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Integration of Agricultural and Municipal Solid Waste in Biohubs in Canada

Final Report

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Integration of Agricultural and Municipal Solid Waste in Biohubs in Canada

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List of Abbreviations

AAC	Annual allowable cut
AOU	Area of undertaking
bdt p.a.	Bone dry tonnes per annum
C&D	Construction and demolition waste
CWD	Coarse wood debris
FCI	Fixed capital investment
FMA	Forest management agreement
FMU	Forest management unit
FRMA	Forest Resources Management Act
GDP	Gross domestic product
GHG	Greenhouse gas
IC	Indirect cost
HIS	Information Handling System
LF	Location factor
ROI	Return on investment
SFMM	Strategic forest management model
TDIC	Total direct and indirect cost
TEA	Techno-economic assessment
TIC	Total installed cost
TPEC	Total purchased equipment cost

Executive Summary

Canada's dedication to transitioning to a low-carbon economy is essential in addressing the urgent challenges posed by global climate change and fulfilling international commitments to combat global warming. This shift not only tackles environmental issues but also aims to establish a sustainable economic framework that promotes innovation, job creation, and the advancement of the alternative energy sector. By focusing on the reduction of greenhouse gas (GHG) emissions, Canada seeks to fulfill its climate commitment while promoting a sustainable economy for future generations. Among the various approaches to mitigating GHG emissions and sustainably reaching its climate objectives, the use of bioenergy emerges as a promising solution. This energy source is derived from several kinds of biomass including whole trees, forest residues, agricultural residues, and organic municipal solid waste (MSW). The forest sector plays a crucial role in contributing to Canada's gross domestic product (GDP) and employment; however, it faces significant challenges because of falling revenues in the pulp and paper industry, brought about by the shift from print to digital media. To revitalize this sector, there is substantial potential to diversify and enhance the use of forest resources for renewable energy production and the development of other sustainable bio-based products.

Canada's agricultural sector holds significant potential for the production of biofuels and bioproducts, driven by the growing demand for bio-based energy and materials derived from agricultural residues. Agricultural biomass typically includes grain-based products and residual biomass or post-harvest waste. Municipal solid waste (MSW) refers to a wide range of materials generated from the residential, institutional, commercial, and construction and demolition sectors. This diverse waste stream typically comprises organic matter such as food scraps and recyclables like paper products, plastics, textiles, metals, glass, and inert materials. In Canada, once collected, the waste is transported to transfer stations, which are critical hubs in the waste management system. At these facilities, waste is sorted and aggregated before being directed for treatment and disposal. The organic portion of MSW is a key potential feedstock in the production of biofuels and bioproducts.

This study set out to develop a framework for assessing the availability of all of these biomass resources in various regions of Canada and to evaluate the economic feasibility of producing biofuels and bioproducts through biohubs. Biohubs are essential in establishing a value-added supply chain, enhancing biomass accessibility and supporting emerging bio-based industries. They facilitate biomass storage, sorting, processing, and transportation to various sectors, contributing to a robust bioeconomy. Their flexible configurations allow for a wide range of operations, from primary storage and reloading to advanced processing and conversion into bio-based intermediates. This versatility makes biohubs critical components in Canada's transition to a renewable energy future, ensuring efficient use of biomass resources while fostering sustainable industry growth. Furthermore, biohubs can adapt to different scales and operational needs, addressing various industrial requirements from simple biomass storage to advanced bioproduct manufacturing. Ultimately, they represent crucial infrastructure that could link forest biomass, the organic portion of MSW, and agricultural biomass to the broader bioeconomy, facilitating Canada's shift toward biomass-based energy and products. Biohubs can catalyze Canada's bioeconomy's growth while reducing the nation's carbon footprint by integrating bioenergy production with sustainable resource management.

This study's overall objective is to develop and enhance an existing tool (CANBIO-HUB) to conduct techno-economic assessments (TEAs) of biohubs in Canada. The specific objectives are to:

- Review the amount and types of agricultural, MSW (including construction and demolition [C&D] waste) and forest biomass available in different regions in Canada to integrate with forest biomass-based biohubs.
- Calculate the costs of different pathways of agricultural, MSW, and forest biomass processing at a biohub.
- Estimate the total cost of various types of agricultural, MSW, and forest biomass feedstock prepared for supply.
- Develop biohub cost estimates for three regions in Canada – Western, Central, and Eastern – while accounting for the unique industry characteristics of each.
- Integrate the TEA of agricultural and MSW biomass in the CANBIO-HUB tool for forest biomass-based biohubs and make the tool "plug and play" for stakeholders in Canada and elsewhere.
- Integrate GHG footprint assessments into the new tool.
- Make the new tool available for conducting assessment of real biohubs in Canada and in member countries of the International Energy Agency's Task 43.

This research represents the first comprehensive study assessing biohubs in Canada by examining a wide range of biomass sources, specifically whole trees, forest and agricultural residues, and the organic portion of MSW. The study thoroughly reviews the availability of biomass feedstocks and explores various production pathways for bioproducts. A significant aspect of this study is the development of techno-economic models in order to evaluate the feasibility of biohub operations and introduce CANBIO-HUB 2.0, a specialized tool designed for biohub analysis.

This study uses a GIS-based approach to estimate biomass distribution across Canada, based on a whole tree biomass yield of 84 odt/ha, an agricultural residue yield of 3.71 odt/ha, and a forest residue yield of 24.7 odt/ha. The highest yields for forest residues are observed in British Columbia (361 m^3/ha) and Alberta (278 m^3/ha) and the lowest in Yukon and the Northwest Territories. The highest agricultural residue yields are in Ontario. The report discusses several potential bioproducts derived from these biomass sources, specifically wood chips, firewood, bark, pellets, torrefied pellets, biochar, and bio-oil, along with their respective production pathways from forestry and in-field operations. Figure E1 illustrates the pathways from biomass to biofuels and bioproducts, including the conversion processes at the biohubs. This comprehensive assessment not only enhances the understanding of biomass resources in Canada but also supports the development of sustainable biohub strategies that could significantly contribute to the country's bioeconomy.

This study is an in-depth techno-economic assessment of biofuel and bioproduct production costs and GHG emissions at biohub facilities, providing valuable insights into their economic viability and environmental impact. The report gives a thorough overview of the assumptions and methods used for cost estimation, focusing on essential components such as capital costs, feedstock costs, and operating and maintenance expenses. The assessment also considers factors like the geographical location of the biohub, the type of feedstock used, and the plant's capacity, all of which significantly influence the overall costs of bioproducts. By integrating these elements, the study aims to present a holistic understanding of financial and environmental implications of production of biofuels and bioproducts, ultimately guiding decision-making related to biohub development and operations.

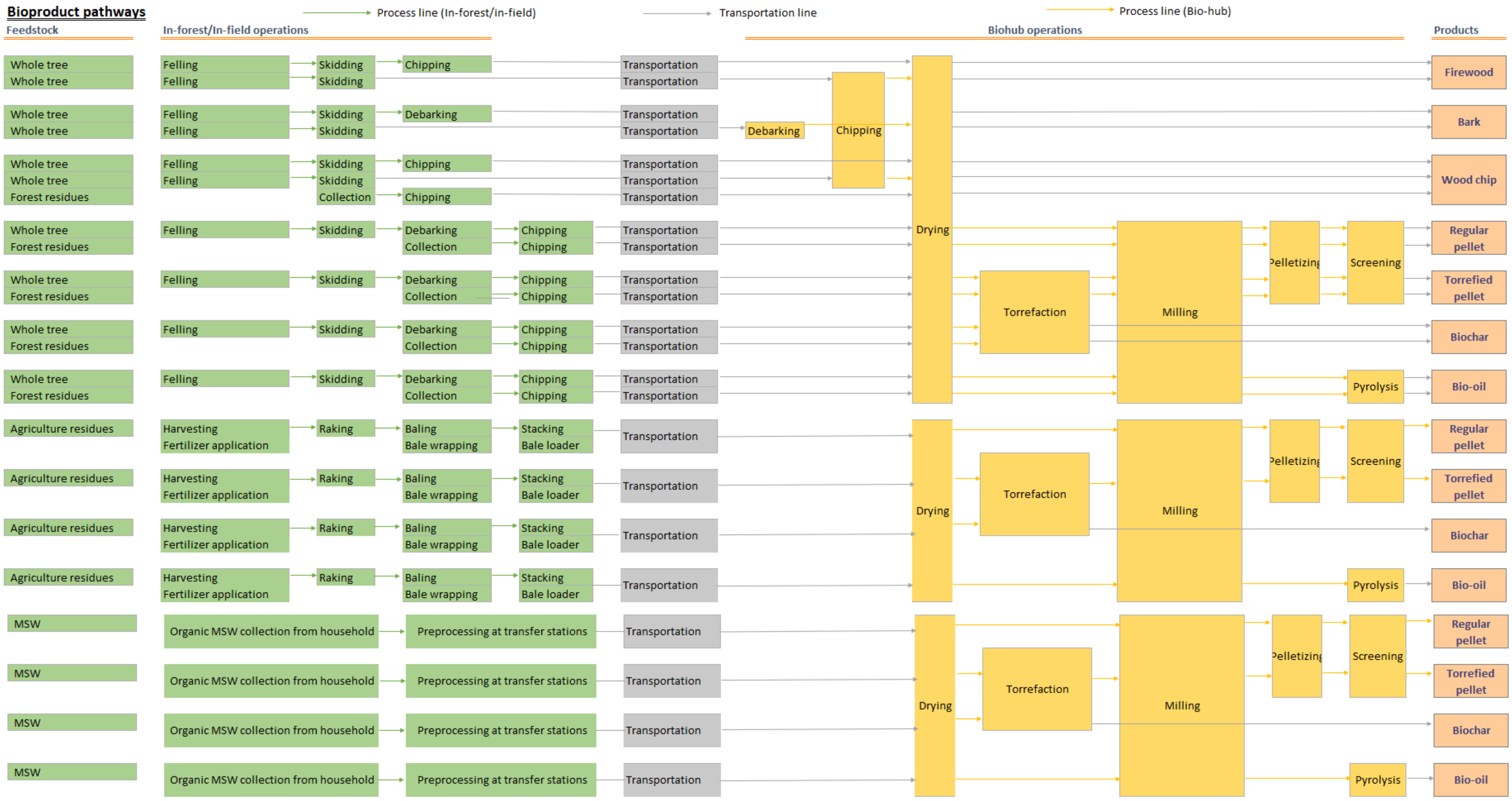
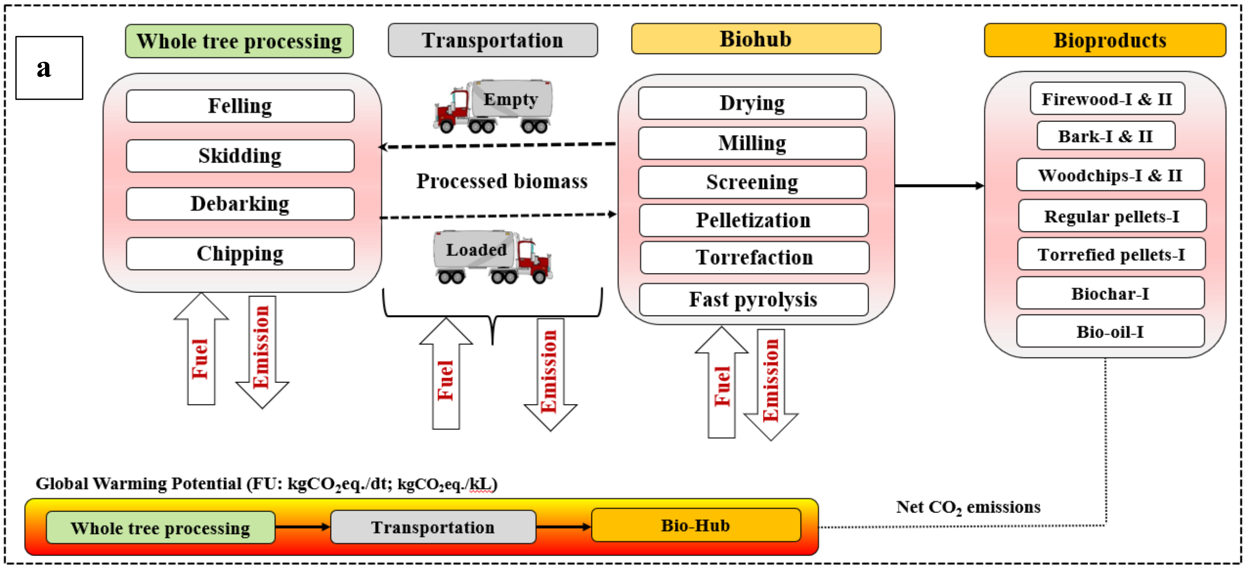


Figure E1: Biomass to bioproducts production pathways

A key objective of this study was to estimate the GHG emissions produced during the conversion of lignocellulosic biomass (whole tree, forest residues, agricultural residues, and organic MSW) into various biofuels and bioproducts (firewood, bark, wood chips, regular and torrefied pellets, biochar, and bio-oil). It was assumed that the locations of biohub operational facilities are forest mills for forest biomass (whole trees and forest residues), transfer stations for MSW, and nearby road infrastructure for agricultural residues; the travel distance (average biomass collection radius) is calculated according to the designated locations of the biohubs; and the GHG emissions associated with road construction and nutrient replacement for the feedstocks are not included. In this study, GHG emissions are estimated for the following key stages: (i) in-forest/in-field operations, i.e., harvesting and logging trees in the forest and in-field harvesting of agricultural residues followed by shredding, raking, and baling; (ii) transportation, i.e., transporting trees, branches, and tree tops as chips (wet) and agricultural residues as bales (wet) to a biohub operating facility; and (iii) biomass processing, i.e., processing biomass into the desired bioproducts in a biohub.

The GHG footprint assessment in this study was performed as shown in Figure 5-12, which illustrates in detail the system boundary. The figure depicts the processes that were investigated to estimate the GHG emissions from the production of the biofuels and bioproducts. The GHG footprint of each bioproduct comprises three processes: biomass production (in-forest/in-field operation), transportation, and processing in a biohub operating facility. For this study, the system boundary includes the direct input of fossil fuel in every stage of the entire life cycle, as shown in Figure 5-1E2. The functional unit, that is, the unit used as the basis for analysis, is one unit of the bioproduct or biofuel (1 dt or 1 kL).



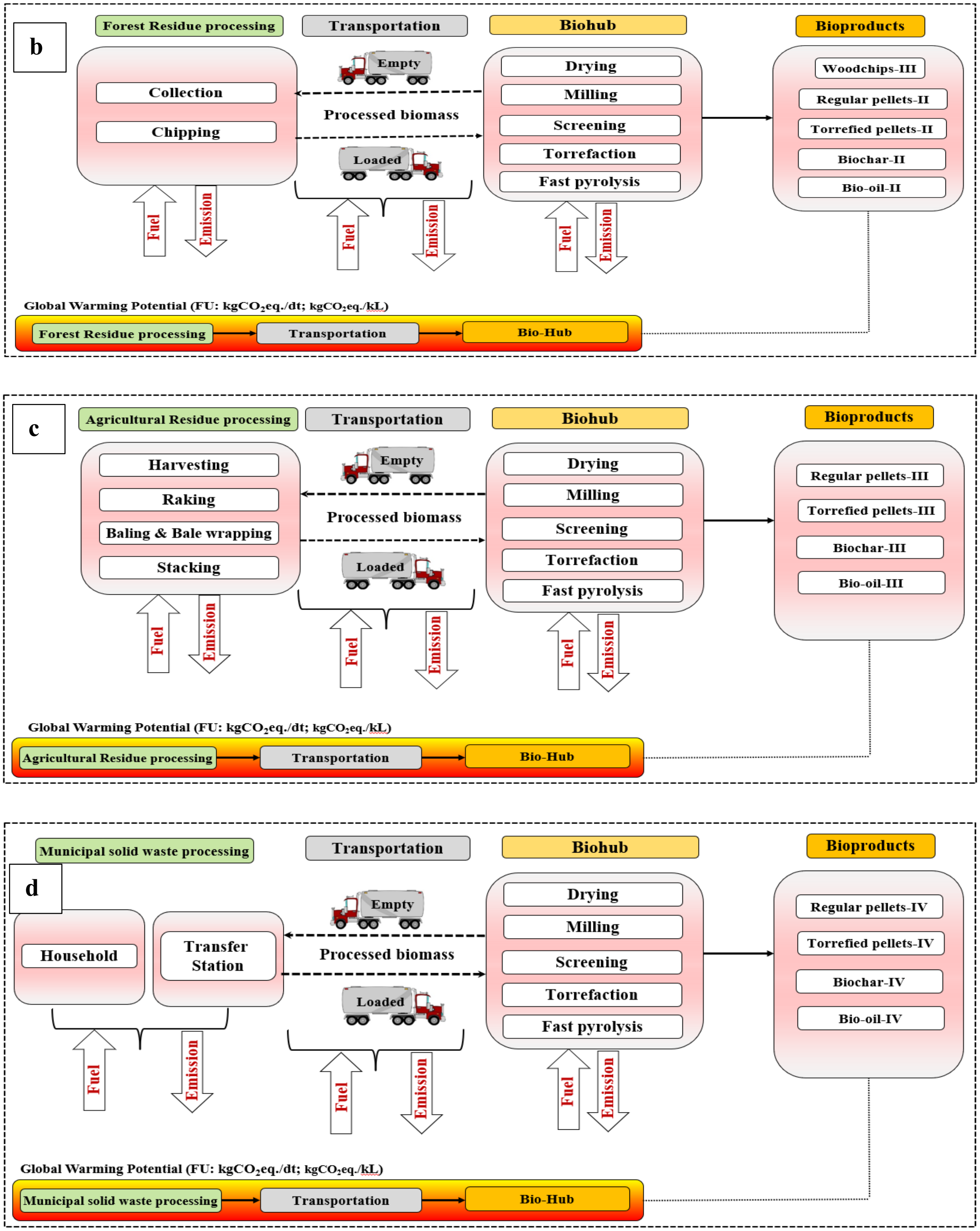


Figure E2: System boundaries for (a) Forest residue, (b) Whole tree, (c) Agricultural residue, and (d) MSW processing

The cost and GHG emission estimation tool for biohubs (CANBIO-HUB 2.0) provides a comprehensive summary of the costs and GHG emissions (in $kgCO_2eq.$) associated with various bioproducts derived from whole tree processing in Western Canada, at a processing capacity of 1,500 dry tonnes per day (dt/d). Among the bio-oil production pathways in this study, the highest production cost is $385.32/kL and, in this pathway, 106.16 $kgCO_2eq.$/kL GHGs are generated. Biochar is a more affordable alternative at $118.72/dt and with lower GHG emissions of 60.60 $kgCO_2eq.$/dt. Other bioproducts, such as torrefied and regular pellets, also offer competitive pricing, at $178.18/dt and $136.52/dt, respectively, with slightly lower GHG emissions of 61.03 and 53.84 $kgCO_2eq.$/dt. Wood chips and firewood stand out because of their low cost and relatively low GHG emissions, with wood chips priced at $52.48/dt and emitting 31.19 $kgCO_2eq.$/dt, and firewood costing $60.22/dt with GHG emissions of 32.65 $kgCO_2eq.$/dt. Interestingly, despite being the least expensive at $13.91/dt, bark has the highest GHG emissions at 154.33 $kgCO_2eq.$/dt. This analysis determined the potential of wood chips and firewood as cost-effective and environmentally friendly options for bioproducts while also revealing that bio-oil and bark, despite their respective price points, carry the highest environmental costs, warranting careful consideration in future biohub production strategies.

