

**UTILIZATION OF SECONDARY PROCESSING MILL RESIDUES IN MAINE TO
PRODUCE RAW MATERIALS FOR MANUFACTURING WOOD-PLASTIC
COMPOSITES (WPCs)**

By

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Thesis Advisor: Dr. Douglas J. Gardner

An Abstract of Thesis Presented
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The overall objective of this study was to explore the potential of utilizing secondary processing mill residues generated in Maine (1.6 million tons annually) in Wood-Plastic Composites (WPCs). Attributable to the huge shipping costs for transporting wood flour over long distances, wood pellets are explored as alternative feedstock for WPCs manufacturing. The mill residues from four species based on their abundance and potential applicability for utilization in WPCs manufacturing were used to make the two different feedstocks. The properties of the wood flour and pellets were studied along with the comparison of the properties of polypropylene-based WPCs using both of these feedstocks separately. In addition to this, the Network Analyst tool in ArcGIS and Sensitivity analysis were used for the transportation cost analysis on shipping these materials via truck transportation. Lastly, SimaPro software was used for life-cycle assessment (LCA) analysis to analyze the potential environmental impacts of wood flour and pellet production utilizing the mill residues and then transporting them to WPC manufacturers.

On average, the conversion of residues to wood flour and then wood flour into pellets reduced the moisture content by 54% and 52% respectively and increased the bulk density by 119% and 276% respectively. The physical and mechanical properties of WPCs using wood flour or pellets separately mixed with polypropylene were similar for both controls and formulations using coupling agents. On average, the transportation costs of wood pellets via a truck were reduced by at least 25% compared to wood flour and up to 70% in other transportation mediums having a larger weight limit. Based on the LCA analysis of the case study, transportation had the highest impact on the environment in contrast to other input variables related to production. Likewise, for similar quantities, the production and shipping of wood pellets appears to be more environmentally friendly than wood flour. Effects of global warming potential (GWP) for one ton (characterization) and one truckload (normalization) was higher by 8% for wood flour as compared to the pellets.

It is expected that this study will ultimately encourage investors to establish an industry segment supplying raw materials for WPC production in ME and ensure the efficient outlet of mill residues. Furthermore, WPC manufacturers would benefit from the minimization of the raw material transportation costs through the utilization of an alternative wood feedstock that would positively impact their overall production process.

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CHAPTER 1

BACKGROUND/MOTIVATION

1.1 Overview of the Project

The state of Maine (ME) has more than 100 sawmills and turning mills in commercial operation (Maine Woodland Owners 2017). Many forest-based industries including sawmills and turning mills produce residues often termed “secondary processing mill residues”. They are the remnants once timber is utilized in the wood mills for processing primary products such as lumber. The residues are usually clean, uniform, on-site, and low in moisture content with potential for further applications. Sawdust, planar shavings, small chips, etc. are some of the examples of residues. Wood residues have several direct or indirect applications such as the production of heat and energy, raw material for particleboards, pellets or char, for agricultural use (livestock bedding), and landscape applications. ME generates around 1.6 million tons of green residues from wood mills each year. In the state, roughly 800 million board feet are produced from which around 800, 000 tons of clean chips and 800, 000 tons of bark and sawdust are generated (FOR/Maine 2018). Kingsley 2017 reported as a decent rule of thumb, for every 1000 board feet of lumber produced, 2 tons of residues are produced out of which 1 ton is clean chips (free from bark, adhesives, metals, microorganism attack, etc.).

One of the potential applications of secondary residues is the production of wood flour using different comminution equipment. The produced wood flour can be classified through different screening methods. A major application of wood flour is in the manufacture of wood-plastic composites (WPCs). Utilization of wood flour in thermoplastics has been occurring since the 1970s and within the past several decades its utilization in decking and railing production in

North America has been significant (Gardner et al. 2015). The impact of COVID-19 resulted in significant commercial production reductions in 2020 and 2021 mostly attributable to the limits placed on international trade, although WPC production is expected to grow from 2022 onward. Barrette Outdoor Living, Inc. is the only WPC industry in the state of ME (located in Biddeford) and is one of the largest manufacturers of fencing, railing, and outdoor living products in the USA. This company has facilities in 14 different locations in North America with the source of raw material mostly from Canadian producers.

Economic analyses are fundamental in contributing to investment decisions in any industry, guiding the choice of the best projects, and, or, production alternatives. Transportation is crucial in terms of ensuring the supply of demanded products on time. Transportation costs are largely a function of time traveled, transportation form, and energy density of the product. Similarly, life-cycle assessment (LCA) analysis is a technique to understand the potential environmental impacts associated in the manufacturing and consumption of any products in an attempt to protect the environment (ISO 14044 2006). LCA analysis is vital before any manufacturing and consumption process to understand how the processes will impact planet earth and its ecosystems.

1.1.1 Motivation for the Project

Forest products industries are a key part of the state economy in ME, particularly in rural areas where there are fewer alternative employment opportunities. Compared to the past few years, the forest products business industry is changing where engineered wood products, biofuels, high-performance fibers, and natural chemicals are gaining higher market share

(FOR/Maine 2018). Most of the secondary processing mill residues in ME are combusted for energy, used to make solid fuel pellets for residential wood stoves, biomass power plant, wood bedding for horses, etc. Usually, clean chips are exported to paper mills, however since 2014, pulp and paper mills at Bucksport, Lincoln, East Millinocket, and Madison have been closed. Besides paper mills, biomass power plants, and pellet mills in the state are also struggling with their stability (Kingsley 2017). This has caused a great problem in the outlet of mill residues. Maine sawmills and turning mills have reported that the amount they are paid for these residues is dropping. It has been forecasted that in a worst-case scenario these mills would have to pay the disposal fee for the residues. Out of 1.6 million tons of green residues, they would be paying a large sum of money annually as disposal fees that would put these mills at a great disadvantage (FOR/Maine 2018). The average tipping fee for solid waste in the Northeast region was \$67.39 per ton and \$78.50 per ton in ME in 2018 (EREF 2019).

On the other hand, despite being a home to WPC manufacturer (Barrette Outdoor Living, Inc.), the manufacturer currently has to source the wood flour feedstock from out of state (St. Hyacinth Quebec, Canada). This company would be open to sourcing the wood flour feedstocks locally if the costs were optimal (Personal communication, Mike Hurkes). But currently, there is no commercial production of wood flour in ME that can economically utilize those mill residues. Likewise, wood flour having very low bulk density imparts greater transportation costs when shipped over longer distances. Thus, in this project, compressing wood flour into pellets and then utilization into WPCs for the cost-effective transportation of the feedstock has been explored. WPCs were made from wood flour or wood pellets from the species of (Northern White Cedar (*Thuja occidentalis*), Eastern White Pine (*Pinus strobus*), Eastern Spruce-Balsam Fir (*Picea rubens*-*Abies balsamea*), and Red Maple (*Acer rubrum*)) and compared in terms of material

properties. Equally important for the study is another aspect focusing on the logistics and supply chain of the wood feedstock products, which often are a major factor deciding on the final cost of the end-product. Thereby, a transportation cost analysis of shipping wood flour and pellets via a truck and comparing the cost-effectiveness of pellets with respect to flour was evaluated. Similarly, works on life-cycle assessment (LCA) were carried out to understand the environmental impacts of the manufacturing and transportation of these wood feedstocks to WPC manufacturers (cradle-to-gate analysis). The manufacturing-consumption process and environmental aspects need to go side by side.

We expect WPC industries within and out of ME would benefit from the utilization of locally produced wood feedstocks in the production of WPCs. This study provides an alternative solution to the current problems faced by the wood products industries in ME that produce significant residues.

1.1.2 Goal and Objectives

The main goal of this research is to explore the potential of wood feedstock production i.e., wood flour and pellets from secondary processing mill residues in Maine to supply to the wood-plastic composites (WPCs) manufacturers.

The specific objectives include:

- 1) Compare the properties of wood flour and wood pellets produced from mill residues of select hardwood and softwood species.
- 2) Study the physical and mechanical properties of polypropylene (PP)-WPCs manufactured using wood flour or pellets.
- 3) Perform a transportation cost analysis of wood flour and pellets to supply WPC manufacturers.

- 4) Perform a life-cycle assessment (LCA) analysis of the production and transportation of wood feedstocks: wood flour and pellets to manufacture WPCs.

1.2 Structure of Thesis

In this thesis, the use of mill residues generated in large amounts in ME, for producing feedstocks to the WPC industry in the state, that currently rely on other sources paying huge shipping fees has been studied. There are six chapters including the current chapter presenting the general background/rationale along with objectives of the project, research activities being carried on, and the final conclusions and recommendations. The current chapter i.e., Chapter 1 covers overall overview, rationale, goals/objectives, and structure of the thesis. Chapter 2 includes the properties of wood flour versus wood pellets produced from mill residues from four local wood species. Chapter 3 describes the properties of WPCs made using PP, wood flour or wood pellets. Chapter 2 and 3 are published in the “Polymers” Journal from “MDPI” (Pokhrel et al. 2021a and Pokhrel et al. 2021b respectively). Chapter 4 is a study based on the transportation cost analysis on shipping wood flour versus pellets via a truck and is accepted for publication in “Bioresources” Journal (Pokhrel et al. 2022). Chapter 5 describes the LCA analysis of the wood flour and pellets, including production from mill residues to transportation to WPCs producers which is intended to be submitted soon for publication. Chapter 2, 3, 4, and 5 being the full length articles/manuscript contain certain statements may be repeated in different chapters. Finally, Chapter 6 points out the overall conclusions and future recommendations.

1.2.1 Production of wood flour and wood pellets

In Chapter 2, properties of wood flour from the four different wood species: white cedar, white pine, spruce-fir, and red maple are described. Particle size distribution, morphology through scanning electron microscopy (SEM), bulk density, and moisture content of wood flour for each species is studied. Likewise, properties of wood pellets made from 40 mesh and unsieved wood flour of each species i.e., moisture content, bulk density, ash, durability, and dimensions is studied. Comparison of the change in moisture content and bulk density as residues changes to wood flour and then into pellets is examined.

1.2.2 Manufacturing of wood-plastic composites (WPCs)

In chapter 3, the physical and mechanical properties of WPCs from PP, wood flour or pellets in the presence or absence of coupling agents were studied. Altogether, there were 16 different formulations. The physical properties: density, distribution/dispersion of particles and morphology through microscopy images were studied. Similarly, the mechanical properties: tensile, flexural, and impact properties of the WPCs samples were determined. Properties of WPCs based on wood flour or pellets, presence or absence of coupling agents were correlated.

1.2.3 Transportation cost analysis

Chapter 4 covers the transportation cost analysis of shipping wood flour and pellets in the study region via a truck. Sensitivity analysis on changing the input variables related to trucking, material properties and distances for each wood feedstock was performed. This analysis is based on the case-study of the Northeast region of the US.

1.2.4 Life-cycle assessment (LCA) analysis

In chapter 5, comparative LCA analysis of the production and transportation of wood flour versus pellets was being carried out. The analysis doesn't cover the production process of mill residues in saw mills as well as the utilization of wood feedstock in the manufacturing of WPCs. This is a cradle-to-gate analysis. SimaPro software version 9.2.0.2, databases based on USLCI and US EI 2.2., and method of North American TRACI 2.1, US-Canadian 2008 was used.

1.2.5 Conclusions and Recommendations

Chapter 6 presents the overall conclusions of the thesis work. Similarly, further studies that could be carried out in the future are suggested.

CHAPTER 2

COMPARATIVE STUDY OF THE PROPERTIES OF WOOD FLOUR AND WOOD PELLETS MANUFACTURED FROM SECONDARY PROCESSING MILL RESIDUES

2.1 Chapter Summary

The generation of secondary processing mill residues from wood processing facilities is extensive in the United States. Wood flour can be manufactured utilizing these residues and an important application of wood flour is as a filler in wood–plastic composites (WPCs). Scientific research on wood flour production from mill residues is limited. Among the largest costs involved in the supply chain of WPCs manufacturing are the transportation costs. Wood flour, constrained by low bulk densities, is commonly transported by truck trailers without attaining allowable weight limits. Because of this, shipping costs often exceed the material costs, consequently increasing raw material costs for WPC manufacturers and the price of finished products. A bulk density study of wood flour (190–220 kg/m³) and wood pellets (700–750 kg/m³) shows that a tractor-trailer can carry more than three times the weight of pellets compared to flour. Thus, this study focuses on exploring the utilization of mill residues from four wood species in Maine to produce raw materials for manufacturing WPCs. Two types of raw materials for the manufacture of WPCs, i.e., wood flour and wood pellets, were produced and a study of their properties was performed. At the species level, red maple 40-mesh wood flour had the highest bulk density and lowest moisture content. Spruce-fir wood flour particles were the finest (d_{gw} of 0.18 mm). For all species, the 18–40 wood flour mesh size possessed the highest aspect ratio. Similarly, on average, wood pellets manufactured from 40-mesh particles had a lower moisture content, higher bulk density, and better durability than the pellets from unsieved wood flour. Red maple pellets had the lowest moisture content (0.12%) and the highest bulk density

(738 kg/m³). The results concluded that the processing of residues into wood flour and then into pellets reduced the moisture content by 76.8% and increased the bulk density by 747%. These material property parameters are an important attempt to provide information that can facilitate the more cost-efficient transportation of wood residue feedstocks over longer distances.

2.2 Introduction

Many forest-based industries, including sawmills and turning mills, produce residues often termed “secondary processing mill residues”. Secondary processing mill residues are the remnants after timber has been utilized in the wood mills for the processing of primary products such as lumber. Secondary processing residues are usually clean, uniform, on-site and low in moisture content and can be prepared for further utilization. Some of the examples include sawdust, planar shavings, small chips, etc. They have several direct or indirect applications such as the production of heat and energy, as the raw material for particleboard, pellets or char, for agricultural use (livestock bedding), and landscape applications. In the US, the volume of wood residues generated in 2019 was 15,288,915 m³ and the volume of wood chips and particles was 46,355,003 m³ (FAO 2019). The state of Maine generates around 1.6 million tons of green residues from the wood mills each year. Maine produces roughly 800 million board feet of lumber, from which roughly 800, 000 tons of clean chips and 800, 000 tons of bark and sawdust are produced (Butler 2018). Kingsley 2017 has mentioned, as a decent rule of thumb, that for every 1000 board feet of lumber produced, 2 tons of residues are produced, out of which 1 ton is clean chips (free from bark, adhesives, metals, microorganism attack, etc.).

One of the applications of mill residues can be grinding them into a powder form referred to as “wood flour” or “wood fiber”. Wood flour is a finely ground wood cellulose. It is a highly

comminuted wood material with a very fine particle size distribution typically produced from mill residues using several grinder types and sized by mechanical or air screening methods (Reineke 1966). Wood flour is composed of fine particles passing through a screen with 850-micron openings or 20 US standard mesh (Reineke 1945). Such reduced particle sizes can be achieved by fine grinders (e.g., hammermill, disc refiner, pin mill or chain mill). The reduction in biomass size changes the particle size and shape, increases bulk density, improves flow properties, increases porosity, and generates new surface area (Drzymala 1993, Bitra et al. 2009). Compared to the other grinding mills, hammer mills have an advantage because of their ability to finely grind a greater variety of materials (Scholten 1985). Nominal biomass particle sizes produced by hammer mill grinding depend on the processing characteristics of the mill. The two material variables that distinguish wood flour are the species and size (Stark and Berger 1997). High-quality wood flour can be made from hardwoods attributable to their durability and strength. Commercial production of wood flour started in 1906, and the first commercial product from wood flour was a gear shift knob for a Rolls Royce automobile in 1916 (Gordon 1988). Wood flour uses can be grouped into absorbent, chemically reactive substances, chemically inert fillers, modifiers of physical properties, mildly abrasive materials, and decorative materials. Species mostly preferred for wood flour production include white pine (eastern, western and sugar pines), aspen, spruce, hemlock and, to some extent, balsam fir, paper birch, and the southern pines. In the US, 75% of wood flour is manufactured from white pine. The greatest application of wood flour is its utilization as lignocellulosic fiber for reinforcing plastics. Wood filler is compounded into the polymer matrix to enhance the properties of the polymer to behave more similarly to wood than a polymer. Wood-plastic composites (WPCs) have significant

advantages from material, environmental, and economic perspectives (Kim and Pal 2010, Kutnar and Muthu 2016, Rangappa et al. 2021).

Similarly, the other application of mill residues can be as a source of raw material for manufacturing pellets. Sources of raw materials for wood pellets include fallen branches, thinning and broken stems from the forest, and residues generated in sawmills such as sawdust, chips, etc. Wood pellets are 0.5–3 cm long and cylindrical (6–8 mm) compressed materials produced in pellet mills under high pressure (≈ 300 MPa) and high temperature (≈ 120 °C) (Nielsen et al. 2010)]. Compression of the biomass or residues into pellets involves elastic and plastic deformation of particles and softening of natural binders such as starch, protein, lignin, fats and fibers for binding the particles together (Gilvari et al. 2020). The type and amounts of extractives contribute to the fundamental difference between the softwood and hardwood pellets (Nielsen et al. 2009). According to Calderon et al. 2019, the utilization of wood pellets throughout the world has increased from approximately 12 million metric tons in 2008 to 56 million metric tons in 2018.

Transportation of wood flour is conducted using multi-walled paper bags (approximately 23 kg or 50 lbs) or bulk bags (typically 1.5 cubic meters or 55 cubic feet) or by bulk trailers (Drzymala 1993). Wood flour, being a low-density fluffy material, occupies less bulk weight for transportation. Considering shipment to the point of destination, the cost is often more than that for sawdust (Reineke 1945). Wood flour transportation over longer distances can incur excess shipping costs as compared to the material price. Compared to other biomass fuels, pellets are easy to handle, store and transport (Proskurina et al. 2016). Wood pellets, compared to other fibrous materials of wood and solid biofuel materials, have an increased energy output per unit volume (Thraen et al. 2017). The average bulk density of wood flour is 190–220 kg/m³ or 12–14

lb./ft³ (Clemons 2010) and the bulk density of wood pellets is 700–750 kg/m³ or 43–47 lb./ft³ (Tumuluru et al. 2010). This comparative study shows that the average bulk density of wood pellets is four times greater than wood flour, which suggests the storage footprint area for wood pellets is reduced by four times.

Very little information is available in the literature and technical sources regarding the secondary processing mill residues and their applications. On the other hand, there is no recent research on wood flour production from mill residues and its properties' characterization. Studies on wood flour production are quite outdated (Reineke 1945, Tumuluru et al. 2010). This suggests there is a wide gap to find current research on wood flour production. Nevertheless, a comparative study of the properties of wood flour based on different wood species and various mesh size level is still lacking. Literature regarding the applications of mm dimension residues on the pelletization of wood pellets is abundant. However, fine micron scale wood fibers being processed into pellets is limited in the scientific literature. There has been considerable research on WPC manufacturing using wood flour and studies on its properties, but only limited work has been reported on WPC manufacturing using wood pellets. Butylina et al. 2011 reported on the comparative properties of WPCs using wood flour, wood pellets and heat-treated fibers in a polypropylene matrix. This study is focused on comparing wood flour and wood pellets with the overall goal of reducing the transportation costs of wood fillers for WPC manufacturing.

In addressing all the above-mentioned motives, one of the objectives of this study is to produce wood flour using the clean mill residues in Maine and characterize its properties. The characterization, i.e., the study of the morphology, moisture content, bulk density, particle size distribution and aspect ratio of the wood flour from each of the four Maine species (Northern White Cedar, Eastern White Pine, Spruce-Fir and Red Maple) can help better understand their

specific properties. The second objective is the application of fine wood flour from each wood species in the manufacturing of wood pellets, and the studying of its properties. Finally, a comparative analysis of the mill residues, flour and pellets, focusing mostly on the parameters that affect production and transportation, i.e., in terms of moisture and density, is carried out. This study hopes to convey how each processing step causes a change in these material parameters. We expect this study will be a baseline study for future work on wood and polymer composite manufacturing from different raw materials in an attempt to gain maximum manufacturing efficiency.

2.3 Experimental Procedures

2.3.1 Materials

Mill residues of around 100–150 kg typical planar shavings, sawdust, and small chips were obtained from local wood mills in Maine. Northern White Cedar (*Thuja occidentalis*) (Katahdin Forest Products, Oakfield, ME, USA), Eastern White Pine (*Pinus strobus*) -(Hancock Lumber, Pittsfield, ME, USA), Eastern Spruce-Balsam Fir (*Picea rubens-Abies balsamea*) (Pleasant River Lumber, Dover-Foxcroft, ME, USA) and Red Maple (*Acer rubrum*) -(Lumbra Hardwoods, Milo, ME, USA) were obtained through on-site visits. Figure 2.1 below presents the images of secondary processing mill residues of four different wood species in the study area. The scale bar is 3 cm in length. These residues were clean and free from bark, adhesives, metals, etc., and were either air-dried or kiln-dried. These residues were utilized to manufacture wood flour and then wood pellets. The raw material for manufacturing wood pellets, i.e., wood flour, was produced in the lab.

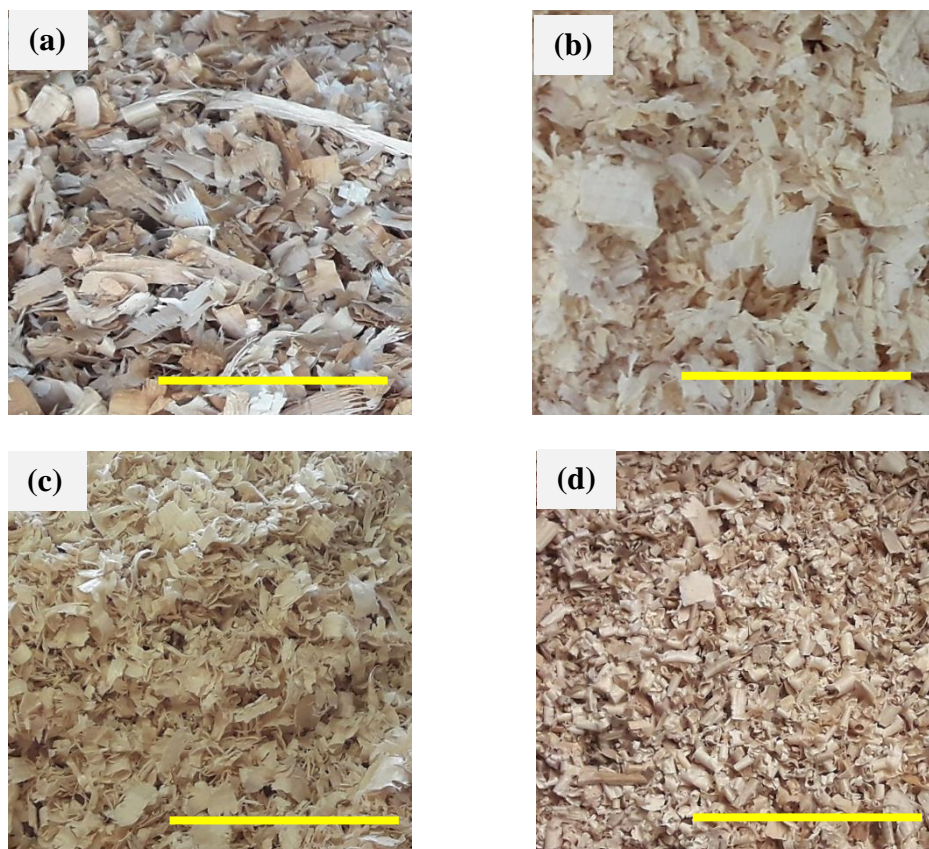


Figure 2.1 Mill residues of (a) White Cedar (b) White Pine (c) Spruce-Fir (d) Red Maple.

2.3.2 Manufacturing process of wood flour and wood pellets

A Bliss Eliminator Hammermill (Bliss Industries LLC, Ponca City, OK, USA) with a screen size of 0.5 mm was used to produce wood flour. The residues were manually fed into the hopper of the hammermill separately for each species. The faces, edges, and corners of the hammers cut and shattered the material and threw it forcibly against the casing. Further size reduction took place in the layers of the material retained on the screen. The wood flour was then removed from the collection box. A Gilson screen shaker (Gilson Company Inc., Worthington, OH, USA)) was then used for screening the wood flour fractions into 20, 40, 60, 80, and 100

mesh sizes to study different characteristics of the wood flour, including morphology and other physical properties.

Usually, for the manufacturing of wood pellets that have other applications, for example, as biofuels, raw materials of up to 2 mm in size are preferred. However, in our experiments, the particle sizes were smaller ($<500\text{ }\mu\text{m}$). Several literature sources describe material characteristics, processing methods, and production parameters for wood pellet production (Kaliyan and Morey 2009, Peksa-Blanchard et al. 2007, Wilson and Buffington 2010). For each species, two categories of wood pellets, one with unsieved flour and the other with a 40-mesh size fraction, were used for the manufacturing of pellets. The wood pellets were pelletized at the Technology Research Center (TRC) in Old Town, ME, USA. A Lawson Mills Pellet Mill LM72A (Lawson Mills Biomass Solutions Ltd., North Wiltshire, PE, Canada) was used for the production of wood pellets. An integrated fines removal system captured fines for recycling. This machine allows up to two additives for binding. Even though the capacity of the pelletizer depends on the raw material, this machine processes as much as 160 kg of materials per hour. The ground wood flour from the hammer mill had a relatively low moisture content as compared to the requirement for pelletizing into pellets; therefore, water was added and mixed manually to ensure the equal distribution of moisture throughout the wood flour. Depending on the wood species, the moisture content of the wood flour was maintained between 10 and 15%. Maciejewska et al. 2006 mentioned that the wood particles must be brought to the moisture content of 12–17% of weight by volume as required by the pellet press. Under high temperature and pressure, the wood flour was fed into a pellet mill and forced through a round opening called a “die” of quarter-inch thickness where the flour is compacted to form a solid mass of pellets. The high temperature in the machine allows the lignin in the wood to heat and this acts as a

binder for the formation of pellets (Guo et al. 2015). Van der Waals electrostatic force or hydrogen bonding contribute to the process of pellet formation (Schineberger 1971, Tumuluru and Wright 2010). The wood pellets were then allowed to cool.

2.3.3 Characterization of mill residues, wood flour, and wood pellets

The moisture content of the mill residues, hammer mill grindings and screened wood flour, as well as of the wood pellets, was determined for each species. The American Society of Testing and Materials (ASTM) Standard D4442–20 Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials (ASTM international, West Conshohocken, PA, USA) was followed. Moisture content, according to ASTM D9–20, (ASTM international, West Conshohocken, PA, USA) is the amount of water contained in the wood, usually expressed as a percentage of the mass of the oven-dry wood. The oven-dry method was followed where the samples were kept in the oven for 24 h at 103 ± 2 °C. The moisture content of the samples was calculated using the following formula:

$$\text{Moisture content (\%)} = \frac{\text{Original mass} - \text{Oven dry mass}}{\text{Oven dry mass}} \times 100 \quad (2.1)$$

Similar to moisture content, the bulk density was also measured for the mill residues, hammer mill grindings, screened wood flour, and wood pellets. The ASTM E873–82 Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels (ASTM International, West Conshohocken, PA, USA) was followed. Bulk density is the mass per unit volume of loose materials, powders and other divided “solids” at specified moisture content levels. A wooden cube of volume $1/4 \text{ ft}^3$ (7079 cm^3) was taken and weighed to record its weight. Then, the samples were poured with at least 5 droppings of the box from a height of 150 mm to ensure

enough settling of the samples at the bottom and filled up to a pre-determined line as marked.

