellets being almost four times heavier than wood flour are packaged in PE bags and wood flour in PP bags. From an environmental point of view, both being thermoplastics are easier to recycle. However, for large-scale production of WPCs, the feedstocks are never bagged and silos are used that do not require plastic bags. Extra lubricating oil/grease was required for the pellet mills to make pellets. Similarly, variation in the equipment to produce wood flour i.e., hammermill, and for pellets i.e., pellet mill consumed different amounts of electricity. The average electricity used in the production of one tonne of wood flour by hammermill was 6 kWh and wood pellets by pellet mills was 18 kWh. One tonne of bone-dried wood residues can produce one tonne of bone-dried wood flour or pellets (100% yield) [57]. In our case study, the quantity of wood residues at 45-50% moisture content (MC) required is almost double compared to the quantity of produced wood flour or pellets at 5-7% MC. This suggests it is the weight of the moisture responsible for the heavier weight of the residues. Table 2 shows the values of heat energy of the dryer/boiler to reduce the MC and weight of the residues in the mill. All the MC (%) values are based on a wet basis in this study.

Table 2 Properties of residues in the dryer before and after drying. The heat energy required for drying the residues with the initial moisture content of 45% and 50% at different firing and thermal load rates are being presented. The data were obtained from the mill visit.

Properties of residues before drying	Properties of residues after drying	Firing rate (FR) and thermal load (TL) conditions	Heat energy (MJ/tonne water removed)
Weight of residues 26.59 tonnes at a MC of 45%	Weight of water removed 10.87 tonnes, Weight of dried residues 15.73 tonnes at a MC of 7%	Low FR and low TL	2427
		Low FR and high TL	2913
		High FR and low TL	2913
		High FR and high TL	3495
Weight of residues 29.25 tonnes at a MC of 50%	Weight of water removed 13.53 tonnes, Weight of dried residues 15.73 tonnes at a MC of 7%	Low FR and low TL	1950
		Low FR and high TL	2340
		High FR and low TL	2340
		High FR and high TL	2808

3.2 Impact Assessment of One Tonne Wood Flour and One Tonne Pellets

The impacts from material and energy flows (wood residues, lubricants, electricity, diesel, propane, plastics, and transportation) in the production and shipping of one tonne of wood flour and pellets are shown in Figure 2 and Figure 3 respectively. The impacts calculated using the TRACI method are presented. The eutrophication impact is primarily caused by chemicals containing nitrogen or phosphorus into air or water, resulting nutrients runoff in an aquatic ecosystem and harm to biological productivity. Ecotoxicity is measured by the emission of heavy metals such as silver and barium into the water from the extraction process. Ozone depletion occurs with the release of chloromethane and bromomethane into the air during coal combustion. Sulfur oxides (SO_x), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate pollutants are the main sources of smog, acidification, and respiratory effects. Carbon dioxide (CO_2) emissions are separated by two sources, biogenic (biomass-derived) and anthropogenic (fossil fuel-derived). Biogenic CO_2 may be considered carbon neutral as the CO_2 emitted is reabsorbed during the growth of the tree and released on decomposition or burning of the tree. Although the CO_2 emissions from the biomass combustion does not account for the GWP impact, the release of other components including NO_x, SO_x, and VOCs within biomass combustion have the most major contribution to the other environmental impacts. A detailed study on Global warming potential (GWP) will be discussed in section 3.5 below.
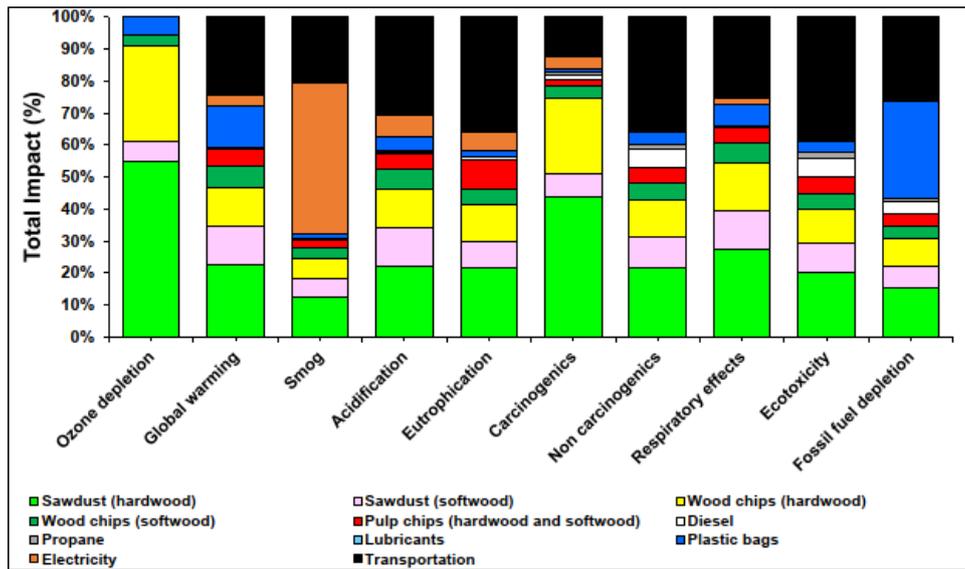
Figure 2 Impact assessment graph showing the relative contribution of the inputs for one tonne of wood flour.
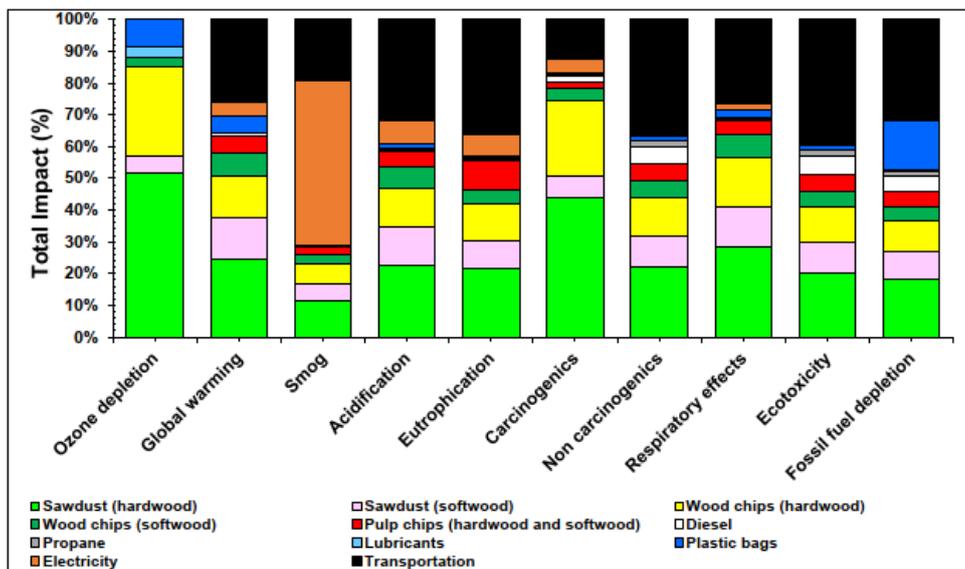