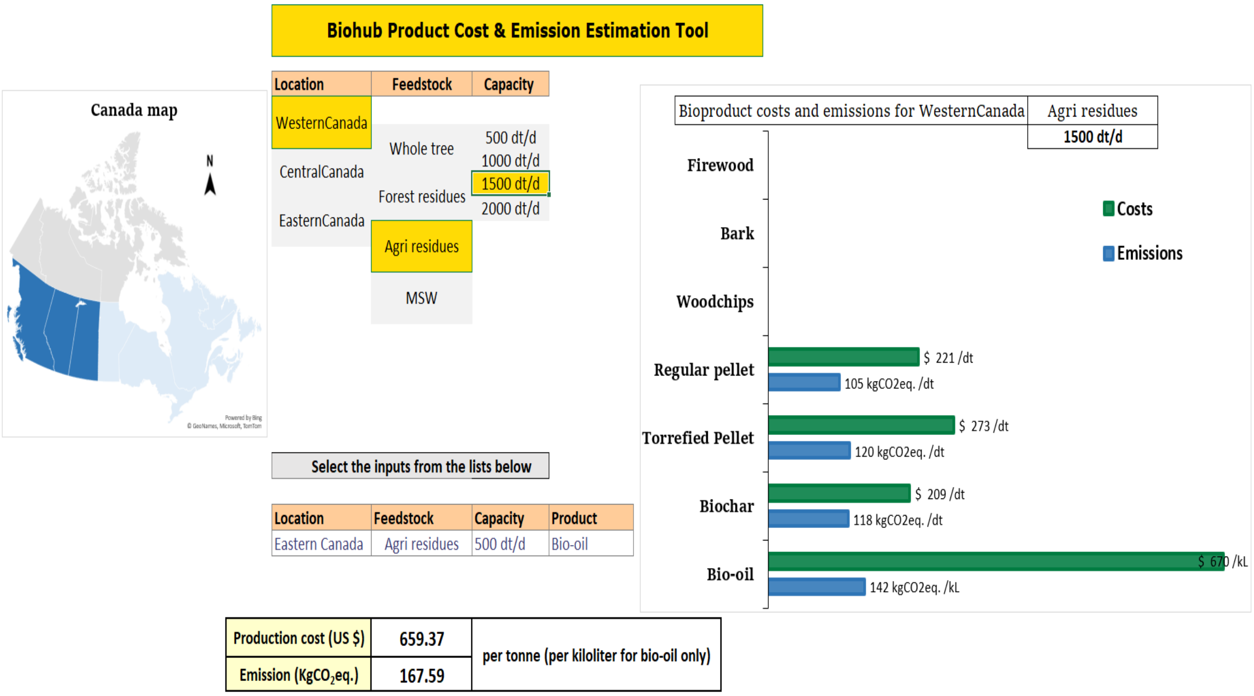
Among bioproducts derived from forest residues at a biohub, the cost and GHG emissions profile varies significantly, with bio-oil being the most expensive option at $362.30/kL and generating the most GHG emissions at 65.48 $kgCO_2eq.$/kL. In contrast, biochar is more economical, priced at $100.74/dt and with relatively low GHG emissions of 27.21 $kgCO_2eq.$/dt. While slightly costlier at $155.58/dt, torrefied pellets emit 26.64 $kgCO_2eq.$/dt GHGs, fewer than bio-oil. Regular pellets are even more affordable at $116.38/dt, with GHG emissions of 23.34 $kgCO_2eq.$/dt. Wood chips are the most cost-effective at just $53.33/dt and generating the lowest GHG emissions, only 17.40 $kgCO_2eq.$/dt. Overall, bioproducts derived from forest residues demonstrate a promising balance of cost-effectiveness, and environmental sustainability, with wood chips and regular pellets standing out as particularly advantageous choices. This analysis underscores the potential for optimizing resource use in biohub operations, contributing to a more sustainable and economically viable bioeconomy.

Of the bioproducts sourced from the organic portion of MSW at a biohub, bio-oil has the highest cost, $563.31/kL, and emits substantial GHGs of 87.80 $kgCO_2eq.$/kL. Biochar costs $114.20/dt and emits the lowest GHGs at 28.54 $kgCO_2eq.$/dt, thus presenting an environmentally friendly solution for biomass use. Torrefied pellets are available at $185.16/dt, with GHG emissions of 35.30 $kgCO_2eq.$/dt, positioning them as another viable option for reducing carbon footprints. Regular pellets, while more affordable at $142.74/dt, generate 40.02 $kgCO_2eq.$/dt GHG emissions, a slightly higher environmental impact than torrefied pellets.

Collectively, bioproducts derived from the organic portion of MSW at a biohub have lower GHG emissions than those obtained from whole trees or agricultural residues yet generate higher GHG emissions than those from forest residues. Biochar and torrefied pellets from MSW stand out as cost-effective and environmentally sustainable solutions, underscoring the potential of MSW-derived bioproducts to contribute positively to developing a more sustainable bioeconomy.

Among the various bioproducts assessed from agricultural residues at a biohub, bio-oil costs $670.42/kL and generates significant GHG emissions of 141.97 $kgCO_2eq.$, raising important environmental considerations. In comparison, biochar is available at $208.71/dt and generates 117.70 $kgCO_2eq.$/dt GHG emissions, indicating a relatively lower environmental impact, yet still substantial. Torrefied pellets, priced at $273.24/dt, have a GHG emissions footprint of 120.14 $kgCO_2eq.$/dt. Regular pellets, based on agricultural residues, cost $221.22/dt and produce comparatively lower GHG emissions of 104.80 $kgCO_2eq.$/dt, making them a more environmentally conscious choice in this assessment.

Overall, while agricultural residues generate higher emissions than those derived from whole trees, forest residues, and the organic portion of municipal solid waste at a biohub, both regular pellets and biochar have comparatively moderate environmental impacts. The snapshot of the developed biohub tool is illustrated in Figure E3, which shows CANBIO-HUB 2.0 and its significance in understanding the trade-offs between cost and environmental sustainability in bioproduct production.



Biohub Product Cost & Emission Estimation Tool

Location	Feedstock	Capacity
WesternCanada	Whole tree	500 dt/d
CentralCanada	Forest residues	1000 dt/d
EasternCanada	Agri residues	1500 dt/d
	MSW	2000 dt/d

Select the inputs from the lists below

Location	Feedstock	Capacity	Product
Eastern Canada	Agri residues	500 dt/d	Bio-oil

Production cost (US $)	659.37	per tonne (per kiloliter for bio-oil only)
Emission (KgCO$_2$eq.)	167.59	

Figure E3: The biohub tool used to determine costs and emissions for several bioproducts

Through the CANBIO-HUB tool, the study evaluates costs and GHG emissions of the production of biofuels and bioproducts at a biohub in several Canadian regions. Bioproducts like wood chips and biochar were found to be cost-effective and environmentally friendly, and biohubs play a key role in supporting Canada's bioeconomy.

1. Introduction

1.1. Background

Canada, with its vast 347 million hectares of forest and an estimated 47 billion cubic meters of forest wood, is a significant global player in agricultural production and exportation. Despite not being a key player in biofuel production, Canada has substantial potential to enhance the biomass sector because of its vast reserves of agricultural and forest residues [1]. The forest industry is integral to Canada's economy, contributing approximately 1.8% to the national gross domestic product (GDP) and providing jobs for over 200,000 Canadians, primarily in traditional sectors like pulp and lumber manufacturing Natural Resources Canada [2]. However, the transition to digital media has precipitated a decline in revenues in the pulp and paper industry, with some mills facing closure or downsizing [3]. Canadian forest resources can be leveraged sustainably to address renewable and non-energy demands over the long term. For instance, converting wood residues into wood pellets has emerged as a viable alternative to coal for heating and electricity generation, aligning with Canada’s commitments to greenhouse gas (GHG) emissions reduction [4].

Furthermore, forest biomass can be converted into various liquid fuels, such as bio-oil and ethanol, through advanced biochemical processes, offering an environmentally friendly substitute for fossil fuels [5]. Instead of incinerating forest residues from logging operations to mitigate wildfire risks, these materials can be strategically used to produce renewable fuels, fostering a economic growth in the forestry sector [6]. This shift enhances the economic viability of forest management and contributes to the broader objective of achieving sustainable energy systems in Canada.

The Canadian Prairies are rich in agriculture biomass resources, with roughly 35.4 million hectares of farmland dedicated to crop production as of 2019, with a substantial 83% of this agricultural land situated in the Prairie provinces [7]. This fertile landscape supports traditional crops and also presents significant potential for cultivating dedicated biomass energy crops, which can contribute to sustainable biofuel production [8]. Moreover, Canadians produce the second-most municipal solid waste (MSW) per capita globally, after the United States, at 2.58 kg per capita per day [9]. Canada's high waste generation rate creates environmental issues, such as more landfill use and increased GHG emissions. However, it also opens up opportunities for waste-to-energy conversion, improved recycling efforts, and sustainable waste management practices. By turning waste into a resource, Canada can reduce its environmental impact and support a circular economy where resource recovery and reuse are prioritized [10].

This framework positions Canada favourably for future growth in biofuel production. In 2021, Canada’s total annual energy consumption was estimated at 12.6 EJ, of which fossil fuels accounted for approximately 8.24 EJ [11, 12]. Transitioning to biomass-based resources can significantly reduce reliance on fossil fuels, thereby addressing pressing environmental concerns that have spurred interest in alternative energy sources. Unlike fossil fuels, biomass energy use is generally considered to be nearly carbon neutral, as the CO_2 emitted during biomass combustion is offset by the CO_2 absorbed during the growth of biomass feedstock (i.e., trees and crops) [13, 14]. Additionally, forestry products and by-products are widely considered to be environmentally friendly, promoting sustainable forest ecosystem management while aiding in carbon sequestration efforts [15].

To revitalize forest industry and capitalize on its abundant agricultural residues, innovative practices are essential for ensuring that biomass products, by-products, and residues are available at competitive prices. The biohub model serves as a strategic framework to create a value-added biomass supply chain that enhances accessibility of biomass and value, catering to the evolving demands of biorefineries and other bio-based industries [16]. These biohubs act as pivotal centers for the storage, loading, and processing of biomass, facilitating the efficient transportation of feedstock to various industrial applications.

Biohubs offer versatile operational configurations tailored to diverse needs within the biomass supply chain. They can function primarily as facilities for storage and reloading, ensuring efficient biomass handling. For more sophisticated operations, biohubs may incorporate sorting capabilities to enhance the quality and suitability of the biomass before reloading. Furthermore, advanced biohub setups are equipped to process biomass, transforming it into various intermediates such as bio-oil, biochar, or pellets. This adaptability optimizes the logistics of biomass transport and enhances the overall efficiency of biomass use, supporting the development of a robust bioeconomy. By integrating these different functions, biohubs can play a pivotal role in maximizing the value of biomass resources while addressing the specific requirements of emerging biorefineries and bio-based industries.

To effectively develop biohubs across Canada, it is paramount to gain a deep understanding of the various cost components and their associated GHG emissions. This requires a multifaceted approach that includes the application of advanced techno-economic and GHG emissions estimation models, which consider not only the amount and characteristics of the biomass but also its quality. Furthermore, these models must incorporate region-specific factors that influence biomass availability and processing requirements, as these parameters can vary significantly across Western, Central, and Eastern Canada.

For instance, Western Canada, with its vast agricultural landscapes and forest resources, may have different biomass characteristics than the densely populated urban regions of Central Canada or the maritime provinces of Eastern Canada, which rely more heavily on coastal resources. Understanding these regional differences allows for the optimization of biohub operations, enabling stakeholders to tailor their processes and infrastructure to local conditions. This could include the selection of appropriate biomass feedstocks, investing in processing technologies suitable for specific biomass types, and implementing logistics strategies that enhance transportation efficiency.

Moreover, decision-makers can develop strategies that minimize costs while maximizing environmental benefits by accurately assessing the cost components associated with biohub operations such as capital expenditures, operational costs, and potential revenue streams from bioproduct sales. Effective cost management will be crucial in ensuring the economic viability of biohubs, particularly in a competitive bioeconomy landscape where price sensitivity is high.

In addition to cost considerations, evaluating the GHG emissions associated with various biomass processing and conversion pathways is essential for aligning biohub development with global climate goals. By adopting practices that minimize GHG emissions, such as using low-carbon technologies and optimizing biomass transportation distances, biohubs can contribute positively to Canada’s overall emissions reduction targets.

Ultimately, successfully establishing biohubs enhances Canada’s capacity for sustainable biomass use and is critical in the transition to a more circular and sustainable bioeconomy. This approach fosters innovation, stimulates local economies, and promotes environmental stewardship, thereby positioning Canada as a leader in the global transition to sustainable energy and resource management. By strategically leveraging its rich biomass resources, Canada can enhance its energy security, reduce its dependence on fossil fuels, and create value-added products that support a more sustainable future.

This study is Phase 2 of an earlier study (i.e. Phase 1) on development of biohub model for forest biomass [95]. In the Phase 1 study, a techno-economic model called as CANBIO-HUB was developed which could be used for estimation of cost of production of fuels and products at the biohub. In Phase 2, CANBIO-HUB model has been enhanced with the integration of agricultural residue and municipal solid waste utilization for production of fuels and products at the biohub. In addition, this phase of the study also focuses on the estimation of the environmental footprints of the fuels and the products at the biohub. The objectives of this study are discussed in the next section.

1.2. Objectives

The research aims at conducting techno-economic assessment (TEA) of a biohub using multiple feedstocks including forest biomass, agricultural biomass and MSW. This research also aims at understanding the environmental footprints of various fuels and products produced at the biohub. A tool is developed for evaluating the costs and emissions of various bioproducts from biohubs in Canada. The specific objectives are to:

- review the amount and types of agricultural, MSW (including construction and demolition [C&D] waste) and forest biomass available in different regions in Canadian to integrate with forest biomass-based biohubs;
- calculate the costs of different pathways for agricultural, MSW and forest biomass processing at a biohub;
- estimate the total cost of various types of agricultural, MSW and forest biomass feedstock prepared for supply;
- develop cost estimates for biohubs in Western, Central, and Eastern Canada, taking into account the unique industry characteristics of each region;
- integrate the TEA of agricultural and MSW biomass in the CANBIO-HUB tool for forest biomass-based biohubs and make it “plug and play” for various stakeholders in Canada and elsewhere;
- integrate GHG footprint assessment into CANBIO-HUB;
- make the new tool available for conducting of real biohubs in Canada and in member countries of Task 43.

2. Biomass resources

2.1. Canada’s forest biomass resources

Forest biomass constitutes Canada’s largest biomass source, encompassing over 347 million hectares and accounting for nearly 10% of the world’s forested area [17]. The forestry sector is vital to Canada’s economy, contributing approximately $74 billion annually through established supply chains, particularly for wood products and mill-based pellets [2]. The provinces of British Columbia and Quebec is at the forefront of forest resource management, particularly in biorefinery and bioenergy based on their diverse and abundant forest ecosystems.

A comprehensive biomass inventory is essential to develop and enhance Canada’s forest bioeconomy effectively. This inventory should include a thorough assessment of whole tree biomass and forest residues. Forest residues are categorized into three main types: primary (harvest residues), secondary (industrial by-products), and tertiary (construction and demolition waste). Most of these residues are utilized Each type differs significantly in its application and potential for biomass use. Primary residues, i.e., branches, bark, and tree tops left after harvesting, are the main feedstock for bioenergy production because of their immediate availability and high energy content [18].

The challenge is accurately estimating forest residues' economically feasible, operationally viable, and environmentally sustainable potential. The complexity arises from various factors, including geographical differences, operational constraints, and market dynamics that influence residue availability and use [4]. While bioenergy primarily relies on primary residues, secondary and tertiary residues also present significant opportunities for value-added products, such as biofuels, biochar and biocomposites, which can reduce waste and enhance carbon sequestration [19].

Moreover, the environmental balance of using forest residues for bioenergy must be carefully assessed to avoid unintended consequences, such as habitat loss and soil degradation. Therefore, developing a strategic framework that incorporates robust biomass inventory data, economic analysis, and environmental impact assessments is critical for promoting sustainable forest biomass use and advancing Canada’s bioeconomy. By responsibly leveraging its vast forest resources, Canada can enhance its energy security, foster innovation in the bioenergy sector, and contribute to global efforts in mitigating climate change.

2.2. Agricultural residues

Canada's agricultural sector holds substantial potential for producing bioenergy and bioproducts, driven by the growing demand for bio-based energy and materials sourced from agricultural residues. There are two main classes of agricultural biomass: virgin biomass, which includes lignocellulosic materials and grain-based products, and residual biomass, representing the waste generated after harvesting [20]. While information on virgin biomass is widely accessible, estimating the amount of available agricultural residues is complex, necessitating careful evaluation of constraints such as seasonal and regional variations and different agricultural practices [21].

In addition to Alberta’s vast fossil fuel reserves, there is significant potential for biomass resources, particularly for production of biofuels and bioproducts. Alberta is Canada's second-largest wheat producer and the leading barley producer. Currently, during the harvesting of wheat and barley, while grain is extracted, most of the straw is left on the field to decompose, which represents an underused resource [22-25]. Some straw is collected for use as animal bedding or, in rare cases, as animal feed, but most is left untapped. Given the abundant availability of wheat and barley straw, there is a compelling opportunity to valorize this biomass into bio-based clean fuel, thereby aiding in the reduction of dependency on fossil fuels [26].

The Prairie provinces (i.e., Alberta, Saskatchewan, Manitoba) dominate Canada's agricultural output, accounting for the largest production share, followed closely by Ontario and Quebec. This regional distribution highlights the Prairies' significance in the national agricultural landscape, reflecting their extensive farmland and favourable climatic conditions for crop production. However, a significant challenge in using biomass to produce biofuels is the high transportation cost from the source to processing facilities. Agricultural biomass, including straw, typically has low energy density, resulting in higher transportation costs. The expenses associated with collecting, transporting, and handling biomass contribute to overall delivery costs. Unlike fossil fuels, biomass lacks a standardized distribution infrastructure, complicating logistics.

We developed a comprehensive county-by-county inventory of readily available agricultural residues to address these challenges, including supply cost curves for the major agricultural regions across the country. This inventory provides insights into the potential biomass availability and estimates the costs associated with harvesting, transporting, and delivering straw to processing facilities. By strategically harnessing agricultural residues and improving logistics, Canada can significantly enhance the production capacity of biofuels and bioproducts and contribute to a more sustainable energy future.

2.3. Municipal solid waste (MSW)

MSW refers to a wide range of materials generated from the residential, institutional, commercial, and construction and demolition sectors. This diverse waste stream typically comprises organic matter such as food scraps and recyclables like paper products, plastics, textiles, metals, glass, and inert materials [27]. Each of these presents unique challenges and opportunities for waste management and resource recovery. In Canada, once collected, the waste is transported to transfer stations, which serve as critical hubs in the waste management system. At these facilities, waste is sorted and aggregated before being directed for treatment and disposal. This study assumed that the biodegradable fraction of MSW is diverted to biohub facilities, where it can be processed into valuable biofuels and bioproducts, thus promoting a more sustainable approach to waste management [28-30].

This study considers waste from residential and non-residential sources. The latter includes construction and demolition (C&D) debris, as well as industrial, commercial, and institutional (ICI) waste [30, 31]. The characterization of these waste streams is crucial for understanding their potential for recycling and energy recovery. Typically, MSW is composed of approximately 40% biodegradable material (with a moisture content of 50%) and 40% non-biodegradable material (with a moisture content of 15%), with the remaining 20% being disposed of in landfills [29, 32-34]. For instance, enhancing the sorting and recycling processes can significantly reduce the amount of waste sent to landfills, thereby lowering environmental impacts. Moreover, improving the diversion of biodegradable materials to biohub facilities can help in the recovery of energy and nutrients. The integration of waste processing technologies, such as anaerobic digestion and composting, can optimize the recovery of resources from biodegradable waste, in keeping with the goals of a circular economy. The insights gained from this study can help inform policymakers and waste management professionals in their efforts to enhance resource recovery initiatives and develop sustainable waste management strategies.