The formula to determine the bulk density is:

$$\text{Bulk Density (kg/m}^3\text{)} = \frac{\text{Weight of cubical box sample} - \text{Weight of cubical box}}{\text{Volume of cubical box}} \quad (2.2)$$

A Zeiss NVision 40 Scanning Electron Microscope (SEM) (Carl Zeiss Microscopy, LLC, White Plains, NY, USA) with a capacity of up to 1.2 nm resolution was used to observe the morphology of each mesh size fraction of wood flour for each species. The wood flour samples were sputter-coated with an Au/Pd conductive layer before the SEM observations. The thickness of the Au/ Pd coating was 6 nm. Since the particle size of wood flour is comparatively bigger for observation using SEM images, the magnification of the images was 50 \times and with a surface area of 100 μm in a high vacuum 3.56×10^{-6} Torr; the electron source voltage was 3 kV.

A Ro-Tap Shaker (Retsch Inc., Newton, PA, USA) was used for the particle size analysis of the wood flour. The American National Standards Institute/American Society of Agricultural Engineers (ASAE) S319.4 Method of Determining and Expressing Fineness of Feed Materials by Sieving (ASAE, St. Joseph, MI, USA) was followed. The geometric mean diameter or medium size of particles by the mass, geometric standard deviation of log-normal distribution by mass in ten-based logarithm, and geometric standard deviation of log-normal distribution by mass in natural logarithm were calculated based on the standard.

Similarly, the aspect ratio, which is the ratio of the images' width and height that describes the particles' shape, was calculated for each mesh size of each species. The small sample of each fraction/mesh size of the wood particles was placed on the black background

with a scale and the image was taken through a digital camera. Image J software was used to express the average aspect ratio. The formula for the calculation of the aspect ratio is:

$$\text{Aspect ratio of wood flour} = \frac{\text{Major axis}}{\text{Minor axis}} = \frac{\text{Width}}{\text{Height}} \quad (2.3)$$

The pellet dimensions were determined using a Vernier caliper (Master Gage and Tool Co., Danville, VA, USA). The diameter and length of the pellets were determined. For diameter, two types of measurement, one normal and the other with the angle of 90° of the previous measurement, was taken. Five wood pellets for each sample were taken randomly and the average value was calculated. Similarly, to determine the Pellets Durability Index (PDI), ASAE S269.4 (ASAE, St. Joseph, MI, USA) was followed. A durability tester/tumbler (Seedburo Equipment Company, Des Plaines, IL, USA) was used in the experiment and the formula to calculate PDI is:

$$\text{PDI} = \frac{\text{Mass of pellets retained on the } \frac{1}{8} \text{ inch sieve after tumbling}}{\text{Mass of pellets before tumbling}} \times 100\% \quad (2.4)$$

To measure the ash content of the wood pellets, a thermo-gravimetric analyzer (TGA) 701 from LECO Corporation (St. Joseph, MI, USA), with an operating voltage of ~230 V, was used. To control the atmosphere inside the furnace, pneumatic gas supply/air of 3.10 bars was set up. The allowable temperature range in the TGA was 25–1000 °C. A maximum of 19 samples could be analyzed per batch. To be used in TGA, the wood pellet samples were powdered and loaded in a crucible. After 24 h, the value of the ash content was recorded on the computer system connected to the machine (1.2x TGA701, LECO Corporation, St. Joseph, MI, USA).

2.3.4 Statistical Analysis

A one-way Analysis of Variance (ANOVA) with a 0.05 significance level was used to determine the significant differences in the means of two or more variables. The statistical association of wood species and mesh size with the bulk density, moisture content and aspect ratio of the wood flour was analyzed. Here, wood species and mesh size are the independent variables whereas bulk density, moisture content and aspect ratio are the dependent variables. Tukey's test was performed as post-hoc analysis, whenever applicable, to figure out which groups in the sample differ more or less.

2.4 Results and Discussions

2.4.1 SEM images of wood flour

Figure 2.2 shows the SEM micrographs of the 40-mesh size wood flour for each of the four wood species in the study. Images were taken at 50× magnification and a scale bar of 100 µm. SEM images of 18, 35, 60, 80, and 100 mesh sizes of wood flour, for each of the species, are shown in Figure A.1 in Appendix A. Compared to Cedar and Maple wood flour, the flour of Pine and Spruce-Fir was finer. Softwoods are flexible, whereas hardwoods are stiffer; furthermore, the chemical compositions between these species can contribute to the differences observed (Zazyczny and Matuana 2005). Despite being a softwood, wood flour fibers of Cedar appeared thicker and less fractured than the wood flour of Pine and Spruce-Fir. The presence of extractives in Cedar could cause some lubricity during processing, thus contributing to the observations of thicker fibers. The wood flour particles appear as layered tube wood-like structures (Yin and Hakkarainen 2014, Pfaendner and Melz 2020). The production of wood flour results in fiber bundles rather than individual fibers (Matuana and Stark 2015). Depending on the species, differences can be observed in the appearance of the flour particles. Maple flour appears with a

smoother surface than the other wood species particles. In general, softwood flour fibers are long and thin, which is attributable to the abundance of longitudinal tracheids. Hardwood fibers are short and thick, which is attributable to the abundance of radial and axial cellular components. Because of this, the softwood wood flour appears rougher compared to the maple flour in the SEM images. Even though sieving was performed for a considerable length of time, it was difficult to obtain the diameter of the particles equal to the mesh size (Chaudemache et al. 2018). This results discrepancies in the diameters of the particles for the same mesh size.

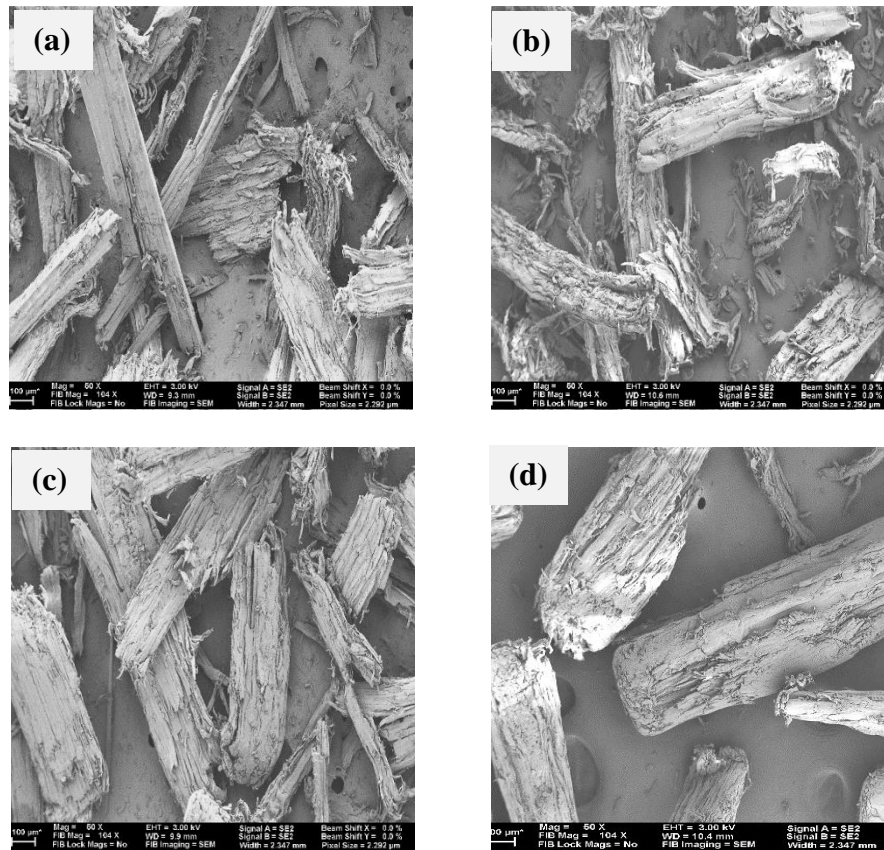


Figure 2.2 SEM images of wood flour: (a) Cedar 40-mesh, (b) Pine 40-mesh, (c) Spruce-Fir 40-mesh, (d) Maple 40-mesh.

2.4.2 Physical properties of wood flour

Two parameters of wood fillers addressed in the study of WPC material properties are the wood species and mesh size (Khonsari et al. 2015). Figure 2.3 is a graphical representation of the relationship between mesh size and moisture content as well as mesh size and bulk density. Compared to other wood species, the moisture content of cedar flour was highest (8.4%), with spruce-fir being the lowest (5.4%), and the bulk density of maple flour was highest (268 kg/m³), with pine flour (142 kg/m³) being the lowest. In the case of softwoods, the moisture content of the flour is proportional to the moisture of the residue feedstock. Wood moisture content is an important controlling parameter in the manufacturing of WPCs as a moisture level above 1% can cause the composite to foam in the extruder, i.e., produce microvoids of irregular and heterogeneous shapes (Rizvi et al. 2000, Matuana and Mengeloglu 2002).

A one-way ANOVA test was run to determine the association of mesh size with moisture content and bulk density. From the statistical test, it was observed that the type of wood species had an association with the moisture content and bulk density of the wood flour. Similarly, the test showed there is no significant difference in the values of moisture content and bulk density with the change in mesh size of the wood flour. However, for all species, comparatively, the 80-mesh flour had the highest moisture content and 40-mesh the lowest moisture content. Similarly, the bulk density of 40-mesh wood flour was highest and of 80-mesh the lowest for all species. This shows there is an inverse relationship between moisture content and bulk density among different mesh sizes of wood flour. Patterson 2001 mentioned that wood filler size between 40 and 80 mesh is the easiest to work with in the manufacturing of WPC products. The abnormality

in the behavior of the moisture content and bulk density of wood flour larger and finer than 40 and 80 mesh, respectively, could also be a contributing reason.

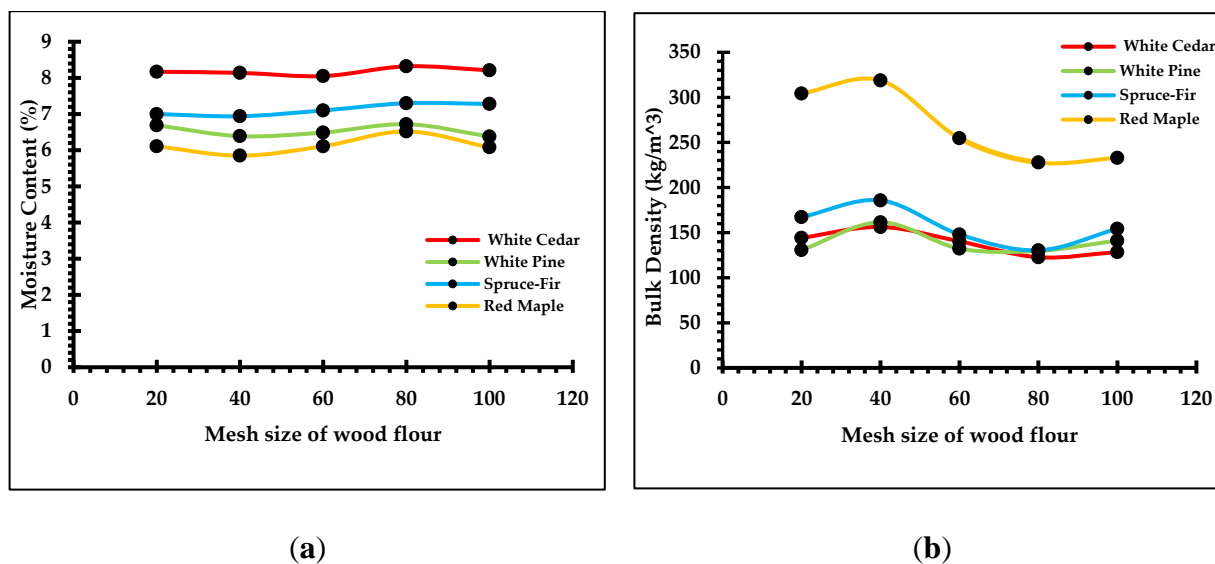


Figure 2.3 Graphs of (a) change in moisture content with mesh size, and (b) change in bulk density with mesh size.

Table 2.1 lists the results of the wood flour particle size distribution analysis. Wood particle size distribution has a great role in the properties of WPCs and the study of particle size distribution on properties has produced different conclusions by different researchers (Tumuluru and Wright 2010). From Table 2.1, it is shown that 68% of the particles are within the range of d_{gw} for 16th and 84th percentile. Even though the same screen size of 0.5 mm was used in the hammer mill for grinding the residues, the mean geometric diameter of the wood flour particles was different among the different species. Spruce-fir wood flour had the smallest sized particles, with a geometric mean diameter of 0.18 mm, and pine flour had the largest sized particles (0.25 mm) compared to the other species. The geometric standard deviation of the diameter of pine flour particles was 0.10 mm, which was the lowest among the different wood species. This might be attributable to the utilization of commercial kiln-dried pine residues in the hammermilling

process, which were highly uniform and clean. The fineness of the wood flour particles depends somewhat on the raw material and the manufacturing process used (Drzymala 1993). The resulting particle sizes obtained through the hammermill process vary widely, which is attributable to the hammer speed, the extent of wear on the hammer and screen, screen area, air flow, method of discharge, kind of raw material, moisture content of the raw material, etc. (Baker 1960, Wilcox et al. 1970).

Table 2.1 Particle size distribution analysis of wood flour for different wood species.

Species Type	Geometric Mean Diameter (d_{gw}) in mm	d_{gw} for 84th Percentile in mm	d_{gw} for 16th Percentile in mm	Geometric Standard Deviation (S_{gw}) in mm	Log-Normal Geometric Standard Deviation (S_{log}) in mm
White Cedar	0.22	0.03	1.84	0.12	0.23
White Pine	0.25	0.03	2.56	0.10	0.17
Spruce-Fir	0.18	0.02	1.57	0.11	0.26
Red Maple	0.21	0.03	1.52	0.14	0.27

Figure 2.4 is the graph of aspect ratio for the different mesh sizes of wood flour for each species. Aspect ratio is an important characteristic of wood flour that affects the material properties of WPCs. Typically, the aspect ratio falls in the range of 1 to 5 for wood flour (Tumuluru et al. 2010, Hietala et al. 2011). In this study, the aspect ratio was in the range of 2 to 3.5. The aspect ratio of commercial pine flour is 3.3 to 4.5 (Stark and Rowlands 2003). From a one-way ANOVA, a correlation among wood species and aspect ratio, as well as mesh size with the aspect ratio values, was not apparent. Similar to statistical results, the graph in Figure 2.4 shows certain variation in the aspect ratio values for different mesh sizes of different wood species. The aspect ratio, to some extent, is dependent on the grinding methods, moisture mass fraction, and wood species (Karinkanta et al. 2018). The same authors mentioned that, in general, there is decrease in aspect ratio with the decrease in the particle size of wood. On average, the

18–40 mesh size flour appears to have the highest values of aspect ratio for all species and 100 mesh has the lowest value. From the post-hoc analysis, it was observed that, compared to other mesh sizes, 100 mesh has the greatest association with aspect ratio. This implies that, for all species, 100-mesh size has the smallest value of aspect ratio. However, it should be noted that obtaining pure mesh size flour fractions from the sieving process is an arduous task.

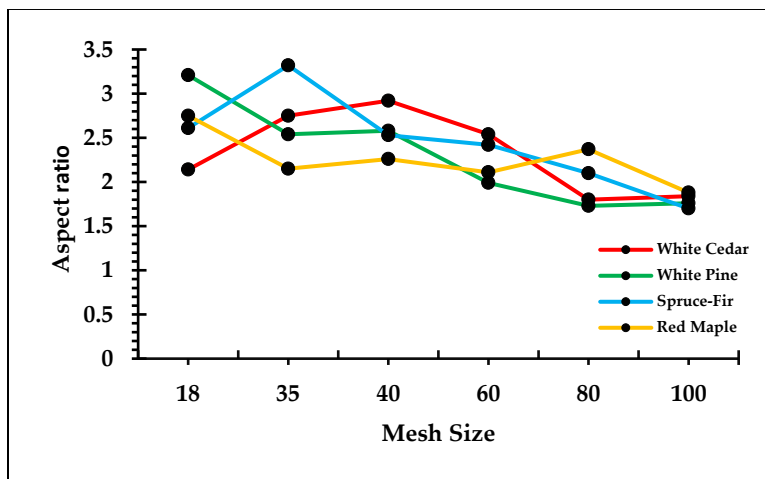


Figure 2.4 Relation of aspect ratio with different mesh sizes.

Figure 2.5 shows how the moisture content and bulk density changes with the processing steps of mill residues into flour and then into pellets. On average, when the residues are ground into wood flour, the moisture content is reduced by 54%, compressing wood flour into pellets reduced moisture content by 52.3%, and overall, when processing residues into pellets, moisture content is reduced by 76.8%. On average, the moisture content of residues was 2.2 times higher than the wood flour, and wood flour had 3.2 times higher moisture content than the pellets. The moisture content of residue feedstock was 7.4 times greater than that of the pellets. This change in moisture content was significant for cedar, contributing a reduction in moisture content of around 94% in the manufacture of pellets. This might be because of the higher extractives and lignin in cedar contributing to higher adhesion and bonding to form pellets. Bardfield and Levi

1984 reported a decrease in wood pellet quality when lignin together with extractive content increases above a threshold level of 34%. Chen et al. 1989 also observed the increase in bonding and overall pellet strength with the higher percentage of extractives and lignin. Converse to moisture content, the bulk density increases, which is attributable to processing from residues to flour to pellets. On average, when grinding residues into wood flour, the bulk density increased by 119%, converting from flour to pellets, the bulk density increased by 276%, and, on converting residues into pellets, the bulk density increased by 747%. In other words, the bulk density of wood flour was 2.2 times greater than that of residues, that of pellets was 3.8 times greater than that of flour, and then that of pellets was 8.5 times greater than that of the residues. The change in bulk density was significant for pine, contributing an increase of around 1075% in the bulk density of pellets compared to the residue feedstock. This might be attributable to the utilization of fluffy compressed kiln dried commercial residues of pine with a lower bulk density than the other species. Thus, on average, the moisture content of pellets was 3.2 times less and the bulk density 3.8 times greater than for the wood flour. Mani et al. 2006 suggested the size of raw materials has an inverse relation in the bulk density of pellets, i.e., smaller particles produce pellets with higher density because of the larger particle surface area, and vice-versa. However, Bergstrom et al. 2008 showed almost equal densities of the pellets irrespective of the variation in particles sizes of the raw feedstock materials.

2.4.3 Change in moisture content and bulk density on processing mill residues to wood flour and then pellets

In Table 2.2, the physical properties of the wood pellets manufactured using 40-mesh wood flour and unsieved wood flour are presented. In most cases, the ash content of hardwood

pellets is around three times greater than those manufactured from softwoods. However, we observed that cedar pellets have a greater ash content than the maple pellets, which is attributable to the presence of higher extractives in the heartwood of cedar. Since a quarter-inch die was used in the pelletizing process, the diameter of the pellets is near to the value. The length of the produced pellets had a greater range of sizes. Compared to the normal greater size of raw materials used in the pelletizing process, the particle size of the raw materials in this study was smaller, which might be the main reason influencing the variation in dimensions of the pellets, i.e., basically the length. Samuelsson et al. 2012 observed a smaller correlation between the pellet length and the bulk density. However, they observed higher correlation in the effect of moisture content of raw materials to the pellet length. On the other hand, the durability of cedar and pine pellets was highest, which represents higher bonding of the materials in these pellets. The authors of (Tumuluru and Wright 2010, Kaliyan and Morey 2009) reported moisture in the biomass, to a certain limit (<23%), which acts as a binder during pelletization. Cedar and pine particles had higher moisture content than the rest of the two wood species, which might have contributed to higher bonding of the materials.

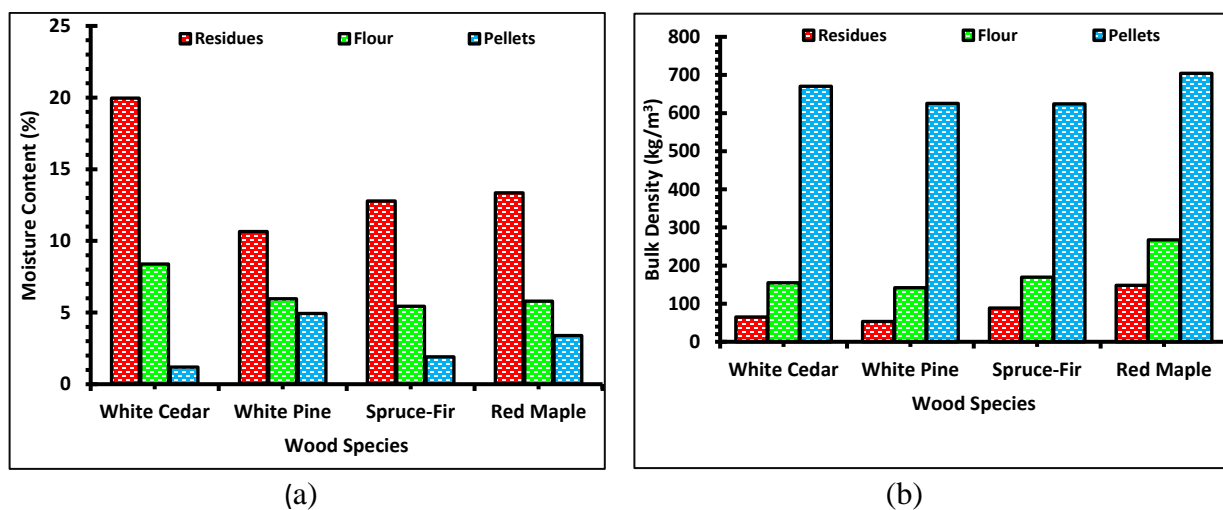


Figure 2.5 Plots of (a) change in moisture content with wood processing steps, and (b) change in bulk density with different wood processing steps.

2.4.4 Physical properties of wood pellets

The images of wood pellets using 40-mesh size wood flour raw material are shown in Figure 2.6. Each of the scale bar is 3 cm in length. The production process of wood pellets from softwood wood flour was easier. For maple, during the pellet manufacturing from the wood flour, a large number of fine particles were generated in the waste collection chamber relative to the softwoods. Less desirable chemical composition of the particles is one of the important causes behind the higher generation of fines (Tumuluru and Wright 2010). This might be attributed to the lower lignin content in maple that reduces binding of the particles and induces higher friction during pelletization (Thiffault et al. 2019). Some of the past researchers: Chen et al. 1989, Holm et al. 2006 have mentioned that producing pellets from hardwood raw materials is arduous attributable to higher frictional forces in the compression channels of the die compared to the softwoods, leading to blockage of the pellet mill. On the other hand, researchers such as Thiffault et al. 2019 have suggested that, under adequate conditioning and pelletizing, hardwood residues can still be processed into pellets. In our experiment, pellets from maple were manufactured successfully. However, there was significant production of fine particles during the manufacturing process. The type and amount of extractives contributes to the fundamental differences between hardwoods' and softwoods' pelletizing properties (Ekman 2000). Extractive content influences the pelletizing process and pellets' quality (Samuelsson et al. 2012, Gilvari et al. 2020). The role of lignin plasticization when the biomass is processing has been studied by several authors. The authors: Back 1987, Bouajila et al. 2005 are some of those who suggested that, as the temperature increases, lignin becomes more flexible, thus increasing the flow of molecules. This results in the enhancement of surface contact between particles, enabling the inter-penetration of polymer chain ends and segments between adjacent fibers. Consequently,

new secondary bonds and entanglements are established once the polymer is cooled down below the glass-transition temperature of lignin. In a comparative study of the properties of pellets produced using unsieved wood flour and 40-mesh wood flour, it was observed that using the fractionated 40-mesh wood flour produced better quality pellets than the unsieved wood flour. This might be attributable to the greater uniformity of the particle size distribution of the fibers for the fractionated 40-mesh flour. The uniform size of the particles is also responsible for the smooth appearance of the wood pellets, which increases ease of storage and transportation.

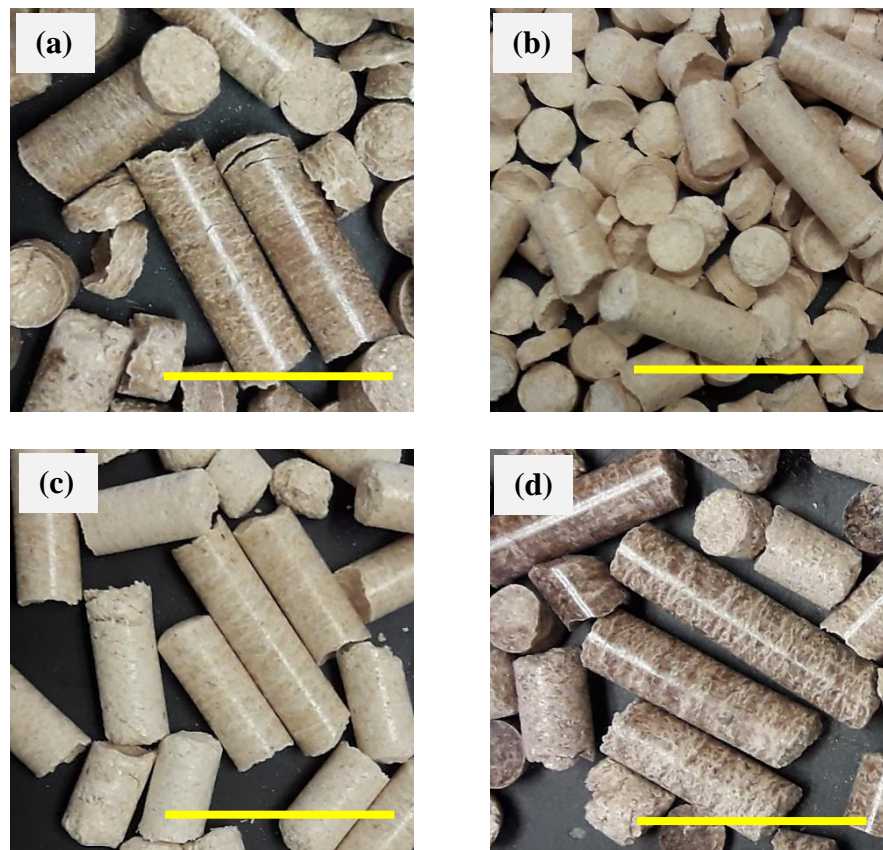


Figure 2.6 Wood pellets manufactured from 40 mesh wood flour: (a) White cedar, (b) White pine, (c) Spruce-fir, (d) Red maple.

Table 2.2 Various properties of wood pellets pelletized from unsieved and 40-mesh flour.