Figure 3 Impact assessment graph showing the relative contribution of the inputs for one tonne of wood pellets.

For both wood feedstocks, on average, the highest contribution to the different impact categories was observed mostly from transportation followed by the green sawdust produced at sawmills from hardwoods, and then from electricity. The use of diesel fuel in truck transportation intensifies greenhouse gas (GHG) emissions. Off-road transportation of the wood feedstock by trucks, front-end loader, forklifts, etc. consumed the most fuel i.e., diesel in a previous LCA study to produce softwood lumber [59]. Similarly, the hardwoods either as sawdust or chips had a higher negative impact on the environment as compared to the softwoods. Attributable to their much greater stiffness and density than softwoods, the hardwoods, in general, require more energy to harvest as well as mill process and the higher shipping costs. We used more sawdust than chips in this study which resulted in more impacts from sawdust than the chips. Previous studies [60, 61]

have shown differences in the energy consumption or environmental impacts between hardwood and softwood lumber manufacturing is attributable to the differences in the density of the wood species and regional electricity profiles. Briquetting logging residues for combined heating and power generation systems in the US have shown the electricity usage in preprocessing plants by far the greatest parameter for the overall GHG emissions [62], and the feedstock preparation stage had the largest share in global warming (GW) impact, mainly resulting from the drying process, followed by transportation [63]. Besides GHG emissions, the impact of wood processing steps was severe to the eutrophication attributable to electricity [64]. However, in our study, since Maine's electricity generation was dominated by biomass energy, the effect is less severe to the environment compared to some other inputs such as transportation and green sawdust from hardwoods.

The impact from transportation was the most severe to the global warming, acidification, eutrophication, noncarcinogenic, and ecotoxicity for both wood flour and pellets. The impact from electricity use was the highest for smog production. The green sawdust from hardwood contributes most to ozone depletion, carcinogenic, and respiratory effects. In a study of hybrid timber building, it was observed that on increasing the wood materials the influence on ozone depletion was the most and on global warming potential the least [65]. The effect of plastic bag use was also noticeable to the ozone depletion, global warming, and respiratory effects. The effect of diesel was mostly observed on non-carcinogenic, ecotoxicity, and fossil fuel depletion for both feedstocks. The prominent effect of lubricating oil/grease was ozone layer depletion. Likewise, the effect of propane was higher for noncarcinogenic, ecotoxicity, and fossil fuel depletion. The effect of pulp chips was most noticeable to eutrophication for either of the materials. Besides, the influence of sawdust and wood chips from softwoods were severe to global warming and plastic bags on fossil fuel depletion.