2.4. Quantification of biomass resources

2.4.1. Method and model development

We used published sources and government databases to estimate forest residue across Canada, particularly data from Natural Resources Canada. Our assessment of biomass availability focused on specific study areas, considering various factors such as harvesting policies and forest classifications (coniferous, deciduous, and mixed forests). We used ArcMap 10.8 to analyze biomass density and geographical distribution across Canada's western, eastern, and central regions. Wood and Layzell found an average biomass yield for Alberta of 78 odt/ha [11], while an earlier study [35] determined the whole tree yield to be 84 odt/ha. Biomass availability was calculated using the equation below:

$$Q = \sum_{i=1}^{n} k a_i \qquad \textbf{Equation 2-1}$$

In this equation, Q represents the total amount of whole trees available, k denotes the biomass yield (odt/ha), a_i refers to the area of the polygons (ha) that make up the study area, and n indicates the number of polygons into which the study area has been divided in the GIS environment.

2.4.2. Estimation of quantities of agricultural residues

To estimate the agricultural residues' potential for bioenergy production, it is necessary to identify the key crops cultivated in each province and assess their suitability for energy conversion processes. Agriculture and Agri-Food Canada (AAFC) provides detailed data on the annual harvested areas and gross yields for the major crops in each province. With this information, we can calculate the total amount of straw available after harvest using the straw-to-grain (S/G) ratios specific to each crop species, in conjunction with gross grain production data from Statistics Canada [36]. The S/G ratios offer insights into how much residual biomass, particularly straw, is generated per unit of harvested grain, which is crucial for determining its potential as a bioenergy feedstock. These S/G ratios for various crops grown in Canada, listed in Table 2-1, are derived from published studies and have region-specific values that reflect both crop type and agricultural practices. Understanding these ratios, combined with grain production figures, allows for a more accurate assessment of the total biomass available for energy conversion, particularly in the form of agricultural residues. This method not only helps determine the volume of biomass resources but also helps us evaluate the logistical and economic feasibility of collecting and transporting this biomass for use in bioenergy applications.

Table 2-1: Straw to grain (S/G) ratios of several crop varieties in Canada [37, 38]

Crop	S/G Ratio
Wheat (all types, incl. spring, winter, and durum)	1.10

Crop	**S/G Ratio**
Barley	1.00
Canola	1.00
Oats	1.50
Dry Peas	1.00
Flax	1.20
Corn for grain	1.00
Soybean	1.00

The amount of recoverable straw for biofuels and bioproducts purposes can be estimated after determining the gross straw yield. Several factors were assumed to calculate the net yield of straw available for bioenergy production:

- Some straw must be kept on the field to preserve soil health and inhibit erosion.
- The efficiency of harvesting equipment impacts the amount of straw collected, with some straw left behind during the process.
- A certain amount of straw is allocated for other purposes, such as animal bedding and feeding.
- Straw can be lost or degraded during collection, transportation, and storage because of mechanical handling and exposure to environmental conditions.
- The moisture level of the straw affects the actual dry mass available, as higher moisture content reduces the amount of usable straw for energy conversion.

Accounting for these variables allows us to accurately assess the net straw yield, enabling better resource management and optimizing biomass use for sustainable energy production.

To maintain soil health and minimize erosion, leaving a portion of straw in the field after harvest is essential. Previous studies have proposed varying amounts of straw for this purpose. For instance, Patel, Vaezi [24] and Stephen [39] suggest leaving 0.75 tonne/ha for soil conservation, while others recommend leaving up to 1 t/ha [40, 41]. This analysis adopts the more conservative estimate of 0.75 t/ha for soil conservation. In addition to soil conservation, some straw is used for animal bedding, feed, and mulch. According to research by Sokhansanj, Mani [40], Alberta's annual straw requirement for livestock is 3.2 tonnes for a land area of 4.85 ha. This study assumes 0.44 t/ha of straw is allocated for these uses [24, 38]. Some crops, such as canola and soybean, are not typically used for energy generation due to their high bulk density [42], which negatively affects ignition properties [43]. Instead, they are often directed towards animal feeding and bedding. Corn silage is also used as animal feed in Canada.

Harvesting processes result in a portion of straw being lost before it can be used for energy production. According to the Prairie Agricultural Machinery Institute (PAMI), technological limitations during harvest can result in no recoverable straw, particularly in low-yield conditions. Furthermore, minor losses can occur during storage and transportation. In this study, a 30% loss was assumed for harvesting. Additional losses, as reported in an earlier study, include 3% for field operations, 5% during handling, and 7% during storage [24]. Crops such as canola and soybean experience greater losses due to natural degradation processes [44]. The moisture content of straw is another critical factor in determining its usability. For this analysis, we used the average moisture content of 14% on a wet-weight basis [38]. Understanding these factors enables the calculation of net straw yield, which is crucial for determining the volume of agricultural residues that can be sustainably recovered for renewable energy generation. Figure 2-1 illustrates the method used to estimate the net amount of agricultural residues that can be sustainably extracted for the production of biofuels and bioproducts.

This systematic approach is vital for optimizing biomass resources and aligning agricultural residue management with broader sustainability and renewable energy goals. Addressing key variables such as conservation needs, alternative uses, and potential losses ensures a balanced and effective use of agricultural biomass for bioenergy applications.

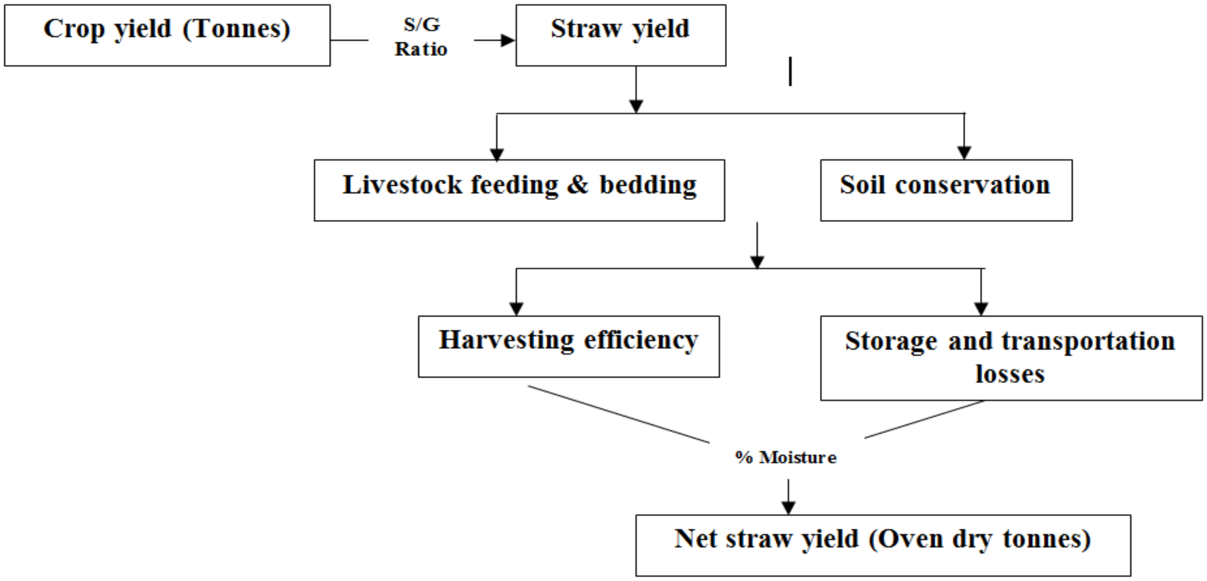


Figure 2-1: Parameters for estimating agricultural residues

2.4.3. Municipal solid waste (MSW)

A typical MSW transfer station (TS) collects waste from nearby communities, where it is sorted and diverted before being sent for landfill disposal or processing. This study assumed that 40% of the biodegradable fraction is directed to biohub facilities for further treatment. However, given the lack of comprehensive MSW data for each transfer station across Canada, this research used the Thiessen polygon method to estimate MSW for each TS. This spatial interpolation technique divides a geographical area into polygons, with each polygon assigned to the nearest TS. The method ensures that all locations within a polygon are serviced by their closest TS. To estimate the MSW potential for each region, the 2016 Canadian census population data was combined with the per capita disposal rate [45], expressed in wet tonnes per year [46]. This allowed for a more precise calculation of the MSW generation for each area. Both the organic (biodegradable) and inorganic portions of MSW were included in the total waste estimates sent to landfills, as these components represent the bulk of the waste stream in typical urban settings. By incorporating population data and waste disposal rates, this method provides a robust framework for estimating MSW volumes and their potential for diversion towards more sustainable waste management practices, such as biohub integration.

This approach underscores the importance of accurately estimating waste streams to optimize the capacity of biohub facilities and support the development of effective waste-to-energy conversion processes. A detailed understanding of the spatial distribution of MSW is crucial for designing efficient waste handling and processing systems across different regions, ultimately contributing to improved sustainability and resource recovery efforts.

2.5. Biomass availability and geographical distribution

2.5.1. Forest biomass

Around 58% of Canada’s forests are available for commercial harvesting, with only 0.4% of this area harvested annually. British Columbia and Alberta report the highest biomass yields per hectare, and the Yukon and the Northwest Territories significantly lower yields given their less favourable growing conditions and limited forest accessibility. Given their substantial forested areas and relatively high biomass yields, Canada has considerable potential for forest residue recovery which can be used to support bioeconomy by implementing advanced biomass harvesting techniques and residue management strategies. This would help in reducing waste and contributing to carbon mitigation.

Figure 2-2 provides a detailed overview of the distribution and availability of residual forest biomass across Canada, highlighting the significant potential of these resources in supporting a low-carbon, bio-based economy. In summary, Canada’s diverse forest landscapes have varying levels of residue recovery potential, with the vast majority of it in British Columbia, Alberta, Northwest Territories and Yukon. A comprehensive understanding of biomass yields and advanced forest management and harvesting practices will be critical to maximizing Canada's forest resources' economic and environmental benefits.

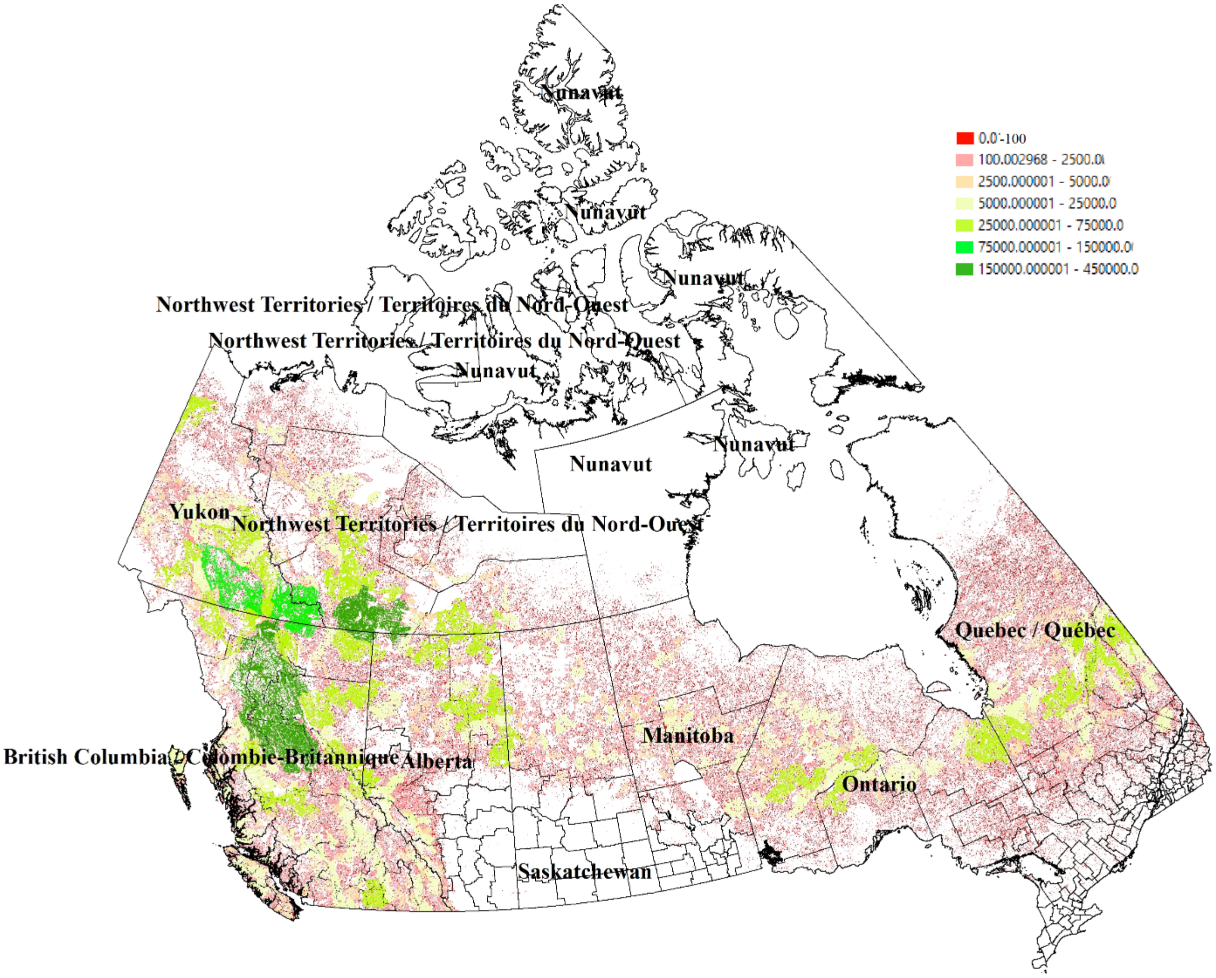


Figure 2-2: Forest residue biomass in Canada (odt/ha)

2.5.2. Agricultural residues

A bottom-up approach was applied using data from Statistics Canada to estimate the gross and net yields of the country’s major crops, with a focus on the potential of agricultural residues for production of biofuels and bioproducts. The Prairie provinces (Alberta, Saskatchewan, and Manitoba) dominate agricultural production, generating substantial amounts of barley, wheat, oats, and canola. Competitive uses of these residues, such as livestock feeding, bedding, and soil conservation, were also factored into the analysis, significantly impacting the net yield of available biomass. In Ontario and Quebec, corn residue also holds considerable potential for production of biofuels and bioproducts production because of the large area dedicated to corn cultivation in these provinces. However, practical challenges, such as moisture content and straw quality, affect the efficiency of straw use in conversion processes.

This study's bottom-up approach highlights a more conservative estimate of net residue yields than previous top-down approaches, which may have overestimated biomass availability for bioenergy applications. Competitive uses of residues, field losses, and handling inefficiencies were incorporated into this analysis to provide a more realistic assessment of net biomass availability [47]. The moisture content of the straw, field conservation needs, and technological limitations in residue collection are critical factors in determining the net yields.

Figure 2-3 illustrates the geographical distribution of agricultural residues (in oven-dry tonnes per year) in six provinces in Canada; the significant contributions of the Prairie provinces, as well as the contributions from Ontario and Quebec, are evident. These regions offer substantial potential for advancing Canada's bioeconomy through improved biomass recovery and the development of biorefineries.

This study provides a foundational understanding for optimizing residue use in energy generation and bioproduct manufacturing by accurately assessing agricultural residues' gross and net availability. This comprehensive evaluation is essential for developing sustainable bio-based solutions that reduce reliance on fossil fuels and support Canada's transition to a circular economy.

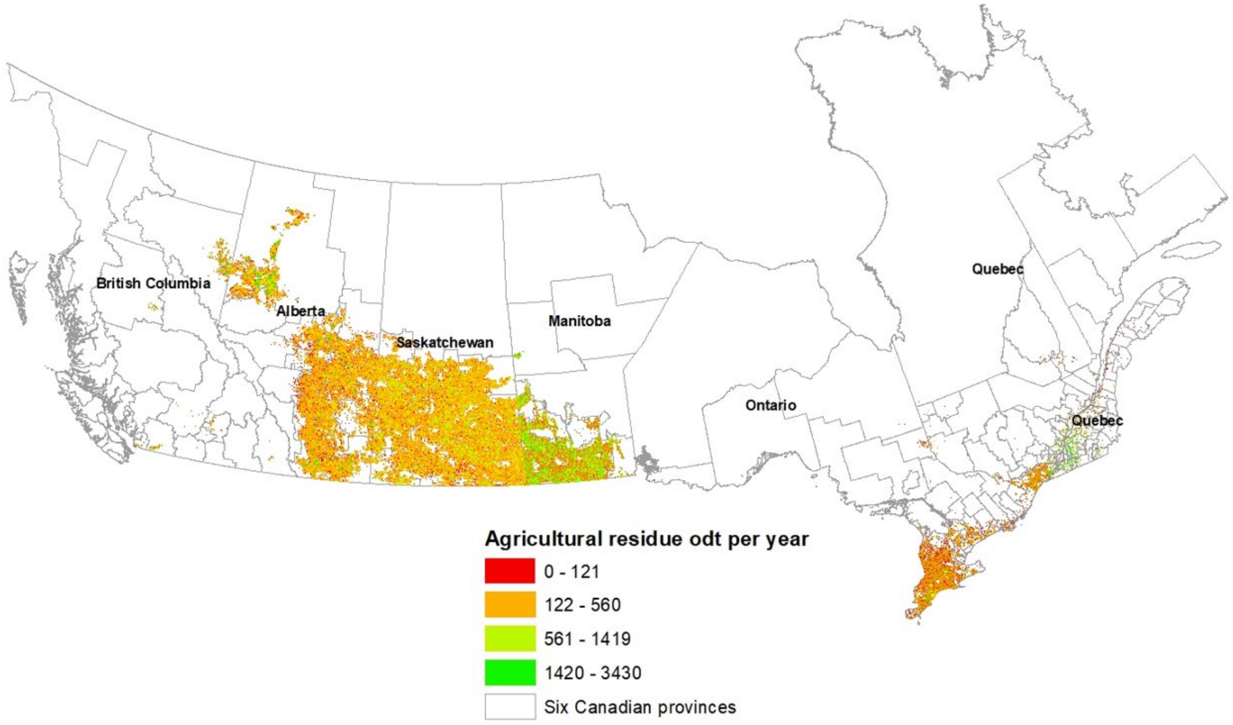


Figure 2-3: Agricultural residue distribution in Canada

2.5.3. MSW

In this study we calculated the MSW amount in each polygon by multiplying the MSW density by the polygon’s area, with each polygon centred around a transfer station (TS) [48, 49]. This calculation provided the available waste volume for each respective TS, reflecting the total MSW collected from nearby communities. The larger circle in Figure 2-4 represents the higher MSW amounts found in larger cities, corresponding to their higher population densities. Canada's estimated annual MSW potential in 2022 was approximately 26 million wet tonnes.