Wood Species	Moisture Content (%)	Bulk Density (kg/m³)	Ash (gm)	Avg. Diameter (inches)	Avg. Length (inches)	Avg. Range of Length (inches)	Durability (%)
White Cedar (unsieved)	1.19	670	0.53	0.24	0.40	0.16–0.67	95
White Cedar (40 mesh)	2.67	699	0.45	0.24	0.40	0.14–0.73	97
White Pine (unsieved)	4.94	625	0.18	0.24	0.35	0.12–0.60	93.8
White Pine (40 mesh)	4.12	634	0.19	0.24	0.40	0.14–0.73	97
Spruce-Fir (unsieved)	1.91	624	0.32	0.24	0.48	0.19–0.93	75.8
Spruce-Fir (40 mesh)	2.57	671	0.28	0.23	0.46	0.17–0.84	82.5
Red Maple (unsieved)	3.39	705	0.41	0.24	0.49	0.17–0.93	67.2
Red Maple (40 mesh)	0.12	738	0.44	0.23	0.48	0.17–0.95	83.8

2.5 Conclusions

- On average, when grinding residues into wood flour, moisture is reduced by 54%, pressing wood flour into pellets reduces moisture by 52.3%, and overall, when processing residues to pellets, moisture content is reduced by 76.8%. A decrease in moisture content is a critical factor from a transportation perspective.
- On average, the bulk density increased by 119% on the comminution of residues into wood flour, it increased by 276% when converting wood flour to pellets, and, when converting residues into pellets, this value increased, on average, by 747%. An increase in bulk density is an important factor from a transportation point of view.
- Compressing fine wood flour into pellets produced pellets with a higher range in terms of dimensions, and this value varied based on species in the study.

- It was found that 40-mesh fractionated wood flour produced better quality pellets than the unsieved wood flour.
- It is challenging to obtain the pure fractionated mesh sizes of the wood flour in terms of dimensions and aspect ratio even after sieving for a longer period of time. Because of the tendency of fibers with different mesh sizes to exhibit different physical properties, it is difficult to find direct relationships between material properties.

CHAPTER 3

PROPERTIES OF WOOD-PLASTIC COMPOSITES MANUFACTURED FROM TWO DIFFERENT WOOD FEEDSTOCKS: WOOD FLOUR AND WOOD PELLETS

3.1 Chapter Summary

Driven by the motive of minimizing the transportation costs of raw materials to manufacture wood–plastic composites (WPCs), Chapter 2 and the current Chapter 3 of this thesis explore the utilization of an alternative wood feedstock, i.e., pellets. Chapter 2 of this study reported on the characteristics of wood flour and wood pellets manufactured from secondary processing mill residues. Chapter 3 reports on the physical and mechanical properties of polypropylene (PP)-based WPCs made using the two different wood feedstocks, i.e., wood flour and wood pellets. WPCs were made from 40-mesh wood flour and wood pellets from four different wood species (white cedar, white pine, spruce-fir and red maple) in the presence and absence of the coupling agent maleic anhydride polypropylene (MAPP). With MAPP, the weight percentage of wood filler was 20%, PP 78%, MAPP 2% and without MAPP, formulation by weight percentage of wood filler was 20% and PP 80%. Fluorescent images showed wood particles' distribution in the PP polymer matrix was similar for both wood flour and ground wood pellets. Dispersion of particles was higher with ground wood pellets in the PP matrix. On average, the density of composite products from wood pellets was higher, tensile strength, tensile modulus and impact strength were lower than the composites made from wood flour. Flexural properties of the control composites made with pellets were higher and with MAPP were lower than the composites made from wood flour. However, the overall mechanical property differences were low (0.5–10%) depending on the particular WPC formulations. Statistical analysis also showed there was no significant differences in the material property values of the

composites made from wood flour and wood pellets. In some situations, WPC properties were better using wood pellets rather than using wood flour. We expect if the material properties of WPCs from wood flour versus wood pellets are similar and with a greater reduction in transportation costs for wood pellet feedstocks, this would be beneficial to WPC manufacturers and consumers.

3.2 Introduction

With global awareness in addressing environmental impacts and minimizing the emission of harmful pollutants, the wood composites industry is seeking more environmentally friendly materials for their products. With the utilization of recycled plastics and waste wood-based fillers, wood plastic composites (WPCs) manufacturing can be considered a green technology (Borah 2016). The concept of WPCs is not new where its modern application began in the 1970s and since the 1990s, the popularity of WPCs in North America has increased in decking and railing production (Gardner et al. 2015). WPCs are any composite products manufactured using plant (wood or non-wood) fibers, thermoplastic or thermoset resins and a small number of additives. WPCs offer the advantages of enhancing mechanical properties with higher strength and stiffness, decreases in density and abrasion compared to inorganic filler composites (Bledzki and Gassan 1999, Malkapuram et al. 2009, Braghiroli and Passarini 2020) and compared to solid wood, higher water and decay resistance, better acoustic performance, reduced weight, lower production costs and biodegradability (Wolcott and Muszynski 2008, Thompson et al. 2010). They have wide applications in the automotive, and construction industrial sectors.

In general, the processes followed in manufacturing WPCs are: extrusion, injection molding, and compression molding or thermoforming (pressing) (Gardner et al. 2015). Similarly, the newer production technologies are additive manufacturing processes based on extrusion processes and with laser sintering (Wendel et al. 2008, Gebhardt 2011, Jiang et al. 2013, Ibrahim et al. 2014, Gardner et al. 2015). WPC compounding can be performed in an extruder (single-screw extruder, twin-screw extruder, conical twin-screw extruder or a combination type extruder) or high-speed mixers of the Henschel type. A Henschel mixer is a high intensity vertical mixer (causing the materials to move freely regardless of their size, density, friction coefficient, etc.) or melt type (used for making master batches with wax or materials with wax-like properties). Additive manufacturing or 3D printing consists of three general steps: usage of computer-aided design (CAD) to model the part, processing the model in 3D space through the slicing software, and with the G-codes printing and production of the part (Lamm et al. 2020). On an industrial scale, industries that manufacture WPCs either compound all the raw materials, i.e., wood filler, polymers, additives themselves or purchase pre-compounded WPC pellets. In 2019, the global market size of WPCs was USD \$4.77 billion out of which North America (major application in decking) stood highest in market share with USD \$2.12 billion (Fortune Business Insights 2020). Zion Market Research 2017 has predicted that the WPCs global market in 2022 to reach to USD \$8.76 billion in 2022. The expected mean annual growth rate is 12.3% between 2017 and 2022.

Thermosetting plastics cannot be melted repeatedly once cured whereas thermoplastics can be repeatedly melted. Thermosetting resins include epoxy and phenolics whereas polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC) and polystyrene (PS) are the

thermoplastic resins. PP has advantages of cost-effectiveness, lower material weight, better processability, resistance to extreme environmental conditions and reusability. Further, PP-based composites have applications in automotive, packaging and building materials (Harper 2000). Additives such as colorants, coupling agents, stabilizers, blowing agents, reinforcing agents, foaming agents and lubricants can be used based on the target area of application. In North America, commercial WPCs are mostly manufactured from wood shavings, sawdust or wood chips produced from industrial processes (Stark and Rowlands 2003, Ashori 2008, Migneault et al. 2009, Braghiroli and Passarani 2020). Different wood species can be used to manufacture WPCs. To effectively utilize the wood-based fillers in the thermoplastics, a basic knowledge in morphological and chemical characteristics is vital (Stokke and Gardner 2003). Depending on the woody material, different properties of the composite material can be obtained. However, from a commercial standpoint, usually materials that are conveniently available from the supply side are utilized rather than based on the characteristics of the fibers (Tanaka 2014). In Southeast Asia, hemp, ramie, kenaf and so on are mostly used as fillers as they are abundant there. However, in the US, species mostly utilized as fillers are the softwoods such as white pine, spruce, hemlock; and hardwood such as aspen. In general, the size of wood flour for manufacturing WPCs ranges from 1 mm-100 μm (18 mesh-140 mesh). However, the particle size of wood flour most preferable for composite products is in the range of 180–425 μm (40–80 mesh size) (Clemons 2010). Larger filler sizes offer an advantage in terms of cost of pulverization and higher filler content in composite but with the disadvantage of lack of water resistance and difficulties in fabrication during injection molding. Similarly, smaller filler sizes offer the advantages in terms of mechanical properties and durability but disadvantages in terms

of comminution costs and filler contents. The risk of a dust explosion increases for fine powders as well (Tanaka 2014).

Equally important is another aspect focusing on the logistics and supply chain of the product, which is often a major factor deciding the final cost of the end product. Most of the time the manufacturers of WPCs purchase the raw material of wood flour from the wood mills that can manufacture wood flour or other authorized manufacturers of wood flour. As of now, there is no advancement in technology that can compress fluffy wood flour to ship over long distances. Wood flour because of its lower bulk density has a larger volume and standard truck trailers are not able to reach the maximum weight load limits (40 tons). The low density and higher volume of the wood flour make longer distance transportation disadvantageous in terms of cost. Being a fluffy material, its shipment costs over longer distances exceed the actual material price. The higher price in purchasing raw material consequently has a negative impact on the production, distribution, trade, and/or retail sale on manufacturing the WPCs. Motivated by this problem, the current study aims at exploring the utilization of a compacted wood flour, i.e., wood pellets to manufacture WPCs. Then, the physical and mechanical properties of the resulting composite products are studied. Wood pellets are easier to transport and handle as well. Production of wood pellets might have slightly more costs than wood flour. However, a comparative analysis of bulk density of wood flour (190–220 kg/m³) and wood pellets (700–750 kg/m³) reveals that roughly three and half times more wood pellets can be transported in a truck trailer than wood flour by weight. This suggests it is economical to transport wood pellets over longer distances. Very limited articles such as Butylina et al. 2011 have reported the application of wood pellets to manufacture WPCs. However, no research has focused on transportation of raw materials for

WPCs manufacturing in a cost-effective way. The first part of this study presented the results on the characterization of the properties of wood flour and wood pellets produced from secondary processing mill residues (Pokhrel et al. 2021a). Wood flour and wood pellets were made from four different wood species: Northern White Cedar (*Thuja occidentalis*, Eastern White Pine (*Pinus strobus*), Eastern Spruce-Balsam Fir (*Picea rubens-Abies balsamea*) and Red Maple (*Acer rubrum*).

In this Chapter, discussion on WPCs manufactured utilizing wood filler as flour and pellets separately in a PP polymer matrix are presented. Utilizing wood pellets is a novel concept in the commercial manufacturing process of WPCs. Thus, a study of WPCs' physical and mechanical properties through the application of wood flour and wood pellets separately as a raw material source of wood feedstocks are highlighted in this study.

3.3 Experimental Procedures

3.3.1 Materials

For the manufacturing of WPCs, the raw material based on wood, i.e., wood flour and wood pellets were prepared in the laboratory using local mill processing residues in Maine, USA. Part I of this paper series (Pokhrel et al. 2021a) has detailed information on equipment used and processing parameters followed during manufacturing of wood flour and wood pellets. The mill residues were clean (free from barks, adhesives, metals, etc.) and low in moisture content. They were grinded in a hammermill (Bliss Industries LLC, Ponca City, OK, USA) using a screen size of 0.5 mm. The produced wood flour was classified into different mesh sizes. Wood pellets made from 40-mesh wood flour was utilized as a wood feedstock in the manufacturing of WPCs. A

pellet mill (Lawson Mills Biomass Solutions Ltd., North Wiltshire, PE, Canada) with a quarter inch thickness die was used for the production of wood pellets. Wood flour ground in hammermill had a relatively low moisture content. The low moisture of wood flour caused hindrance in the binding of particles to form pellets. Thus, water was added and mixed manually with the wood flour and the moisture content was maintained between 10–15% depending on the wood species. Under high temperature and pressure, pellets were formed from the wood flour. It should be noted that for each of the four wood species, the 40-mesh sized wood flour and the wood pellets pelletized from the 40 mesh-sized wood flour were utilized separately in the composite product manufacturing. Figure 3.1 below shows the 40-mesh wood flour and wood pellets made with 40-mesh flour for each of the wood species. Each scale bar is 2 cm in length. Similarly, Polypropylene (PP) was purchased from ExxonMobil Chemical Company ((Houston, TX, USA) with the melt flow index (MFI) of 20 g/min at 230 °C and a density of 0.900 g/cm³. This nucleated, medium MFI rate homopolymer is suitable for general injection molding purposes. The coupling agent maleic anhydride polypropylene (MAPP) was purchased from the SI Group Inc. (Schenectady, NY, USA) with a MFI rate of 115 g/10 min at 190 °C and density of 0.6 g/cm³. The application of MAPP offers advantage as a compatibilizer and adhesion promoter and thus improving the mechanical properties (Kim et al. 2007).

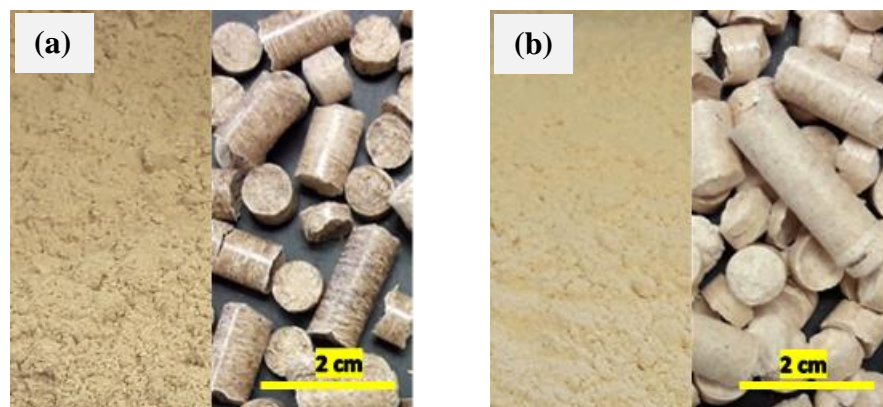


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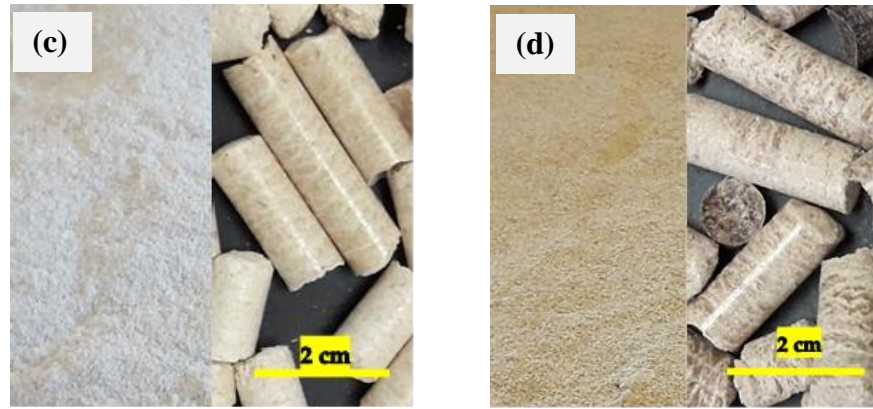


Figure 3.1 Wood flour and wood pellets used as wood feedstock in WPCs (a) Cedar, (b) Pine, (c) Spruce-fir, and (d) Maple. (Image source for wood pellets: Pokhrel et al. 2021a).

3.3.2 Manufacturing process of WPCs

PP-based WPCs using wood fillers of wood flour and pellets separately were manufactured. For each of the wood species, 40-mesh wood flour and wood pellets pelletized from 40-mesh wood flour were utilized. As mentioned in the Introduction section, composites from 40–80 mesh wood fibers show better material properties. Similarly, the decking manufacturers mostly prefer using 40-mesh wood flour. Hence, wood feedstock of 40-mesh flour was utilized in this study. Initially, the wood flour and wood pellets of different wood species were dried in oven at 103 ± 2 °C for at least 24 hours. The moisture content of the wood feedstocks was ensured to be below 1% during the manufacturing process. For each of the wood species, there were four different formulations with different percentages of wood filler, PP and MAPP additives by weight. A total of 16 different formulations were formulated to study the properties of WPCs. Table 3.1 below shows the four types of formulations for each of the wood species with the weight percentages of different raw materials.

Table 3.1 Four different raw materials' formulations of WPCs for each wood species.

Raw Materials	1 st Formulation	2 nd Formulation	3 rd Formulation	4 th Formulation
Wood flour	20%	0%	20%	0%
Ground wood pellets	0%	20%	0%	20%
PP	80%	80%	78%	78%
MAPP	0%	0%	2%	2%

Danyadi et al. 2006 have reported larger wood content in the composite product leads to particle aggregation causing the lower strength of the WPCs so the wood filler of 20% was used. Similarly, Lu et al. 2005 found the maximum values of tensile and flexural strength at 15% and 35 % of wood particles by weight respectively.

For producing the WPCs using wood pellets, the wood pellets before extruding were ground into powder using a knife grinder (C.W. Brabender Instruments, Inc., South Hackensack, NJ, USA) using a screen size of 7.96 mm. It should be noted that the wood pellets discussed in this study represents the ground wood pellets using a knife grinder. The 2nd and 4th formulations, as mentioned in Table 3.1, were applicable on utilizing the wood pellets as feedstock for each of the wood species. After grinding the wood pellets, each component was first mixed manually for the equal mixing of the raw materials. A Brabender Twin Screw Extruder (Messrs. C.W. Brabender Instruments Inc., South Hackensack, NJ, USA) with a diameter of 20 mm, screw length L/D 40, flight depth of 3.75 mm, and screw speed of 150 min⁻¹ was used for the extrusion process. The temperature profile of the extruder was set at 200 °C for the heating zones. The frequency of feeder was 15 Hz. Each formulation was fed to the extruders' feed throat. When the materials start to pass along the barrel, the plastic materials start to melt and results in compounding of the raw materials. The compounded materials are forced through a die to make strands of the composites. When the materials were falling from the feeder at a constant rate, the

feed rate of the different formulations was also measured during extrusion. For this, the raw materials mixture from each formulation were collected in a small container and weighed after one minute. The WPC filaments after allowing them to cool were pelletized in the similar knife grinder (C.W. Brabender Instruments, Inc., South Hackensack, NJ, USA) used in grinding wood pellets using a screen size of 7.96 mm. Once the WPC pellets were ground, the pellets were then dried in oven at $103 \pm 2^\circ\text{C}$ for at least 24 hours before injection molding. Samples were injection molded using a Mini-Jector Injection Molder Model #55E (Miniature Plastic Molding, Solon, OH, USA) with a ram pressure of 17 MPa at 200°C . They were then left in the molds for 10s to cool. Molds used provided the samples with dimensions as specified in ASTM D638-14 (Type I) and ASTM D790-17 for testing of the properties. Before testing, the samples were conditioned for at least 40 h at $23^\circ\text{C} \pm 2^\circ\text{C}$ and $50\% \pm 10\%$ RH. For producing the WPCs using wood flour, the first step followed when using wood pellets filler, i.e., grinding of wood pellets using a knife grinder was not applicable. Besides this step, the other similar processes were followed. The 1st and 3rd formulations seen in Table 3.1 were applicable on utilizing the wood flour as wood feedstock for each of the wood species.

3.3.3 Testing of physical and mechanical properties of WPCs

A Zeiss NVision 40 scanning electron microscope (SEM) (Carl Zeiss Microscopy, LLC, White Plains, NY, USA) and a capacity of up to 1.2 nm resolution was utilized to study the distribution of materials in the WPC samples. A Rotary Microtome (Warner-Lambert Technologies Inc., Buffalo, NY, USA) was used to make the flat and smooth cross-sections of the WPC samples. Coating of the samples was done with an Au/Pd conductive layer of 4 nm thickness before the SEM observations. The images were magnified 100 \times , with a surface area of

100 μm in a high vacuum $2.24 \cdot 10^{-6}$ Torr, and the electron source voltage was 3 kV. The samples were also observed under a fluorescent microscope to observe the distribution more clearly. An Olympus BH2 fluorescent microscope (Olympus Scientific Solutions Americas Corp., Waltham, MA, USA) with a wide blue fluorescent filter: 450–480 nm excitation, mirror 500 nm, barrier filter 515 nm and a CHIU technical Corporation M-100 100W mercury illuminator was used. Samples for fluorescent microscopy were the thin wood polymer films prepared from the same rotary microtome used in making samples for the SEM. SHUR/Mount (Triangle Biomedical Sciences Inc., Durham, NC, USA) was used as a mounting medium and the samples were mounted properly on the coverslip. Thus, the WPC samples for observation in SEM were flat and smooth cross-sections and for fluorescent microscope were the thin films. Both the microscopes used a Zeiss Axiocam ERc 5s camera and Zen Blue software (1.1.1.0, Carl Zeiss Microscopy, LLC, White Plains, NY, USA). Image J software (National Institutes of Health and the Laboratory for Optical and Computational Instrumentation, Madison, WI, USA) was run to study the wood fillers' particle dispersion in the polymer matrix. The area of each particle was calculated using the Image J software. Since the particles had variation in area, the number of particles for each area range (on every 50 square microns) was differentiated.

The American Society of Testing and Materials (ASTM) Standard D792-20 Standard Test Methods for Density and Specific Gravity (relative density) of Plastics by Displacement (ASTM International, West Conshohocken, PA, USA) was followed for determining the density of each sample after injection-molding. For each sample, five specimens were considered for the density testing. The temperature of the water was maintained at $23\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$. Any bubbles

observed were removed. Density was derived from the specific gravity calculation. The formulas to calculate specific gravity and density are:

$$\text{Specific gravity} = \frac{a}{a+w-b} \quad (3.1)$$

where, a is the apparent mass of specimen, without wire or sinker, in air, b is the apparent mass of specimen (and of sinker, if used) completely immersed and of the partially immersed wire in liquid, and w is the apparent mass of totally immersed sinker (if used) and of partially immersed wire.

$$\text{Density} = \text{Specific gravity} \times 997.5 \quad (3.2)$$

where, 997.5 is the density of water at 23 °C.

ASTM D 638-14 Standard Test Method for Tensile Properties of Plastics (ASTM International, West Conshohocken, PA, USA) was followed to determine the tensile properties of the WPCs. Tests were performed at room temperature of 23 ± 2 °C and 50 ± 10 % RH. A universal testing machine Instron 5966 (Instron, Norwood, MA, USA) with a 10 kN load cell was used. A mounted extensometer in the Instron measured the elongation of the samples. The tensile test speed was set at 50 mm/min for breaking the specimen within 5 min. For each sample, 15 replicates were tested to report the average value.

ASTM D 790-17 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials (ASTM International, West Conshohocken, PA, USA) was followed for measuring the flexural strength and modulus of elasticity. The room temperature of 23 ± 2 °C and 50 ± 10 % RH was maintained for the testing. A universal testing machine Instron 5966 (Instron, Norwood, MA, USA) with a 10 kN load cell

was used. The support span length was 52.8 mm with an average depth of the beam of 3.3 mm. The outer fiber strain rate was 0.01/min and the crosshead motion rate was 1.5 mm/min. For each sample, 15 replicates were tested and the average value was reported.

ASTM D 256-10 Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics (ASTM international, West Conshohocken, PA, USA) was followed to determine the impact strength of the samples. A Ceast Izod Pendulum Impact Tester (Ceast U.S.A., Inc., Charlotte, NC, USA) with hammer energy of 2.75 J was used for impact testing. Before testing, the samples were prepared following the recommended dimensions in the standard. The recommend length of the specimens was 63.5 ± 2 mm and depth of notch 10.16 ± 0.05 mm with the angle of the notch $45 \pm 1^\circ$. Notches were prepared using a milling machine and the appropriate length was cut on a band saw. Fifteen replicates for each sample were tested to report the average value.

3.3.4 Statistical Analysis

A three-way Analysis of Variance (ANOVA) with a significance level of 0.05 was used for testing of the statistical significance in the means of the variables. The statistical association of type of wood filler, presence or absence of MAPP, and wood species with the density, tensile properties, flexural properties and impact properties of the WPC samples was analyzed. Here, type of wood filler, presence or absence of MAPP, and wood species are the three independent input variables and their two-way or three-way interaction on the output variables was studied. The dependent output variables are the physical and mechanical properties determined in the study.

3.4 Results and Discussion

3.4.1 SEM images and particle distribution in WPCs

For the WPCs manufactured using wood pellets and flour, the SEM images did not show significant differences in dispersion or distribution or uniformity of particles in the matrix of polymer. Lee et al. 2010 mentioned that the quantitative determination of the fibers organization in the WPC profiles is difficult using SEM images. Thus, fluorescent images were also taken to study these parameters. Figure 3.2 below shows the fluorescent images of WPCs manufactured from four different species using wood flour and wood pellets in the presence of MAPP. Fluorescent images of WPCs for four different wood species with wood flour and wood pellets separately in controlled formulation are shown in Figure A.2 of Appendix A. In the fluorescent images, the wood fillers can be clearly observed. The black portion represents the polymer matrix alone or the polymer matrix with MAPP. PP and MAPP could not be separated in the fluorescent images. These images showed that the particles are more uniform in size for wood flour utilized WPCs than the pellet samples. Similarly, the distribution of particles is similar for both WPCs made with flour and pellets but the dispersion was higher for those manufactured with pellets than flour. This could be attributable to the grinding action of the knife grinder to the pellets that created particles with less uniformity than the sieved 40-mesh wood flour. Analysis was done on the dimensions of wood pellet and wood flour particles in the polymer matrix. The major axis, i.e., length of the wood pellets particles ranged from finer particles of 4 microns to the larger particles of 427 microns and the minor axis, i.e., width ranged from 2 to 220 microns. The size range had a greater deviation. For the wood flour particles, the major axis ranged from finer sizes of 4 microns to larger 295 microns and the minor axis from 2 to 180 microns with lesser variation than the former case. Likewise, the average aspect ratio of the 40-mesh wood

flour particles on the polymer matrix for cedar was 2.2, pine 2.1, spruce-fir 2.4 and of maple 2.3. For the ground wood pellets, the average aspect ratio of cedar was 2, pine was 2.2, spruce-fir 2.1 and the maple 2. The biggest wood particles appear more or less rectangle in shape whereas the smallest particles are more irregular in shape (Yang et al. 2020). Because of high temperature and shear forces, wood fiber length is reduced but not the width during compounding and molding (Bengtsson et al. 2007, Peltola et al. 2014). On comparing the hardwoods and softwoods, it can be clearly observed that the distribution and dispersion of particles is higher in softwoods than the hardwood maple. This might be because of the softwood fibers being flexible and hardwood fibers stiffer. Hardwood fibers are shorter (about 1 mm) and softwood fibers are longer than the hardwoods (about 3–8 mm). The discrepancies between hardwood and softwood fibers in terms of density, morphology and aspect ratio influences the dispersion of the fibers and consequently, the reinforcing for the polymer (Maldas et al. 1989). The color of WPC samples for each wood species was different correlating with the color of mill residues, wood flour and wood pellets. During the melt processing, the orientation and dispersion of fibers in the polymer is affected as well (Peltola et al. 2014). Mechanical behavior of the composites is greatly influenced by the consistency of the lignocellulosic materials concentration in the polymer (Raj et al. 1989, Chen et al. 2006). Thus, on comparing the physical properties of wood pellets after pelletizing and then grounding operation with the original wood flour, the ground pellets had greater variation in sizes and were bulkier. The particle size variation of the ground pellets was smaller attributable to the usage of uniform size of the wood flour (Manouchehrinejad and Giesen 2018). As the particles are smaller, the circularity of the particle sizes increases (Masche et al. 2021). The same authors also suggested drier pellets produce finer particles. Studies have been conducted related to the particle shape of the ground pellets. Some authors have suggested

the mill type influences (Rose 1960) whereas others have suggested the material properties affect the particles' shape (Bond 1954). Jet mills produce particles with the highest aspect ratio. Likewise, in a dry condition, the chemical constituents of wood such as cellulose, hemicellulose and lignin usually do not change until reaching a temperature of around 200 °C (Karinkanta et al. 2018). However, surface energy of the particles might be reduced attributable to the thermal friction encountered by the particles during the milling operation. Grinding can change the surface properties of particles (Galet et al. 2009).