The impact of plastic bags was the most to fossil fuel depletion in the case of wood flour (Figure 2) whereas, for pellets, transportation had the most negative influence on fossil fuel depletion (Figure 3). This was attributable to the severe impact of PP compared to PE and for the same amount of the wood feedstock, the quantity of plastic bags required to bag the wood flour is higher than the pellets. For wood flour, after fossil fuel depletion, the major impact of plastic bags was on global warming whereas, for pellets, it was more on ozone depletion. Effect of lubricant was higher for wood pellets than flour as more lubricant was used in the four pellets mills. Meanwhile, an attributional LCA [40] conducted on the WPCs found the environmental impacts for the WPCs are lower because of the impacts from wood feedstocks attributable to the less fossil fuel consumption.

3.3 Comparative Inventory Assessment

Table 3 is the inventory of major emissions to the air, water, and soil generated from the production and shipping of the two feedstocks. Table 3 also lists the most influential emission sources. The input variables causing the maximum emissions were the same for wood flour or pellets except SO_x emissions. The major emissions to air were from hardwood sawdust and for water was transportation. The hardwood sawdust contributes either the most (highest impacting inputs) or the second in all the listed air emissions in Table 3. Emissions to air especially the VOCs from wood pellets depend on the drying temperature, raw materials nature, and self-heating of the pellets [66]. There was no impact from diesel, propane, lubricants, and electricity on SO_x emissions for both wood feedstocks. COD and BOD5 were not impacted by the lubricants. Bark was only generated from pulp chips without the influence of other production or transportation inputs.

Table 3 Emissions to air, water, and soil associated with the production and transportation of one tonne of wood flour and pellets from the mill residues. The most highly impacting inputs for each emission from both feedstocks are the same except SO_x emissions.

Emissions	Wood Flour Production (kg)	Transportation (kg)	Wood pellets Production (kg)	Transportation (kg)	Highest impacting inputs
Emissions to air					
a. CO_2 (fossil)	101.9	34.1	95.9	34.1	Transportation
b. CO_2 (biogenic)	105.97	$2.75*10^{-2}$	166.97	$2.75*10^{-2}$	Electricity
c. Acetaldehyde	$1.53*10^{-4}$	$9.42*10^{-8}$	$1.53*10^{-4}$	$9.42*10^{-7}$	Hardwood sawdust
d. Acrolein	$2.42*10^{-4}$	$1.01*10^{-7}$	$2.42*10^{-4}$	$1.01*10^{-7}$	Hardwood sawdust
e. Formaldehyde	$4.26*10^{-4}$	$1.97*10^{-6}$	$4.24*10^{-4}$	$1.97*10^{-6}$	Hardwood sawdust
f. Phenol	$1.03*10^{-10}$	$2.39*10^{-12}$	$3.26*10^{-9}$	$2.39*10^{-12}$	Lubricants
g. NO_x	0.799	0.261	0.819	0.261	Hardwood sawdust
h. SO_2	0.3385	0.0205	0.3155	0.0205	Hardwood sawdust
i. SO_x	$1.54*10^{-2}$	$2.12*10^{-7}$	$7.86*10^{-3}$	$2.12*10^{-7}$	Pellets-hardwood sawdust, Flour-PP
j. Methane	0.1501	$4.69*10^{-2}$	0.1481	$4.69*10^{-2}$	Hardwood sawdust
k. Particulates (unspecified)	0.741	$3.51*10^{-3}$	0.742	$3.51*10^{-3}$	Hardwood sawdust
l. VOCs (unspecified)	$3.03*10^{-2}$	$1.61*10^{-2}$	$2.51*10^{-2}$	$1.61*10^{-2}$	Transportation
Emissions to water					
a. Biological oxygen demand (BOD5)	0.1227	$7.3*10^{-3}$	0.1217	$7.3*10^{-3}$	Hardwood sawdust
b. Suspended soils	3.18	1.88	3.1	1.88	Transportation
c. Chemical oxygen demand (COD)	$2.4*10^{-2}$	$1.39*10^{-2}$	$2.29*10^{-2}$	$1.39*10^{-2}$	Transportation
d. Chloride	2.43	1.44	2.38	1.44	Transportation
Emissions to soil					
a. Bark	1.59	0	1.59	0	Pulp chips

In the comparative inventory assessment of one tonne of each feedstock, the quantity (kg) of emissions of bark, acetaldehyde, and acrolein were the same. Emissions of BOD, chloride, COD, suspended soils, (fossil), formaldehyde, methane, SO_2, SO_x, and VOCs were greater for one tonne of wood flour as compared to the one tonne of pellets. The rest of the emissions i.e., CO_2 (biogenic), NO_x, and particulates were greater for the wood pellets than the wood flour and were only air emissions. Likewise, in a comparative inventory assessment of one truckload of wood flour and pellets, the emissions to air, water, and soil as mentioned in Table 3 were higher for wood pellets

compared to wood flour. However, the exception is with SO_x, which was greater for wood flour than the pellets. Similarly, the CO_2 (fossil) emission was the same for both materials. Slightly, higher emissions to air, water, and soil in the production and transportation of one truckload of wood pellets (30 tonnes) compared to the wood flour (22 tonnes) are obvious as more tonnes of production and transportation consume more energy, materials, fuels, etc.