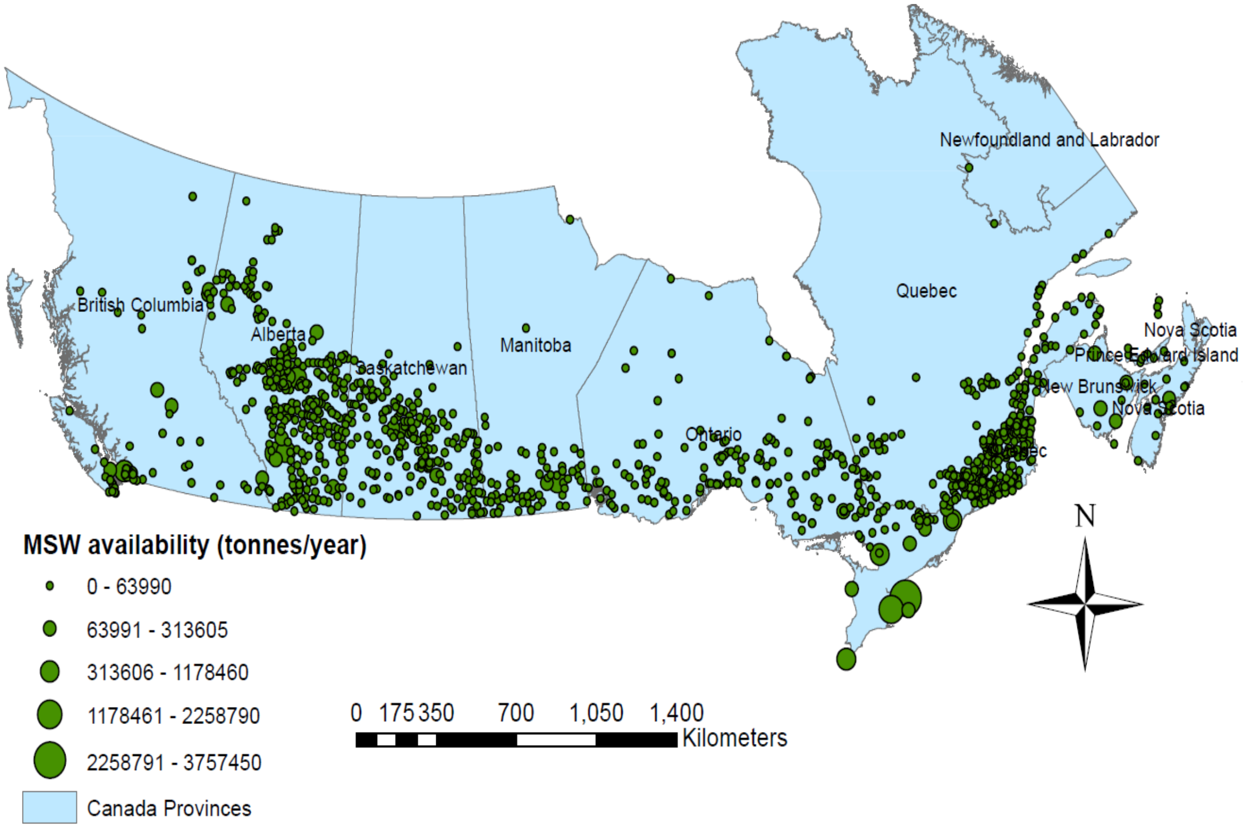


Figure 2-4: Locations of existing MSW TSs along with their annual availability.

Transportation distances from each transfer station to the central city area were calculated for major cities in every province in order to understand the logistical challenges of MSW transport. Subsequently, the available organic MSW (in dry tonnes per year) was plotted against the associated transportation costs.

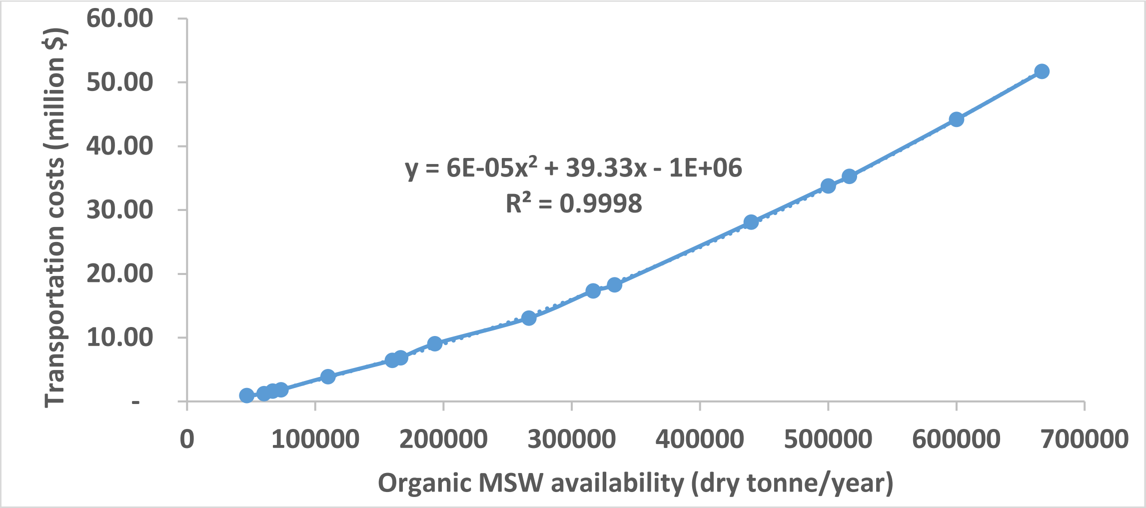


Figure 2-5: Organic MSW transportation cost based on waste availability

3. Bioproducts and biofuels and their production pathways

This section provides an overview of several bioproducts and biofuels produced at biohubs, specifically firewood, bark, wood chips, standard and torrefied pellets, biochar, and bio-oil. The subsections further discuss the specific production pathways for each bioproduct, describing the technologies and processes that convert these raw materials into valuable bio-based outputs. When these pathways are integrated into biohub operations, biomass resources can be efficiently used.

3.1. Firewood

Firewood production in Canada is not well documented because there is no centralized agency tracking its metrics. Hence, a techno-economic model was developed to estimate both the costs and GHG emissions associated with firewood production. The analysis outlines two primary production pathways:

1. Pathway 1: Forest-based chipping and drying: Trees are felled and skidded in the forest and chipped on site. Then the chips are transported to the biohub for drying and processing.
2. Pathway 2: Log transportation to a biohub: In this pathway, logs are transported directly from the forest to a biohub, where chipping and drying occur.

Both pathways involve unique logistical and energy requirements, directly influencing production costs and GHG emissions. Figure 3-1 visually represents the production pathways from biomass to firewood, illustrating the flow of materials and processes.

Through these pathways, the models can assess transportation distances, energy use during chipping and drying, and GHG emissions linked to machinery operations. These factors contribute to a comprehensive understanding of the environmental impacts and economic viability of firewood as a bio-based fuel source.

3.2. Bark

Forest biomass consists of various tree components, among them bark, a valuable feedstock for bioenergy production, primarily due to its high lignin content, which enhances its energy density. Historically, bark was often incinerated or discarded as waste; however, its use has shifted towards providing heat and steam in pulp and paper mills and serving as a low-grade fuel source in other industrial processes. Although accurate data on bark production is not systematically collected, it is recognized as a significant biomass resource. Bark is harvested through several production pathways, including the felling and transportation of whole trees to biohubs for debarking or the collection of bark from sawmills and logging operations. The debarking method varies with the operational scale and processing requirements. Common technologies include drum and flail debarkers, both of which are effective in removing bark from logs, though they differ in efficiency and suitability for various tree species. A key challenge associated with bark use is the cost of transportation. Because of the bulkiness of bark and its relatively low energy density compared to other forest residues, transportation can quickly become a significant cost factor, particularly over long distances. Figure 3-1 illustrates the bark production pathways, beginning with whole tree harvesting and proceeding through various processing stages, highlighting the logistical steps involved in converting this biomass resource into usable energy or materials.

Efficiently managing these pathways is crucial for maximizing bark's economic and environmental benefits in bioenergy systems. When transport logistics and debarking technologies are optimized, bark can become a more competitive resource in Canada's evolving bioeconomy.

3.3. Wood chips

Wood chips, a sizable sawmilling co-product is a critical biomass resource for bioenergy production. In addition to these, wood waste and low-grade logs unsuitable for lumber are frequently processed into wood chips, ensuring that even lower quality timber contributes to the bioeconomy. In Eastern Canada, pulp mills commonly chip entire logs, while in other regions, whole trees are first debarked, delimbed, and then chipped at or near the harvest site. This decentralized approach optimizes transportation and processing efficiency. The quality of the wood chips is crucial in determining the efficiency of biofuel production. Key quality factors include chip size, moisture content, and the precision of processing operations, all influencing conversion rates in bioenergy applications. For instance, chips with high moisture content can lower combustion efficiency and increase drying costs, while chips that are too large or too small can disrupt feeding systems in biomass boilers or bioreactors. The skill and expertise of operators also affect the quality of the wood chips, as consistent sizing and proper handling techniques are essential for optimal processing.

We developed a techno-economic model to estimate wood chip production costs at the biohub, considering several pathways from raw timber to finished product. These models account for factors such as harvesting, debarking, chipping, and transportation logistics, providing insights into the cost structure of wood chip production at different regions and operational scales. By analyzing these pathways, stakeholders can better understand the economic feasibility of using wood chips as a bioenergy feedstock. Figure 3-1 illustrates the wood chip production pathways at the biohub, starting from whole tree harvesting and moving through various processing steps, from debarking and chipping to transportation.

3.4. Regular Pellets

Biomass facilities encounter several operational challenges because of the feedstocks' inconsistent quality and supply, often characterized by low bulk density, reduced heating value, and limited yield [22]. These factors contribute to increased costs for both feedstock delivery and conversion into usable energy products. One solution to address these is pelletization, a pre-processing technique that compacts biomass, significantly increasing its bulk density and heating value. This makes the material more amenable for energy applications, particularly for co-firing with coal in existing power plants, thus enhancing the biomass's overall energy output and efficiency [50, 51]. The primary feedstock for pellets is typically sawdust, a by-product of sawmill operations. However, agricultural residues and organic MSW are promising alternatives for pellet feedstock [52]. These diverse sources provide flexibility in the biomass supply chain and enable the use of waste streams that would otherwise be landfilled or left unexploited.

Globally, the economics of pellet production have been studied extensively. We modeled pellet production costs from sawmill residues, agricultural by-products, and organic MSW for Canada. By analyzing cost drivers such as feedstock acquisition, processing efficiency, and energy output potential, the study aims to offer insights into the economic competitiveness of biomass pellets in

Canada's energy market. Moreover, understanding these cost structures will help guide investment in infrastructure and inform policy decisions to advance pellet’s utilization.

1.1.1 Regular pellet production pathways at the biohub

Below are the pathways which were assessed for regular pellet production. Each pathway considers a different biomass feedstock and its respective processing stages, optimizing the use of available resources for energy production. These production pathways consider the logistical and processing challenges associated with different biomass types, ensuring efficient pelletization for energy use.

1. Pathway 1 (Whole Trees):
    - Whole trees are felled and skidded from forest sites, followed by debarking and chipping at the site or nearby processing locations.
    - The produced wood chips are transported to a biohub, where they undergo drying, grinding, screening, and pelletizing.
    - This pathway assumes the use of the whole tree, allowing for efficient biomass use with minimal waste.
2. Pathway 2 (Forest Residues):
    - Harvesting residues from forestry operations, i.e., branches, treetops, and other by-products, are chipped directly at or near the harvesting site.
    - These wood chips are delivered to biohubs, where they are dried, ground, screened, and pelletized.
    - Large logs from the forestry operations are sent to sawmills or other facilities for further processing into lumber or other products, maximizing resource efficiency.
3. Pathway 3 (Agricultural Residues):
    - Agricultural residues, such as straw or corn stover, are collected directly from fields following raking, baling, and stacking.
    - Then the residues are transported to the biohub to be dried, ground, screened, and pelletized.
4. Pathway 4 (Organic MSW):
    - Organic MSW, primarily composed of food scraps and biodegradable materials, is collected from transfer stations and delivered to biohubs.
    - The MSW is dried, ground, screened, and pelletized at the biohub, then converted into valuable biofuels and bioproducts.

Each of these pathways highlights a sustainable approach to biomass use, ensuring that different types of biomasses—whether from forestry operations, agriculture, or municipal waste—are efficiently converted into pellets. These pellets can then be used as an alternative energy source, supporting the growing demand for bio-based fuels. Moreover, these pathways' technological and logistical considerations are critical to minimizing energy costs and maximizing the overall yield and energy output from pellet production. Understanding and optimizing these processes is essential for advancing Canada's bioenergy sector and reducing dependence on non-renewable energy sources.

Forest residues left alongside logging roads can be efficiently collected for bioenergy production, using existing infrastructure and reducing costs [22, 53]. We have consider nutrient replacement costs and compensation to farmers for the collection of agricultural residues, ensuring sustainable agricultural practices [54]. The collected biomass is ground to reduce size and dried to achieve desired moisture content, typically between 10% and 12%. It is then processed in a hammer mill to a particle size of 3.2 mm or less, which is crucial for pellet quality [55]. The biomass is compressed in a mill using a roller and die mechanism during pelletization, producing dense pellets. After formation, the pellets are air-cooled to around 25°C for stability and durability during storage and transport [56]. Overall, this process underscores the technical precision needed to convert forest and agricultural residues into high-quality pellets for bioenergy.

3.5. Torrefied pellets

Biomass, while a promising renewable energy source, presents several disadvantages compared with traditional fossil fuels like coal. Key limitations include its low bulk density, lower heating value, friability, high moisture content, and inherent non-homogeneity, which can complicate its handling and combustion properties [57]. Despite the benefits of pelletization in improving certain properties of biomass, such as density and uniformity, standard pellets still tend to absorb moisture and may crumble during transport and storage, necessitating careful management during these stages [57]. To address these challenges, torrefaction has emerged as a beneficial thermal pretreatment process that enhances biomass characteristics before pelletization. This process involves heating biomass in an oxygen-limited environment, which improves its heating value, friability, and grindability while simultaneously reducing energy requirements for subsequent size reduction [58]. By increasing energy density, torrefaction also contributes to lower transportation costs and reduced emissions associated with biomass transport.

However, it is essential to note that while torrefaction offers numerous advantages, it can negatively impact pellet durability, especially under severe conditions. This reduction in durability often necessitates using binders to compensate for the decreased lignin content, which serves as the natural binding agent in pellets [59, 60]. Although torrefied pellets typically exhibit greater durability than conventional pellets, further research is essential to determine the economic feasibility of integrating torrefaction with pelletization processes. Preliminary industrial cases have demonstrated successful pelletization of torrefied biomass without the need for binders, suggesting a viable pathway for enhancing biomass use [57]. Overall, implementing torrefaction could potentially increase co-firing rates with coal and improve the overall performance of biomass as a fuel source [57]. By enhancing the energy content of biomass by as much as 21%, torrefaction represents a significant advancement in the effort to make biomass a more competitive alternative to fossil fuels [61]. Thus, ongoing research and development in this area will be critical for optimizing biomass's role in renewable energy systems.

3.5.1. Torrefied pellet production pathways

The production pathways for torrefied pellets, an advanced form of biomass fuel, are:

1. Pathway 1(Whole Trees): In this pathway, whole trees are felled and skidded to designated areas. Once there, they are debarked and then chipped to reduce their size. The chips are trucked to a biohub, where they are dried, ground, torrefied, and ultimately pelletized.
2. Pathway 2 (Forest Residues): In this pathway, harvesting residues generated from logging operations are collected, then chipped to facilitate handling and transportation. The chips are then sent to the biohub for further processing. Concurrently, logs deemed suitable for higher value products are directed to sawmills for additional processing. This approach maximizes resource use by ensuring that both wood chips and logs are effectively processed for different end uses.

3. Pathway 3 (Agricultural Residues): Agricultural residues, such as straw or corn stover, are harvested from the field. After collection, these residues are raked, baled, and stacked. The processed residues are then transported to the biohub, where they are subjected to drying, grinding, screening, torrefaction, and pelletization. This pathway highlights the versatility of agricultural by-products in contributing to sustainable energy production.
4. Pathway 4 (Organic MSW): Organic MSW is picked up from transfer stations and trucked to the biohub where it is dried, ground, screened, and torrefied before being pelletized. This pathway emphasizes the potential of converting organic waste into valuable energy resources while addressing waste management challenges.

Each pathway represents a systematic approach to biomass conversion, demonstrating the feasibility of using various feedstocks for torrefied pellet production. The integration of torrefaction into these processes not only improves the energy content of the final product but also supports the development of sustainable biomass energy systems that contribute to reducing greenhouse gas emissions and promoting a circular economy. Figure 3-1 illustrates the production pathways for torrefied pellets derived from various biomass sources.

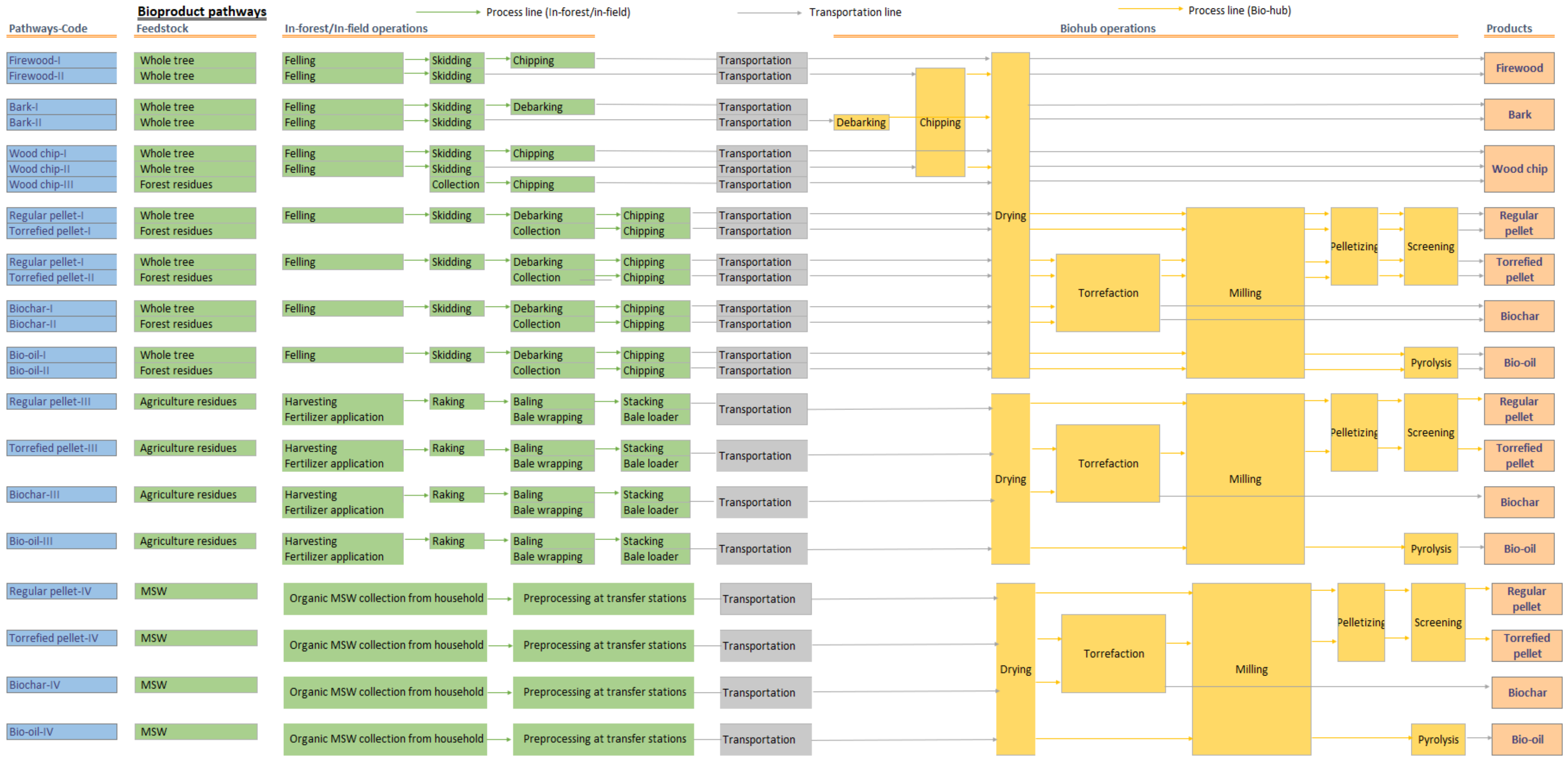


Figure 3-1: Bioproducts and biofuels and their production pathways for biomass processing

3.6. Biochar

Biomass constitutes approximately 10% of global energy production, and its use faces several challenges related to its physical and chemical properties. The energy density of biomass ranges from 2 to 3 GJ/m³, with a heating value of 9 to 12 MJ/kg and a bulk density of 200 to 250 kg/m³. Coal, on the other hand, provides a significantly higher energy density (18.4-23.8 GJ/m³), heating value (23-28 MJ/kg), and bulk density (800-850 kg/m³), along with lower volatile content (approximately 35-40%) and moisture levels (generally less than 10%). Woody biomass's high volatile content (70-75%) and moisture levels (30-45%) further complicate its use as a reliable energy source. Thus, improving the properties of biomass is crucial for establishing it as an effective alternative to fossil fuels.