In this study, pellets were produced from the wood flour without any mechanical treatments. Durable pellets can be produced from the steam explosion mechanism of the raw materials (Lam 2011). Thermal pretreatment of the raw materials by torrefaction produces pellets with lower in properties such as density, hardness and energy yield, but higher in hydrophobicity (Peng et al. 2015). The production factors such as additives, die temperature, pressure and raw materials can affect the properties of wood pellets (Mostafa et al. 2019). With these changes in properties of pellets changes the material properties of WPCs. Butylina et al. 2011 observed the physical and mechanical properties of PP-wood fibers produced from commercially manufactured wood pellets in between the values of wood flour and heat-treated wood fibers. Further detailed research on understanding the properties of wood pellets under different treatments and then its impact on composites manufacturing through different production and grinding treatments are suggested.

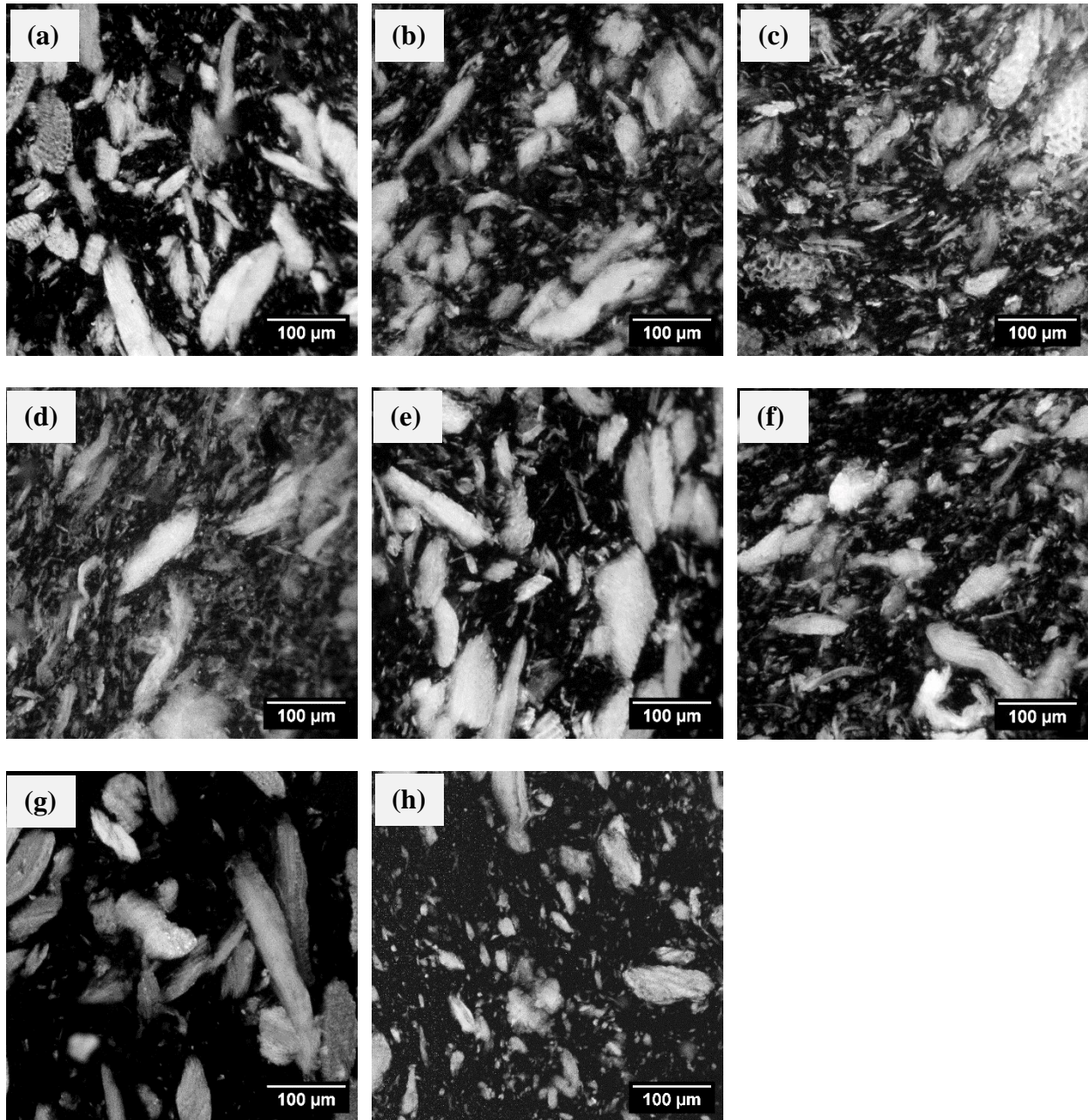


Figure 3.2 Fluorescent images of WPCs with MAPP (a) Cedar flour, (b) Cedar pellets, (c) Pine flour, (d) Pine pellets, (e) Spruce-fir flour, (f) Spruce-fir pellets, (g) Maple flour and (h) Maple pellets.

The feed rate of the raw materials under different formulations is shown in Table 3.2. Either in control or MAPP formulations, the feed rate using pellets was approximately 1.5 times greater than the feed rate using wood flour mixed with PP alone or with MAPP. This effect is

slightly higher for formulations with MAPP than the controls as the weight of MAPP used was slightly more than the PP used. MAPP also acts as a processing aid, i.e., like a lubricant thus contributing to an enhanced production rate. Pellets after being processed in a grinder were bulkier than the wood flour fibers. These results suggest that time and energy are reduced for the processing of WPC pellets in an extruder using wood pellets rather than wood flour. Nevertheless, this is a case during extrusion only. The additional steps of pelletizing the wood flour and grinding operations still needs to be considered. The ground pellets possessed increased fragmentation in the polymer after the grinding.

Table 3.2 Feed rate (g/min) from the feeder of twin-screw extruder.

Wood Species	Controlled Condition		MAPP Condition	
	Flour + PP	Pellets + PP	Flour + PP + MAPP	Pellets + PP + MAPP
White Cedar	26.40	40.81	26.42	40.84
White Pine	22.03	39.62	22.05	39.65
Spruce-Fir	24.51	39.17	24.53	39.20
Red Maple	31.03	43.50	31.05	43.53

1 g of PP = 1.04 g of MAPP.

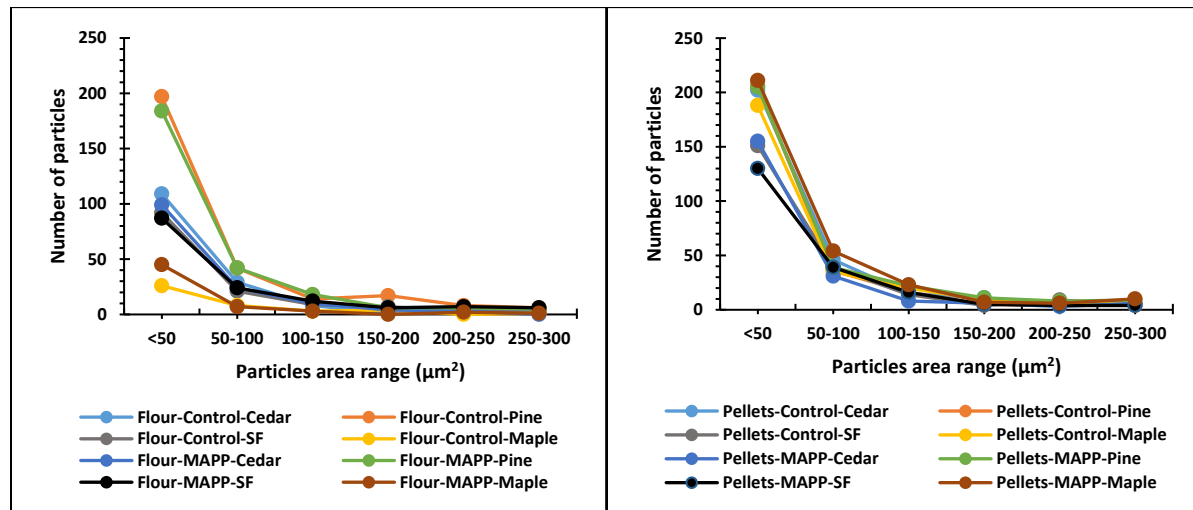


Figure 3.3 Area of wood particles in the polymer matrix (a) wood flour and (b) wood pellets.

The two graphs in Figure 3.3 below show the dispersion of particles in WPCs based on area of the particles. From both the graphs, it can be observed for both wood flour and wood pellets feedstock WPCs, most of the particles falls below 50 square microns followed by 50-100 square microns. However, the WPCs made from pellets have a steeper curve than that of utilizing wood flour. This suggests that within the same range of particles area, a higher number of the pellet particles fall than the flour particles. This then, affects the dispersion of particles in the polymer. A similar trend was observed through the visualization of fluorescent images in Figure 3.2. From the images, it can be inferred that WPCs made from wood pellets had better particles' dispersion than WPCs made from the wood flour. However, proper dispersion and distribution is always challenging for small particles in the polymer matrix (Ess and Hornsby 1986, Danyadi et al. 2006). The clustering of the particles usually can occur with particles having a smaller particle size and higher surface energy (Móczó and Pukánszky 2008).

3.4.2 Mechanical properties of WPCs

The average density of PP is 900 kg/m^3 . Figure 3.4 below shows the density of WPC samples of wood flour and pellets in different formulations. For all sample formulations, the density observed was higher than 900 kg/m^3 . For all cases, WPCs made from wood pellets with MAPP showed a higher density. The increase in density of WPCs made with wood pellets is because of ground wood pellets being denser than the wood flour used. Matuana and Stark 2015 suggested that the compression of cell walls in the wood causes increase in density of the WPCs than the pure plastics. From our results, it can be indicated that the cell walls of pellets squeezed more than the flour. Similarly, in a microscopic level, the cell wall density of hardwoods and softwoods is almost similar that does not create significant differences in the density of

composites. Results of three-way ANOVA showed that the p-value on the one-, or two- or three-way interaction of each variable (wood filler type, wood species, and additives condition) was greater than 0.05 in all conditions except the one-way interaction of wood filler. In the case of density, presence or absence of MAPP and wood species type or their interaction with the wood filler, does not make a notable difference. However, as explained before, filler type alone shows some significant differences as WPCs with pellets have a higher density than those with wood flour. On average, the density of WPCs for the wood flour controls was lower by 0.5% than the pellet formulations. Here, the density was 0.6% and 0.3% lower for the wood flour controls than the pellets for softwoods and hardwood, respectively. Likewise, in the wood flour–MAPP formulations, the average density was 0.6% lower than with pellet–MAPP formulations which was lower by 0.6% and 0.8% for softwoods and hardwoods respectively.

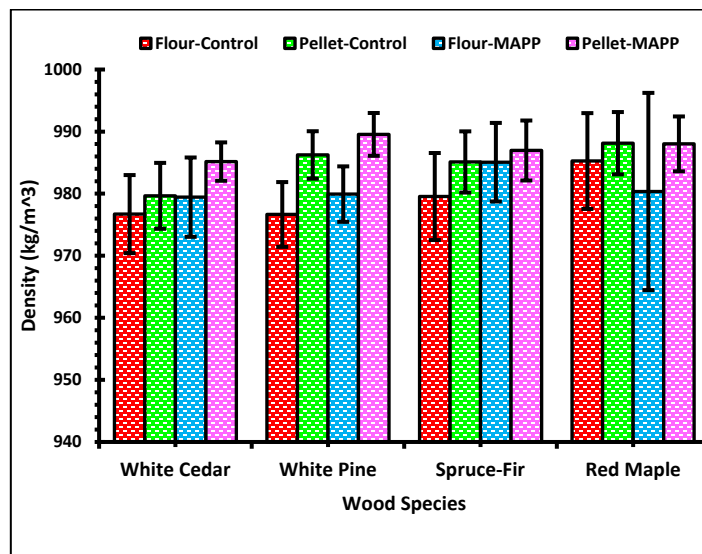


Figure 3.4 Density of WPCs.

The interplay of wood feedstock and the polymer impacts the mechanical properties of WPCs. The processes used in manufacturing WPCs also impact the composite products' mechanical behavior (Soccalingame et al. 2015). The physical and mechanical properties depend

on the nature of wood filler such as the size and distribution of particles, the orientation of fibers, wood species and wood filler contents. Softwood pulps augment the tensile and flexural properties of WPCs as compared to the hardwood pulps (Maldas et al. 1989). However, Berger and Stark 1997 reported PP composites from hardwoods performed better than the softwoods. Either with wood flour or pellets, the tensile and flexural properties of the samples containing MAPP were better than the PP controls. This is obvious as MAPP increases the adhesion between polymer and wood. Tensile flexural and impact properties are improved attributable to MAPP in composite of wood flour and PP (Kord et al. 2011).

Figure 3.5 conveys the results of tensile strength and modulus of the WPCs under different formulations. Similarly, values of the tensile strength at yield and break and % elongation at yield and break are tabulated in Table 3.3.

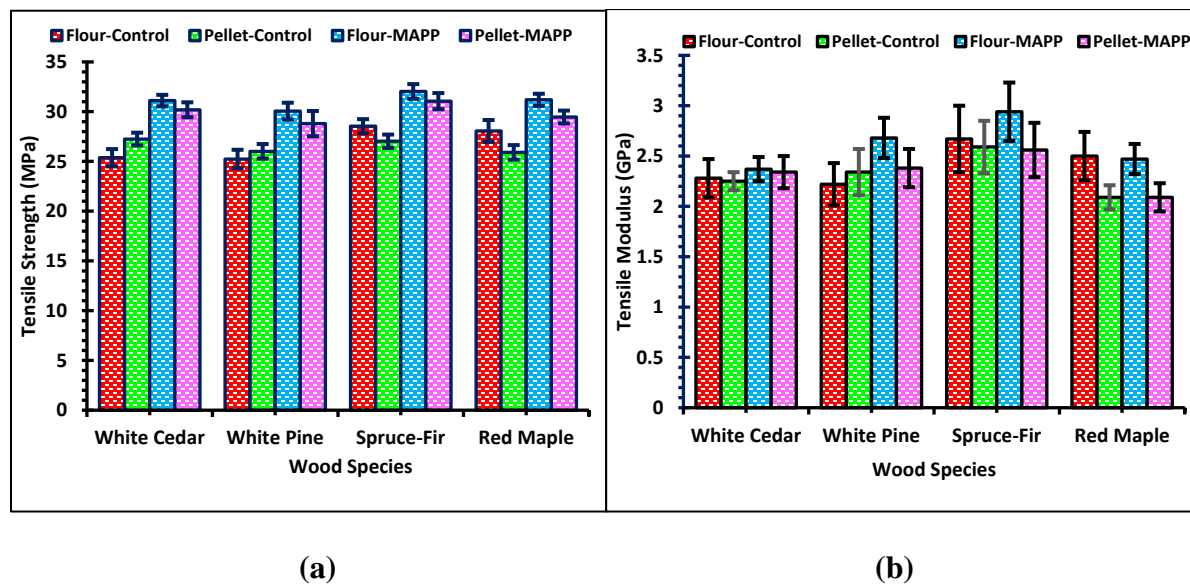


Figure 3.5 Graphs of (a) Tensile strength of WPCs and (b) Tensile modulus of elasticity of WPCs.

Table 3.3 Tensile strength and % elongation at yield and break for different formulations of WPCs.

Wood Species	Formulations	Tensile Strength at Yield (MPa)		Tensile Strength at Break (MPa)		% Elongation at Yield		% Elongation at Break	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
White Cedar	Flour–Control	14.35	0.82	14.82	0.49	2.77	0.40	10.62	1.10
	Pellets–Control	16.56	0.73	16.12	0.32	2.54	0.18	9.35	0.56
	Flour–MAPP	20.22	0.97	18.32	0.47	3.48	0.30	9.21	0.64
	Pellets–MAPP	17.81	0.65	17.60	0.50	3.13	0.26	9.31	0.53
White Pine	Flour–Control	15.43	1.38	14.82	0.64	3.32	0.32	12.72	1.16
	Pellets–Control	16.23	0.88	15.14	0.48	3.07	0.29	11.27	0.82
	Flour–MAPP	18.96	1.19	17.60	0.61	3.16	0.21	9.66	0.66
	Pellets–MAPP	18.69	0.76	16.89	0.74	3.33	0.47	9.43	0.75
Spruce-Fir	Flour–Control	17.74	1.02	16.72	0.52	3.28	0.52	9.73	0.90
	Pellets–Control	15.95	0.85	15.85	0.42	3.03	0.30	11.06	0.73
	Flour–MAPP	19.35	1.48	18.84	0.56	3.25	0.28	9.37	0.69
	Pellets–MAPP	18.77	1.74	18.34	0.48	4.05	1.09	10.50	1.10
Red Maple	Flour–Control	16.48	1.12	16.47	0.64	2.76	0.31	9.16	0.53
	Pellets–Control	15.14	0.82	15.27	0.47	3.11	0.59	10.28	0.90
	Flour–MAPP	18.64	0.53	18.20	0.44	3.42	0.83	10.16	1.01
	Pellets–MAPP	17.37	1.32	17.18	0.39	2.49	0.61	8.69	1.01

Results of the three-way ANOVA showed the three variables alone, i.e., wood filler, additive and wood species or their two-way or three-way interactions indicate some statistical differences in the tensile properties. There was minute statistical difference in the tensile values attributable to the two-way interaction of wood species and the MAPP additive. Tensile properties with or without MAPP did not vary much among the different wood species. Similarly, tensile modulus was not influenced much based on the wood filler type and the three-way effect of filler type, species and MAPP additive. The graph in Figure 3.5 shows WPCs manufactured using pellets or flour had no significant difference in the tensile values of the composite products. Either for the MAPP or control formulations, the wood pellet samples show similar or significantly lower differences in the tensile properties. On average, the tensile strength of the wood flour controls was 0.6% higher than the pellet controls. Tensile strength of

the wood flour controls was lower by 1.7% for the softwoods and higher by 7.7% for the hardwood compared to the pellet controls.

Similarly, the average tensile strength of the wood flour–MAPP samples was 3.9% higher than pellet MAPP samples. The softwoods and hardwood showed increases of 3.4% and 5.5% respectively for the wood flour–MAPP samples compared to pellet–MAPP samples. The average Modulus of Elasticity (MOE) for the wood flour controls was 3.8% higher than the pellet controls. In this case, the MOE of the wood flour control formulation compared to pellet controls were lower by 0.4% for the softwoods and higher by 16.4% for the hardwood sample. The average MOE of the wood flour–MAPP was higher by 10.2% than the pellet–MAPP formulation. The MOE was higher by 8.5% and 15.4% for softwoods and hardwood respectively for the wood flour–MAPP compared to the pellet–MAPP samples. These results show that the tensile property values differ based on the wood species. Rogers and Simonsen 2005 suggested the type of wood species can influence the parameters such as: roughness, feasibility to grinding, and porosity which might regulate the bonding with WPCs. Compared to the other species, the spruce-fir WPCs exhibited the maximum tensile properties for all formulations. This is attributable to the higher fragmentation of fibers in the PP matrix. Spruce-fir fibers possess the highest aspect ratio among the wood species examined. Higher aspect ratio is crucial in influencing the mechanical performance of the WPCs than the length of the particle (Zaini et al. 1966, Liew et al. 2000, Lee et al. 2001, Stark and Rowlands 2003, Migneault et al. 2009, Chaudemanche et al. 2018). Damage to the wood fiber is induced by the grinding process (Thumm and Dickson 2013). WPCs made of hardwood, i.e., maple pellets have the lowest MOE values among the wood species made from pellets. Neagu et al. 2006 reported the correlation

between lignin content and stiffness of the composite materials where they observed maximum stiffness for softwood kraft fibers. These results also show similarities in the findings as maple pellets have less lignin content compared to the other softwood pellets.

Table 3.3 lists the tensile strength at yield and break and % elongation at yield and break for different formulations of the composites. The values show WPCs manufactured using pellets and wood flour did not have significant differences and any differences were small. Spruce-fir WPCs showed maximum strength compared to the other wood fillers on average. Likewise, the elasticity of the composites is indicated by the elongation at break. The percentage elongation at yield is in the range of 2-4% and a break in the range of 8-12% for the WPC samples. Between the pellets and wood flour WPCs, the values indicate minor differences. Compared to the maple and cedar, pine and spruce-fir have greater % elongation at yield and break. The tensile strength and modulus, and % elongation of the WPCs have a positive relation with the finer size of the particles (Sain et al. 1993, Siwek et al. 2018).

In Figure 3.6, the flexural properties of WPCs made with wood flour and pellets in the presence or absence of MAPP are presented. From the three-way ANOVA, it was observed for the flexural properties the variables alone or their two-way or three-way interactions contribute to some significant differences in the bending properties except the one-way interaction of wood filler type. The wood filler either the wood flour or pellets did not influence the flexural strength. MOE was affected by the filler type by small statistical difference. MOE was not influenced by two-way effect of wood species and MAPP additive where, the MOE values with and without MAPP were similar among the different species. The average flexural strength for wood flour

controls was lower by 1.3% than the pellet controls. Flexural strength of the wood flour controls was lower by 4% for softwoods and higher by 6.7% for the hardwood formulation compared to the pellet controls. Similarly, the average bending strength of wood flour–MAPP samples was 4.2% higher than the pellet MAPP samples. The softwoods and hardwood contributed to increase in bending strength by 4.1% and 4.35% respectively on flour–MAPP condition than the pellet MAPP samples. The average bending MOE for the flour–control case was 1.3% lower than the pellet-control case. In this scenario, the MOE for the flour–control formulation contrary to pellet-control formulation was lower by 7.5% for softwoods and higher by 17.5% for the hardwood. The average bending MOE for formulation with flour–MAPP was higher by 8.4% than the pellet–MAPP formulation. The MOE was higher by 8.7% and 7.6% for softwoods and hardwood respectively in flour–MAPP case than the pellet–MAPP case. Looking at the graphs of the bending tests in Figure 3.6, a similar trend to flexural properties existed for formulations with or without additives and with wood flour or pellets. Wood flour or wood pellets WPCs had similar or significantly fewer differences in flexural properties. In some cases, bending properties of WPCs made with pellets were higher than WPCs with wood flour. Wood species had a different impact to the bending properties than to the tensile properties. Compared to the rest of the wood species, red maple exhibited the maximum flexural strength using MAPP for both flour and pellets followed by spruce-fir. However, Pilarski and Matuana 2006 mentioned flexural properties of WPCs produced from rigid PVC and HDPE matrices showed better performance for softwoods than the hardwoods. Higher values of tensile and flexural properties were shown by jack pine and black spruce than the white cedar for HDPE composite (Bouafif et al. 2009). Similarly, the flexural modulus of elasticity of WPCs with red maple pellets was lower for both

controls and MAPP formulations than the other species. This might be attributable to the correlation between lignin content and stiffness as concluded by Neagu et al. 2006.

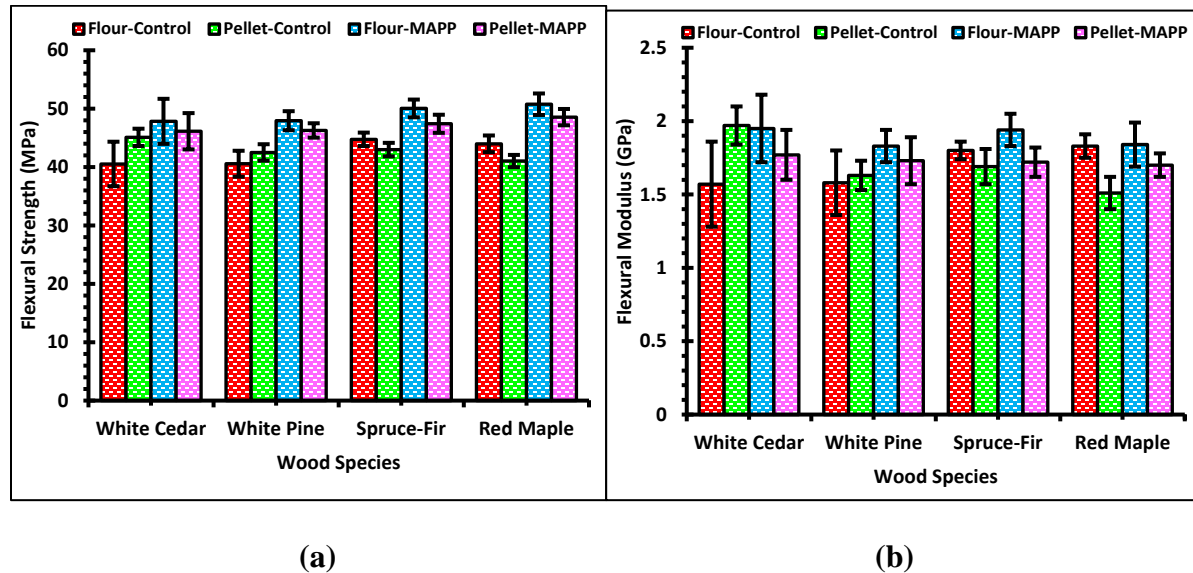


Figure 3.6 Graphs of (a) Flexural strength of WPCs and (b) Flexural modulus of elasticity of WPCs.

Typically, the presence of wood fibers in the body of WPCs causes crack initiation and subsequent failure. The graph in Figure 3.7 shows the impact properties of the different WPC samples. Unlike to the tensile and flexural properties, the presence of MAPP did not contribute to a higher impact strength than in the control formulations. Compared to the tensile and flexural properties, the impact strength values for different wood species had a greater variance from the mean value. On average, WPCs of red maple showed better impact strength than the other wood species. The study conducted by Bledzki and Faruk 2003, on the effect of wood filler geometry on the physico-mechanical properties of PP/wood composites, reported hardwood flour reinforced PP composites had a better impact strength than the other PP composites of different fillers (softwood fiber, long wood fiber and wood chips). However, higher impact strength of PP based composites for ponderosa pine was greater than the hardwoods: oak and maple (Berger

and Stark 1997). The composite samples made with fine wood particles have poorer impact strength than with coarse-wood particles (Maiti and Singh 1986). In our study, the softwood particles were finer than the hardwood. Because of this, on average WPCs from softwoods had a lower impact strength than the hardwood. Similar to the tensile and flexural values, there was not a difference in the impact values attributable to the filler type. The average impact strength for the wood flour controls was 8.3% higher than the pellet samples. At flour-controls, it was higher by 14.3% for softwoods and lower by 9.6% for hardwood than the pellet-controls formulation. For the wood flour-MAPP formulations, the impact strength value was 2.3% higher than the pellet MAPP formulations. For softwoods it was higher by 3.7% and for hardwood lower by 1.8% at flour-MAPP formulation than pellet-MAPP formulation. Results of the three-way ANOVA on flexural properties showed the variables alone or their two-way or three-way interactions contribute to some significant differences in the impact properties. The statistical analysis also revealed that the interaction of wood filler and MAPP additive did not influence the impact strength with a greater difference. It means in each WPC formulation with presence or absence of MAPP, the impact strength for each filler type did not have much variation.