3.4 Comparative Impact Assessment of the Two Feedstocks of Different Functional Units

The impact assessment results for one tonne and one truckload of the two feedstocks are presented in Table 4. Values of each impact associated with the production and shipping of one tonne and one truckload of wood flour and pellets are compared along with the differences in percentages. The difference between the two feedstocks for different functional units are plotted in Figure 4 and Figure 5 for comparison. For one tonne production and transportation of the two feedstocks, wood flour presented higher impacts on the environment than the pellets for most categories except ozone depletion and smog (Table 4, Figure 4). There was no difference in the carcinogenic impacts between the two. The percentage differences ranged from 0-16.5% as shown in Table 4. The major input imparting greater influence on wood flour compared to pellets could be the plastic bags. Higher resource usage on their production and the larger waste generation induces plastics to have a huge effect on the environment [67]. Although the wood pellets production required more electrical energy than flour, the source being biomass for electricity generation, the impact is much reduced. And even though the application of the lubricant varies for flour and pellets, its quantity is much less to make noticeable differences.

Table 4 Environmental impacts associated with the production and transportation of one tonne or one truckload of wood flour and pellets.

| Impact category	Unit	Functional unit (one tonne)			Functional unit (one truckload)		
		Wood flour	Wood pellets	Difference (%)	Wood flour	Wood pellets	Difference (%)
Ozone depletion	kg CFC-11eq	$1.98*10^{-6}$	$2.12*10^{-6}$	6.5	$4.35*10^{-5}$	$6.35*10^{-5}$	31.5
Global warming	kg CO_2eq	146.33	135.20	7.6	3219.19	4055.87	20.6
Smog	kg O_3eq	56.74	60.53	6.3	1248.25	1815.97	31.3
Acidification	kg SO_2eq	1.47	1.44	2.1	32.31	43.13	25.1
Eutrophication	kg Neq	$7.63*10^{-2}$	$7.60*10^{-2}$	0.3	1.68	2.28	26.4
Carcinogenics	CTUh	$4.30*10^{-6}$	$4.29*10^{-6}$	0	$9.45*10^{-5}$	$1.29*10^{-4}$	26.6
Non carcinogenics	CTUh	$1.43*10^{-5}$	$1.40*10^{-5}$	2.3	$3.15*10^{-4}$	$4.19*10^{-4}$	24.9
Respiratory effects	kg PM2.5eq	$5.18*10^{-2}$	$4.96*10^{-2}$	4.3	1.14	1.49	23.4
Ecotoxicity	CTUse	256.08	250.69	2.1	5633.84	7520.82	25.1
Fossil fuel depletion	MJ surplus	283.28	236.52	16.5	6232.07	7095.74	12.2
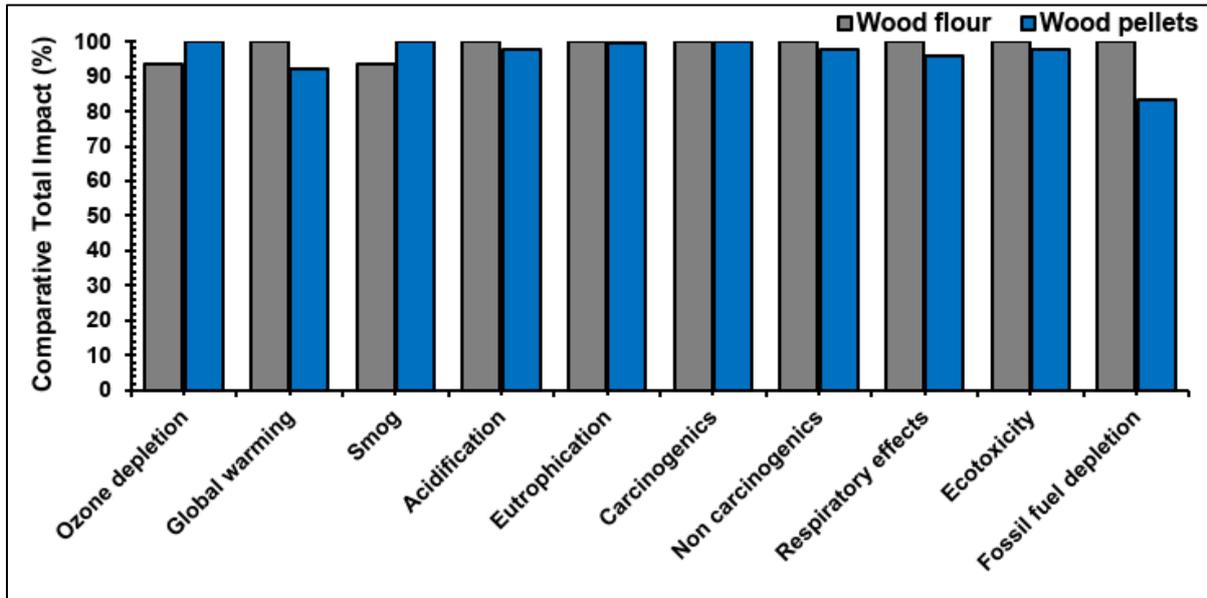
Figure 4 Comparative impact assessments for one tonne of wood flour and pellets.
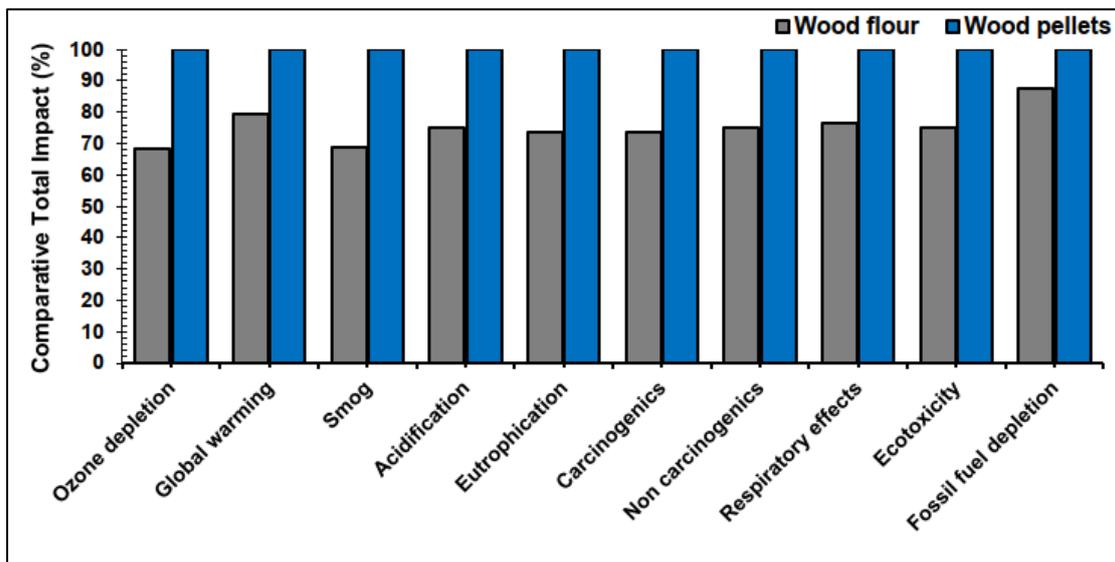

