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LIFE CYCLE SUSTAINABILITY ASSESSMENT

A life cycle sustainability assessment (LCSA) of oxymethylene ether as a diesel additive produced from forest biomass

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Abstract

Purpose Due to efforts to reduce dependence on limited fossil energy reserves and increasing GHG emissions related to fossil fuel extraction and use in transportation vehicles, renewable fuel use is growing rapidly. By adding renewable oxygenated fuel additives such as oxymethylene ether (OME) to conventional diesel, combustion GHG emissions can be reduced significantly without modifications to vehicle engines. However, life cycle sustainability assessments (LCSA) of OME production and its use with diesel are scarce. The objective of this paper is to develop an LCSA model of OME production from forest biomass to be used in vehicles as a diesel additive.

Methods This study conducts an LCSA of OME production from two types of forest biomass as feedstock, whole tree and forest residue. A framework was developed to assess environmental, economic, and social impacts of unit operations along the life cycle for a functional unit of 1 MJ of heat produced from OME. Then, PROMITHEE (Preference Ranking Organization Method for Enrichment and Evaluation) was used to rank and select the best sustainable pathway for OME production and the most sustainable OME-diesel blend based on a number of indicators.

Results and discussion Based on the sustainability assessments results, the forest residue pathway is found to be more sustainable than the whole tree pathway. In addition, the environmental, economic, and social impact results for different OME-diesel blends show that a blend of 10% OME in 90% diesel is the most sustainable fuel mix. Assuming that the GHG emissions from biofuel combustion are offset by CO_2 sequestered during plant growth, the biomass production operation contributes the highest global GHG emissions in the OME life cycle; this is due to the high energy intensity of harvesting operations for both pathways (13 gCO_2eq/MJ for whole tree and 7.13 gCO_2eq/MJ for forest residue). OME production costs are higher for the whole tree (1.92 $/L) than the forest residue pathway (1.71 $/L). All the social indicators (i.e., employment potential and employee wages and benefits) are more favorable in the forest residue pathway.

Conclusions We conducted sensitivity analyses by varying parameters such as sustainability impact weights, threshold values, and indicator impact values. We then determined the parameters' impacts on overall ranking to verify the robustness of the model. This model can be used to assess and rank other energy technologies that integrate environmental, economic, and social sustainability impacts and thereby contribute to policy-making for the energy industry.

Keywords Biofuel · Forest biomass · Life cycle sustainability assessment · Oxymethylene ether (OME) · PROMETHEE

1 Introduction

There are increasing concerns with the use of fossil fuels in the transportation sector. In 2014, the energy industries accounted for around 60% of world's greenhouse gas (GHG) emissions, 24% of which were from transportation sector and production and use of fossil transportation fuels in vehicles (IEA 2016).

In Canada, transportation emissions are responsible for 25% of the country's total GHG emissions, and 76% of these are from road transportation (Mohamadabadi et al. 2009). Alberta, a province in western Canada, contributes a large

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share of these emissions. Alberta's conventional oil industries (including fuel refining and upgrading) emit 17% of the province's total GHGs (Kabir and Kumar 2011), a large share of which is from transportation fuels. To mitigate GHG emissions from the transportation sector, the commercialization of sustainable clean combustion fuels is a potential solution. Biomass is one of the best options to produce green liquid fuels. Several biomass-based fuels and fuel additives have been developed and their environmental impacts discussed in the literature, including diesohol (15% ethanol blended with diesel), E10 (10% ethanol blended with petrol), E85 (85% ethanol blended with 15% petrol), BD20 (biodiesel blended with 80% diesel, and pure biodiesel BD100 (Beer and Grant 2007; Beer et al. 2001, 2002, 2003; Niven 2005).

A renewable fuel solution, oxymethylene ether (OME) is an oxygenated fuel additive with a chemical formula of CH_3–O–(CH_2–O–)$_n$–CH_3. It is preferable over other alternatives because it can be produced from both fossils and renewables (i.e., biomass). It has similar chemical properties to diesel such as high viscosity, a large cetane number, and a high boiling point, which allow for great miscibility with conventional diesel (Pellegrini et al. 2013; Zhang et al. 2014). One of the most important benefits of OME is that it can reduce soot (black carbon) emissions significantly when used as a diesel additive (Pellegrini et al. 2013, 2014). 100% OME as a transportation fuel can reduce black carbon emissions significantly (by up to 77%) from a diesel car engine without modifying the existing engine and without using any diesel particulate filter (Pellegrini et al. 2013).