Torrefaction is a promising thermochemical process designed to address these challenges. Conducted at temperatures between 250°C and 350°C in an oxygen-free environment, torrefaction converts raw biomass into a coal-like material, enhancing its characteristics and making it more suitable for energy production [62-66]. This process, sometimes referred to as mild or slow pyrolysis, yields solid and volatile products, with temperature being a critical factor influencing the quality of the final product [64].

The benefits of torrefaction are manifold, notably enhancing the biomass's carbon content while reducing its oxygen content, significantly improving the heating value and energy density [62, 67-73]. While mass density may decrease because of the release of volatiles during torrefaction, the overall energy density increases, reducing transportation costs. However, variations in raw biomass feedstock, climatic conditions, and supply chains can complicate the maintenance of consistent pelletization quality. Torrefaction aids in standardizing feedstock quality, facilitating a more stable and continuous supply [68, 74]. Moreover, torrefied biomass is amenable to long-term outdoor storage, further reducing storage costs. Its hydrophobic nature results in a 61-68% reduction in moisture content; it produces less water vapour and smoke during combustion, thereby minimizing energy loss [99]. Additionally, torrefied biomass requires 70-90% less energy for grinding than untreated biomass [68]. The applications of torrefied biomass span various sectors, including cement manufacturing, power generation, and steel production [63].

As a high-quality alternative to coal, torrefied biomass, also referred to as biochar, exhibits properties similar to those of coal, thus simplifying milling processes and reducing self-ignition risks during grinding [75]. Its heating value, density, and transportation costs are comparable to those of coal, addressing many handling and transport issues associated with raw biomass [63]. Importantly, torrefied biomass offers stable energy output and does not necessitate changes to existing coal power plant infrastructures. As the demand for cleaner fuels grows and coal power plants face potential closures, the appeal of torrefied biomass as a viable energy source continues to rise, demonstrating clear advantages over raw biomass in power generation [63].

3.6.1. Biochar production pathways

Biochar, a form of torrefied biomass recognized for its promise in carbon sequestration and soil enhancement, is vital for climate change mitigation, soil enhancement, and sustainable waste management. This section presents four key pathways for biochar production, highlighting the various biomass sources and processes that transform them into this valuable carbon-rich material. Figure 3-1 illustrates four pathways for producing biochar. These are:

1. Whole Tree Processing: Entire trees are felled, then debarked and chipped. The chips are dried and torrefied at 200-300°C at a biohub, producing biochar with enhanced energy density and stability.
2. The Use of Forest Residues: Forest residues from logging are gathered, chipped, and transported to biohubs. After drying and torrefaction, these materials are converted into biochar at the biohub.
3. Agricultural Residue Management: Agricultural residues are harvested, baled, and transported to a biohub. There, they are dried and torrefied to create biochar.
4. Organic MSW Use: Organic municipal solid waste is collected and transported to a transfer station before reaching the biohub. After being dried and ground, it is torrefied to produce biochar.

3.6.2. Modeling of Torrefaction

A sequential biomass torrefaction model was developed in Aspen Plus (V14) to produce biochar from a range of biomass-derived feedstocks and organic municipal solid waste. The study used three lignocellulosic feedstocks, spruce, wheat straw, and corn stover. Spruce wood chips (*Picea abies*) were sourced from Weyerhaeuser in Drayton Valley, Alberta, while corn stover (*Zea mays ssp. mays L.*) and wheat straw (*Triticum aestivum L.*) were obtained from southern and northern Alberta, Canada, respectively. The organic municipal solid waste data was collected from Statistics Canada [46]. Each feedstock underwent elemental analysis using a thermogravimetric analyzer (Model SDT Q600). The equations used for calculating proximate and ultimate analyses were drawn from a study by Parikh et al. [76]. In the simulation, the feedstocks were classified as non-conventional solids in Aspen Plus, and their elemental compositions are listed in Table 3-1.

Table 3-1. Elemental analysis of different feedstocks used.

Ultimate (wt%: dry basis)	Wheat Straw	Corn Stover	MSW	Spruce
O_2	48.21	48.25	42.58	45.45
H_2	4.9	4.9	5.85	6.44
N_2	0.5	0.98	0.27	0.18
C	40.09	39.81	48.79	47.48
Moisture (wt%: wet basis)	14	14	25	50
Proximate (wt%: dry basis)				
Volatile matter	75.4	76.32	73.57	83.4
Fixed carbon	18.3	17.62	23.92	16.15
Ash	6.3	6.06	2.51	0.45

3.7. Bio-oil

Global demand for biofuels is increasing. These are considered as an alternative to conventional transportation fuels, recognizing their potential to reduce GHG emissions and fossil fuel dependence [77]. Governments worldwide support the bioeconomy by promoting biomass use for biofuel and bioproducts' production through various incentives and policies [78-80]. Fast pyrolysis is a well-established commercial technology that converts biomass into liquid fuels in a centralized plant setting. This process occurs at temperatures ranging from 400°C to 600°C and at atmospheric pressure, under an oxygen-free environment, with a short residence time (less than 2 seconds). The pyrolysis process produces bio-oil, syngas, and biochar [81-85]. Depending on the feedstock and process conditions, earlier studies have found bio-oil yields of 50% to 75% [86-88]. While bio-oil holds promise as an intermediate for transportation fuel, it poses several challenges for direct application. Notably, its high viscosity and acidity, as well as numerous oxygenated compounds, render it unsuitable for Canada's climate and for blending directly with crude oil [89, 90]. Consequently, bio-oil is refined further through hydro-processing, wherein hydrogen and catalysts convert oxygenated compounds into hydrocarbons. This treatment enhances the bio-oils fuel properties, making it a viable renewable diesel substitute [83, 84, 91].

Research indicates that variations in bio-oil yield stem from differences in biomass feedstocks' chemical and elemental composition. Various reactor configurations, such as fixed bed, bubbling bed, fluidized bed, cyclone bed, and vacuum reactors, have been used. Fluidized bed reactors generally yields the highest bio-oil because of optimal interaction between biomass and the fluidizing medium [83, 92]. This study examines lignocellulosic biomass and evaluates bio-oil production within a fluidized bed reactor framework. The findings indicate that bio-oil yields vary according to biomass source, with forest biomass demonstrating the highest mass yield efficiency. The mass yield of bio-oil from forest biomass is estimated at 75%, with a density of 1.2 t/kL and a moisture content of 25%. Conversely, bio-oil derived from agricultural residues achieves a mass yield of 50% and organic MSW slightly less at 45%, as other studies also found [86-88]. Techno-economic analyses reports the capital costs associated with bio-oil production for a 1000 dry tonne/day plant [91, 93-95]. The capital costs are influenced by feedstock type, biomass procurement costs, bio-oil yield, and capital expenses, which fluctuate based on geographical location, cultivation practices, and transportation logistics.

3.7.1. Bio-oil production pathways

The production pathways for bio-oil are illustrated in Figure 3-1.

1. In Pathway 1, whole trees are felled, skidded, debarked, and chipped in the forest. The resulting wood chips are transported to a biohub where they undergo drying, grinding, screening, and pyrolysis to produce bio-oil and biochar.
2. In Pathway 2, logging residues are collected, chipped, and transported to the biohub for bio-oil production.
3. In Pathway 3, agricultural residues are harvested from the field and raked, baled, and stacked before being transported to the biohub. At the facility, they are dried, ground, screened, and pyrolyzed to yield bio-oil and biochar.
4. In Pathway 4, organic MSW is collected and transported to a transfer station before reaching the biohub. The waste is then dried, ground, screened, and ultimately pyrolyzed to produce bio-oil and biochar.

3.7.2. Pyrolysis

This section described the biomass pyrolysis model we developed using Aspen Plus, as illustrated in the schematic process flow diagram presented in Figure 4-2. The simulation incorporated three biomass feedstocks and organic municipal solid waste as inputs for the pyrolysis reactions. Proximate and ultimate analysis values for all feedstocks are listed in Table 3-1. Based on their respective proximate and ultimate analyses, all feedstocks were categorized as non-conventional solid components in Aspen Plus.

4. Techno-economic assessment

4.1. Delivered cost

Delivered biomass costs include preparation and pre-processing expenses (e.g., felling, skidding, chipping, debarking for forest biomass or residue collection, shredding, raking, baling, nutrient replacement fees, payments to farmers, bale wrapping, bale collection, and storage for agricultural biomass) as well as transportation costs. The delivered cost of each feedstock is estimated based on its cost before transport to the biohub facility based on the data found in the literature and through modeling. Average transportation costs are calculated based on the distance to the biohub. The total delivered cost combines the feedstock and transportation costs for each feedstock across different distances.

4.2. Feedstock cost

We estimated the delivered costs for the feedstocks for each proposed bioproduct, as described in the following subsections.

4.2.1. Whole tree

Whole tree biomass is derived from trees that are felled and chipped. The field cost refers to the expenses associated with gathering and processing the entire tree. Costs related to road construction were excluded since existing roads are used for biomass transportation. Silviculture costs and nutrient replacement expenses are included. Table 4-1 lists the cost components for the whole trees considered in this study based on previous research conducted by our team.

Table 4-1: Costs components of whole tree in-forest operations [22, 96]

Biomass harvesting cost	Value (adjusted to the year 2024) ($/dt)
The whole tree felling costs	6.03
The whole tree skidding costs	5.00
The whole tree debarking costs	14.47
Whole tree chipping costs	3.86
Royalty fee	15.15
Total cost	**44.52**

4.2.2. Forest residues

For this study, it is assumed that all the forest residues are transported to a biohub facility. It is further presumed that the residues arrive at the facility with a moisture content of 35%, following a period of drying in the forest. This drying process typically reduces the initial moisture content from approximately 50% to 35%, optimizing the residues for efficient handling and processing.

Forest residues can be chipped either at the roadside or at the processing plant. Once chipped, the biomass is transported to the plant in large chip vans specifically designed to handle the bulk and weight of the material while ensuring minimal degradation during transit. The second method, bundling and transporting residues to be chipped at the plant, is not commonly used in Canada because of the high supply chain costs, despite some trial implementations in various regions. Consequently, the more prevalent practice involves transporting residues in chipped form, facilitating ease of handling and processing, thus streamlining operations at the biohub. Table 4-2 lists the cost components of the forest residues examined in this study.

Table 4-2: Components used to calculate residue in-forest operations costs [22, 96]

Residue harvesting cost ($/dt)	Value (adjusted to the year 2024) ($/dt)
Residue collection and chipping	14.56
Total cost	14.56

4.2.3. Agricultural residues

The total cost of harvesting agricultural biomass is $48.93 per dry tonne (dt), which includes shredding, raking, and baling, as well as expenses for nutrient replacement, farmer payments, and bale storage.

Table 4-3: Components used to calculate biomass in-field operations costs [22, 96]

Biomass harvesting cost	Value (adjusted to the year 2024) ($/dt)
Shredding operation costs	4.03
Operation costs of raking	2.54
Operation costs of baling	4.01
Nutrient replacement cost	24.59
Fee to the farmer	6.43
Bale wrap operation costs	0.54
Bale collection operation costs	4.67
Bale storage cost	2.13
Total biomass processing costs	**48.93**

4.2.4. Transportation

It is assumed that biomass is uniformly distributed within a circular area around the biohub facility, linked to forest mills for whole trees and forest residues and to transfer stations for MSW and local road infrastructure for agricultural residues. The average transportation costs were calculated; these comprise a fixed loading/unloading cost ($/tonne) that is distance-independent and a variable distance cost ($/tonne/km) that includes expenses like fuel and driver wages, which depend on transportation distance. Earlier studies show fixed and variable transportation costs of $7.26 per dry tonne and $0.26 per dry tonne per kilometer, respectively [24, 49, 97]. All the costs are reported in the base year 2024. After the estimation of the availability of each feedstock within the radii of the biohub locations, we calculated the transportation distances using road networks.

The total transportation cost of each feedstock to the biohub facility was calculated using transportation distances corresponding to the mentioned radii. With these numbers, we developed the cost curves of the delivered feedstock cost ($/dry tonne) versus the bioproduct for each radius considered in this investigation.

4.3. General assumptions

The cost estimates for bioproducts are categorized into three groups: (1) in-forest/in-field operations, (2) transportation, and (3) biohub operations.

Models developed in earlier studies were used to determine the biomass in-forest/in-field operations costs, i.e., debarking, felling, skidding, chipping for forest biomass and residue collection, shredding, raking, baling, nutrient replacement cost, farmer fee, bale wrap, bale collection, and bale storage cost for agricultural residues [24, 54].

As noted in earlier studies, biomass costs vary from one producer to another and one plant to another. It was assumed that biomass can be stored without the need for a fixed storage facility at the biohub, resulting in negligible storage costs; consequently, no capital cost for a storage facility is reported. For forest biomass, there is no consideration for nutrient replacement. Earlier studies note that typically, forest residues are burned on the roadside after forest operations to prevent forest fires [98-100].

According to earlier studies, forest biomass is trucked on roads constructed for the pulp and lumber industry [22]. Plant capacity influences transportation costs, as the area from which biomass is extracted depends on this capacity; the hauling distance is proportional to the square root of the area [28]. As travel distance decreases, transportation costs decrease.

This study created a simulation model to calculate the mass and energy balance for the drying process. The results were used to map the equipment and determine appropriate sizes for drying. Techno-economic models were then built by incorporating equipment costs. The simulation model outputs include the total purchased equipment cost (TPEC), utility consumption expenses, and manpower requirements.

It was anticipated that the TPEC, including equipment purchase, transportation, installation, and land costs, would be incurred in one year. Canada has a well-trained manpower and a construction industry that operates effectively in frigid conditions despite its cold winters. Therefore, no climate-related capital cost penalty is accounted for in this study. The anticipated maintenance costs, in an earlier study, are 3% of the initial plant capital cost [22]. This study evaluated the operating cost and its components, including plant overhead costs, operating expenses, and general and administrative costs (see Table 4-4). Various cost components were assessed using current market prices in Canada, including utility and wage unit costs. To account for operational disruptions in a biomass facility, a plant capacity factor of 0.80 is assumed [101].

The cost breakdown for a biomass project begins with the TPEC as the base (100%). The total installed cost (TIC) is 302% of TPEC, and the indirect cost (IC) adds 89% to the TPEC. The TIC and IC comprise the total direct and indirect costs (TDIC). A contingency of 20% is added to the TDIC, resulting in the fixed capital investment (FCI). The location factor (LF), calculated as 10% of the FCI, is added to determine the total project investment (TPI). Finally, the capital recovery factor (CRF), based on plant life and interest rate, is used to calculate the annual total project investment (ATPI) by multiplying it by the TPI.

Table 4-4: The techno-economic model key assumptions, from [97]

Parameter	Value
Biohub plant lifetime	30 years
Currency used	USD
Biohub operating hours per year	8000
Internal rate of return	10%
Inflation rate	2%
Plant maintenance expense	3% of ATPI
Operating expenses	A quarter of the operating labour expense
Biohub facility overhead	Half the total operating labour and plant maintenance expense
Summation of subtotal plant operating expense	The combination of operating labour, utility, maintenance, and raw feedstock costs
General & administrative cost (G&A)	8% of the subtotal operating cost

4.4. Pellets

We developed a TEA model to evaluate pellet production costs for Canadian conditions, informed by a thorough literature review and process modeling. The model includes expenses related to in-forest harvesting, residue collection, biomass transportation, pellet production at a biohub facility, and processing costs such as capital, labour, energy, and consumables. Transportation costs are influenced by feedstock yield.

Based on an earlier study, we determined that the facility is designed to produce 44,000 dry tonnes per year (dt/y) at a rate of 6 dt/h, with a pelletization yield of 90%. This unit size was chosen to overcome challenges observed in larger facilities. Capital costs, which cover equipment purchase and installation, were also drawn from literature [38]. A scale factor below 1 indicates that capital costs per unit decrease as production capacity increases up to an optimal size of 50,000 dt/y. Beyond this point, costs per unit begin to rise, affecting the ideal capacity for the pellet plant.

Operating costs include energy, labour, and consumables. According to the literature [102, 103] energy costs consist of both natural gas and electricity required to power the equipment. Natural gas is used primarily for feedstock drying, while electricity costs are determined based on the wattage demands of each piece of apparatus, as outlined in a previous study [104, 105]. Labour costs are the primary expense in pellet production. Our team determined that a facility producing 44,000 dry tonnes per year requires four permanent workers and seven casual workers [38].

With minimized production costs, the optimum pellet plant size is 50,000 dry tonnes per year (dt/y). Economies of scale result in reduction of capital costs per unit output as plant capacity increases up to 50,000 dt/y. However, capital costs per unit output rise beyond this maximum size of the unit since multiple smaller units (e.g., two units of 30,000 dt/y) are required, leading to higher overall production costs than a single 50,000 dt/y plant. These dynamics influence the ideal pellet plant capacity.

Table 4-5: The production costs of pellets (from [38])

Equipment name	Scale factor	Capital cost ($)	Maximum available size of equipment (dt/y)
Dryer	0.6	430,000	100,000
Hammer mill	0.6	150,000	108,000
Pellet mill (with conditioner)	0.85	350,000	50,000
Pellet cooler	0.58	170,000	216,000
Screener/shaker	0.6	18,300	108,000
Bagging system	0.63	450,000	108,000

Table 4-6: General assumptions (from [38, 95])

The power rating used for energy for various kinds of equipment	Value (kW)
Grinder equipment	112
Dryer equipment	120
Hammer mill	75
Pellet mill	300
Cooling	5
Bagging	40
Lighting and heating	112

The cost analysis of pellet production from different feedstocks - whole trees, forest and agricultural residues, and organic municipal solid waste (MSW) - reveals varying production costs. Forest residues based pellets have the lowest production cost at $116.38 per dry tonne (dt), while agricultural residues based pellets are the most expensive at $221.22 per dt. Whole trees and organic MSW based pellets have moderate costs at $136.52 and $142.74 per dt, respectively. Key cost components include in-forest/in-field operations, transportation, and biohub processing, with the overall costs heavily influenced by the type of feedstock used.

Table 4-7: Pellets cost breakdown for a 1500 dt/d biohub in Western Canada at a biohub

Pellets from different types of biomass				
Components	**Whole trees**	**Forest residues**	**Agricultural residues**	**Organic MSW**
Total in-forest/in-field operations cost ($/y)	14,114,794	7,281,564	24,466,499	0
Total transportation cost ($/y)	9,109,689	10,613,689	29,023,822	24,332,000
Total biohub processing cost ($/y)	47,671,834	40,639,540	77,248,338	49,844,273
Pellet yield (dt/y)	349,200	349,200	349,200	349,200
Pellet production cost ($/dt)	136.52	116.38	221.22	142.74

4.5. Torrefied pellets

A techno-economic assessment of torrefied pellet production considers the capital and operational costs of the torrefaction and pelletization units. Transportation cost decreases significantly because torrefied pellets' bulk density is higher than regular pellets'. However, the bulk density of torrefied pellets cannot be accurately determined, as it depends on the efficiency of the pelletization process [62, 65, 68-70]. The estimation of transportation costs for torrefied pellets is based on the ratio of the volume of torrefied and regular pellets [62, 65, 68-70]. The cost of handling and transporting torrefied pellets can be estimated with regular pellet costs.

Torrefied pellet production costs in a biohub were estimated in the same way torrefied biomass and conventional pellets were. The expenses include raw materials and processing costs, utilities (natural gas and electricity), supervisor, labour and personnel, and delivered costs, including feedstock and transportation expenses.