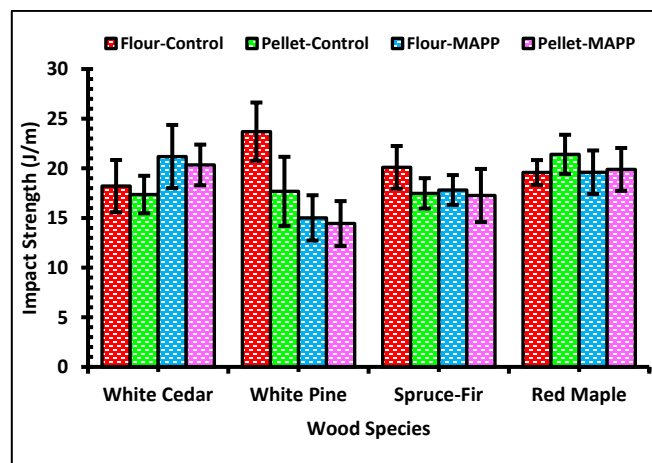


Figure 3.7 Impact strength of WPCs.

Future research work on using wood pellets as a wood feedstock in different polymers, different formulations, changing the properties of wood pellets during manufacturing, etc. are recommended to understand more about the material for its efficient application.

3.5 Conclusions

- The physical and mechanical properties of WPCs made from either the wood flour or wood pellets were similar.
- Distribution of feedstock was similar for both wood flour and pellet formulated WPCs. However, dispersion was greater for WPCs with pellets than with wood flour.
- MAPP improved the physical and mechanical properties of WPCs for each wood feedstock and wood species.
- On average, WPC samples of spruce-fir species possessed the best properties.

CHAPTER 4

TRANSPORTATION COST ANALYSIS ON ALTERNATIVE WOOD FEEDSTOCKS FOR MANUFACTURING WOOD-PLASTIC COMPOSITES (WPCs)

4.1 Chapter summary

This study evaluated and analyzed transportation costs for manufacturing wood-plastic composites (WPCs) using wood flour and wood pellet feedstocks. The study area ranged from Maine (ME) to Massachusetts (MA) in the Northeast region of the United States (US). Wood mills in ME were the raw material providers, and the WPC manufacturers in ME and MA were the destinations. The methodologies included the Origin-Destination (OD) cost matrix feature in ArcGIS to find least-cost pathways from each facility to each destination; baseline scenarios based on trucking costs, travel distances, and wood feedstocks; and sensitivity analyses to study the effects of fluctuating input variables (travel distance, shipment weight, and shipping costs over distance) to the shipping costs by weight. Accordingly, the best and worst-case scenarios were identified. The OD-cost matrix showed that shipping feedstocks from southern ME required shorter travel distances than from other regions because of proximity. Transporting wood pellets in a truck would reduce shipping costs by at least 25% compared to wood flour. The shipping costs by weight were inversely related to the shipment weight. The shipment weight of wood pellets was higher than flour in a truck trailer with fixed volume. It is foreseen that the transportation of wood pellets as opposed to wood flour would be economical.

4.2 Introduction

Wood-plastic composites (WPCs) are hybrid materials of wood, typically comprised of wood flour, thermoplastic or thermoset resins, and several additives. These composite products

are utilized in multiple forms such as decking, automotive, siding, fencing, technical applications, furniture, and other consumer goods. The global market size of WPCs is expanding and is forecasted to reach USD 9.03 billion by 2027 (Fortune Business Insights 2021). Images of WPC samples and the feedstocks that can be used for manufacturing WPCs can be seen in Figure 4.1.

Wood flour, also called “wood fiber”, is a highly comminuted wood material with a fine particle size distribution that is generally used as the raw material for producing WPCs (Reineke 1966). The particle sizes of wood flour can range from 20 to 400 United States (US) mesh (850 to 35 microns). Wood flour is typically manufactured by secondary processing of mill residues. In the US, most of the wood flour comes from shavings and sawdust. Wood flour is not considered a dangerous product to transport, so it is shipped in fleets of dry vans with walking-floor van trailers or closed-van trailers, in super sacks for large quantities, or as bagged wood flour for small quantities. The bulk density of wood flour is influenced by several factors such as the moisture content, particle size, and species (Clemons and Caulfield 2010).

Wood pellets are a biofuel manufactured using compressed organic matter or biomass. In this study, wood pellets were considered as the alternative feedstock to wood flour in the manufacturing of WPCs. Wood pellets are produced in a temperature range of 110 °C to 130 °C and a pressure range of 210 MPa to 450 MPa (Nielsen et al. 2009). The manufacturing process creates the elastic and plastic deformation of particles and the softening of natural binders such as starch, protein, lignin, fat, and fibers (Gilvari et al. 2020). The raw materials that are used to manufacture wood pellets are drawn from multiple sources including unmerchantable

roundwood from the forest, sawdust and board edging residues from sawmills, wood chips and odd pieces from furniture production, and stalks and straws from agriculture. The utilization of wood pellets has increased throughout the world from approximately 12 million metric tons (MT) in 2008 to 56 million MT in 2018 (Calderón et al. 2019). Nearly one-third of global wood pellet production is exported to Europe from the US and Canada.

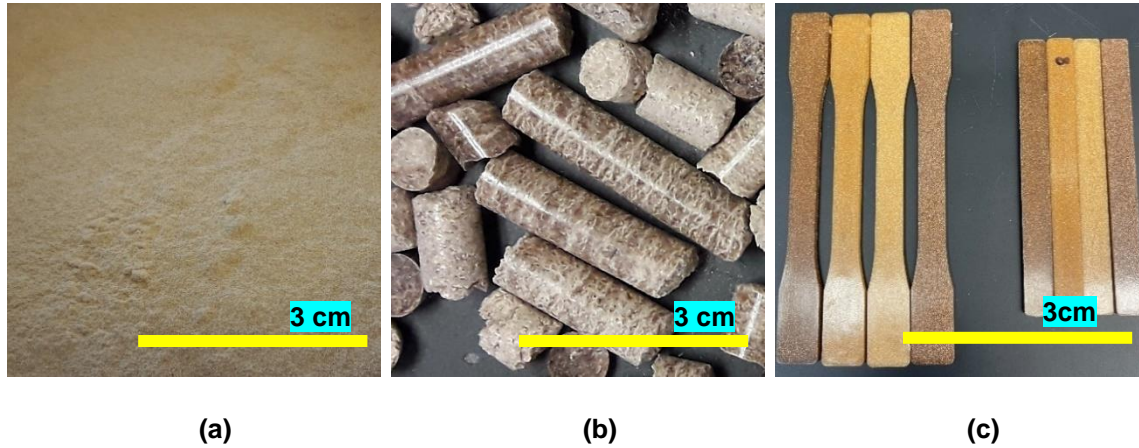


Figure 4.1 Images of the (a) wood flour, (b) wood pellets, and (c) and WPCs. (Pokhrel et al. 2021b).

In the US, the average hauling distance for primary forest products was highest in the North compared with other regions, which increased the price of the final products made there (Libbey 2000). Transportation costs for woody biomass are a function of the travel time, transportation form, and energy density of the product. Transportation accounts for approximately half of the total woods-to-gate production costs in the forest supply chain (Kizha et al. 2015). Transportation costs can impact supplies from the forestland to processing facilities, and from the processing facilities to the markets (Paulson et al. 2019). The logistics and supply chain of the feedstock are key in determining the final price of the end product (Koirala et al. 2018). Lower costs in freight movement have a positive effect on all entities engaged in the production, distribution, trade, and/or retail sale.

The theoretical comparison of the bulk density of wood pellets (700 kg/m³ to 750 kg/m³) and wood flour (190 kg/m³ to 220 kg/m³) reflects that transporting pellets can be almost four times more economical than the latter (Pokhrel et al. 2021a). The physical and mechanical properties of WPCs formulated using wood flour or groundwood pellets with polypropylene plastics are similar (Pokhrel et al. 2021b). The total energy requirement of pressing wood pellets from wood flour followed by re-grinding to be used for manufacturing WPCs should be determined to ensure that the costs do not exceed the savings obtained from the lowered transportation costs. Knowledge is limited on topics involving the comparison of transportation costs for shipping wood flour and pellets concerning variation in travel distances and shipment weight. Thus, this research aimed to compare the transportation costs for shipping two wood feedstocks for WPC manufacturing - wood flour and pellets- under different scenarios. The discussion on transportation related to wood flour and pellets presented in this study was focused on the perspective of WPC manufacturers, not on the other applications where each of these products has its own indispensable role.

In the US, there has been a shifting from the railway to the road transportation in the forest products industry. This shift has been attributed to the unavailability of railcars, delayed delivery or inflexible rail schedules, and the costs associated with the construction of railways (Kizhakkepurakkal 2012). Fuel costs can always be a challenge for the shipment of lighter weight forest products such as mill residues or wood flour. For lighter weight materials, it might be economical to supply to the local market via a truck rather than transporting farther distances via rail. However, the larger payload in rail transportation makes it more economical to ship to farther distances compared to trucks (Lindholm and Berg 2005). Thus, valuable products could

be hauled economically by rail transport. Railways could have a greater applicability on shipping wood residues or their subsequent products from their collection site to utilization sites if the collection site is near to a railway intermodal terminal (Kizhakkepurakkal 2012).

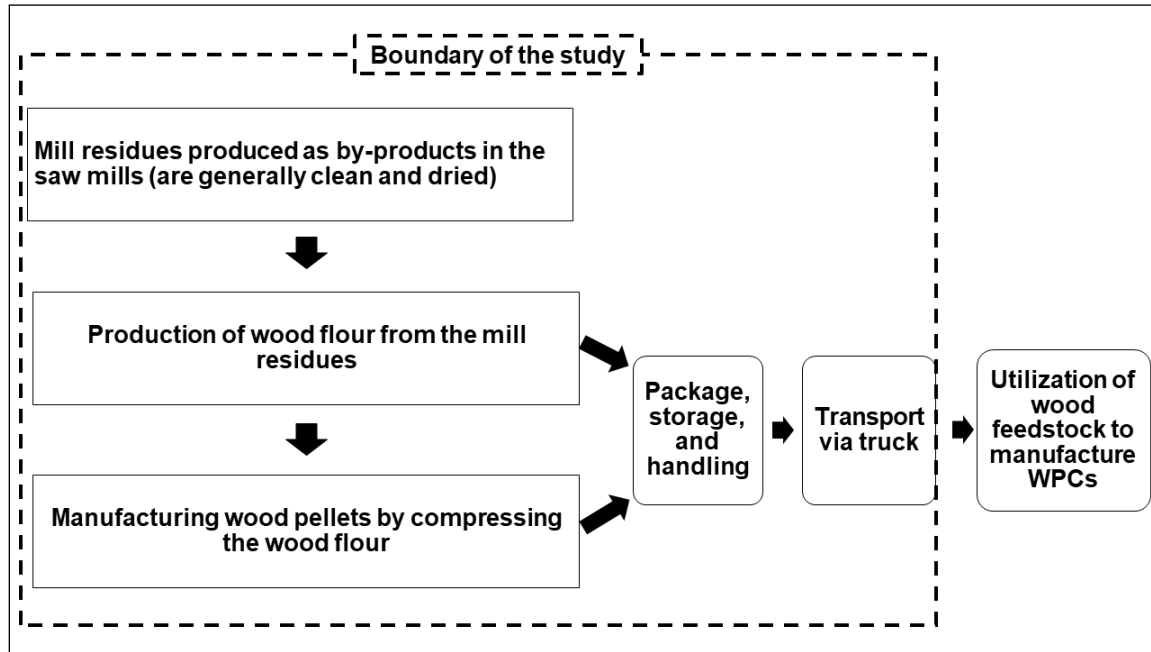


Figure 4.2 The schematic representation and boundaries of transportation cost analysis for utilizing wood flour and wood pellets as feedstock to manufacture WPCs.

This study covered the area from Maine (ME) to Massachusetts (MA) in the Northeast region of the US. In ME, forest products industries are a key part of the state's economy. In recent years, the industry has shifted towards engineered wood products, biofuels, high-performance fibers, and natural chemicals (FOR Maine 2018). As one of the most densely forested states in the nation, ME has many wood mill processors. More than 90% of the wood and wood products are transported via truck (Koirala et al. 2017a). There is a strong interest among stakeholders to understand the potentials of utilizing a compact form of wood flour as a raw material to manufacture WPCs that could be shipped over greater distances. The first

objective of the study was to evaluate the cost of trucking from each origin to each destination. The second objective was to capture the variation in total shipping cost by weight (\$/MT) due to fluctuation in the travel distance (km), shipping cost over distance (\$/km), and the weight of the shipment (MT). A sensitivity analysis was performed for the shipping cost by weight (\$/MT) for both wood flour and wood pellets. Finally, the difference in shipping costs over weight was expressed in percentages of change with respect to each variable for each material type, followed by which the base-case, best-case, and worst-case scenarios were determined. The schematic representation of the manufacturing and transportation process along with the boundary of this study is defined in Figure 4.2.

4.3 Materials and methods

4.3.1 Terminologies used in the study

- **Feedstocks:** Wood feedstocks are required to manufacture WPCs. Wood pellets and wood flour were the two wood feedstocks compared in this study.
- **Shipment weight:** In the state of Maine, the maximum gross vehicle weights for public roads and interstate highways are 45 MT and 36 MT, respectively.
- **Shipment cost by weight (\$/MT):** The transportation cost incurred when shipping 1 MT of the wood feedstock via truck.
- **Shipment cost over distance (\$/km):** The transportation cost incurred when shipping a truck load of the wood feedstocks over a 1 km distance.
- **Travel distance:** The one-way travel distance between facility (origin) and destination (WPC manufacturer) in km.

- Base case scenario: The average values of the input variables related to trucking, wood feedstocks, and travel distance. These were obtained either from personal communication or literature review.
- Best and worst-case scenarios: The input variables were increased and decreased from the base-case values by 15% for the best and worst-case scenarios, respectively. The intention here was to evaluate the effect of fluctuations at different levels. When the input variable was increased or decreased by 15% from the base value, the best case represented minimum shipping cost by weight (\$/MT) and the worst-case represents the maximum shipping cost by weight. The input variables were analyzed at both the individual and combined level.

4.3.2 Case Study

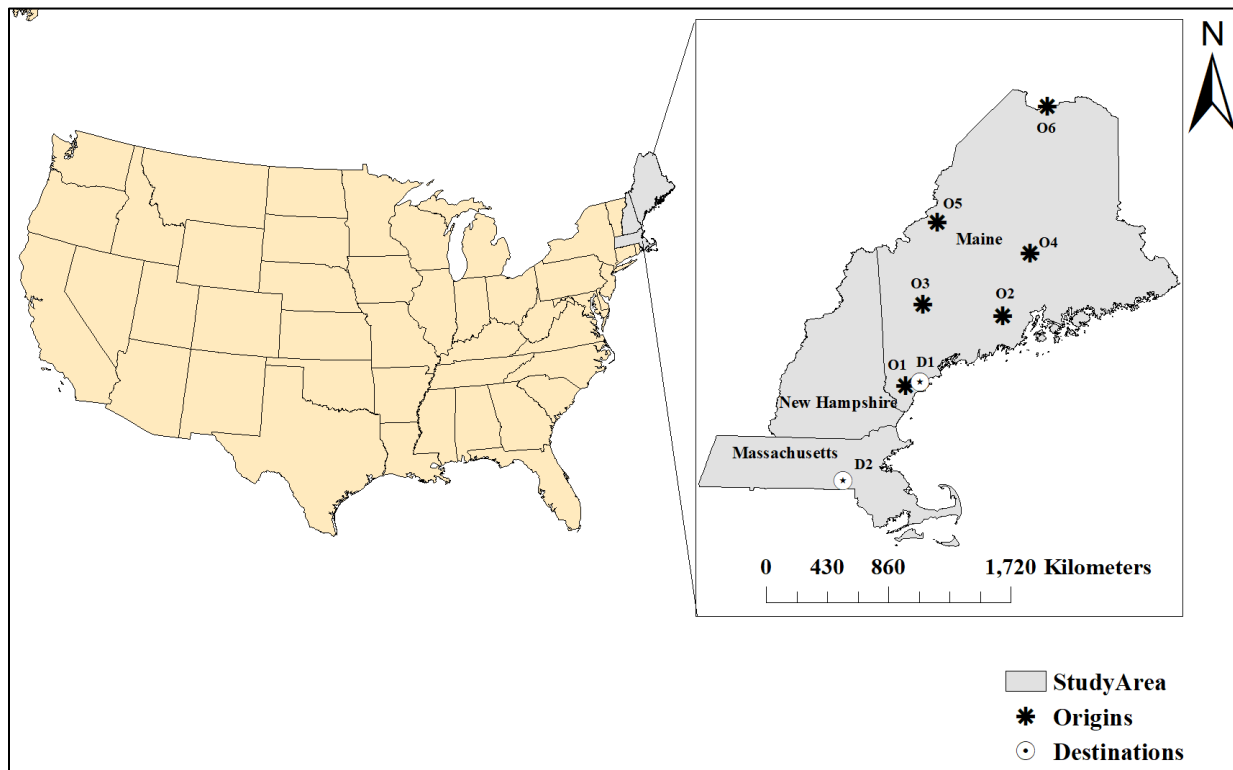


Figure 4.3 Locations of the facilities and destinations utilized for the transportation cost analysis.

The analysis of the transportation costs began by selecting wood mills as facilities from different geographical regions within ME (i.e., east, west, north, south, and central), along with WPC manufacturers in ME and MA as destinations (Figure 4.3). The coordinate data (longitude and latitude) for the locations of the wood mills were obtained from Google Earth and were uploaded to ArcGIS 10.7.1 (Ersi, Redlands, CA). The selected mill in each geographical region was the largest processor for a particular wood species. The study considered shipping of both wood flour and wood pellet feedstocks from each of the selected facilities to the destinations, via trucking.

4.3.3 Roads Network and Building Roads Network Dataset

The datasets for the roads were obtained from the US Census's Topographically Integrated Geographic Encoding and Referencing (TIGER) data set. The speed limit for the different road types (i.e., interstate, state, private, and local roads) were assigned for each state. The assumption was based on the fact that once the feedstock leaves the state of ME, trucks will only be using highways (interstate and state). This doesn't hold when the truck delivers feedstock to the WPC manufacturer in MA after leaving the highway. In ME, the speed limits on the interstate, state, private, and local roads were set at 120, 90, 40, and 50 km/hr, respectively. For New Hampshire, the speed limit on interstate and state roads was 110 and 90 km/hr, respectively; and in MA it was 105 and 90 km/hr, respectively.

4.3.4 Network Analysis and Origin-Destination (OD) Cost Matrix

Using the OD cost matrix feature in the Network Analyst tool in ArcGIS software, least-cost pathways from multiple origins to the two destinations were calculated. The Network

Analyst tool is used for maintaining network dataset through modeling and carrying out network analysis through different features. In the OD cost matrix feature, the origins and destinations were set as the six wood mills (facilities) and two WPC manufacturers, respectively. The default cut-off value or the maximum distance was set at 800 km for this analysis, which was primarily attributed to shipping costs not being economically feasible after that. The line table that represents the OD cost matrix shows the network distance, not the straight line distance (Montgomery et al. 2016).

4.3.5 Baseline Scenario

The range of input variables for the baseline logistics scenario of shipping wood flour and pellets from the wood mills to WPCs manufacturers were obtained from literature review and personal communication. The input variables selected were bulk density (kg/m), market price (\$), shipping volume (m³), travel distance (km), shipping cost over distance (\$/km), and shipment weight (MT). Similarly, the market price of wood flour and pellets also varied depending on several factors including purchasing in bulk vs. small quantities, product quality, supply and demand, travel distance from origin to destination, and production cost.

Two types of trailer configurations are commonly used in the New England region, and they vary based on the length and the maximum volume they occupy. The travel distance from each facility to the destination was obtained from the first objective of the study. The shipment weight (MT) of the wood flour and pellets was derived from the bulk density (kg/m) and the shipping volume (m³) of the trailer. The total shipping cost (\$) was obtained by multiplying travel distance (km) and the shipping cost over distance (\$/km) (Eq. 1). The shipping cost by

weight (\$/MT) was calculated by dividing the total shipping cost (\$) and the weight of the shipment (MT) (Equations 4.2 and 4.3).

$$\text{Shipment weight} = \text{Bulk density} \times \text{Shipping volume} \quad (4.1)$$

$$\text{Total shipping cost} = \text{Travel distance} \times \text{Shipping cost over distance} \quad (4.2)$$

$$\text{Shipping cost over weight} = \text{Total shipping cost} \div \text{Shipment weight} = (\text{Travel distance} \times \text{Shipping cost over distance}) \div \text{Shipment weight} \quad (4.3)$$

Table 4.1 The input variables range and the average values for the feedstocks related to hauling (via truck).

Input variables	Range		Average	
	Wood flour	Wood pellets	Wood flour	Wood pellets
Market price (\$/MT)	265 – 331	221 – 276	298	248
Bulk density (kg/m³)	194 – 224	657 – 705	208	681
Shipment weight*	23– 26	30	22	72
Trailer length (m)	15 - 16		15	
Shipping volume (m³)	98 - 114		106	
Shipping cost over distance (\$/km)	2-3		2	
* derived from bulk density and volume of the trailer (MT)				

The values were obtained from literature search and personal communication with the business personnel in ME. Similar values for both wood flour and pellets are merged in a single cell. The weight and legal GVW of the trailer were 6 and 30 MT, respectively.

The major input variables related to the feedstock properties and transportation were average travel distance, shipping cost over distance, and shipment weight. The average values of the above input variables were determined and used to perform the sensitivity analysis (Table 4.1).

4.3.6 Sensitivity Analysis

A sensitivity analysis was performed to study the effects of fluctuating input variables (travel distance, shipping cost over distance, and weight of the shipment) on the output variable (i.e., shipping cost over weight for both feedstocks). This was done by changing one or more input variables at a time while keeping the others constant. The sensitivity analysis helped provide a better idea of the uncertainty involved in any economic analysis and investment (George et al. 2019). The graphs for the sensitivity analysis were generated on RStudio 4.0.3 (Boston, MA). For this analysis, seven cases of the input variables (travel distance, shipping cost over distance, and shipment weight) with reference to the baseline scenario (fluctuation by %) were considered, including one with the baseline scenario values:

Case I: All input variables were decreased by 15%.

Case II: All input variables were decreased by 10%.

Case III: All input variables were decreased by 5%.

Case IV: All input variables were kept equal to the baseline scenario.

Case V: All input variables were increased by 5%.

Case VI: All input variables were increased by 10%.

Case VII: All input variables were increased by 15%.

For each case, the average increase or decrease of the shipping cost by weight (\$/MT) by percentage for both feedstocks were compared to the base-case value to determine the worst-case and the best-case scenarios.

4.3.7 Assumptions

The following assumptions were made for the analysis:

1. Both the wood flour and wood pellet feedstocks were manufactured in the same facility (even though currently there are no commercial producers of wood flour in ME).
2. Both the wood feedstocks can be utilized to manufacture WPCs without compromising the physical and mechanical properties (Pokhrel et al. 2021b).
3. Even though railways are the most economical mode of land transportation, trucking was the mode of transporting the wood feedstocks. Despite the presence of a railway system in ME, only a few counties have access to them. In this study, the selected origins are based on different geographical locations in ME.

4.4 Results and Discussion

4.4.1 Logistics

Table 4.2 The procurement zones and number of facilities in each procurement zone based on the distances (km) from wood mills in ME to WPC manufacturers in ME and MA via truck.

Within the state of ME		Outside the state of ME	
Procurement zone based on the travel distance range between facilities and destinations	Number of facilities within the procurement zone	Procurement zone based on the travel distance range between facilities and destinations	Number of facilities within the procurement zone
0 – 100	1	200 – 300	1
100 – 200	2	300 – 400	1
200 – 300	2	400 – 500	1
300 – 400	0	500 – 600	2
400 – 500	0	600 – 700	0
500 – 600	1	700 – 800	1
The distances are shown in a range rather than the actual values to protect mill confidentiality and this represents a one-way travel distance range.			

Within ME, the nearest travel distance was within the range of 0 to 100 km and the farthest was 500 to 600 km. Each procurement zone had one mill (Table 4.2). No mills were found within the ranges of 300 to 400 km and 400 to 500 km. Similarly, to reach the WPC manufacturer in MA, the nearest travel distance was within the range of 200 to 300 km and the

farthest was within the procurement range of 700 to 800 km (Table 4.2). There were no wood mills within the travel distance of 600 to 700 km. The average travel distance among all the origin-destinations considered in the study was 372 km.

4.4.2 Factors influencing shipping cost over weight ($\text{\$/MT}^{-1}$)

Four sensitivity graphs were plotted (two each) to illustrate variations in shipping cost by weight ($\text{\$/MT}$) for both feedstocks. The first graph (Figure 4.4a, 4.5a) shows the influence of changing one, two, and three variables. The second graph (Figure 4.4b, 4.5b) shows the influence of each variable individually.

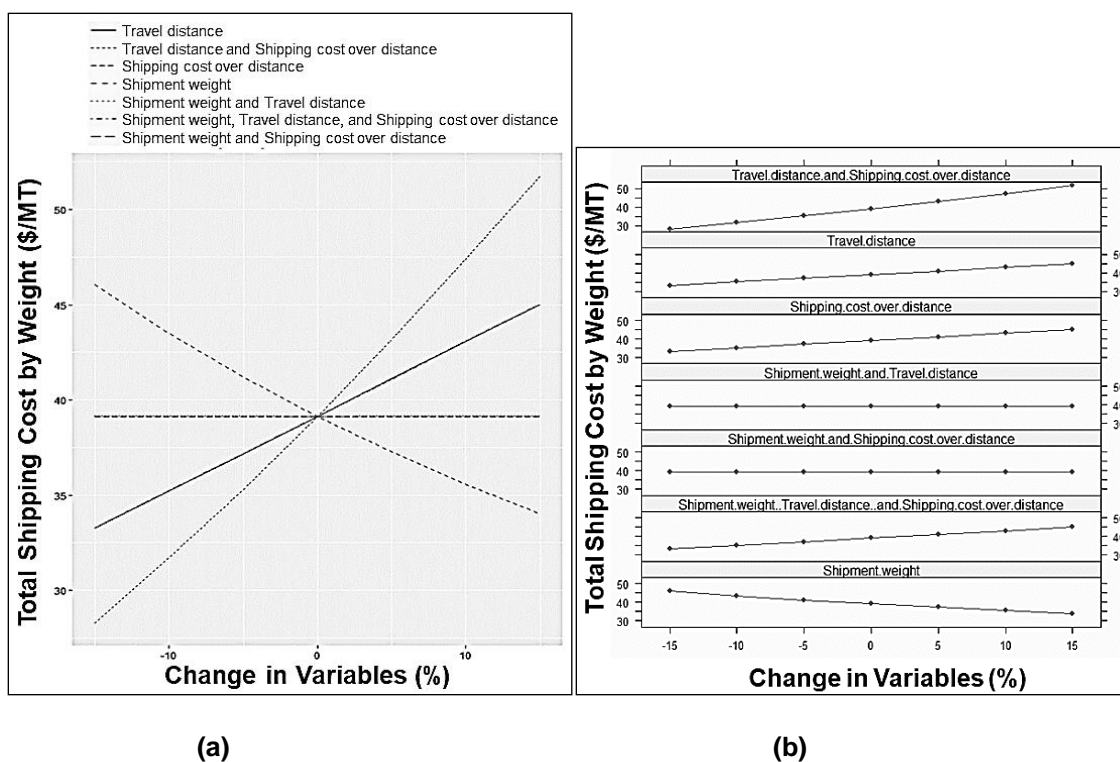


Figure 4.4 The sensitivity analysis conducted on the shipping cost by weight ($\text{\$/MT}$) of wood flour by increasing and decreasing the input variables (travel distance, shipment weight, and shipping cost over distance) by 5, 10, and 15%.