Several sustainability assessment studies (i.e., environmental, economic, social, and technical) have been done of renewable fuels. Luk et al. (2010) conducted a comparative analysis to select a sustainable bioethanol refinery location for five different prairie sites in western Canada. The locations were analyzed and compared based on 12 criteria focusing on socioeconomic aspects, prairie resources, and support from policy-makers or government. Sultana and Kumar (2012) developed a multi-criteria assessment model to compare five different biomass-based pellets to be used as an energy fuel in a power plant. The five alternatives were compared through 13 qualitative and quantitative criteria covering environmental, economic, and technical aspects of sustainability. Mohamadabadi and colleagues compared transportation vehicles using conventional and biomass-derived fuels in terms of GHG emissions, fuel cost, vehicle cost, distance between fuel dispensing stations, and available number of vehicles (Mohamadabadi et al. 2009). Kumar et al. (2006) compared sustainability impacts of different transportation vehicles that used gasoline, hybrid fuel gasoline-electric, E85 blend, fossil diesel, biodiesel, and compressed natural gas. The most sustainable vehicle was selected based on the environmental, economic, and social impacts of the fuels. A multi-criteria decision model was also developed by Kumar et al. (2006) to find the best agricultural biomass collection system among loafer/stacker, baling, and ensiling and to rank the best biomass transportation system among rail, truck, and pipeline. In the studies cited above, different fuels, energy systems, and vehicles were analyzed based on multidimensional sustainability criteria. However, none of them addresses the sustainability of these fuels or energy systems throughout their life cycle.

A sustainability understanding of OME, an emerging alternative fuel technology, is needed but is limited, both in the literature and in industrial experience. Pellegrini et al. (2013) discussed environmental impacts from the combustion of different OME blends in diesel (such as 7.5%, 10%) and 100% OME and found that the particulate matter (soot) emissions can be reduced by 18% to 77% with different blends of OME with diesel (Pellegrini et al. 2013; Pellegrini et al. 2014). However, almost no studies were found in the literature on life cycle sustainability assessments of OME production and blending of OME with diesel. Before the technology can be commercialized, the environmental, economic, and social viability need to be evaluated, and this is a key challenge.

Different types of biomass are used to produce green energy, such as forest biomass, agricultural biomass, wood waste, energy crops, and manures (Cherubini 2010; McKendry 2002; Thakur et al. 2014). Among them, the use of forest biomass to produce bioenergy is rapidly increasing due to the declining pulp and paper industry in Alberta (Kabir and Kumar 2012).

To achieve holistic and better decision-making on sustainability, life cycle assessment (LCA) approaches are used (Ciroth et al. 2011). Though environmental LCAs have wide range of applications, life cycle costing (LCC) and social life cycle assessments (S-LCA) are not commonly used yet. However, because all sustainability assessments (environmental LCAs, LCCs, and S-LCAs) are built on the same ISO standard 14040 (2006), Walter Klöpffer suggested aggregating the three approaches into a single, holistic assessment, namely a life cycle sustainability assessment (LCSA) (Kloepffer 2008). Klöpffer and Renner referred to LCSA as a triple bottom line model, one in which the ISO environmental life cycle assessment is consolidated with economic and social assessments following a life cycle approach (Klöpffer and Renner 2007). The sustainability studies based on the energy sector mostly address a particular aspect of the energy system such as social or technical aspects (Afgan and da Graça Carvalho 2000; Carrera and Mack 2010) or focus on short-term impact assessments of energy systems (Afgan et al. 2000; Afgan and Darwish 2011). Afgan and Carvalho (2000) developed a multi-criteria sustainability assessment on energy systems (Afgan and da Graça Carvalho 2000). But their study was predominantly based on technical and social assessments, which lack the environmental and economic assessments. Dincer (2007) developed a LCSA model on hydrogen and fuel cell energy systems assessing the environmental, economic, social, and resource sustainability (Dincer 2007). However, the developed model was unable to reflect the social sustainability impacts of the considered energy systems. Elghali et al. (2007) proposed an LCSA framework for bioenergy production systems. The authors assessed the social indicators involving stakeholders from the relevant industries (Elghali et al. 2007). Similarly, Assefa and Frostell (2007) used a community survey to assess the social indicators like knowledge, fear, and acceptance by society in the LCSA model (Assefa and Frostell 2007). The LCSA methodologies described in the literature are sometimes ambiguous and inconsistent, making it difficult to understand the practical implications of an LCSA, including all three dimensions of sustainability (Guinée 2016). The lack of case studies on the application of an LCSA framework is a great challenge in the field of sustainability assessments. In addition, there are few studies that compare the life cycle sustainability impacts of energy systems including all three dimensions of sustainability, namely environmental, economic, and social.