The cost breakdown for producing torrefied pellets in a 1,500 dt/d biohub in Western Canada varies considerably depending on the feedstock. Torrefied pellets from forest residues have the lowest production cost at $155.58 per dry tonne (dt), followed by whole trees-based torrefied pellets at $178.18 per dt and organic MSW-based torrefied pellets at $185.16 per dt. Agricultural residues based torrefied pellets, however, are the most expensive at $273.24 per dt. Transportation and in-forest/in-field operations contribute heavily to the overall production cost, with the total annual production cost ranging from $48.4 million to $85 million, depending on the feedstock type.

Table 4-8: Biomass-based torrefied pellets cost distribution from a 1500 dt/d biohub in Western Canada at a biohub

Biomass based torrefied pellets				
Component	**Whole tree**	**Forest residues**	**Agricultural residues**	**Organic MSW**
Total preprocessing, i.e., in-forest/in-field operations cost ($/y)	14,114,794	7,281,564	24,466,499	0

Biomass based torrefied pellets				
Component	**Whole tree**	**Forest residues**	**Agricultural residues**	**Organic MSW**
Total transportation cost ($/y)	9,109,689	10,613,689	29,023,822	24,332,000
Total production cost ($/y)	55,437,879	48,405,585	85,014,383	57,610,318
Pellet yield (dt/y)	311,137	311,137	311,137	311,137
Pellet production cost ($/dt)	178.18	155.58	273.24	185.16

4.6. Biomass-to-biochar modeling

The biomass-to-biochar conversion process primarily relies on torrefaction (mild pyrolysis), illustrated in Figure 4-1. The biomass-to-biochar conversion system was modeled using a kinetic-free, steady-state isothermal approach, with the non-conventional biomass stream characterized by proximate and ultimate analyses. The Predictive Soave-Redlich-Kwong (PSRK) method, used in Aspen Plus, was selected for its strong capability to manage non-ideal thermodynamic behaviour while providing precise predictions of transport properties and phase equilibrium [106]. The PSRK method is particularly effective in accurately predicting phase equilibria, critical for torrefaction, where the material transitions between solid, gas, and liquid phases. This model is especially well-suited to complex systems such as biomass, where the diversity of volatile products and reactions presents challenges for simpler modeling techniques. A Fortran-based flexible program in Aspen Plus facilitates handling complex unit operations, enhancing the system's adaptability to diverse processing conditions.

The key assumptions made through the Aspen Plus simulation are (1) the biomass feed rate is 500-2000 dt/day; (2) the inlet stream enters the system at 25°C and 1 bar; (3) all reactions occur at equilibrium, without pressure drop; (4) the primary volatile products considered are acetic acid ($C_2H_4O_2$), formic acid (CH_2O_2), methanol (CH_3OH), lactic acid ($C_3H_6O_3$), furfural ($C_5H_4O_2$), hydroxylation ($C_3H_6O_3$), carbon dioxide (CO_2), carbon monoxide (CO), and water (H_2O), as described by Haseli [107]; and (5) the study focuses solely on the thermodynamic impact of temperature and pressure, without accounting for catalyst deactivation or reaction kinetics.

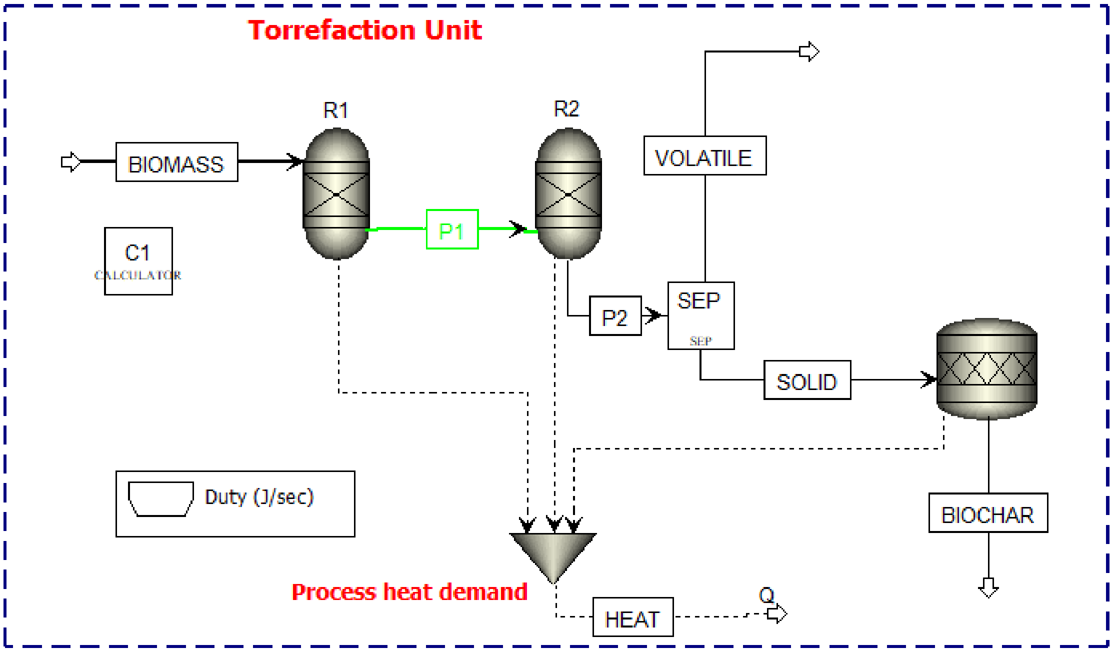


Figure 4-1. Schematic process flow diagram for the torrefaction process

In the conceptual process flow diagram (Figure 4-1), the non-conventional biomass stream (i.e., BIOMASS) is initially introduced into the RYield reactor, decomposing its non-conventional components into conventional components. The yield distribution in the RYield (R1) reactor is determined through a FORTRAN code, based on the ultimate analysis of the feedstock. Given the lack of a widely accepted mechanistic reaction pathway or kinetic constants for torrefaction, the RGibbs reactor (R2) is used to predict the composition of the torrefaction products. This model effectively forecasts the composition of volatile by-products, torrefied biomass, process heat requirements, and CO_2 emissions, ensuring a comprehensive understanding of the overall process.

Torrefaction, a mild form of pyrolysis, takes place in an oxygen-free environment at temperatures of 200°C to 300°C [3]. In this study, a temperature of 300°C was specifically chosen for the torrefaction process for scientifically valid reasons. Hemicellulose decomposes most efficiently at this temperature, releasing a significant amount of volatile organic compounds. This reaction reduces the moisture content and enhances the biomass material's energy density [108]. The result is a hydrophobic, energy-dense product, comparable to low-grade coal, which improves its applicability for co-firing in industrial settings [109].

The release of CO_2 and CO during torrefaction effectively reduces the oxygen content in the biomass, resulting in an increased carbon concentration and a corresponding increase in calorific value [110]. Throughout this process, cellulose and lignin remain structurally stable, thereby preserving both the mass and energy content of the biomass, while also improving its grindability and hydrophobicity. These properties facilitate easier handling, storage, and transportation [67, 111]. As a result, torrefaction proves to be a highly efficient method for converting low-grade biomass into high-energy-density feedstock. The consideration of a 10% volatile matter loss at 300°C for energy calculations in the torrefaction process is justified for the following reasons:

- A 10% volatile loss is a conservative assumption, simplifying energy calculations while ensuring the results remain practical, especially in the absence of detailed experimental data.
- Using a 10% loss provides a consistent basis for comparing results across different studies or experimental conditions, facilitating the evaluation of biomass feedstock performance and process efficiency.
- The use of a modest volatile matter loss allows for streamlined modeling of the torrefaction process, reducing the complexity while still capturing the key impacts on energy yield and feedstock properties.

This approach ensures that the energy calculations remain robust, comparable, and relevant, even when process-specific data is limited. The cost analysis of biochar production using different feedstocks including whole trees, forest residues, agricultural residues, and organic municipal solid waste reveals significant cost variation (see Table 4-9). Forest residues are the most cost-effective, with a production cost of $100.74 per dry tonne, while agricultural residues are the most expensive at $208.71 per dry tonne, mainly due to high transportation and biohub processing costs. Organic MSW, though free from in-field operations costs, still incurs substantial transportation and processing expenses, resulting in a production cost of $114.20 per dry tonne. Despite these differences, each feedstock yields 320,000 dry tonnes of biochar annually.

Table 4-9: Biochar cost breakdown for a 1500 dt/d biohub in Western Canada at a biohub

Biochar				
Parameter	**Whole tree**	**Forest residue**	**Agricultural residue**	**Organic MSW**
Total in-forest/in-field operations cost ($/y)	14,114,794	7,281,564	24,466,499	0
Total transportation cost ($/y)	9,109,689	10,613,689	29,023,822	24,332,000
Total biohub processing cost ($/y)	37,991,794	32,236,226	66,786,508	36,542,413
Biochar yield (dt/y)	320,000	320,000	320,000	320,000
Biochar production cost ($/dt)	118.72	100.74	208.71	114.20

4.7. Modeling of biomass pyrolysis

The complete conversion of biomass to bio-oil was modeled using a steady-state isothermal (PYRO-REC) reactor that operates without specific kinetic considerations. We chose the Peng-Robinson-Boston-Mathias (PR-BM) modeling approach as the primary method, given its suitability for thermodynamic and transport property modeling along with the necessary parameters [112, 113].

The assumptions underlying this study include (1) a biomass feed rate of 500 to 2000 dt/day; (2) an inlet stream temperature of 25°C and pressure of 1 bar; (3) uniform pulverization of the biomass before introducing it into the pyrolysis reactor; (4) uniformity in both gas and solid phase materials, with reactions occurring at equilibrium and without pressure drop; (5) treatment of ash as an inert substance that does not engage in reactions; (6) char being considered 100% carbon; and (7) a purely thermodynamic analysis based on temperature and pressure, without accounting for catalyst deactivation.

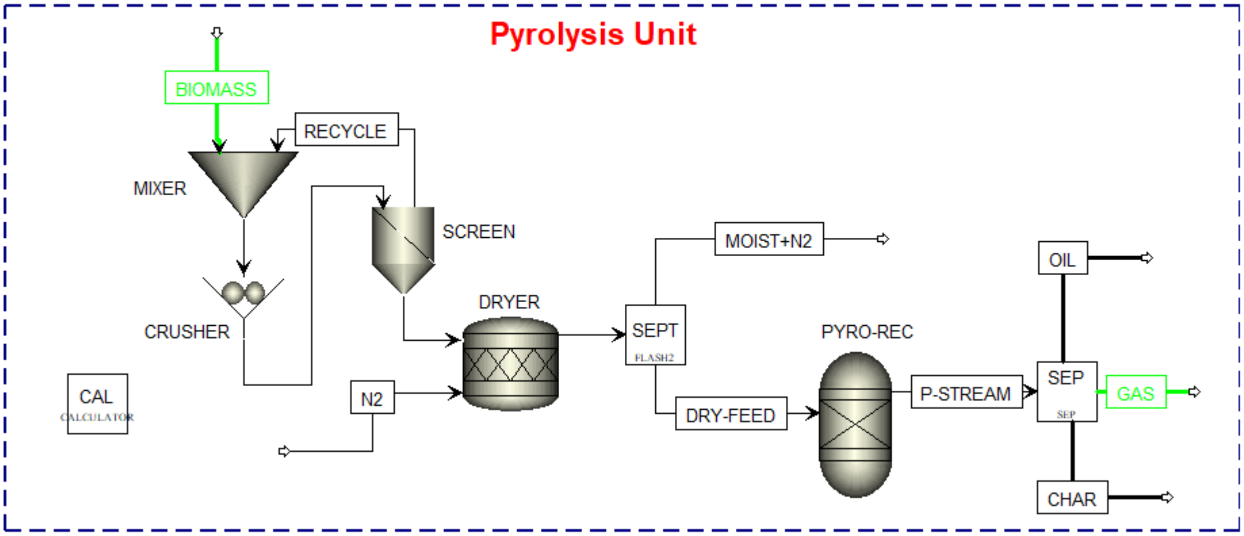


Figure 4-2. Schematic process flow diagram for the pyrolysis process

To start the process, the samples are screened to confirm that particle sizes are smaller than 2 mm, then these are dried to lower moisture content to acceptable levels. This drying stage effectively reduce the water content in the feedstock, and a flash separator is used to separate moisture and nitrogen (N_2) from the feed prior to its introduction into the pyrolysis reactor. The removal of nitrogen, a key inert gas, is essential to optimize the pyrolysis environment and ensure more efficient thermal decomposition of the biomass. The RYield reactor is used for the pyrolysis reaction, with yield values for all feedstocks taken from previous experimental studies [28, 85, 86, 89]. The temperature range for biomass pyrolysis typically falls between 350°C and 600°C, as other studies have found that this range effectively facilitates the thermal decomposition of biomass into bio-oil, syngas, and char [84, 114]. For this work, the temperature of 480 °C is selected because it optimizes product yield by balancing bio-oil and syngas production while minimizing char formation [115, 116]. Operating at this temperature also enhances reaction kinetics, leading to faster biomass decomposition and more effective thermal cracking of intermediates, while also ensuring favourable thermodynamic conditions for heat transfer and energy efficiency. Previous research supports the efficacy of operating at 480°C for efficient biomass conversion and high yields of valuable products [117, 118].

The cost analysis for bio-oil production using several feedstocks including whole trees, forest residues, agricultural residues, and organic municipal solid waste (MSW) shows notable differences in production efficiency (see Table 4-10). Forest residues-based bio-oil show the lowest production cost at $362.30 per kiloliter (kL), while agricultural residues-based bio-oil is the most expensive at $670.42 per kL. This is because of the higher field operations, transportation, and processing costs. MSW-based bio-oil despite having no field operations costs, still incurs significant processing expenses, resulting in a cost of $563.31 per kL.

Table 4-10: Bio-oil cost breakdown for a 1500 dt/d biohub in Western Canada at a biohub

Bio-oil				
Parameter	**Whole tree**	**Forest residue**	**Agricultural residue**	**Organic MSW**
Total in-forest/in-field operations cost ($/y)	14,114,794	7,281,564	24,466,499	0
Total transportation cost ($/y)	9,109,689	10,613,689	29,023,822	24,332,000
Total biohub processing cost ($/y)	96,330,756	90,575,188	111,737,455	84,497,016
Bio-oil yield (kL/y)	250,000	250,000	166,666.67	150,000
Bio-oil production cost ($/dt)	385.32	362.30	670.42	563.31

4.8. Summary

This section presents the detailed techno-economic analysis of biomass processing technologies, including pellet, torrefied pellet, biochar, and bio-oil production in Canada at a biohub. The analysis evaluates key cost components, that is, in-field operations, transportation, and biohub processing, in four primary feedstocks: whole trees, forest residues, agricultural residues, and organic MSW. Pellet production cost at a biohub is least expensive from forest residues at $116.38 per dry tonne and most expensive for agricultural residues at $221.22 per dry tonne. Because of their higher bulk density, torrefied pellets have lower transportation costs, thus forest residues are the most cost-effective feedstock at $155.58 per dry tonne. Biochar production costs at the biohub are lowest for forest residues at $100.74 per dry tonne, while agricultural residue biochar is the costliest at $208.71 per dry tonne. Forest residues offer the lowest bio-oil production cost at $362.30 per kL at the biohub. Overall, the analysis underscores the significant influence of feedstock type and biohub size on production costs, with forest residues consistently emerging as the most economically favourable option among the different biomass conversion processes.

5. GHG emissions estimation for biofuels and bioproducts at the biohub

The carbon footprint assessment conducted in this study to estimate the GHG emission followed the four stages described in ISO 14040: goal and scope definition, life cycle inventory analysis, life impact assessment, and life cycle interpretation [105, 119]. We clarified the goal and scope by specifying the system boundary. We compiled the detailed inventory of GHG emissions produced during the conversion of lignocellulosic biomass (whole tree, forest residues, agricultural residues, and organic MSW) into various biofuels and bioproducts (firewood, bark, wood chips, regular and torrefied pellets, biochar, and bio-oil). We then assigned global warming potentials to the corresponding GHG emissions to accurately assess their effects before estimation of the results, outlined in section 5.3 (Results and discussion).

The following assumptions were made in this study:

- First, the locations of biohub operational facilities are forest mills for forest biomass, including whole trees and forest residues, transfer stations for MSW, and nearby road infrastructure for agricultural residues.
- Second, the travel distance (average biomass collection radius) is calculated according to the designated locations of the biohub.
- The impacts from silviculture (fertilizer and pesticide production and spraying) were disregarded for the feedstock in this study.
- GHG emissions associated with road construction and nutrient replacement for the feedstocks were not included.

5.1. Goal and scope

The first step of a GHG footprint assessment is defining the goal and scope; then the objectives are stated, the system boundaries are developed, and the functional unit of the study are allocated.

5.1.1. Goal

We used unit operations to develop the carbon footprint assessment model, which helps analyze the environmental impacts of the production of biofuels and bioproducts from forest-based biomass using different conversion pathways. The objective was to estimate the GHG emissions resulting from the production of seven bioproducts (firewood, bark, wood chips, pellets, torrefied pellets, biochar, and bio-oil) derived from biomass. The GHG emissions values obtained from this assessment serve as a benchmark for assessing the advantages and commercial viability of biohub operating facilities.

5.1.2. Scope

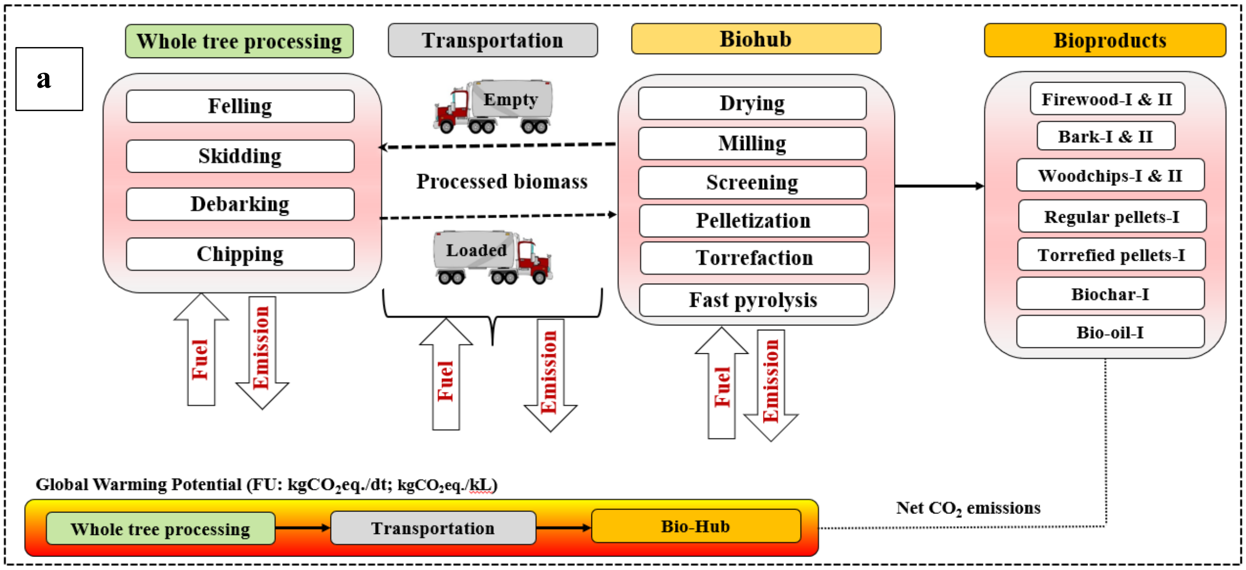
For this study, GHG emissions are estimated for the following key stages: (i) in-forest/in-field operations, i.e., harvesting and logging trees in the forest and in-field harvesting of agricultural residues followed by shredding, raking, and baling; (ii) transportation, i.e., transporting trees, branches, and tree tops as chips (wet) and agricultural residues as bales (wet) to a biohub operating facility; and (iii) biomass processing, i.e., processing biomass into the desired bioproducts in a biohub.