The input variables (i.e., travel distance, shipment weight, and shipping cost over distance) were changed either one, two, or three at a time. The value of the shipping cost by weight for wood flour and pellets ranged between \$20 and \$50 per MT and \$20 and \$38 per MT, respectively. The average of the total shipping cost for both feedstocks was \$866 per trip. In addition, the shipping cost by weight over distance for the wood flour and the wood pellets was \$0.11 and \$0.08 per MT·km, respectively.

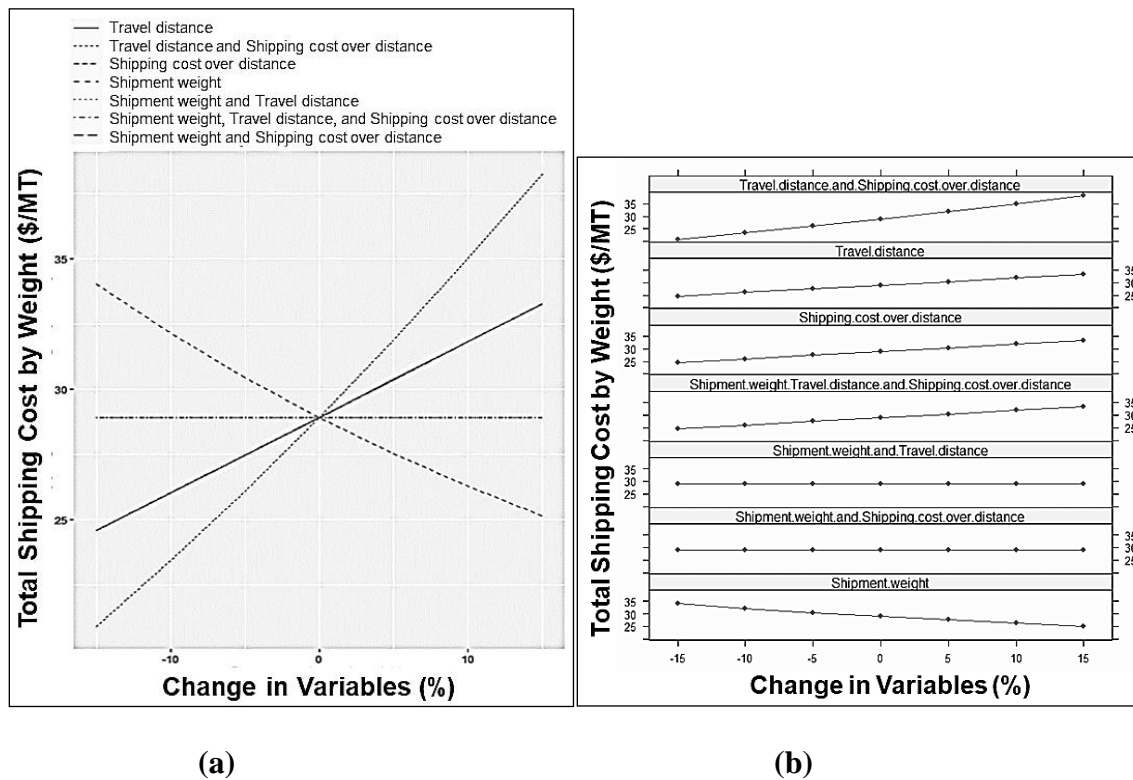


Figure 4.5 The sensitivity analysis conducted on the shipping cost by weight (\$/MT) of wood pellets by increasing and decreasing the input variables (travel distance, shipment weight, and shipping cost over distance) by 5, 10, and 15%.

The sensitivity analysis showed that total shipping cost by weight was directly related to the travel distance and shipping cost over distance for both feedstock (Figures 4.4 and 4.5). The shipment weight (MT) was inversely related to the transportation cost by weight (\$/MT) and had the highest impact on the latter while keeping other input variables constant. Conversely, the

combined change induced to the other variables (i.e., shipment weight and travel distance; and shipment weight and shipping cost over distance) did not affect the shipping cost by weight.

4.4.3 Logistics Scenarios

Fluctuation in shipment weight

The total shipping cost of wood flour by weight (\$/MT) increased by 5, 11, and 18% in response to a 5, 10, and 15% decrease in the shipment weight, respectively, when compared to the baseline (i.e., Case III, II, and I). However, when increased by the same values (i.e., Case V, VI, and VII), the total shipping cost by weight decreased by 5, 9, and 13%, respectively. Similar percentage changes were obtained for the wood pellets (Table 4.2).

Table 4.3 The shipping cost by weight (\$/MT) with the change in shipment weight (MT) of wood flour and wood pellets.

Cases	Wood flour		Wood pellets	
	Shipment weight (MT)	Shipping cost by weight (\$/MT)	Shipment weight (MT)	Shipping cost by weight (\$/MT)
I	19	46	26	34
II	20	44	27	32
III	21	41	28	30
IV (baseline)	22	39	30	29
V	23	37	31	28
VI	24	36	33	26
VII	25	34	34	25

Fluctuation in travel distance and shipping cost over distance

Table 4.4 The shipping cost by weight (\$/MT) with the change in travel distance (km) and shipping cost over distance (\$/km) separately.

Cases	Travel distance (km)	Shipping cost over distance (\$/km)	Shipping cost by weight (\$/MT)	
			Wood flour	Wood pellets
I	316	1.98	33	25
II	334	2.10	35	26
III	353	2.21	37	28
IV (baseline)	371	2.33	39	29
V	390	2.45	41	30
VI	409	2.56	43	32
VII	427	2.68	45	33

When the travel distance was decreased and increased by 5, 10, and 15% from the base value, the total shipping cost by weight also decreased and increased by 5, 10, and 15%, respectively (Table 4.4). Both the wood flour and the wood pellets had the same trend in terms of similar fluctuation of shipping cost over distance (\$/km) on shipping cost by weight (\$/MT).

Effect of combined changes

The combined changes in shipment weight and travel distance as well as combined changes in shipment weight and shipping cost over distance had no effects on the shipping cost over weight. The shipping cost over weight for the wood flour and pellets remained a constant of 39 and 29 \$ MT⁻¹ (respectively) for both cases.

Table 4.5 The Shipping cost by weight (\$/MT) with the change in the travel distance (km) and the shipping cost over distance (\$/km) as well as the change in the weight of the shipment (MT), distance (km), and shipping cost over distance (\$/km).

Cases	Shipping cost by weight with a change in the distance and shipping cost over distance		Shipping cost by weight with a change in weight of the shipment, distance, and shipping cost over distance	
	Wood flour	Wood pellets	Wood flour	Wood pellets
I	28	21	33	25
II	32	23	35	26
III	35	26	37	28
IV (base case)	39	29	39	29
V	43	32	41	30
VI	47	35	43	32
VII	52	38	45	33

The shipping cost by weight of both wood feedstocks decreased by 10, 19, and 28% when the travel distance and shipping cost over distance decreased together by 5, 10, and 15%, respectively (Case III, II, and I). Likewise, the shipping cost by weight increased by 10, 21, and 32% when these variables increased by 5, 10, and 15%, respectively, from the base values (i.e.,

Case V, VI, and VII) (Table 4.5). On the other hand, as the shipment weight, travel distance, and shipping cost decreased over distance by 5, 10, and 15% (Case III, II, and I), the shipping cost by weight decreased by 5, 10, and 15%, respectively. When these three variables increased by 5, 10, and 15% (Case V, VI, and VII), the shipping cost by weight increased by the same percentage, respectively (Table 4.5).

The analysis showed that changing the three variables (shipment weight, travel distance, and shipping cost over distance) in varying degrees resulted in an average increment of 26% shipping cost by weight in wood flour compared to that of wood pellets.

4.4.4 Raw material supply chain

The OD cost matrix tool computes the most appropriate travel route based on road types and their speed limits. Since both the WPC manufacturers were in the southern part of the states, wood mills near them have the advantage of shorter travel distances. However, the wood resources (timberlands) are concentrated in the northern and western part of ME. Although the southern region has less travel distance to supply the wood feedstocks for WPC, the northern and western mills have much more access to the timber supply at a lower delivery cost.

Wood processing facilities are dispersed throughout ME. The higher concentration of wood facilities towards the southern part of ME is because of the potential markets for the final product (wood flour and wood pellets), rather than the procurement zone of the raw material. There is a cluster of these companies ranging from secondary wood products manufacturers to biomass energy and power firms to sawmills. They have a greater connection and dependency on one another for the development and raw material procurement (Colgan et al. 2002). The wood-

based facilities export a significant amount of forest-based products to New England, New York, and the Mid-Atlantic states (Department of Conservation-Maine Forest Service and Maine Technology Institute 2005).

4.4.5 Sensitivity analysis graphs

Of the seven different sensitivity analyses performed, only four showed a distinct trend (Figure 4.4a and Figure 4.5a). The combined changes in the shipment weight of wood feedstocks and the shipping cost over distance, as well as combined changes in the shipment weight and the travel distance presented straight lines parallel to the x-axis, as they did not influence the shipping cost by weight (\$/MT). Furthermore, the values of the shipping cost by weight versus the travel distance, shipping cost over distance, and combination of all three (shipment weight, travel distance, and shipping cost over distance) remained the same. Here, the shipping cost by weight increased as the percentage values of input variables increased and vice-versa. In summary, the wood flour and wood pellet sensitivity graphs follow a similar pattern but with different numerical values of shipping cost by weight (\$/MT).

In general, residues (feedstock) generated from forest products industries have low-value and bulk density attributable to which cost-effective means of transportation becomes a challenge (Department of Conservation-Maine Forest Service and Maine Technology Institute 2005). Density is an important factor that affects the transportation of wood products (Abdoli et al. 2018). Shipping wood flour costs more than shipping sawdust (Reineke 1966). The volume of the goods to be shipped can directly affect the road transportation costs (Mokhirev et al. 2019). The lower bulk density of wood flour can result in the shipping cost exceeding the feedstock's

actual price (Pokhrel et al. 2021a). This is because the loaded truck trailer has not attained the maximum legal load capacity. Likewise, factors such as moisture content, particle size, composition of the feedstocks, pressure, temperature, and die diameter of the pellet mill can affect the unit or bulk density of wood pellets (Tumuluru 2016). Materials with a higher moisture content, a larger particle size, and a higher temperature and pressure during processing of the materials can increase the unit/bulk density (Beauchemin and Tampier 2008).

4.4.6 Logistics scenario evaluation

Based on the shipment weight for both feedstocks, the best case of shipping cost by weight was observed when the shipment weight increased by 15% (Table 4.3). Likewise, the worst-case was observed when the weight of the shipment decreased by 15% from the base-case scenario.

On the other hand, individually considering the travel distance and shipping cost over distance yields a converse result. For both these input variables fluctuation, the best-case scenario was observed by decreasing their respective values by 15% (Table 4.4). Likewise, the worst-case scenario was observed on increasing their respective values by 15%. The reduced travel distance resulted in more trips per day, which enhanced the truck utilization. The savings from the longer travel distance of the wood pellets over wood flour could compensate for the extra step of compacting wood flour into pellets before transportation, followed by pulverizing the pellets back to wood flour after reaching the WPC processors. The optimum economic shipping distance and weight for similar feedstocks such as wood chips were within 386 km and

30 tons, respectively (Gonzales et al. 2013). The authors suggested that shipping via truck is economical to reach shorter destinations by carrying the goods with less volume.

The shipping cost by weight did not have best or worst-case scenarios based on the combined changes in the shipment weight and the travel distance along with the combined changes in the shipment weight and the shipping cost over distance. Considering the combined changes in travel distance and shipping cost over distance, decreasing by 15% from the baseline gave the best-case of shipping cost by weight for both wood feedstocks. Likewise, the worst-case was observed on increasing the values by 15% (Table 4.5).

In addition, in changing three variables at a time, the best case was also observed by decreasing all the variables below the baseline scenario and worst case by increasing all the variables above the baseline by 15%, respectively (Table 4.5). The shipping cost by weight had a direct relation with two variables (i.e., travel distance and shipping cost over distance) and an inverse relation with the shipment weight. Attributable to the combination of variables having more influence than just one, there is a direct relationship between the increase or decrease of a pair of variables and the shipping cost by weight.

Increasing the weight of the shipment from the baseline value reduced the total shipping cost over distance. However, trucks cannot be loaded over their legal GVW, which limits the applicability of the effect of shipment weight on reducing the transportation costs (Department of Conservation-Maine Forest Service and Maine Technology Institute 2005).

4.4.7 Shipping of wood flour and pellets via truck

With respect to other biomass fuels, wood pellets are easy to handle, store, and transport (Proskurina et al. 2016). When transporting wood pellets, bulk density is expected to decrease as the pellets break and produce smaller particles during long-distance transportation (Sjöström and Blomqvist 2014). Pellets may break either through splitting into two or more pellets but keeping their cylindrical shape, weakening of pellet surfaces and ends, and crushing of the whole pellet (Thomas 1998; Boac et al. 2008; Oveisi et al. 2013). However, this could be advantageous for WPC manufacturers, as the wood feedstocks needs to be re-ground for feeding into the extruders. Low-density biomass creates difficulties during feeding, handling, and transportation (Tumuluru 2016). During road transportation, wood flour is limited by volume whereas pellets are limited by shipment weight. For example, a fully loaded containment with wood flour wouldn't reach the maximum GVW and conversely, the containment with the wood pellets that had the same weight as the wood flour would have extra space available.

The selection of an appropriate truck and trailer depends on the geography, road conditions, and climate (Koirala et al. 2017b). Trucks are popular because of their ease of accessibility and well-developed road network in the region. Based on the theoretical calculations of bulk density and total volume for wood pellets, the shipment weight of a fully loaded truck should be approximately 72 MT. This would then reduce the shipment cost by weight for wood pellets by approximately 69% compared to wood flour. The described ideal situation of reducing the cost for shipping wood pellets as opposed to wood flour could be attainable through other forms of transportation that can carry huge shipment weights (e.g., train). However, because of the shipment weight limits on trucks, the transportation cost of wood

pellets is 25% less expensive than wood flour. The handling and transportation costs for the densified biomass are lower than that of the unprocessed feedstock (Gonzales et al. 2013). As a result, densifying products for long distance transportation is a procedure worth exploring. Decreasing the size of the compressed biomass can increase the number of unit operations involved such as grinding (Sokhansanj and Turhollow 2004).

4.4.8 Alternatives to trucking

Considering other forms of transportation, railroad lines can accommodate loaded railcars of 130 MT or greater but significant portions of the rail network in ME can only accommodate 120 MT rail cars (ME Department of Transportation 2014). Maine has 1,770 km of rail oriented predominantly east-west where the forest products industry is the primary customer base (ME Department of Transportation 2014; ME Department of Transportation 2017). For railway transportation, the major factors that affect the costs can be ownership of the railcar, service provider, shipment origin and destination, and competition with the other transportation modes (Gonzales et al. 2013). However, rail transportation in general offers higher shipment weights and lower long-distance transportation costs than trucks. Therefore, rail could be considered the best mode for shipping wood feedstocks over longer distances. Improving accessibility to rail transport, increasing the numbers and size of rail cars, and private (shipper-owned and controlled) car fleets can improve railway transportation (Wilbur Smith Associates 2003).

4.5 Conclusions

- This study was carried out to address the current issue of high shipment costs of wood flour over long distances to supply WPC manufactures and explore the effects of various variables on the transportation costs. Furthermore, the increased interest of concerned stakeholders to explore

densified forms of wood flour in the region has led to the concept of utilizing wood pellets as feedstock for WPC manufacturing.

- The sensitivity analysis showed that in the study area, road transportation of wood pellets was at least 25% more cost-effective than the alternative feedstock, wood flour. We expect this could be at least 69% more cost-effective when considering other forms of transportation where the shipment load limit is high.
- Sourcing the wood feedstocks from the wood mills located in southern ME can lower the transportation costs, as they have closer proximity to WPC manufacturers.
- The best-case scenario was observed when increasing (maximum at 15%) the shipment weight of the feedstock and decreasing (maximum at 15%) the travel distance and shipping cost over distance from the baseline scenario. Increasing the shipment weight of the wood feedstocks decreased the shipping cost by weight the most compared to other input variables. The weight of the shipment is also related to the bulk density.
- The densification of the wood flour would benefit the WPC manufacturers in terms of transportation costs.

CHAPTER 5

LIFE CYCLE ASSESSMENT (LCA) OF ALTERNATIVE WOOD FEEDSTOCKS FOR MANUFACTURING WOOD-PLASTIC COMPOSITES (WPCs)

5.1 Chapter Summary

This study is a progression of previous studies that were focused on the material properties and transportation costs of the two wood feedstocks for manufacturing wood plastic composites (WPCs): wood flour and pellets. Besides material properties and cost analysis, life-cycle assessment (LCA) is equally important to assess the environmental impacts of alternative wood feedstocks to manufacture WPCs and gain the knowledge of influences from the manufacturing and transportation process. The main goal of this study was to compare the environmental impacts of the production and transportation of wood flour and pellets utilized in WPC manufacture. Wood pellets as alternative feedstocks were compared to commercially utilized wood flour. The environmental impacts on air, water, soil and human health, as well as energy consumption for one ton and one truckload production and transportation of the 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 starting from processing of the mill residues to manufacturing the two feedstocks and transporting them to commercial WPC manufacturers. LCA analysis showed that transportation of either of the two feedstocks had the highest impact on the environment as opposed to the inputs associated with production. The global warming potential (GWP) from one ton production and shipment of wood flour was higher by 8% compared to the pellets. One ton production and shipment of wood pellets appears more environmentally friendly compared to wood flour. Normalization results of one truck load of wood flour (22 tons) and pellets (30 tons) showed similar environmental impacts. From this

study, from an environmental perspective, it is inferred that besides use as bio-fuels, wood pellets could be an alternative raw material feedstock for the manufacture of WPCs.

5.2 Introduction

The global movement towards sustainability has increased interest in the utilization of natural resources. Wood and wood-based products are among the most important resources leading towards a sustainable future. Wood applications in several industries such as building materials, renewable energy, chemicals, biofuel, etc. and more current research explorations have increased demand on forest resources. In the United States, the contribution of wood and wood-based fuels for the production and consumption of renewable energy sources was around 20% in 2017 (US EIA 2019). The concept of renewable energy is more prominent especially in transportation, electricity, and heating sectors with greater demand for wood fuels (Oliver & Khanna 2017). By 2030, due to the higher demand, there are concerns that wood from sustainably managed forests may become scarce (Sommerhuber et al. 2017, Mantau et al. 2010). Thus, efficient utilization of forest resources becomes a prime focus for society. One of the principles for this is the cascading use of biomass. This concept drives the end-of-life (EoL) alternatives to prioritize alternative ways in finding applications for wastes or waste management through prevention, re-use, recycling (without incineration), recovery (e.g., energy), and disposal. Besides cascading, for the recycling and circulation of waste materials, the idea of the circular economy is highlighted in the European Union (European Commission (EC) 2011, EP 2015) as well as ProgRess in Germany (BMUB 2015) with a focus on minimizing the consumption 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 (EC 2018).

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 impacts from each life cycle stage of a product/system to the environment (Hunt et al. 1992, Curran 1996). LCA is a tool to help measure sustainability. The entire life cycle of a product from “cradle-to-grave” or “cradle-to-cradle” is a holistic way to analyze the total environmental impacts from acquisition of raw materials, processing, consumption, and transportation, to final disposal of a product (Xu et al. 2008). Shifting from one life cycle stage to another without any hurdles, identification of major “hot spots” in the life cycle, and accounting for impacts to the environment and resource use are the merits of LCA analysis (Rajendran et al. 2012). Use of standards-based tools from the International Organization for Standardization (ISO) is critical in performing the analysis where ISO 14040 and ISO 14044 are the major standards. Results of LCA have greater implications in several sectors for decision making (Baumann et al. 2002), waste management (Correia et al. 2011), materials (Scharnhorst et al. 2005), design and processing technologies (Alves et al. 2010), and industrial ecology (Baas & Boons 2004). Similarly, the cumulative energy demand (CED) is useful method in assessing the direct and indirect energy usage in all life cycle stages of a product. Renewable energy (RE) and non-renewable energy (NRE) consumption can be analyzed from the CED outputs.

Secondary processing of mill residues generated from wood production facilities (once the wood is utilized for products manufacturing) have various potential applications including manufacturing. The subsequent products made utilizing the residues from wood processing can have low carbon emissions and also less impact on the forest (WWF 2016). One of the promising applications of wood residues is producing the raw materials for manufacturing wood plastic

composites (WPCs). WPCs are bio-based composites with applications in building materials such as decking (Bolin & Smith 2011; Sun et al. 2017), automotive such as the interior parts (Ashori 2008), and other consumer products. WPCs are attractive to industries attempting to address bio-economy concepts. WPCs have greater potentialities towards the efficient use of biomass than recovering the biomass for energy applications (Teuber et al. 2016). WPCs can be more environmentally friendly compared with pure plastic products but can be less environmentally friendly than pure wood products. Recycled plastic-based composites can have more environmental benefits than virgin-based plastics (WRAP 2016). Additives used during WPC manufacturing to enhance the performance are synthesized from polymers that may have a negative influence on human health and surroundings (Thompson et al. 2009). Petroleum-based polymers such as polyethylene (PE), polypropylene (PP), polyvinyl chloride, etc. incorporated in WPCs have deleterious effects in the cradle-to-grave life cycle (Rajendran et al. 2012). Significant research work on the application of different types of natural fillers such as fibers from flax, sisal, hemp, kenaf, jute, and many more have been carried out. Wood fiber reinforced polymers exhibit the most desirable performance properties over alternate natural fibers. While wood fiber fillers can increase the weight for automotive applications, these product applications can still lead to sustainability (Witik et al. 2011). With an important functional characteristic being material density, the environmental impacts of pure PP products were severe in comparison to wood flour – PP composites (Xu et al. 2008).

Literature on past LCA evaluations of WPCs focused on a comparative study of WPCs using different raw materials (e.g., wood, fiberglass, etc.) and based on the recyclability of the raw materials (virgin versus recycled materials) (Liikanen et al. 2019). LCA research from

Sommerhuber et al. 2015, Vantsi & Karki 2015 have suggested that WPCs made with the use of wood feedstocks from recycled waste wood have lower environmental impacts for the different categories such as global warming, acidification, eutrophication, and abiotic depletion compared to virgin wood. A similar case holds with the use of virgin versus recycled PP. Wood flour is a popular raw material commonly used in the commercial manufacture of WPCs which can be produced from mill residues. Pokhrel et al. 2021 (a) and Pokhrel et al. 2021 (b) have pointed out that besides wood flour, wood pellets can be an alternative wood feedstock with the potential to be used as a filler in the plastic matrix. Wood pellets, which are a compressed form of wood flour were explored. The main goal was to reduce the transportation cost of shipping the raw materials over long distances. The authors focused on the material properties of the composite products using wood flour and pellets separately in a PP matrix along with processing additives. Pokhrel et al. 2022 also discovered with respect to wood flour, transportation of pellets can be cost effective by at least 25% in a truck and at least 69% in other transportation mediums having a higher shipment weight limit.

This study is a follow-up to that study to understand the environmental effects during the production and transportation of wood flour versus wood pellets. LCA analysis on the manufacturing of wood pellets is abundant. However, an LCA study on wood flour is not available in the literature. Based on the material types, sizes, as well as management strategies, there are several classifications of wood pellets (Deviatkin et al. 2019). Conversion of materials into pellets makes it convenient for collection, storage, and transportation. The global wood pellet market was up to 6.87 billion units in 2018 (Nicholas 2020) and in 2019, the production was 123 million for European Pellets Association (EPAL) approved wooden pellets and from

other carriers (EPAL 2020). The highest market share is of wood pellets followed by plastic pellets (Leblanc 2020, Khan et al. 2021). Koc1 2019 mentioned that the weight of the pellets has a notable impact on the environmental performance of this product. 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, focusing on CO₂ emission and CED, of the two feedstocks i.e., wood flour and pellets during the production process to the logistics over a truck transportation. This is a cradle-to-gate analysis considering one metric ton (MT) and one truckload of the two feedstocks as the functional units for two separate LCA analysis to study the environmental impacts and compare 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 with the input variables in SimaPro software, impact assessment (characterization) under the categories as 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 two feedstocks were compared. Similarly, using CED-LHV methodology, the consumption of different renewable (biomass, water, and wind, solar, geothermal) and non-renewable (fossil, nuclear, and biomass) energy sources for the two wood feedstocks are compared.

5.3 Experimental Procedures

5.3.1 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 (Maine Woodland Owners). The wood mills generate around 1.6 million tons of residues each year (FOR Maine 2018). However, several ups and downs in the state with closure of many paper mills, instability of biomass power plants and pellet mills, etc. have caused a great problem in the outlet of these residues (Indufor North America LLC 2018). 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 is motivated to find potential solutions to effectively and efficiently use these residues. As mentioned in the introduction section, we already carried out a material property focused study. In this study, we are focusing on the prospective impacts on air, water, soil, or human health as well as depletion of renewable and non-renewable energy sources attributable to the production and transportation of two different wood feedstocks: wood flour and pellets from mill residues. Furthermore, this study can be a representative study for the NE region of the US.

5.3.2 Goals and Scope of the study

As mentioned in the introduction section, this study is a follow-up to the previous studies 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. 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, comparative CED analysis is also carried out. The mill residues as byproducts for the production of 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.

Researchers, practitioners as well as business personnel, basically targeted in WPC applications or other potential applications are the focused users of the output of this study. 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, 71.03% and 73.42% were from sawmill operations for hardwood and softwood respectively. Pulpwood chipped offsite by the pellet plant was 28.97% and 26.58% for hardwoods and softwoods respectively (J. Linkletter, personal communication, October 5, 2021). 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 towards creating a more thorough understanding of the entire manufacturing process.

5.3.3 Life Cycle Assessment (LCA) Comparative analysis

ISO 14040 (2006) and ISO 14044 (2006) were followed in this LCA analysis. The LCA results are compared for the two wood feedstocks: wood flour and pellets in their production and transportation process to supply to the WPC manufacturers. The transportation process has a considerable negative impact on energy consumption (Magelli et al. 2009) thus, we have included transportation of the feedstock 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 acquiring raw materials with transportation to the manufacturing site, and the manufacturing of the products – wood flour and pellets (Yu & Chen 2008), then transportation of the wood feedstocks to the WPC manufacturers. During the cradle-to-gate LCA analysis, the input and output datasets are considered to be convenient, concise, and appropriate as they are directly obtained from the manufacturers of the products (Magelli & Bi 2007, Vink et al. 2007). 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.

5.3.4 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 (ISO 14040). 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 metric ton (MT) of the feedstock products and the other as the one truckload of the feedstock products. One truckload can hold 22 tons of wood flour or 30 tons of pellets based on the vehicle weight limit and truck size in our study region. One ton 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.

5.3.5 Unit processes and system boundary

The unit processes and system boundaries are shown in Figure 5.1 below. 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.