The objectives of this paper are as follows:

- To investigate the life cycle environmental, economic, and social performance of OME production from two forest biomass feedstocks, whole tree, and forest residue
- To propose a life cycle sustainability assessment framework to evaluate OME production sustainability based on nine criteria over the life cycle stages from biomass harvesting to combustion of the OME product.
- To understand the sustainability of the OME production technology pathway
- To conduct a case study for Alberta, a western province in Canada

2 Methods

This section presents a framework for a life cycle sustainability assessment (LCSA) of oxymethylene ether (OME) production and multi-criteria decision-making in selecting the most sustainable pathway from different feedstocks (see Fig. 1). Environmental, economic, and social assessments in this study are based on a functional unit of 1 MJ of produced OME.

2.1 System boundary selection and definition of the base case

Defining the system boundary is the basis for conducting a life cycle sustainability assessment. The OME production life cycle system boundary includes unit operations such as forest biomass growth, harvesting, biomass transportation to the plant, chemical conversion within the plant, fuel transportation to blending, vehicle combustion, and disposal of material. These unit operations are identified based on current practices and existing literature (Mahbub et al. 2017). Figure 2a, b shows the life cycle system boundary for OME production from whole tree and forest residue, respectively; the arrows represent inputs/outputs to the unit operations.

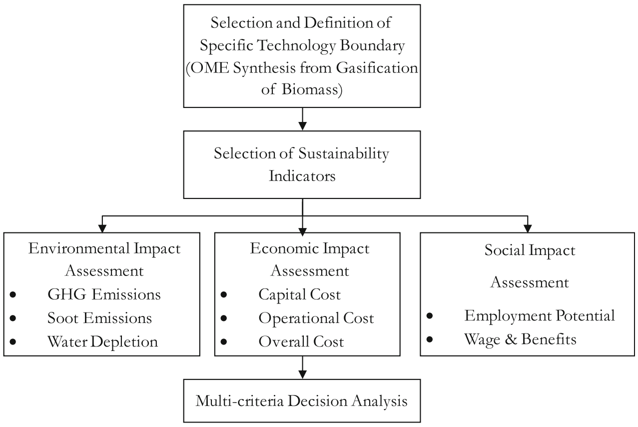

Fig. 1 Life cycle sustainability framework for OME production from forest biomass

Yield of 84 dry tonnes per hectare of whole tree (both hardwood and softwood) and 0.0247 dry tonne per hectare of forest residue harvested over a 100-year rotation were considered in this study (Mahbub et al. 2017). The whole tree pathway includes silviculture. Silviculture involves the application of fertilizer and pesticides for biomass growth and nutrient replacement (Kabir and Kumar 2011; Smith et al. 1997). In Alberta, to harvest whole trees, stands are cut and skidded to the roadside. Then trees are delimbed and the stems are chipped on the roadside into chips that is transported to the plant (Kabir and Kumar 2011, 2012; Thakur et al. 2014). Thus, the whole tree harvesting operation includes feeling, skidding, and chipping. Forest residues, consisting of tops, limbs, and branches, which are generated from the logging operations, are forwarded to the road, chipped, and then transported to the plant (Kabir and Kumar 2012). Forest residues are assumed to be readily available and exclusive to whole tree production. It is assumed that forest residues are available in the forest even though whole trees are not used for energy production. Hence, the energy and emission impacts from the biomass growth stage are assumed to be zero in the forest residue pathway. In Alberta, if forest residues are not used, they are usually burned in order to prevent forest fires (Shahrukh et al. 2016a), and burning them leads to a significant amount of environmental pollution. In part to avoid the climate change impacts of forest fires and in part due to the declining pulp and paper industries in Alberta, there is a move towards alternative uses of forest biomass in the western provinces in Canada, such as bioenergy production (Government-of-Canada 2016; Mahbub et al. 2017). It is assumed in this