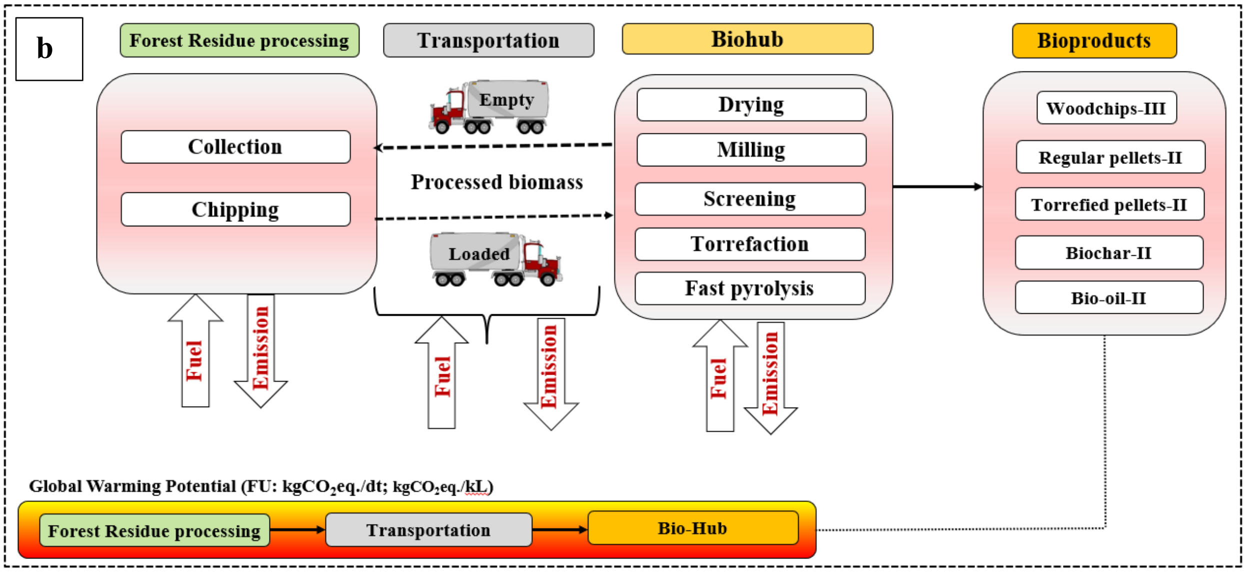
5.1.3. System boundary, functional unit, and GHGs

The GHG footprint assessment in this study was performed as shown in Figure 5-1, which illustrates in detail the system boundary. The figure depicts the processes that were investigated to estimate the GHG emissions from the production of the biofuels and bioproducts. The GHG footprint of each bioproduct comprises of three processes: biomass production (in-forest/in-field operation), transportation, and processing in a biohub operating facility. For this study, the system boundary includes the direct inputs of fossil fuel in every stage of the entire life cycle, as shown in Figure 5-1. The forest residue-based biomass pathway incorporates the effects of forwarding and chipping forest residues in the forest. Thus, the GHG assessment includes the impacts of manufacturing the forwarder and chipper and operations using fossil fuel (diesel) to produce the biomass. The activities associated with producing whole tree-based biomass are felling, skidding, debarking, and chipping whole trees. Thus, the GHG assessment accounts for emissions from the manufacturing and operation of the feller, skidder, debarker, and chipper. The agricultural residue-based biomass pathway includes the emissions associated with the operation of harvester, raker, bailer, and fertilizer application of agricultural residue in the field. We assumed that the organic MSW is preprocessed at the transfer stations and did not consider any emissions related to this. We also assumed that wet wood chips would be transported to the biohub in trucks on existing road networks. Consequently, the impacts of road construction are not factored in when considering the transportation of these feedstocks to the biohub. However, we did account for the environmental effects of truck manufacturing and operation in both loaded and empty conditions. The functional unit, that is, the unit used as the basis for analysis, is one unit of the bioproduct or biofuel (1 dt or 1 kL). The assumed global warming potentials of CO_2, CH_4, and N_2O ($CO_{2eq.}$) are 1, 25, and 298, respectively [103, 120, 121].

5.1.4. Allocation method

A method of allocation is required to distribute each products' inputs and outputs throughout the system, along with their corresponding environmental impacts [122]. In this study, mass allocation was used. Mass allocation refers to allocating the environmental burdens of a process among its various co-products or outputs based on their physical mass. It is commonly used when co-products have comparable functionalities and their masses can be accurately measured. The method implies that environmental burdens are distributed among co-products based on their respective masses. Therefore, the greater the bulk of a co-product, the greater its proportion of environmental impacts. The rationale behind mass allocation is that the mass of a product or co-product is frequently directly proportional to the amount of resources consumed, waste produced, or emissions generated during its production.


a
Whole tree processing
Transportation
Biohub
Bioproducts
Felling
Skidding
Debarking
Chipping
Empty
Processed biomass
Loaded
Drying
Milling
Screening
Pelletization
Torrefaction
Fast pyrolysis
Firewood-I & II
Bark-I & II
Woodchips-I & II
Regular pellets-I
Torrefied pellets-I
Biochar-I
Bio-oil-I
Fuel
Emission
Fuel
Emission
Fuel
Emission
Global Warming Potential (FU: kgCO$_2$eq./dt; kgCO$_2$eq./kL)
Whole tree processing
Transportation
Bio-Hub
Net CO$_2$ emissions


b
Forest Residue processing
Transportation
Biohub
Bioproducts
Collection
Chipping
Empty
Processed biomass
Loaded
Drying
Milling
Screening
Torrefaction
Fast pyrolysis
Woodchips-III
Regular pellets-II
Torrefied pellets-II
Biochar-II
Bio-oil-II
Fuel
Emission
Fuel
Emission
Fuel
Emission
Global Warming Potential (FU: kgCO$_2$eq./dt; kgCO$_2$eq./kL)
Forest Residue processing
Transportation
Bio-Hub

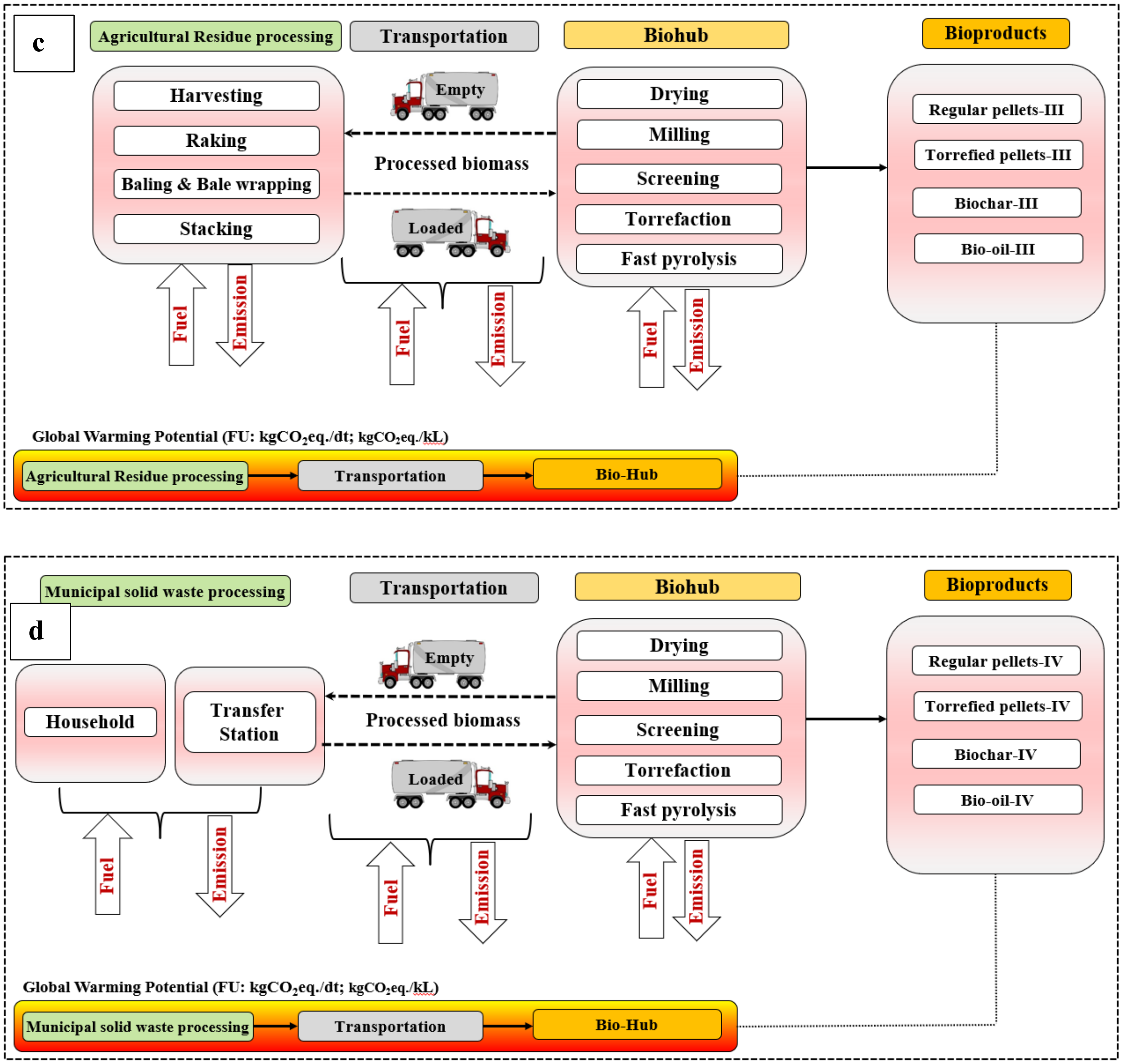


Figure 5-1: System boundaries for (a) Forest residue, (b) Whole tree, (c) Agricultural residue, and (d) MSW processing

5.2. Data inventory

The data inventory includes all the critical direct energy inputs in the system, GHG emissions, and material requirements for every unit operation involved in the production of biomass and its corresponding bioproducts. We assumed a biohub is used for the production of bioproducts.

5.2.1. Biomass harvesting and collection

For in-forest/in-field operations, only the GHG emission impacts of manufacturing the equipment and operating the feller, skidder, debarker, chipper, harvester, raker, bailer, and bail loader with fossil fuels were included. Emissions factors for the material and equipment associated with the system and the data for biomass production, transportation, and processing are from literature [102-105]. Earlier studies report that whole trees are harvested using a feller buncher, which consumes approximately 0.67 L of diesel/m^3 of wood and that grapple skidders are used to transport the trees over an estimated skidding distance of 150 meters to a roadside chipper, with a fuel consumption rate of 0.75 L of diesel/m^3 of wood [22, 103]. Both the harvesting and skidding processes use ultra-low sulfur diesel (ULSD) fuel with a GHG emission coefficient of 2,727 gCO_2eq./L [123, 124]. The trees are chipped by a roadside chipper, and these chips are transported to the biohub plant using 3.33 liters of diesel per dry tonne [103]. Table 5-1 gives the input quantities required for each subunit operation in a biohub operating plant with an annual biohub capacity of 500,000 dt. The table also lists the input quantities of fossil fuels and their corresponding emissions factors that are used to estimate the GHG emissions of the bioproducts ($kgCO_2eq$./functional unit of the bioproducts).

Forest residue-based biomass production includes biomass forwarding and chipping. Therefore, as for whole tree harvesting, the impacts of the manufacturing and operation of the equipment were included in this study. Fuel consumption estimates from earlier research indicate that the forwarder consumes approximately 0.52 L of ULSD/m^3 while chipping requires around 3.93 L of ULSD per dry tonne (Table 5-1) [103]. Chipping forest residues is less efficient than chipping whole trees because of the differences in size and density. Forest residues are also transported in the form of wet chips to be dried and thermochemically processed.

The agricultural residue harvesting process involves several activities, each contributing to GHG emissions through diesel consumption. Harvesting requires 3.53 L of diesel/ha, emitting 2727.18 gCO_2eq./L. Subsequent operations include raking, which consumes 0.00047 L of diesel/kg, baling at 0.0029 L/kg, and bale wrapping at 0.055 L/kg, all contributing to CO_2 emissions (2727.18 gCO_2eq./L). Additionally, bale stacking uses 0.00083 L/kg, and bale loading consumes 0.328 L/dt.

5.2.2 The transportation of biomass to a biohub operating plant

Whole trees are chipped and the wet chips are transported to a biohub via trucks on existing road networks. The forest biomass collection area is assumed to be circular. As mentioned above, road construction is not included in the assessment, but the impacts of truck manufacturing and operation (loaded/empty) are. We used the values given in an earlier study for a truck capacity of 17.5 tonnes; the truck has an efficiency of 0.33 L of diesel per kilometer when it is loaded with wet chips; the return trip, when the trucks are empty, uses 0.24 L of diesel per kilometer [125].

Trucks are also used to send chips to a biohub, with an annual capacity of 500,000 dt, and the distances to the biohubs were determined. We also assumed that the truck size and fuel efficiency for transporting forest residue and whole tree chips are the same.

It was assumed that a truck is loaded with 12.6 tonnes of agricultural biomass and consumes 0.33 liters of diesel per kilometer. For the return trip, when the truck is empty, fuel consumption drops to 0.24 liters per kilometer [125].

5.2.3. Biomass processing in biohubs

Biomass processing in biohubs includes the energy-intensive unit operations drying, grinding, screening, torrefaction, pelletization, and fast pyrolysis. In some pathways, debarking and chipping takes place at the biohub operating facility. The details on the biomass processing pathways to produce bioproducts are assessed in detail in Section 4.

This assessment includes the GHGs emitted from operation of the equipment, considering the consumption of both natural gas and electricity. An earlier study reports that whole tree and forest residue have a relatively high moisture content (50% and 35%, respectively) [126]. Therefore, considerable natural gas is consumed for drying at a biohub. This evaluation also considers the environmental effects from building the biohub and producing bioproducts in it.

Table 5-1: Energy consumption and GHG emissions coefficient for harvesting and transporting whole trees, forest residue chips, and agricultural residues [124, 127]

Whole trees		
Operations	Input quantity	Emission coefficient
	Used values (unit)	Used values (unit)
Felling (diesel)	0.61 L/m^3	2727.18 gCO$_2$eq./L
Skidding (diesel)	0.75 L/m^3	2727.18 gCO$_2$eq./L
Chipping (diesel)	3.33 L/dt	2727.18 gCO$_2$eq./L
Chips transportation (diesel)	0.24, 0.33 L/km	2727.95 gCO$_2$eq./L
Forest residue		
Forwarding (diesel)	0.52 L/m^3	2727.18 gCO$_2$eq./L
Chipping (diesel)	3.93 L/dt	2727.18 gCO$_2$eq./L
Chips transportation (diesel)	0.24, 0.33 L/km	2727.95 gCO$_2$eq./L
Agricultural residue		
Harvesting (diesel)	3.53 L/ha	2727.18 gCO$_2$eq./L
Raking (diesel)	0.00047 L/dry kg	2727.18 gCO$_2$eq./L
Baling (diesel)	0.0029 L/dry kg	2727.18 gCO$_2$eq./L
Bale wrapping (diesel)	0.055 L/ dry kg	2727.18 gCO$_2$eq./L
Bale Stacking (diesel)	0.00083 L/ kg	2727.18 gCO$_2$eq./L
Bale Loading (diesel)	0.328 L/ dt	2727.18 gCO$_2$eq./L
Transportation of residues (diesel)	0.24, 0.33 L/km	2727.95 gCO$_2$eq./L

5.3. Results and discussion

The allocation method, key assumptions, and system boundary for all feedstocks were defined, and the corresponding GHG emissions for manufacturing bioproducts from two forest biomass sources were estimated, as detailed in Sections 5.3.1-5.3.6. The GHG emissions include the environmental impacts for 1 dt of bioproduct, specifically firewood, bark, wood chips, regular and torrefied pellets, and biochar, and 1 kL of bio-oil. Agricultural residue-based pathways generate the highest GHG emissions of the biomass sources. This is primarily attributed to agricultural residues' inherently lower energy density, requiring more material to produce the same energy output as forest biomass. Consequently, fuel consumption for transportation and energy use in processing increases, leading to higher overall emissions. The low bulk density of agricultural residues also contributes to higher transportation costs per unit of energy, as larger volumes must be moved to achieve equivalent energy yields, which further intensifies the GHG emissions footprints. GHG emissions from the whole tree-based pathways are higher than from the forest residue-based pathways because of the higher moisture content of whole tree feedstock (50%)

compared to forest residue feedstock (35%). From the GHG emissions perspective, forest residue-based bioproducts are preferred for biomass-based bioproduct generation at a biohub over whole tree-based bioproducts.

5.3.1. Firewood

The two pathways assessing the production of firewood from whole trees, Firewood-I and II, highlight the differences in processing approaches and their associated GHG emissions. In the case of Firewood-I, chipping is done in the forest, whereas for Firewood-II, it is done at the biohub. On average, for a 1500 dt/d capacity biohub, the estimated GHG emissions associated with Firewood-I and II are 33.35 kilograms of carbon dioxide equivalent (kg CO2eq.) per dt (1.79 kgCO2eq./GJ) and 41.86 kg CO2eq.) per dt (2.25 kgCO2eq.GJ), respectively. These GHGs are emitted in various stages of the processing pathways, i.e., tree harvesting in the forest, biomass transportation, and biomass processing in the biohub. Harvesting in the forest includes felling, skidding, and chipping the wood, which require equipment that uses diesel derived from fossil fuels. Feedstock drying at the biohub facility uses natural gas, which releases CO2. The main contributors of GHG emissions in both pathways are the transportation of biomass and its production in the forest. These unit operations contribute 94% and 80% to the overall GHG emissions. More GHGs are generated in Firewood-II than Firewood-I because in the latter, chipped wood is used, reducing the mass transported and thus generating comparatively fewer emissions from transportation. The estimated GHG emissions associated with each unit operation and the total GHG emissions are presented in Table 5-2.

Table 5-2: GHG emissions of unit operations in firewood production (biohub capacity: 1500 dt/d) in Western Canada

GHG emissions of unit operations: Firewood (kgCO$_2$eq./dt)		
Operations	**Firewood-I**	**Firewood-II**
Harvesting	26.42	17.28
Transportation	5.22	5.78
Biohub	1.72	9.50
Total (kgCO$_2$eq./dt)	33.35	41.86
Total (kgCO$_2$eq./GJ)	1.79	2.25

5.3.2. Bark

The GHG emissions associated with bark extraction from whole trees are estimated to be 65.20 kg of CO$_{2eq}$. per dry tonne of bark (3.2 kgCO$_2$eq./GJ). These GHG emissions are largely a result of debarking. Debarking is the process of removing the protective outer layer of bark from trees, which typically requires the use of machinery and energy-intensive methods powered by diesel.

5.3.3. Wood chips

The pathways considering wood chips produced from whole trees are referred to as Wood chips-I and II and forest residues as Wood chips-III, respectively. Both generate GHG emissions. The GHG footprint of Wood chips-I pathway is 32 kgCO$_2$eq./dt (1.71 kgCO$_2$eq./GJ). Similarly, Wood chips-II pathway's GHG footprint is 32 kgCO$_2$eq./dt (1.74 kgCO$_2$eq./GJ) and for Wood chips-III pathway, the GHG footprint is 20 kgCO$_2$eq./dt (3.4 kgCO$_2$eq./GJ). These emissions are influenced by several factors, such as the moisture content of the biomass, its transportation, and the harvesting techniques. The transportation of biomass from the source to the biohub is necessary for both types of biomass and typically involves trucks operated by fossil fuel (diesel) that emit CO_2. Transportation accounts for approximately 50% and 78% of the total GHG emissions for the respective wood chips. Harvesting contributes to overall GHG emissions through the machinery for felling, skidding, chipping, and forwarding, also propelled by diesel. The estimated GHG emissions associated with each unit operation and the total GHG emissions for the wood chips are presented in Table 5-3.