Figure 5 Comparative impact assessments for one truckload of wood flour and pellets.

For one truckload production and shipping of the two feedstocks, wood flour showed less impacts in all the categories (Table 4) in this study, primarily attributable to the mass difference in the one truckload shipment. Compared to the one truckload of wood pellets (30 tonnes), the impact on the environment from one truckload of wood flour (22 tonnes) was smaller for all impact categories (Figure 5). The differences in the impact ranged from 12-30% on average as shown in Table 4. Wood flour, in general, seems to have less impact on ozone depletion and smog compared to the pellets. However, their impacts on fossil fuel depletion and global warming are quite remarkable compared to the pellets. More tonnes of wood pellet production and transportation can have more environmental impacts when examined on the truckload functional unit. Still, the impacts are considerable for the wood pellets rather than flour for one truckload, with a difference of eight tonnes of production and shipping. However, this may not be in favor to the cost analysis.

3.5 Normalization of Impacts for One Truckload of the Feedstocks

For one truckload of wood flour and pellets, normalization results as derived from the SimaPro outputs are shown in Figure 6. For each of the impact categories, the difference in normalization scale is quite low between the two feedstocks. The slightly higher difference is seen in the carcinogenics and smog with wood pellets contributing more than flour. Wood pellets, basically the ash can contain heavy metals (quantity depends on species) that may induce the carcinogenic effects [68]. However, the differences in the rest of normalizations for wood flour and pellets (one truckload) were notably low. Likewise, the results of characterization showing different units for each impact category creates difficulty in recognizing the major impact to the environment. Thus, with SimaPro's normalization of the impact values across the categories, it was observed that the major impact was on carcinogenics followed by smog and ecotoxicity and the least on ozone depletion. The effects on global warming, acidification, eutrophication, respiratory effects, and fossil fuel depletion were minor for each wood feedstock type. Since the major focus is on GWP, the contribution from wood flour or pellets is similar and in a lower scale range. Normalization scale in SimaPro is the average of all the LCA impact indicators across all industry sectors. Thus, this might not be representative of the wood products industry.
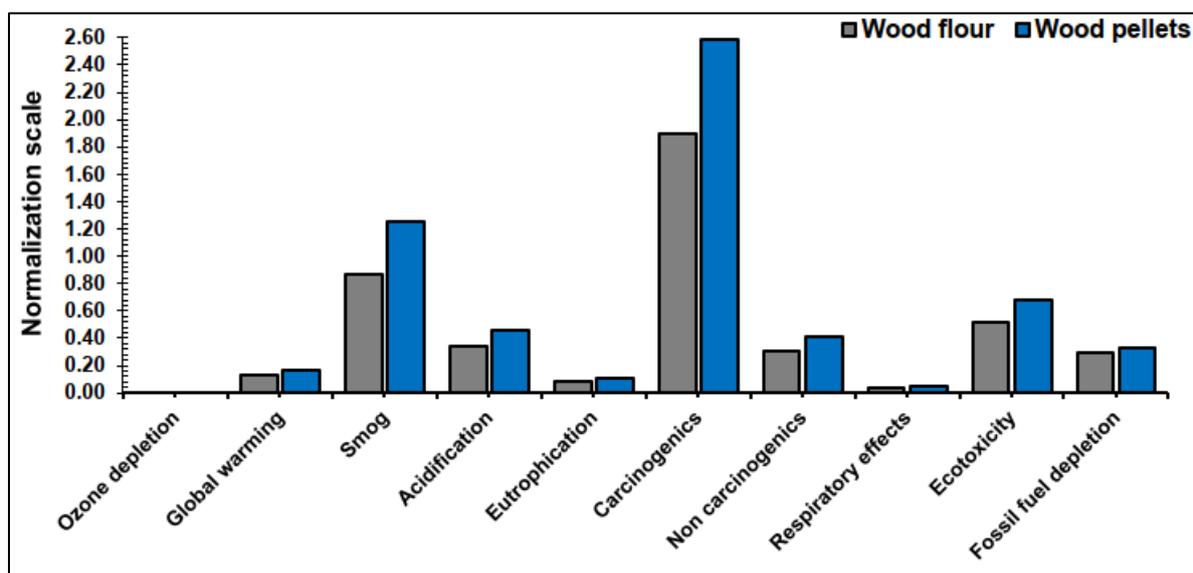