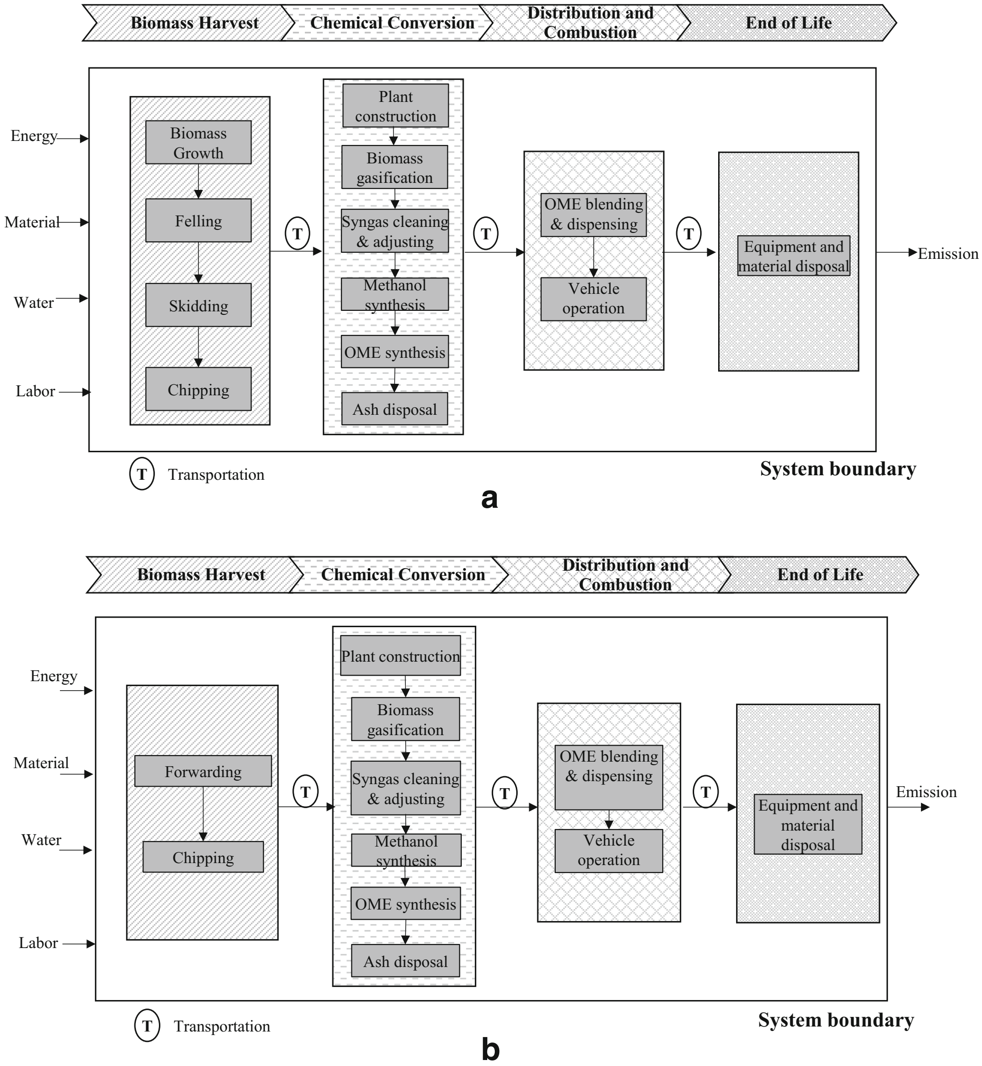

Fig. 2 **a** Life cycle system boundary for OME production from whole tree. **b** Life cycle system boundary for OME production from forest residue

study that the ash produced during the chemical conversion process is disposed of in the forest and used as a fertilizer to increase the tree growth rate and carbon sequestration potential. The ash balances the soil organic carbon stock that is reduced through biomass removal and its impact on climate change (Kabir and Kumar 2011; Mahbub et al. 2017). The depletion of soil organic carbon (SOC) and the carbon stock reduction due to forest residue use are not considered in this study, since in both cases ash is returned to the forest (Kabir and Kumar 2012).

It is assumed that sustainable management practices are followed when whole trees are used to produce energy, just as when whole trees are used in the paper, pulp, and lumber industries (Kabir and Kumar 2012). This study also includes operations such as OME plant construction, road construction, equipment manufacturing, operating the equipment, natural resource extraction, and equipment fuel consumption and disposal (Fig. 2). Table 1 shows the life cycle inventory of the operations included in the whole tree and forest residue pathways. Detailed specifications of the equipment used in biomass harvesting, data related to their construction, and energy consumptions can be found in Appendix A1 (Electronic Supplementary Material). Energy and emissions impact factors for road construction, plant construction, raw materials, and fuels considered in this study are given in Appendix A2 (Electronic Supplementary Material). The base case assumes diesel is used as fuel for the biomass transportation operation. A scenario using OME as a transportation fuel will be discussed in the sensitivity analysis section.