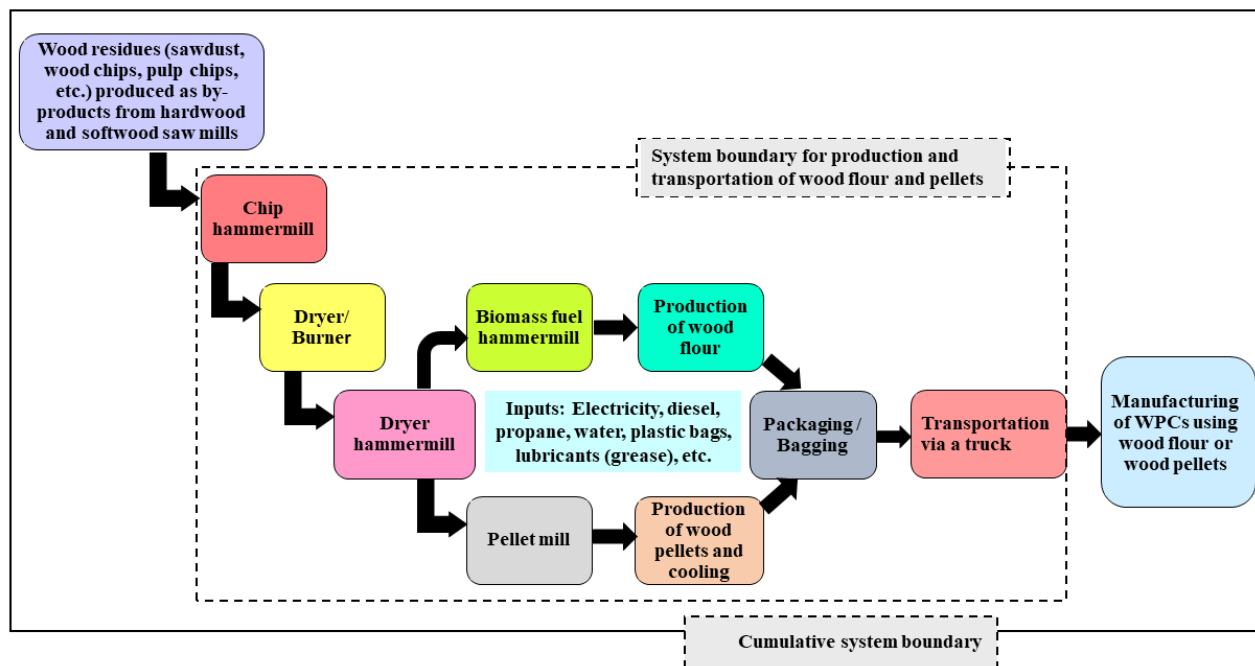


Figure 5.1 Unit processes and system boundary of the study.

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 hardwood species used in the production include almost all found in the region, mostly maple and birch except poplar and oak. Similar to hardwoods, almost all softwood species available in the region, mostly spruce-fir and hemlock were used except cedar attributable to considerable ash generation of the combusted product. The requirement of residues in terms of weight was double in comparison to the amount of the pellets formed e.g., to produce one ton of pellets required two tons of residues. The average initial moisture content of the residues was 45-50%.

b) Chip hammer mill: Since a majority 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 500 HP.

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 50 MMBTU which could dry the residues up to 7-10% of moisture content (wet basis). Less than one ton of the residues (0.74 tons) were dried per hour. However, during winter, more heat energy is required for drying the frozen biomass. Propane is required for the burner in a dryer. 80 gallons (302.83 liters) 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 500 HP. 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 named 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 this hammermill. There were two screens used with the size being 1.6 mm. The machine capacity was 250 HP producing wood flour at the rate of 0.75 tons/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 used in the plant with the capacity of each 400 HP and a total of 1600 HP 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 tons of pellets per hour. The moisture content of the produced pellets is 5-6% (wet basis).

g) Cooling: Once the pellets are pelletized, they are very hot so, need to cool to the ambient temperature. A cooler of 0.25 HP motor was used to cool them that would take about 20 minutes to cool the pellets of about three feet deep.

h) Packaging/Bagging: Pellets were fed by conveyor to the bagging station where the packaging robots running through electricity could pack the pellets. PE bags were used for bagging. They are packed into 18.14 kg (40 lbs) plastic bags and 50 bags of these were packed together by another outer plastic cover. Each full stack of 50 bagged pellets contains one ton of pellets. Similarly, silos used by the customers who want a bulk of pellets don't require any plastic bags. The plant had silos of 68 tons, 113 tons, 408 tons, and 32,658 tons. On the other hand, 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 45 ft³ volume and 0.45-4.81 tons 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, 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 MT with volume ranging from 98-114 m³. 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 operations. The mill would shut down for cleaning once every two weeks and this would require 20 gallons (75.71 liters) of water each time. The water could be well water or the water stored in a fire hydrant (225,000 gallons of water). Similarly, lubricants (grease) per pellets machine were purchased in barrels. Each pellet mill would require 12 ounces of grease per hour. So, four pellet machines require $4 \times 12 \times 24 =$

1152 ounces (34.07 liters) per day and loaders require 1000 ounces (29.57 liters) of 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, we were able to collect the data for each component of the pelletization. The source was 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 hammermill 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.

5.3.6 Life cycle inventory (LCI) for modeling

The questionnaires related to the consumption of resources/fuels/materials from each unit processes 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 almost all 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 tons of pellets or 318-

363 tons of pellets per day. The plant operates 24 hours and 7 days a week. The pellet mill is not collocated with other wood products 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, the New England region, or Canada. Thus, hardwood and softwood sawdust at sawmill (green), hardwood and softwood wood chips at sawmill (green), and pulp chips at 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 5.1 of the results section. 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) were chosen to source the LCI datasets since they are based on the US manufacturing and electricity data included in the 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 in the system boundary. Life Cycle Impact Analysis (LCIA) can calculate the environmental loads for each unit process concerning the considered functional unit.

5.3.7 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 (Bare 2011). The TRACI method is focused on the US prepared by the US Environmental Protection Agency. It is a midpoint-oriented method. Besides, environment-related impacts, impacts to human health were also examined in the assessment process. A total of 10 impact categories were reported for both wood flour and pellets comparative study. These include: ozone depletion (kg CFC-11-eq), global warming (kg CO₂-eq), smog (kg O₃-eq), acidification (kg SO₂-eq), eutrophication (kg N-eq), carcinogenic (CTUh), non-carcinogenic (CTUh), respiratory effects (kg PM_{2.5}-eq), Ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus). Likewise, the total primary energy input was quantified based on the LCI results using the Single-issue method – CED version 1.00. 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 of 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 alternative wood feedstocks, normalization of impact categories relative to the reference in SimaPro (Ryberg et al. 2014) 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/ton and wood pellets is 19,538 MJ/ton. Besides these

factors, economic indicators could also be a basis for normalization but this is beyond the scope of the study.

5.3.8 Assumptions

- 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 very fine like wood flour so, we have considered it as “wood flour” for comparison with the wood pellets.
- 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.
- All the equipment in the pellet plant was single in number 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.

5.3.9 Limitations

The wood flour produced in this case study was not applied in WPC manufacturing, instead was used 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 in 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 residues types. Wood flour typically uses secondary residues that are already partially dried whereas pellet producers can use green as well as dried feedstocks. Additional drying process of the raw materials changes the LCA results in a large way (Hagberg et al. 2009). Most of the time wood flour facilities are collocated with the industries producing wood products, generating residues as their byproducts. Similarly, for large-scale production of WPCs, wood flour is never obtained in bags and for industrial wood pellets as well bags are not used, but for residential, lots of bags are used. 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 collocated 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.

5.4 Results and Discussion

5.4.1 Material Flows

The values of the input variables considered in this study are presented in Table 5.1. As described in the methodology section, the production step of both wood flour and pellets is

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 (Reed et al. 2012); which applies to our case study as well. A similar situation holds for the wood flour which is clearly explained in section 2.5.

Table 5.1 Input variables for the production and transportation of one ton of wood flour and pellets along with their LCI dataset chosen in SimaPro. All the inputs datasets' name are similar for wood flour and pellets except the plastic bags used for bagging/packaging.

LCI Dataset	Values for wood flour	Values for 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

All the inputs' values for both feedstocks were 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 (IQS Directory). That is why wood pellets with almost four times

heavier density than wood flour are packaged in PE bags and wood flour in PP bags. From an environmental point of view, both of the plastics 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 pellets i.e., pellet mill consumed different amounts of electricity. The average electricity used in the production of one ton of wood flour by hammermill was 6 kWh and wood pellets by pellet mills were 18 kWh. One ton of bone-dried wood residues can produce one ton of bone-dried wood flour or pellets (100% yield) (Reed et al. 2012). 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 heavyweight of the residues. Table 5.2 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 5.2 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 is obtained from the mill in the visit.

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

5.4.2 Analyzing impact assessment for one ton of wood flour and wood pellets

The different impacts from input variables (wood residues, lubricants, electricity, diesel, propane, plastics, and transportation) and material flow in the production and shipping of one ton of wood flour and pellets are shown in Figures 5.2 and 5.3 respectively. 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 emission 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. Particulates and CO_2 are typically measured, although other emissions are frequently monitored from boilers to ensure regulatory compliance. Wood and coal combustion efficiency are typically measured by the amount of particulate emitted.

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 application of diesel in truck transportation intensifies the 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 an LCA study of the production of softwood lumber (Bergman and Bowe 2010). 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 the softwoods, hardwoods, in general, require more energy to harvest as well as mill process and also the higher shipping costs. In our study, the weight of hardwood sawdust is higher compared to the hardwood chips, thus its influence is more than the hardwood chips.

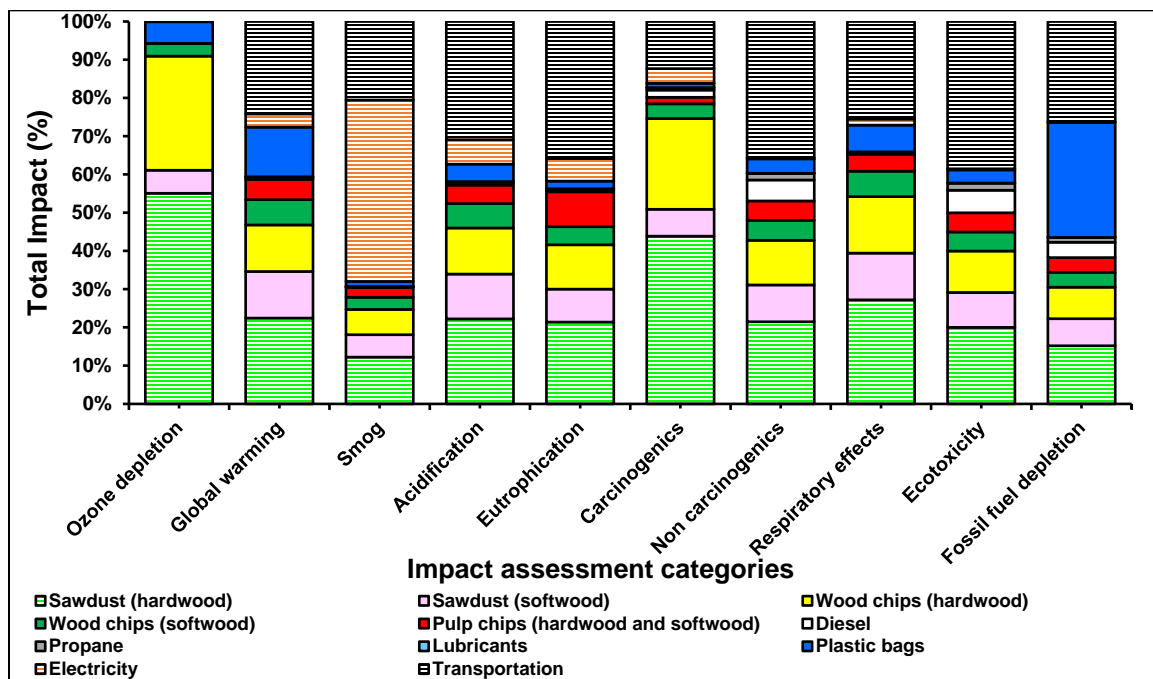


Figure 5.2 Impact assessment graph showing the relative contribution of the inputs for one ton of wood flour.

Previous studies (Milota et al. 2005, Bergman and Bowe 2008) have shown differences in the energy consumption or environmental impacts between the hardwood and softwood lumber manufacturing is attributable to the differences in the density of the wood species and electricity

profile in between different regions. However, in our study the electricity profile is considered in a similar region. Past LCA studies have shown the impact of electrical energy, based on coal and natural gas to be highest on the environment. Usually, the combustion of coal and natural gases in the generation of electricity increase GHG emissions. The highest impact for GHG emissions was from electricity and pellet mills used the most energy for the agricultural pellet plants (Maryam et al. 2020). Drying consumes the highest proportion of fuel (Bergman and Bowe 2008). Similar to that, Bergman and Sevda 2016 observed electricity and natural gas consumption had the maximum impacts. Besides GHG emissions, the impact of wood processing steps was severe to the eutrophication due to electricity (Sevda et al. 2021). However, in our study, since the electricity was generated from biomass the effect is less severe to the environment compared to some other inputs such as transportation and green sawdust from hardwoods.

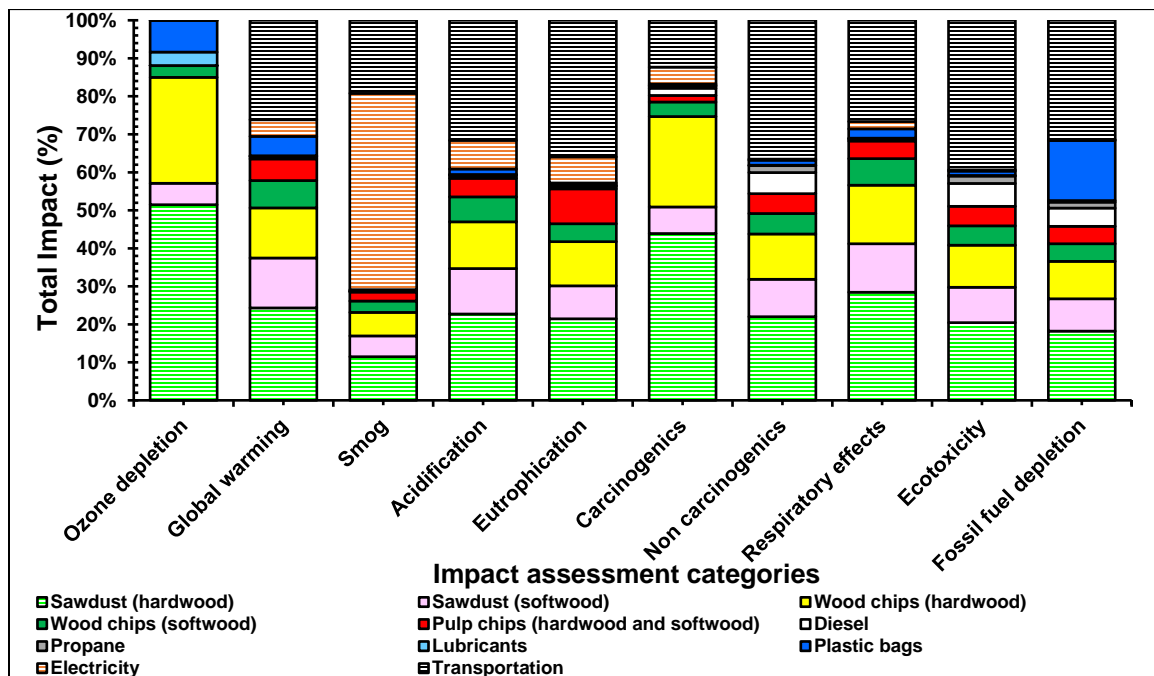


Figure 5.3 Impact assessment graph showing the relative contribution of the inputs to the one ton of wood pellets.

The impact from transportation was the most severe to global warming, acidification, eutrophication, noncarcinogenic, and ecotoxicity for both wood flour and pellets. While, the impact from electricity use was the highest for smog production. The green sawdust from hardwood contributes most to the ozone depletion, carcinogenic, and respiratory effects. The effect of plastic bags 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 feedstock materials. The prominent effect of lubricating 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 whereas, for pellets, transportation had the most negative influence on fossil fuel depletion. This could be attributable to the severe impact of PP compared to PE and for the same quantity of the wood feedstock, the quantity of plastic bags required to bag the wood flour is higher than bagging 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 lubricants are used in the four pellets mills.

5.4.3 Comparative inventory assessment

Table 5.3 is the summary of major emissions to the air, water, and soil during the operations involving the production and shipping of the two feedstocks. The table also lists the

most influencing emission sources. The input variables causing the maximum emissions as well as not influencing the emissions were the same for wood flour or pellets except SO_x emissions. CO₂ (biogenic) and acrolein were not emitted from plastic bags. 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. The major emissions to air were from hardwood sawdust and for water was transportation. Bark was only generated from pulp chips without the influence of other production or transportation inputs. Thus, the major emissions were from hardwood sawdust and the other emissions (CO₂-fossil and biogenic, phenol, SO_x (only for wood flour), VOCs, suspended soils, COD, chloride, and bark) where it was not the top contributor, was the second major contributor.

In the comparative inventory assessment of one ton of each feedstock, the quantity (kg) of emissions of bark, acetaldehyde, and acrolein were the same. Emissions of BOD, chloride, COD, suspended soils, CO₂ (fossil), formaldehyde, methane, SO₂, SO_x, and VOCs were greater for one ton of wood flour as compared to the one ton of pellets. The rest of the emissions i.e., CO₂ (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 5.3 were higher for wood pellets compared to wood flour. However, the exception is with SO_x, which was greater for wood flour than pellets. Similarly, the CO₂ (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 tons) compared to the wood flour (22 tons) are obvious as more tons of production and transportation consumes more energy, materials, fuels, etc.

Table 5.3 Emissions to air, water, and soil associated with the production and transportation of one ton of wood flour and pellets from the mill residues. The most highly impacting inputs for each emission from each feedstock are the same except SO_x emissions.

Emissions	Wood Flour		Wood pellets		Highest impacting inputs
	Production (kg)	Transportation (kg)	Production (kg)	Transportation (kg)	
Emissions to air					
CO ₂ (fossil)	101.9	34.1	95.9	34.1	Transportation
CO ₂ (biogenic)	105.97	2.75*10 ⁻²	166.97	2.75*10 ⁻²	Electricity
Acetaldehyde	1.53*10 ⁻⁴	9.42*10 ⁻⁸	1.53*10 ⁻⁴	9.42*10 ⁻⁷	Hardwood sawdust
Acrolein	2.42*10 ⁻⁴	1.01*10 ⁻⁷	2.42*10 ⁻⁴	1.01*10 ⁻⁷	Hardwood sawdust
Formaldehyde	4.26*10 ⁻⁴	1.97*10 ⁻⁶	4.24*10 ⁻⁴	1.97*10 ⁻⁶	Hardwood sawdust
Phenol	1.03*10 ⁻¹⁰	2.39*10 ⁻¹²	3.26*10 ⁻⁹	2.39*10 ⁻¹²	Lubricants
NO _x	0.799	0.261	0.819	0.261	Hardwood sawdust
SO ₂	0.3385	0.0205	0.3155	0.0205	Hardwood sawdust
SO _x	1.54*10 ⁻²	2.12*10 ⁻⁷	7.86*10 ⁻³	2.12*10 ⁻⁷	Pellets-Hardwood sawdust, flour-PP
Methane	0.1501	4.69*10 ⁻²	0.1481	4.69*10 ⁻²	Hardwood sawdust
Particulates (unspecified)	0.741	3.51*10 ⁻³	0.742	3.51*10 ⁻³	Hardwood sawdust
VOCs (unspecified)	3.03*10 ⁻²	1.61*10 ⁻²	2.51*10 ⁻²	1.61*10 ⁻²	Transportation
Emissions to water					
Biological oxygen demand (BOD5)	0.1227	7.3*10 ⁻³	0.1217	7.3*10 ⁻³	Hardwood sawdust
Suspended soils	3.18	1.88	3.1	1.88	Transportation
Chemical oxygen demand (COD)	2.4*10 ⁻²	1.39*10 ⁻²	2.29*10 ⁻²	1.39*10 ⁻²	Transportation
Chloride	2.43	1.44	2.38	1.44	Transportation
Emissions to soil					
Bark	1.59	0	1.59	0	Pulp chips

5.4.4 Comparative impact assessment of the two feedstocks of different functional units

In Table 5.4, the different impact categories associated with the production and shipping of one ton and one truckload of wood flour and pellets are compared along with the differences in percentages. Similarly, in Figures 5.4 and 5.5, the impacts differences for one ton and one truckload of each feedstock at different categories are represented (by %) respectively.

Table 5.4 Environmental impacts associated with the production to transportation of one ton and one truckload of wood flour and pellets.

Impact category	Unit	Functional unit (one ton)			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 ₂ eq	146.33	135.20	7.6	3219.19	4055.87	20.6
Smog	kg O ₃ eq	56.74	60.53	6.3	1248.25	1815.97	31.3
Acidification	kg SO ₂ eq	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 depletion	fuel MJ surplus	283.28	236.52	16.5	6232.07	7095.74	12.2

For one-ton production and shipping of the wood feedstocks, relative to the wood flour, the impact on the environment attributable to the pellets were less for all categories except ozone depletion and smog. There was no difference in the carcinogenic impacts in between one ton wood flour and pellets. Thus, the percentage differences ranged from 0-16.5% as shown in Table 5.4. The major input imparting greater influence on wood flour compared to pellets could be the plastic bags. Wood pellets production required more electrical energy than flour, but the source being biomass for electricity generation the negative influence is much reduced by pellets. And even though the application of the lubricant varies for flour and pellets, its quantity is much less to make noticeable differences.

For one truckload production and shipping of the two feedstocks, wood flour showed higher reduction in all the evaluated impact indicators in this study, primarily attributable to the mass difference in the one truckload shipment. Compared to the one truckload of wood pellets (30 tons), the impact on the environment from one truckload of wood flour (22 tons) was smaller for all impact categories. The differences in the impact ranged from 12-30% on average as shown in Table 5.4. 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 tons of wood pellets production and transportation can have more environmental impacts when examined on the truckload functional unit. Still, the impacts are considerable to the wood pellets than flour for one truckload, with a difference of 8 metric tons of production and shipping. However, this may not be in favor to the cost analysis.

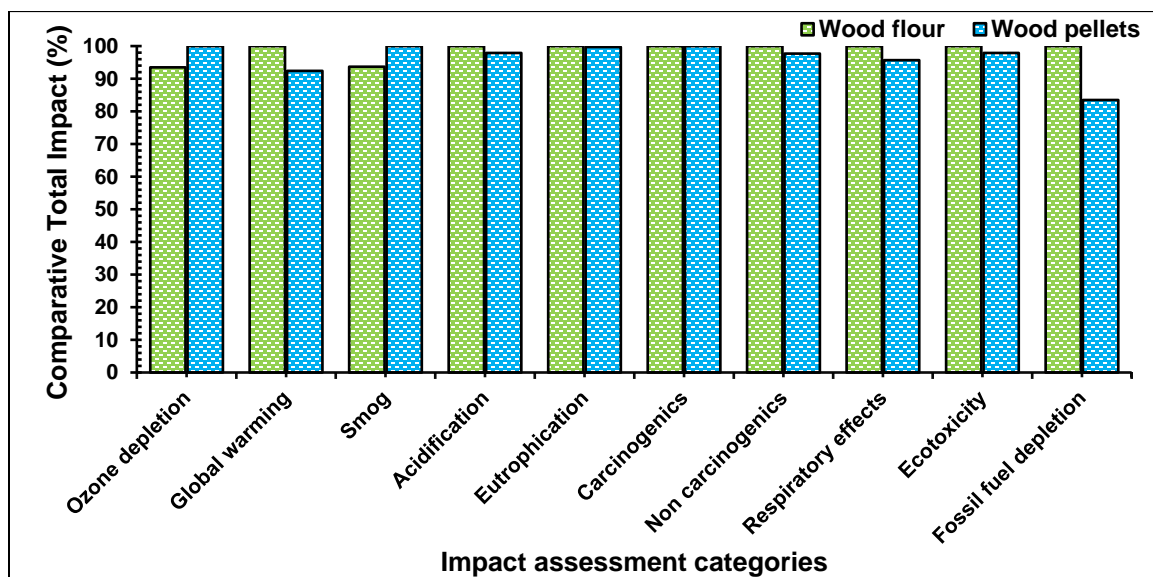


Figure 5.4 Comparative impact assessments for one ton of wood flour and pellets.

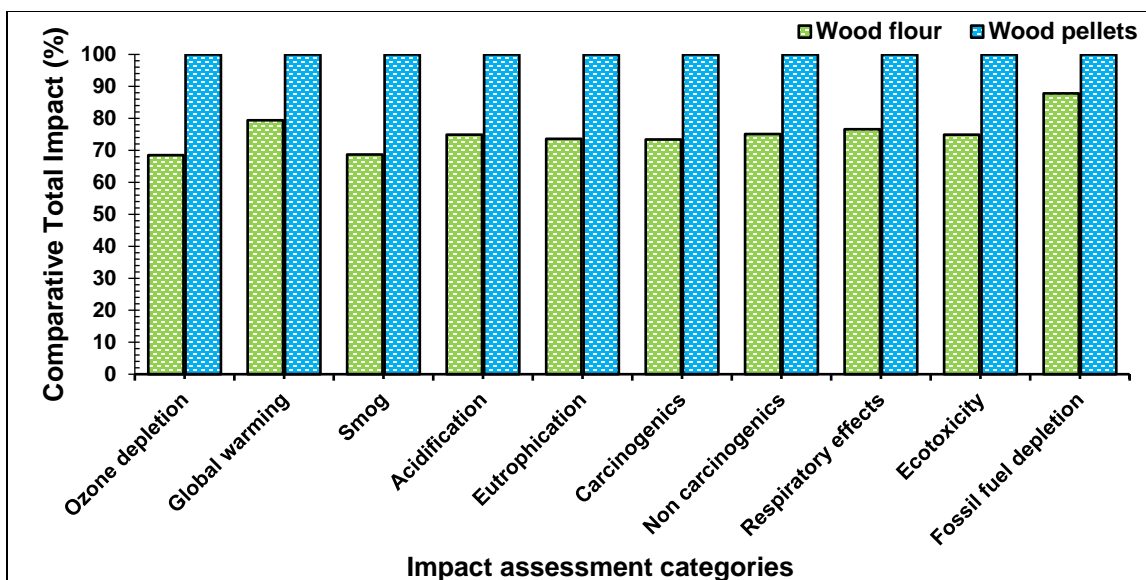


Figure 5.5 Comparative impact assessments for one truckload of wood flour and pellets.

5.4.5 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 is shown in Figure 5.6. 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. However, the differences in the rest of impact categories 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, in SimaPro by normalization, 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 for the present context, 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 the representative of the wood products industry.