Figure 6 Comparative normalization based on SimaPro normalization factors.

In addition, normalization based on the LHV of the feedstocks indicated a negligible difference among the different impact categories for one truck load of both wood feedstocks (Table 5 and Figure 7). Heating values emphasize energy efficiency as well as analyzing the cost-effectiveness of a combined heat and power plant. LHV is related to the products of combustion containing water vapor and the heat in the water vapor not being recovered. The LHV-based normalization values are presented in Table 5 and the difference in percentage are shown in Figure 7. The values of different impacts are similar for one truckload of wood flour and pellets. GWP difference of 7.8% between the two feedstocks is observed. The variation in the resulting impacts to the different aspects of environment such as: air, water, and soil as well as human health were similar for one truckload production and transportation of wood flour and pellets. These results indicate that besides the

difference in weight of the truckload of two feedstocks i.e., eight tonnes, the variation in the impacts for the truckload is also influenced by the total heating values of the feedstocks.

Table 5 Comparative normalization values for wood flour and pellets (one truckload) based on their LHV.

| Impact categories	Wood flour	Wood pellets	Difference (%)
Ozone depletion	$1.0*10^{-10}$	$1.1*10^{-10}$	6.4
Global warming	$7.5*10^{-3}$	$6.9*10^{-3}$	7.8
Smog	$2.9*10^{-3}$	$3.1*10^{-3}$	6.1
Acidification	$7.5*10^{-5}$	$7.4*10^{-5}$	2.3
Eutrophication	$3.9*10^{-6}$	$3.9*10^{-6}$	0.5
Carcinogenics	$2.2*10^{-10}$	$2.2*10^{-10}$	0.2
Non carcinogenics	$7.3*10^{-10}$	$7.2*10^{-10}$	2.5
Respiratory effects	$2.7*10^{-6}$	$2.5*10^{-6}$	4.5
Ecotoxicity	$1.3*10^{-2}$	$1.3*10^{-2}$	2.3
Fossil fuel depletion	$1.5*10^{-2}$	$1.2*10^{-2}$	16.7
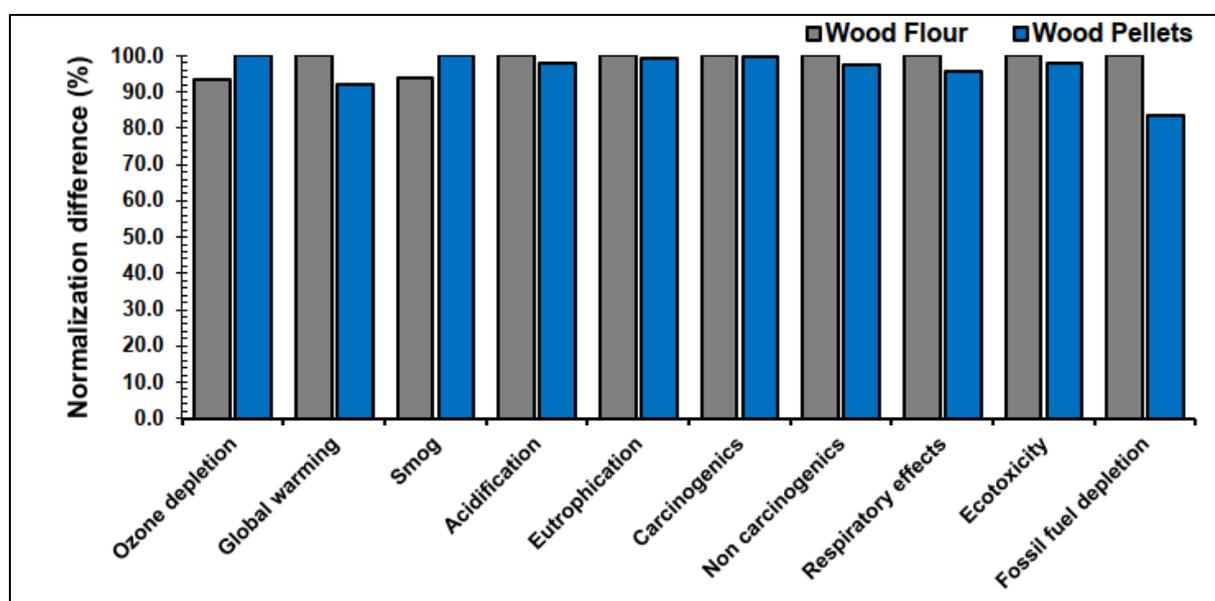
Figure 7 Comparative normalization based on the LHV of the wood feedstocks.