Table 5-3: GHG emissions of unit operations in wood chips production (biohub capacity of 1500 dt/d in Western Canada)

GHG emissions of unit operations: Wood chips ($kgCO_2eq./dt$)			
Operations	Wood chips-I	Wood chips-II	Wood chips-III
Harvesting	25.25	16.54	11.18
Transportation	4.98	5.51	7.58
Biohub	1.63	10.34	0.82
Total ($kgCO_2eq./dt$)	31.86	32.39	19.58
Total ($kgCO_2eq./GJ$)	1.71	1.74	1.05

5.3.4. Pellets

Torrefied pellets derived from whole trees, forest residues, agricultural residues, and organic MSW were assessed through pathways named Torrefied pellet-I, II, III, and IV, respectively. For Torrefied pellet-I and II, biomass processing in the biohub contributes 71% and 73.4%, respectively, to the overall GHG emissions. These GHG emissions are attributed to torrefaction and pelletization, which are energy-intensive.

Regular pellets derived from whole trees, forest residues, agricultural residues, and organic MSW, known as Pellet-I, II, III and IV, also generate GHG emissions during processing in the biohub. 73% and 75% of the total life cycle GHGs, respectively, are emitted in the operations in the biohub for Pellet-I and II. Processing in the biohub also impacts the GHG emissions for torrefied pellets given the substantial consumption of utilities (natural gas and electricity) for pelletization and torrefaction.

The GHG emissions for both regular and torrefied pellets are listed in

Table 5-4. In terms of GHG emissions per unit energy ($kgCO_2eq./GJ$), Pellet-II and Torrefied Pellet-II are the most efficient, emitting only 1.29 $kgCO_2eq./GJ$ and 1.47 $kgCO_2eq./GJ$, respectively.

Table 5-4: GHG emissions of unit operations for pellet production (biohub capacity: 1500 dt/d) in Western Canada

GHG emissions of unit operations: Pellets ($kgCO_2eq./dt$)

Operation	Pellet-I	Pellet-II	Pellet-II	Pellet-IV	Torrefied pellet-I	Torrefied pellet-II	Torrefied pellet-III	Torrefied pellet-IV
Harvesting	44.82	12.70	64.19	0	50.48	14.26	72.06	0
Transportation	5.68	8.64	43.90	37.02	6.38	9.71	51.78	41.59
Biohub	3.54	2.61	2.02	3.58	4.40	3.35	2.61	4.40
Total ($kgCO_2eq./dt$)	54.04	23.94	110.11	40.60	61.26	27.32	126.19	45.99
Total ($kgCO_2eq./GJ$)	2.91	1.29	5.92	2.18	3.29	1.47	6.80	2.47

5.3.5. Biochar

The production of biochar from whole trees, forest residues, agricultural residues, and organic MSW (Biochar-I, II, III, and IV) generates different levels of GHG emissions, as shown in Table 5-5. Biochar-III has the highest GHG emissions (124.44 $kgCO_2eq./kL$), given its high harvesting (70.04 $kgCO_2eq./kL$) and transportation emissions (50.29 $kgCO_2eq./kL$). Biochar-II has the lowest overall emissions (28.47 $kgCO_2eq./kL$), a result of minimal transportation and biohub processing contributions. Biochar-I and Biochar-IV show moderate level emissions; Biochar-IV has no harvesting-related emissions, and thus a lower total of 32.96 $kgCO_2eq./kL$. From an energy-efficiency perspective, Biochar-II and Biochar-IV have the lowest GHG emissions per unit of energy, at 1.26 $kgCO_2eq./GJ$ and 1.46 $kgCO_2eq./GJ$, respectively, while Biochar-III is the least efficient at 5.51 $kgCO_2eq./GJ$.

Table 5-5: GHG emissions of unit operations for biochar production (biohub capacity: 1500 dt/d) in Western Canada

GHG emissions of unit operations: Biochar				
Operations	**Biochar-I**	**Biochar-II**	**Biochar-III**	**Biochar-IV**
Harvesting	49.03	13.85	70.04	0
Transportation	6.20	9.43	50.29	27.84
Biohub	6.21	5.19	4.10	5.12
Total ($kgCO_{2eq}./kL$)	61.43	28.47	124.44	32.96
Total ($kgCO_{2eq.}/GJ$)	2.72	1.26	5.51	1.46

5.3.6. Bio-oil

The GHG emissions for bio-oil production derived from whole trees, forest residues, agricultural residues, and organic MSW vary considerably. The bio-oil produced from agricultural residues, Bio-oil-III, has the highest total GHG emissions, at 144.78 $kgCO_2eq./kL$, largely due to high transportation GHG emissions (66.26 $kgCO_2eq./kL$). Bio-oil-II, from forest residues, has the lowest GHG emissions, 66.70 kgCO_2eq./kL, due to lower harvesting and biohub processing GHG emissions. In terms of energy efficiency, Bio-oil-II also has the lowest GHG emissions per GJ (1.95 kgCO_2eq./GJ) and Bio-oil-III the highest (4.23 kgCO_2eq./GJ). Bio-oil-I (whole trees) and Bio-oil IV (MSW) generate moderate level GHG emissions in both total and per GJ figures, reflecting their respective feedstock characteristics (see Table 5-6). Bio-oil's significantly higher GHG emissions are due to the energy-intensive units in the biohub. Bio-oil-III has high GHG emissions of 144 kgCO_2eq. per dry kL.

The conversion of biomass into biochar and bio-oil typically involves high temperatures and energy-intensive unit operations, which rely on fossil fuels (diesel and natural gas) and electricity. Whole tree's higher moisture content contributes more GHG emissions than forest residue because of the additional drying energy.

Table 5-6: GHG emissions of unit operations in bio-oil production (biohub capacity: 1500 dt/d in Western Canada)

GHG emissions of unit operations: Bio-oil				
Operation	**Bio-oil-I**	**Bio-oil-II**	**Bio-oil-III**	**Bio-oil-IV**
Harvesting	61.26	18.24	41.01	0
Transportation	8.17	12.42	66.26	56.33
Biohub	37.38	36.04	37.51	39.75
Total (kgCO_2eq./kL)	106.81	66.70	144.78	96.08
Total (kgCO_2eq./dt)	89.01	55.58	120.65	80.08
Total (kgCO_2eq./GJ)	3.12	1.95	4.23	2.81

5.4. GHG emissions from power plants

The GHGs emitted from the combustion of wood chips, regular pellets, and torrefied pellets to produce 1 kWh of electricity are substantially different from coal; for every kilowatt-hour of electricity produced from coal, around 984.6 g CO_2eq. are released into the atmosphere [128]. Wood chips, regular pellets, and torrefied pellets emit far fewer GHGs, less than 1/10th of the coal-based power GHG emissions. These biomass-derived bioproducts therefore offer a significant advantage. By using them, power plants can reduce their carbon footprint and contribute to mitigating climate change. The lower GHG emissions associated with wood chips and pellets make them environmentally favourable alternatives to coal combustion.

5.5. Summary

The GHG emissions associated with firewood, bark, wood chips, pellets, biochar, and bio-oil production in Western Canada vary depending on the feedstock and unit operations. Firewood-I and II from whole trees show GHG emissions of 33.35 kgCO_2eq./dt and 41.86 kgCO_2eq./dt, respectively, with higher GHG emissions from Firewood-II because of biohub chipping operations. For bark production case, the GHG emissions are 65.20 kgCO_2eq./dt, driven mainly by the energy-intensive debarking process.

Wood chips from whole trees (Wood chips-I) and forest residues (Wood chips-III) have GHG emissions of 31.86 kgCO_2eq./dt and 32.39 kgCO_2eq./dt, respectively, largely a result of harvesting and transportation activities. Similarly, producing pellets at a biohub contributes significantly to total GHG emissions, particularly for torrefied pellets derived from agricultural residues (Torrefied pellet-III), which emit 126.19 kgCO_2eq./dt.

Biochar and bio-oil production show significant GHG variations, with Biochar-III pathway based on agricultural residues having the highest emissions (124.44 kgCO_2eq./dt) and Biochar-II based on forest residues has the lowest emissions (28.47 kgCO_2eq./dt). Bio-oil III pathway based on agricultural residues has the highest emissions (144.78 kgCO_2eq./kL), driven by high transportation emissions, and Bio-oil II pathway based on forest residues has the lowest emissions (66.70 kgCO_2eq./kL). Energy-intensive biohub operations, transportation, and feedstock type significantly impact the GHG emissions of each bioproduct and biofuel.

6. Development of biohub product cost and emission estimation tool – CANBIO-HUB 2.0

6.1. Cost and GHG emission estimation tool from production of biofuels and bioproducts in a biohub

This section presents the CANBIO-HUB 2.0, a spreadsheet-based biohub product cost and emission estimation tool. The tool has an intuitive interface, enabling users to calculate bioproduct costs under varying input conditions. The tool also has a variety of features and techno-economic parameters, enabling users to assess bioproducts based on cost and location. It is designed to support economic decision-making for biohubs throughout Canada.

6.2. Method

The cost and emission estimation tool, built using Microsoft VBA 7.1, is designed to calculate costs and GHG emissions for production of biofuels and bioproducts in biohubs across Canada, as mentioned earlier. Three regions and considered including Western, Central, and Eastern Canada. Prestored biomass resource data, including yields for whole trees, forest residues, agricultural residues, and organic MSW, is available for each region (see Section 2), allowing users to simply select their region without manually entering biomass data.

CANBIO-HUB 2.0 is structured into three components: in-forest/in-field biomass production cost estimation, cost estimation of transportation to a biohub, and overall cost estimation of biofuels and bioproducts in a biohub. For whole trees, the in-forest costs are felling, skidding, debarking, and chipping operations and, for forest residues, these are collection and chipping. For agricultural residues, the in-field costs are raking, baling, and stacking. Users can choose from “Whole tree,” “Forest residues,” “Agricultural residues,” and “MSW” in the feedstock section. The biohub capacity is modeled to estimate biofuel and bioproduct costs based on user-defined capacity targets ranging from 500 dt/d to 2000 dt/d. Figure 6-1 illustrates a system overview.

In summary, the tool requires three main user inputs:

Region (Western, Central, or Eastern Canada),

Feedstock type (whole tree, forest residues, agricultural residues, or MSW) and

Biohub capacity (500 dt/d, 1000 dt/d, 1500 dt/d, or 2000 dt/d).

Using the provided inputs, CANBIO-HUB 2.0 calculates cost and GHG emission estimates for various biofuels and bioproducts, including bark, firewood, wood chips, regular and torrefied pellets, biochar, and bio-oil. Users can modify critical financial variables, i.e., plant capacity factor, scale factor, inflation rate, interest rate, and annual operating hours. This is beyond the main dashboard, which functions as the tool for estimating biohub product costs and emissions. Figure 6-1 shows a detailed view of the dashboard.

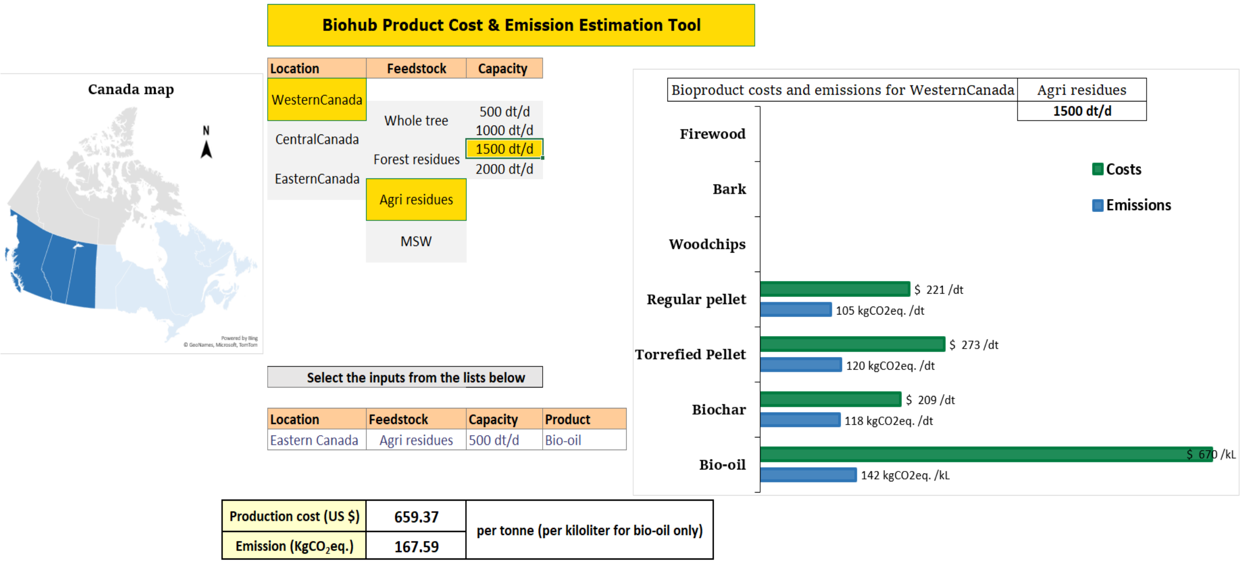
There are two methods to determine biofuel and bioproduct costs in excel:

1. Through the interactive dashboard to determine cost and GHG emissions for several biofuels and bioproducts (preferred);
2. Through the drop-down menu to select the inputs dashboard to determine the cost and GHG emissions for a single biofuel and bioproduct.

For method 1 (interactive dashboard) (preferred):

In Figure 6-1, the selected location is Western Canada, with agricultural residues as the feedstock type and a capacity of 1500 dt/d. For these inputs, the bioproduct costs and emissions are as follows:

- Regular pellet: \$221/dt, 105 kgCO_2eq./dt
- Torrefied pellet: \$273/dt, 120 kgCO_2eq./dt
- Biochar: \$209/dt, 118 kgCO_2eq./dt
- Bio-oil: \$679/kL, 142 kgCO_2eq./kL


Biohub Product Cost & Emission Estimation Tool

Location	Feedstock	Capacity
WesternCanada	Whole tree	500 dt/d
CentralCanada	Forest residues	1000 dt/d
EasternCanada	Agri residues	1500 dt/d
	MSW	2000 dt/d

Select the inputs from the lists below

Location	Feedstock	Capacity	Product
Eastern Canada	Agri residues	500 dt/d	Bio-oil

Production cost (US \$)	659.37	per tonne (per kiloliter for bio-oil only)
Emission (KgCO_2eq.)	167.59	

Figure 6-1: An overview of CANBIO-HUB (Version 2)

For method 2 (drop-down menu):

To calculate the cost and emissions of bio-oil from agricultural biomass at a biohub with a 500 dt/d capacity in Eastern Canada (refer to Figure 6-1):

Choose “Eastern Canada” in the “Location” menu

Set “500 dt/d" in the “Capacity” menu

Select “Agri residues" under “Feedstock”

Choose “Bio-oil" under “Product”

With these selections, the bio-oil cost is \$659.37/kL, and the associated emissions are 167.59 kgCO_2eq./kL.

7. Summary

Around 10% of global energy is derived from biomass resources [65, 129]. However, variability in biomass quality and quantity, along with low density, heating value, and yield, present challenges for large-scale use. These factors lead to high delivery and conversion costs. This report introduced CANBIO-HUB 2.0, a techno-economic and GHG estimation model developed for Canada to address these issues.

The following are the key focus areas of this study:

1. The study discussed the various approaches to developing methods of quantifying whole trees, forest residues, agricultural residues, and organic MSW.
2. Potential products from a biohub, specifically firewood, wood chips, bark, pellets, torrefied biomass or biochar, torrefied pellets, and bio-oil, were examined.
3. Pathways for biomass processing and end-product production in a biohub were defined, with the GHG emissions estimation for various stages of each product.

The pathways describe the various feedstocks and their corresponding final products flows. The feedstocks assessed here for processing in biohubs are whole trees, forest residues, agricultural residues, and organic MSW. Each feedstock undergoes a series of specific processing steps that transform it into different biofuels and bioproducts.

For whole trees, the process typically starts with in-forest operations (felling, followed by skidding and chipping), eventually yielding firewood, wood chips, and bark. Similarly, forest residues, which consist of leftover branches and non-merchantable parts of the tree, are processed into biochar, wood chips, firewood and biofuels.

Agricultural residues, such as crop leftovers, are raked, baled, and stacked before being processed into biochar, bio-oil, and pellets. Organic MSW, derived from urban waste, can be converted into higher-value products like bio-oil and torrefied pellets, which have enhanced energy density for industrial fuel use.

The pathways effectively map how different feedstocks move through a series of processing steps to create diverse bioproducts, highlighting the flexibility in biomass use. The final outputs, i.e., biochar, bio-oil, firewood, and torrefied pellets, provide valuable renewable energy and material solutions.

A spreadsheet-based biohub model (CANBIO-HUB 2.0) for the estimation of product cost and GHG emissions was developed. The biohub product costs and emissions are summarized as follows:

The tool evaluates the costs and GHG emissions (kgCO_2eq.) of various bioproducts derived from biomass in Western Canada at a processing capacity of 1500 dry tonnes per day. Among whole tree products, bio-oil is the most expensive at $385.32/kL with high GHG emissions of 106.16 kgCO_2eq.; biochar offers a cheaper alternative at $118.72 with 60.60 kg$CO_2$eq. Wood chips ($52.48) and firewood ($60.22) are cost-effective, with lower emissions of 31.19 and 32.65 kgCO_2eq, respectively. Though the cheapest at $13.91/dt, bark has the highest GHG emissions at 154.33 kgCO_2eq/dt.

Bio-oil from forest residues is the costliest option (among the forest residue pathways) at $362.30/dt with GHG emissions of 65.48 kgCO_2eq, while biochar ($100.74/dt) and torrefied pellets ($155.58/dt) have lower costs and GHG emissions. Wood chips are the most affordable and least polluting at $53.33/dt and 17.40 kg$CO_2$eq/kL.

For organic MSW, bio-oil is priced at $563.31/kL with 87.80 $kgCO_2eq$, while biochar remains the eco-friendly option at $114.20/tonne and 28.54 $kgCO_2eq$. Agricultural residues have the highest costs and GHG emissions, with bio-oil reaching $670.42/kL and 141.97 $kgCO_2eq/kL$. Wood chips, biochar, and pellets are the most cost-effective and environmentally friendly options.

8. Future work

The following aspects could give a deeper understanding and more effective implementation of biohubs:

1. Actual biomass source points and collection points should be identified in three regions in Canada. Doing so could show the annual availability of various biomass types and amounts, which is crucial for determining the optimal configuration of biohubs in each region. The integration of the geographical information systems will be critical.

2. Techno-economic models should be developed for various biohub processing pathways. These models could be specifically tailored for each specific end product, considering the unique characteristics of different bioproducts. By simulating the entire production process from raw biomass input to final product output, these models will provide accurate estimates of costs and resource consumption for each pathway in the biohubs. The total production cost for each end product could be estimated, incorporating various feedstocks supplied to the biohubs from different regions. This could also involve a thorough analysis of regional biomass availability, transportation logistics, and processing efficiencies, ensuring that the cost calculations reflect real-world supply chain dynamics for different feedstock sources (whole trees, forest residues, agricultural residues, and organic MSW).

3. A web-based dashboard should be developed to replace the current Visual Basic-based techno-economic analysis (TEA) tool. This dashboard would offer greater accessibility, user-friendliness, and scalability, allowing users to interact with the tool from any device with internet access. A web-based platform would also enable real-time data updates, integration with cloud-based analytics, and enhanced visualization capabilities, providing a more dynamic and efficient interface for estimating the costs and emissions of biohub products.

4. There is a need to include socio-economic factors and dynamic market conditions that influence biomass supply chains to biohubs. There is also a need to include stakeholder involvement, which is crucial for ensuring the developed tools and models for biohubs effectively address real-world challenges and user needs.

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