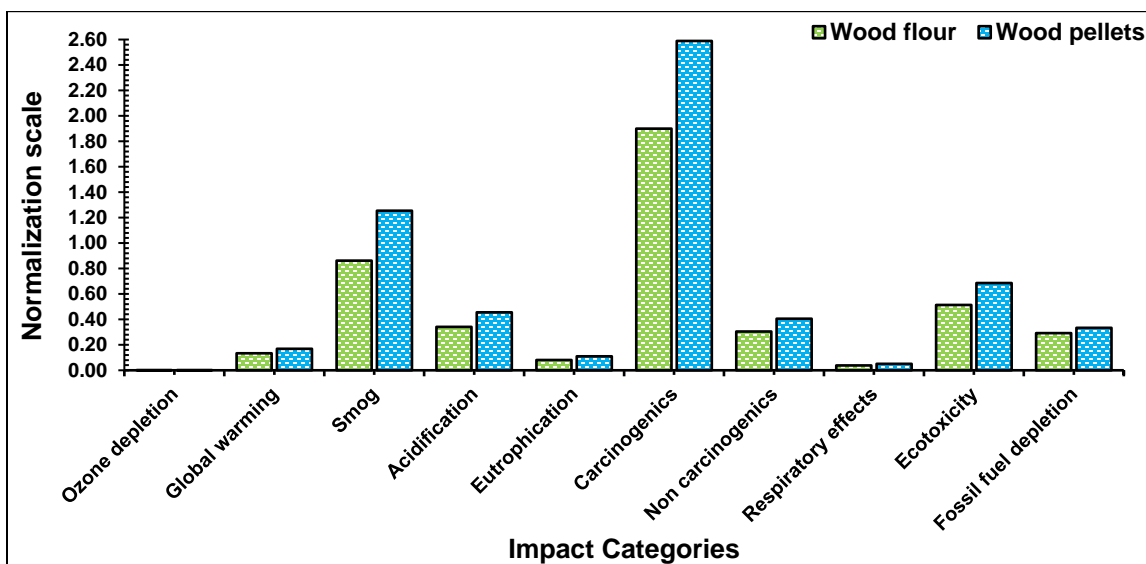


Figure 5.6 Comparative normalization based on SimaPro outputs.

In addition, normalization based on the LHV of the feedstocks indicated a negligible difference among the different impact categories for one truckload of each wood feedstock (Table 5.5 and Figure 5.7). Heating values emphasize the 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 values are represented in Table 5.5 and the difference in percentage are shown in Figure 5.7. 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 resulted impacts to the different aspects of environment such as: air, water, and soil as well as the 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

tons, the variation in the impacts for the truckload of wood flour and pellets are also influenced by the total heating values of the feedstocks and the normalization factors in SimaPro software.

Table 5.5 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

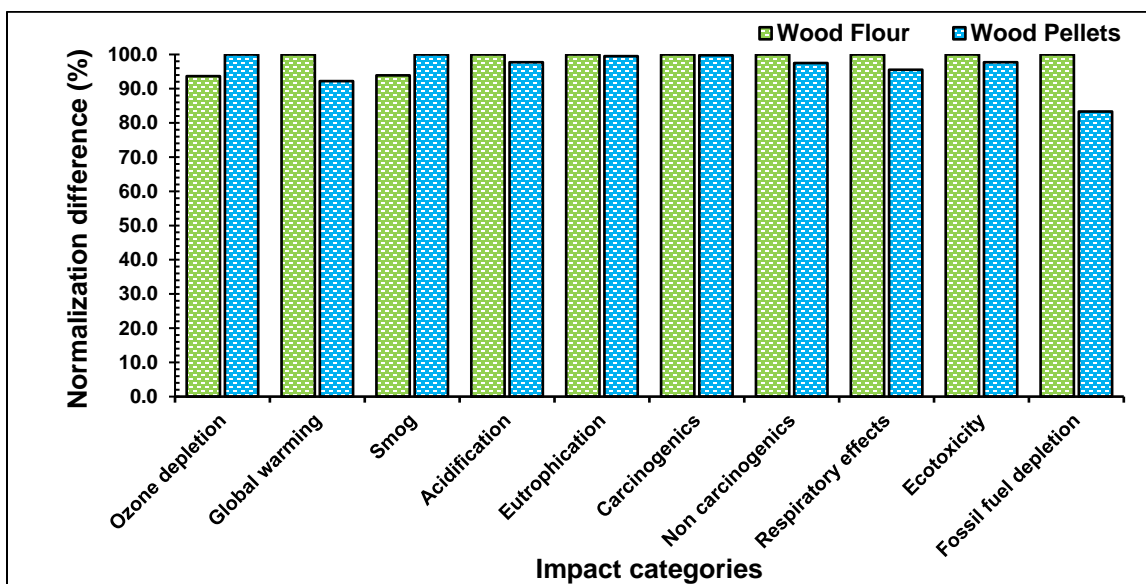


Figure 5.7 Comparative normalization based on the LHV of the wood feedstocks.

5.4.6 Global warming potential (GWP)

Out of several impact categories, the major focus is on the global warming potential (GWP) at present. The greenhouse gases (GHG) emission reduction strategies have been of keen

interest as the earth's temperature is increasing. Carbon tracking is crucial for global policy decision making tasks. CO₂, methane, and NO_x are the major contributing gases for the 100 year global warming potential (Maryam et al. 2020). The production and shipping of one ton of wood flour emitted more CO₂, methane, and NO_x compared to the pellets in this study. Similarly, the emission of these gases was higher for 30 tons of wood pellets (by 21%) than 22 tons of wood flour. After fossil fuel depletion (difference of 12%), in contrast to other impacts types, the GWP impact of one truckload of wood flour was less different than one truckload of pellets. In addition to this, the initial moisture content of the mill residues is pretty high (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 (Sahoo et al. 2021). The authors recommended air drying of the high moisture containing residues to lower the ecological and economical burdens. Similarly, Alanya et al. 2021 in their study on the wood pallet 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.

5.4.7 Cumulative Energy Demand (CED)

Table 5.6 lists the different renewable and non-renewable energy sources consumed during manufacturing to the hauling of one ton and one truckload of the wood feedstocks. The percentage difference in the amount of renewable energy (RE) and non-renewable energy (NRE)

consumed by each feedstock for each functional unit (one ton and one truckload) along with labeling the value are shown in Figures 5.8a and 5.8b respectively.

Table 5.6 Renewable and non-renewable energy consumed during one ton and one truckload production to transportation of the two wood feedstocks.

Impact category	Functional unit (one ton)		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, geotho (MJ)	0.12	0.05	2.62	1.40
Renewable, water (MJ)	1.11	0.35	24.53	10.43

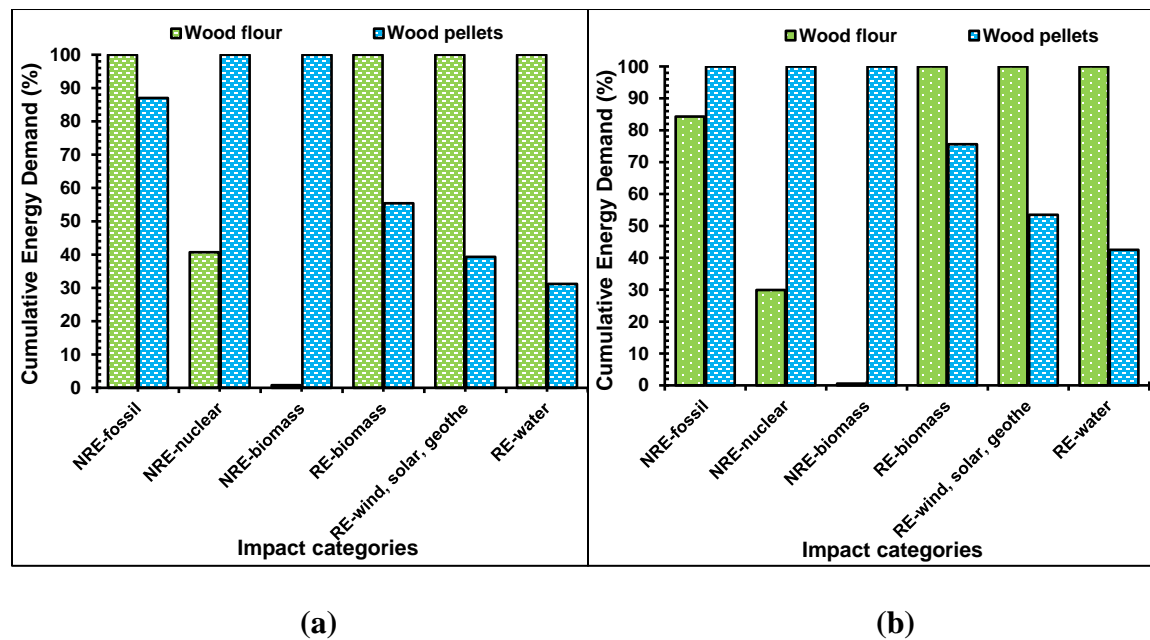


Figure 5.8 Comparative CED diagram for wood flour and pellets (a) one ton and (b) one truckload.

For the production of one ton of wood flour and pellets, the input variable consuming highest amount of renewable energy i.e., biomass, water, wind, solar, and geothermal were similar but with differences in 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 consume more renewable energy sources than non-renewable sources (Bergman and Alanya-Rosenbaum 2016). Similarly, the inputs consuming non-renewable energy source i.e., biomass was same for both wood flour and pellets but the inputs dominating fossil and nuclear energy were different. Non-renewable biomass energy was only consumed by the lubricants. Fossil feedstock exploitation was dominated by plastic bags followed by transportation and hardwood sawdust for wood flour whereas for pellets was dominated by transportation and hardwood sawdust. Nuclear energy was depleted the most by hardwood sawdust and chips followed by softwood sawdust and chips with least impacts by lubricants for wood flour. However, for pellets, nuclear sources were consumed the most by lubricants followed by hardwood sawdust and wood chips, and softwood sawdust and wood chips. Only the fossil-based energy was depleted by all the materials, fuels, electricity, transport, and ancillary inputs for both the wood feedstocks. Non-renewable energies being consumed more by the materials i.e., wood residues could be attributable to the electricity usage beyond the pellet plant.

One ton production and transportation of wood flour consumed more renewable and non-renewable energy sources as compared to the wood pellets except the non-renewable sources based on nuclear and biomass. Similar situation holds for one truckload functional unit but with a smaller percentage difference, except fossil energy is consumed more by wood flour than the pellets. The percentage differences in the consumption of energy sources for one ton production and transportation of the feedstocks 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 differences in the consumption of energy sources for one truckload production and transportation of the feedstocks are: NRE-fossil by 16%, NRE-nuclear by 70%, NRE-biomass by 99%, RE-biomass by 24%, RE-wind, solar, geothermal by 46%, and RE-water by 58%. The major difference during one ton and one truckload production and transportation is the consumption of nuclear and water sources. Even though the percentage differences for non-renewable biomass is the highest, the actual values of energy are below 1 for one ton or one truckload functional units. Likewise, even though the percentage differences for fossil consumption for the two feedstocks seems small, the values difference in MJ of energy is the highest compared to the other energy sources. Maryam et al. 2020 mentioned difference in the amount of fossil energy usage was caused by variation in electricity usage between coal or 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 grease are the direct major factors for this. This shows, in general, the production and shipping of wood flour consumes less non-renewable energy sources and more renewable energy sources with respect to the wood pellets.

5.5 Conclusions

- For both the wood feedstocks, the greatest impact to the environment was from transportation followed by the wood residues from hardwood processing.
- The impact of electricity in the pellet plant was not consequential as it was biomass generated electricity.
- All the impact categories for production and transportation of one ton of wood flour were higher than wood pellets except smog and ozone depletion. For one truckload of wood flour (22 tons)

and pellets (30 tons), 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. GWP of one-ton production and transportation of wood flour is higher than one ton of wood pellets by 11.13 kg CO₂eq (8% more).
- The production of wood pellets as well as shipping via a truck appear to be more environmentally and economically friendly than the wood flour for the same quantity of the materials in this study.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study aimed to find practical and commercially viable options for the utilization of wood residues produced by wood mills in Maine. The focus of this research was to produce feedstocks for WPC manufacture in the state. Material, economic, as well as environmental perspectives were studied which have produced encouraging findings. The overall results of the research are summarized below:

- 1) On average, the moisture content of wood residues was reduced by 54% and 52.3% by grinding the residues into wood flour and pressing wood flour into pellets respectively. Overall, conversion of residues into pellets decreased the moisture content by 76.8%.
- 2) On average, the bulk density increased by 119% and 276% on comminution of residues to wood flour and pressing wood flour into pellets, respectively. The overall increase in bulk density on processing residues into wood pellets was 747%.
- 3) There were no significant differences in the physical and mechanical properties of WPCs made utilizing either the wood flour or wood pellets.
- 4) Use of a coupling agent (MAPP) in WPC manufacture improved the mechanical properties compared to control samples and WPCs from spruce-fir wood species revealed the best overall properties.
- 5) The effect of shipment weight was higher on shipping costs over weight compared to the travel distance and shipping cost over distance for each wood feedstock. Shipment weight is directly related to the bulk density of the materials.

- 6) Sensitivity analysis conveyed that transportation of wood pellets via a truck (based on maximum load capacity at study region) was more economical by at least 25% compared to the wood flour. If the shipment weight capacity is high as e.g., rail transport, this can be can increase up to 70%.
- 7) LCA results showed that the impact from transportation was the most severe as opposed to the other input variables related to production for either wood feedstock.
- 8) The production and transportation of wood pellets was more environmentally sustainable as compared to wood flour for one ton (on characterization) as well as one truckload (on normalization) functional unit. GWP difference of one ton (characterization) and one truckload (normalization) is similar with higher contribution from the wood flour by 8%.

6.2 Recommendations for Future Work

Following are some of the research work that is recommended to be carried out in further studies:

- 1) Future research work on processing flour into pellets along with using additives used in WPC manufacturing, application with different polymers and different formulations, etc. for a better comparative study is highly recommended.
- 2) Besides truck transportation, the other feasible means of transport that can transport larger shipment weight needs to be analyzed in detail.
- 3) The LCA analysis should be extended to analyze the environmental impacts of manufacturing WPCs using wood flour or wood pellets and final end use or circularity could be potential studies to perform. Besides, wood flour production should be carried out to the actual facility supplying the feedstocks to manufacturing WPCs, if wood pellets production is collocated in the same facility, it should be performed for the comparative study between the two of them.

- 4) More interaction with the direct stakeholders to provide a more thorough evaluation of techno economic information is essential as well as the demand for wood feedstocks by WPC manufacturers in ME or at regional level, is required. This is key to encourage them to make a decision in establishing the industry producing and supplying wood feedstocks for WPC manufacturers.

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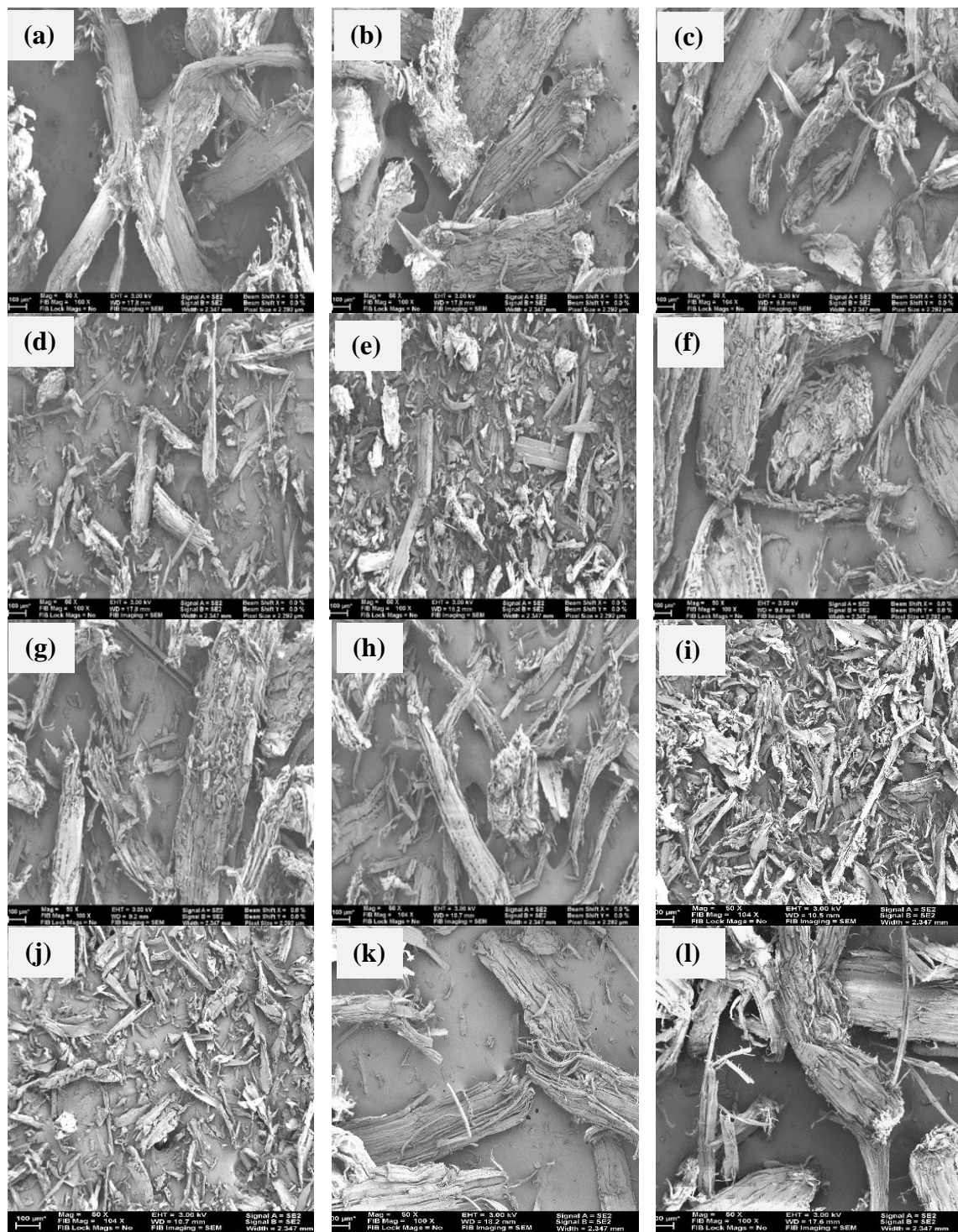
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APPENDIX

Appendix A



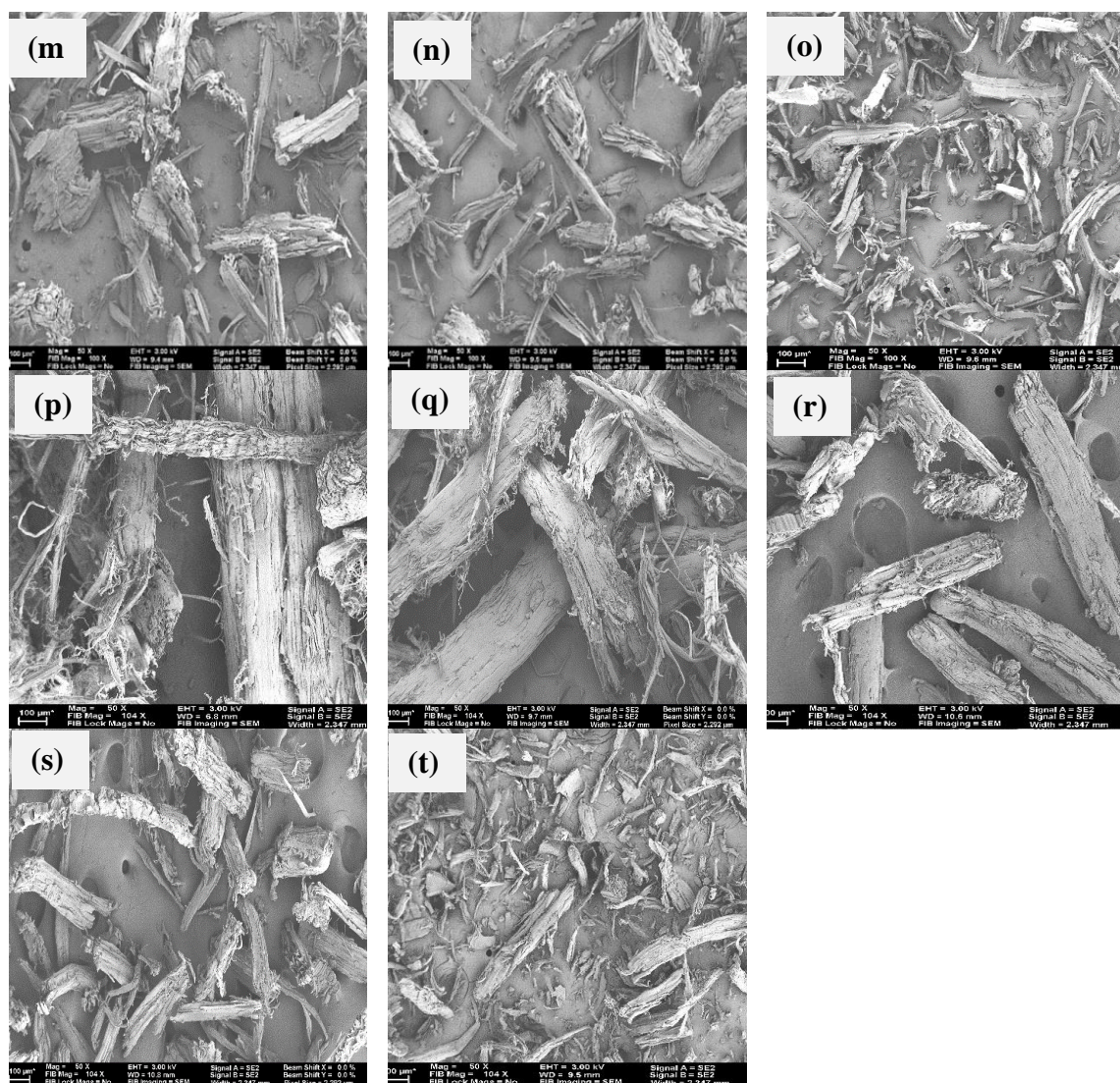


Figure A.1 SEM images of wood flour: (a) Cedar 18 mesh, (b) Cedar 35 mesh, (c) Cedar 60 mesh, (d) Cedar 80 mesh, (e) Cedar 100 mesh, (f) Pine 18 mesh, (g) Pine 35 mesh, (h) Pine 60 mesh, (i) Pine 80 mesh, (j) Pine 100 mesh, (k) Spruce-Fir 18 mesh, (l) Spruce-Fir 35 mesh, (m) Spruce-Fir 60 mesh, (n) Spruce-Fir 80 mesh, (o) Spruce-Fir 100 mesh, (p) Maple 18 mesh, (q) Maple 35 mesh, (r) Maple 60 mesh, (s) Maple 80 mesh, (t) Maple 100 mesh.

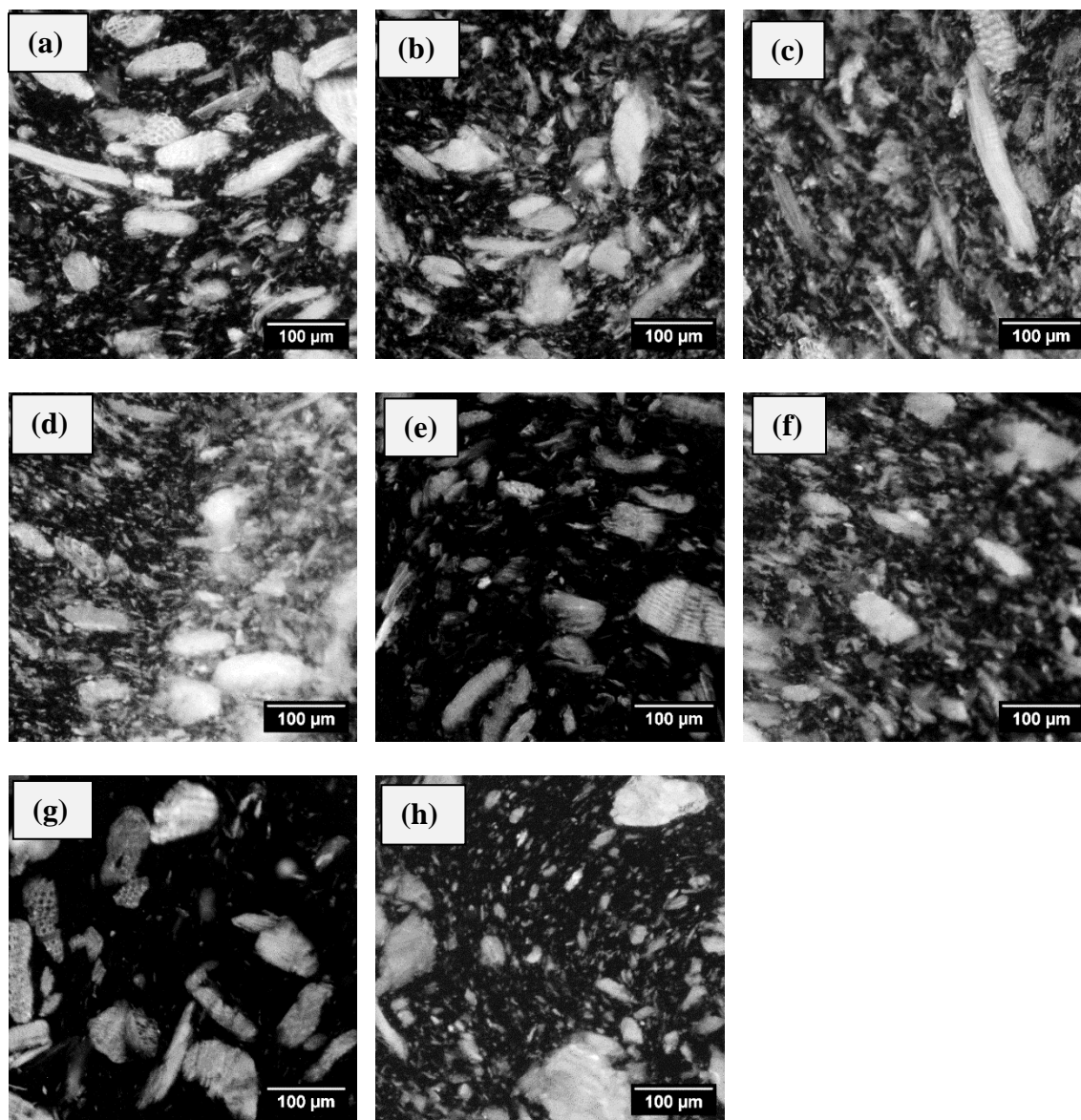


Figure A.2 Fluorescent images of WPCs in controlled condition (a) Cedar flour, (b) Cedar pellets, (c) Pine flour, (d) Pine pellets, (e) Spruce-fir flour, (f) Spruce-fir pellets, (g) Maple flour and (h) Maple pellets.

BIOGRAPHY OF THE AUTHOR

Geeta Pokhrel was born in July 12, 1995 in Nepal. She was raised in a small city of Nepal, Pokhara. She graduated with her undergraduate degree in Forestry from the Institute of Forestry, Tribhuvan University, Nepal in 2019. Her undergraduate research was focused on medicinal plants in Nepal. Prior to joining University of Maine, she had some work and research experiences in Nepal. In January 2020, Geeta was awarded Graduate Research Assistantship to pursue Master of Science in the School of Forest Resources at the University of Maine. At Maine, she gained valuable skills and experiences in a multicultural environment for her academic and professional development. Geeta is a candidate for the Master of Science degree in Forest Resources with a concentration in Bioproducts Engineering from the University of Maine in December, 2021.