3.6 Global Warming Potential (GWP)

Out of several impact categories, the major focus is on the global warming potential (GWP) at present as it determines the future climatic conditions on earth and a basis for carbon pricing. The greenhouse gases (GHG) reduction strategies have been of keen interest as the earth's temperature is increasing. Carbon tracking is crucial for global policy making. CO_2, methane, and NO_x are the major contributing gases for the 100-year global warmings [62]. The production and shipment of one tonne of wood flour emitted a greater amount of CO_2, methane, and NO_x compared to the pellets in this study. Similarly, the emission of these gases was higher for 30 tonnes (one truckload) of wood pellets (by 21%) than 22 tonnes (one truckload) of wood flour. In addition to this, the initial

moisture content of the mill residues is elevated (45-50% on a wet basis) in the selected pellet plant. The moisture content of the feedstock is vital as this is responsible for global warming impacts as well as costs attributable to the application of propane in drying [69]. The authors recommend air drying of the high moisture containing residues to lower the ecological and economical burdens. Similarly, Alanya et al. [64] in their study on the wood pellet sector in the US mentioned the supply of raw materials and the manufacturing stages contributed most to different impacts categories. During manufacturing, the most influence on GHG emissions was through electricity consumption in wood processing processes. After manufacturing, raw materials transportation had a vital role in the GWP. The authors reported an increase in transportation distance from a minimum of 250 km to a maximum of 1250 km results in a 35% increase in the total GW impact.

3.7 Cumulative Energy Demand (CED)

With the CED single-issue method output from the SimaPro LCA model, the different renewable and non-renewable energy consumed for manufacturing and hauling of one tonne or one truckload of the wood feedstocks are summarized in Table 6. The percentage difference between the two feedstocks in the amount of renewable energy (RE) and non-renewable energy (NRE) consumed for each functional unit (one tonne or one truckload) are shown in Figure 8a and Figure 8b, respectively.

Table 6 Renewable and non-renewable energy consumed during one tonne and one truckload production to transportation of the two wood feedstocks.

| Impact category	Functional unit (one tonne)		Functional unit (one truckload)	
	Wood flour	Wood pellets	Wood flour	Wood pellets
Non-renewable, fossil (MJ)	2310	2009	50825	60274
Non-renewable, nuclear (MJ)	0.12	0.30	2.65	8.87
Non-renewable, biomass (MJ)	0.00	0.00	0.00	0.00
Renewable, biomass (MJ)	0.02	0.01	0.53	0.40
Renewable, wind, solar, geothermal (MJ)	0.12	0.05	2.62	1.40
Renewable, water (MJ)	1.11	0.35	24.53	10.43
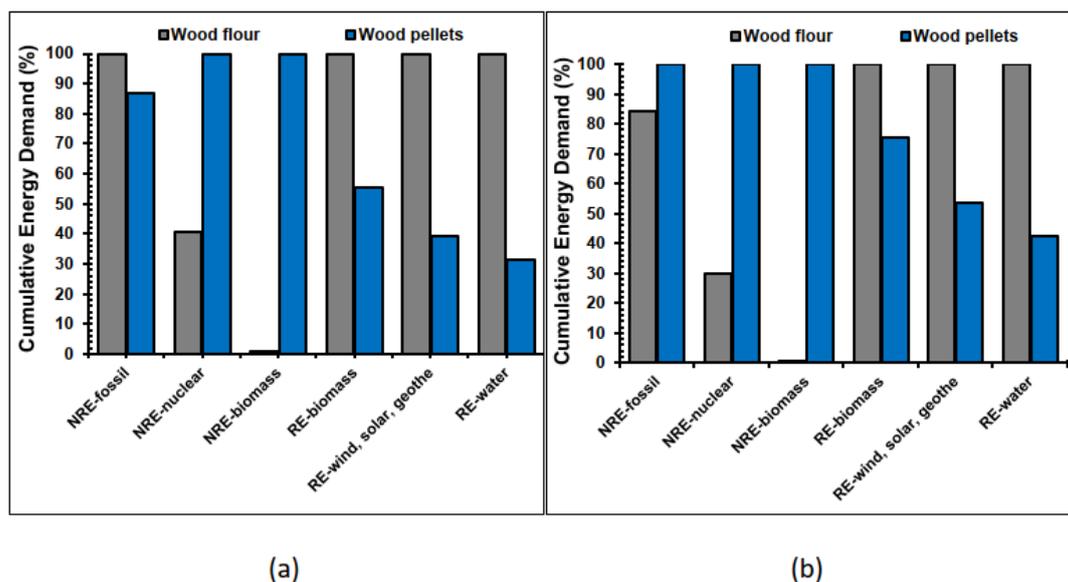
Figure 8 Comparative CED diagram for wood flour and pellets as functional unit of (a) one tonne and (b) one truckload.

The production of one tonne of wood flour or pellets consumes the highest amount of REs i.e., biomass, water, wind, solar, and geothermal but with differences in the percentage of total energy consumption. Renewable biomass, water, wind, solar, and geothermal energy were only depleted by plastic bags to the most and then the lubricants for each feedstock. However, wood products typically the woody biomass consumes more RE sources than NRE sources [70]. A lot of bioenergy was consumed during the biomass feedstock drying process, and most non-renewable fossil-based energy was consumed in the manufacturing of poly-lactic acid (PLA) based WPCs [71]. Fossil-based NRE use was primarily from the plastic bags followed by transportation and hardwood sawdust for wood flour, whereas for pellets was mainly from transportation and hardwood sawdust. The fossil-based energy was depleted by all the materials, fuels, electricity, transport, and ancillary inputs for both the wood feedstocks. NREs being consumed more by the materials i.e., wood residues could be attributable to the electricity usage beyond the pellet plant.

Production and transportation of one tonne of wood flour consumed more REs and NREs than the same unit of wood pellets except the non-renewable nuclear energy. A similar situation holds for one truckload functional unit but with a lower percentage of difference, except the fossil energy was consumed to a greater extent by the wood flour than the pellets. The percentage of differences in the cumulative energy demand for one tonne of the feedstocks from different sources are: NRE-fossil by 13%, NRE-nuclear by 59%, NRE-biomass by 99%, RE-biomass by 45%, RE-wind, solar, geothermal by 61%, and RE-water by 69%. Comparably, the percentage of differences in the CED for one truckload of the feedstocks from different energy sources are: NRE-fossil by 16%, NRE-nuclear by 70%, RE-biomass by 24%, RE-wind, solar, geothermal by 46%, and RE-water by 58%. For NRE-biomass, even though the difference observed is 99%, the value for either of the feedstocks is 0.00 and these very small numbers may be generated attributable to the noise, not true values. The major difference between the one tonne and one truckload of the feedstocks is the consumption of nuclear and water sources. Even though the percentage of differences for non-renewable fossils consumption appears small, the actual values in MJ are the highest compared to the other energy

sources. Nejad et al. [62] pointed out that the difference in the amount of fossil energy usage was caused by variation in electricity usage between coal and natural gas to generate heat and power for the palletization of Napier grass-based feedstock. Differences in the consumption of plastic bags, electrical energy, and lubricating oil/grease are the direct major factors in this study. Composites made from natural fibers on average can reduce energy consumption by 60% per ton compared to glass fiber composites according to Pervaiz and Sain [72]. This study also showed the production and shipping of one truckload of wood flour consumed lesser NRE sources and more RE sources compared to the one truckload of wood pellets.

4. Conclusions

- For both wood feedstocks, the greatest impact to the environment was from transportation followed by the wood residues from hardwoods processing.
- The impact of electricity in the pellet plant was not essential as it uses biomass generated electricity.
- All the impact categories for production and transportation of one tonne of wood flour were higher than wood pellets except smog and ozone depletion. For one truckload of wood flour (22 tonnes) and pellets (30 tonnes), the impact from one truck load of pellets is higher than flour with a difference ranging from 12-30%. However, after normalization of one truckload of the feedstocks, the impacts were similar for either feedstock.
- GWP is the major topic of interest at present. For one tonne production and transportation, GWP from wood flour is higher than from wood pellets by 11.13 kg CO_2eq (8% more).
- For the same quantity of materials, the production and shipping via a truck appear to be more environmentally and economically friendly for wood pellets than the wood flour in this study.
- The findings of this study can be applied to the WPCs industry to encourage the utilization of wood pellets feedstocks to attain economic and environmental benefits.

Author Contributions

Geeta Pokhrel – Conceptualization, data collection, data analysis, software use, manuscript preparation; Hongmei Gu – Data analysis, visualization, supervision, manuscript review; Douglas J. Gardner – Conceptualization, data analysis, supervision, funding acquisition, resources, manuscript review; Shane O'Neill – Data collection, data analysis, resources, manuscript review.

Competing Interests

The authors have declared that no competing interests exist.

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