An OME plant is assumed to be located at the center of a circular biomass harvest area for which a geometric factor of 1 and a tortuosity factor of 1.27 are assumed to determine the average biomass collection distance (Kabir and Kumar 2012; Mahbub et al. 2017; Sultana et al. 2010). High capacity trailer trucks (23 wet tonnes biomass) are used to transport biomass from the harvesting area to the chemical conversion plant and to transport ash from the plant to the landfill and OME from the plant to the retailer. Truck fuel consumption is calculated

Table 1 Data inventory and assumptions for the whole tree and forest residue pathways

Unit operations	Data inventory	Units	Whole tree	Forest residue	References
Biomass harvesting	Biomass yield	dry tonnes/ha	84	0.247	(Kumar et al. 2003)
	Higher heating value	MJ/dry kg	20	20	(Kumar et al. 2003)
	Moisture content	wt.%	50	35	(Kumar et al. 2003)
	Annual biomass requirement	dry tonnes/year	166,667	166,667	Calculated
	Harvest area	ha	2106	572,976	Calculated
Biomass transportation	Transportation distance	km	8.65	36.17	Calculated
	Truck capacity	dry tonnes biomass	8.75	10.73	(Kabir and Kumar 2012)
	Truck life time	years	7.5	7.5	(Mann and Spath 1997)
	Truck number	N/A	20	45	calculated
	Bulk density of wet biomass	kg/m^3	250	230	(Kabir and Kumar 2011)
	Payload of truck	tonnes	23	23	(Kabir and Kumar 2012)
	Diesel consumption by truck (empty/fully loaded)	L/km	0.24/0.33	0.24/0.33	(Kabir and Kumar 2012)
	Actual load carried by truck (WT)	tonnes	17.5	16.5	(Kabir and Kumar 2012)
	Actual fuel consumption by truck	L	0.31	0.30	Calculated
	Primary rad construction required in 20 years	km	69.2	N/A	Calculated
	Secondary road construction required in 20 years	km	82	N/A	Calculated
	Tertiary road construction required in 20 years	km	54	N/A	Calculated
	Truck capacity (by volume)	m^3	70	70	(Kabir and Kumar 2012)
	Steel used in truck	tonnes/truck	14.7	14.7	(Kabir and Kumar 2012)
Chemical conversion	Capacity of gasifier	dry tonnes/day	500	500	Calculated
	Plant life	years	20	20	
	Capacity factor				
	Year 1	N/A	0.7	0.7	(Kabir and Kumar 2012; Kumar et al. 2003)
	Year 2	N/A	0.8	0.8	
	Year 3 and onwards	N/A	0.85	0.85	
	Ash percentage	wt%	1	3	(Kumar et al. 2003)
	Ash spreader lifetime	hours	1200	1200	(Kabir and Kumar 2011)
	Ash spreader capacity	hectare/hour	4.41	4.41	

using equations from previous studies (Kabir and Kumar 2012; Mann and Spath 1997).

Based on a discussion on Alberta's forest road networks with subject matter expert Fulton Smyl (Business Analyst, Alberta Innovates-Technology Futures on June 28, 2016), there are three road types that are considered in this study for the whole tree pathway. These are primary or permanent roads, secondary or semi-permanent, and tertiary or temporary roads (OMNR 1994). Around 69.2 km of primary roads, 82 km of secondary roads, and 54.3 km of tertiary roads are constructed prior to harvesting operations. The energy and emissions factors for primary road construction are taken from Kabir and Kumar (2011, 2012 and Stripple (2001). It is assumed that crawler tractors are used for the construction of secondary and primary roads. The operating efficiency of crawler tractors during the construction of these roads is taken from (Winkler 1998). For the forest residue pathway, however, no road construction is required as forest residues are assumed to be readily available in forests (Kumar et al. 2003) and are harvested on existing logging roads.

The OME plant is assumed to have a 20-year production life with 8000 operating hours per year (Kabir and Kumar 2011, 2012; Van Vliet et al. 2009). The chemical conversion includes plant construction, biomass gasification, syngas cleaning and adjusting, methanol production, OME production from syngas, and ash withdrawal. The energy and emissions impacts for plant construction, plant decommissioning, and construction material withdrawal are included in the system boundary. The method to estimate the amount of construction material and assumptions related to scale factors, plant decommissioning, and construction material withdrawal are based on previous studies (Kabir and Kumar 2011, 2012; Mahbub et al. 2017; Moore 1959; Sarkar and Kumar 2010a, b). For an OME plant with a capacity of 500 dry tonnes of biomass/day (producing 97,701 kg OME/day), around 2618 tonnes of steel, 8092 tonnes of concrete, and 22 tonnes of aluminum were estimated for construction. The method used to calculate the amount of plant construction material, plant decommissioning, and construction material withdrawal are directly taken from Mahbub et al. (2017). It is assumed that the plant decommissioning impacts are 3% of plant construction impacts. Among the construction materials, 100% of the concrete and aluminum are landfilled, whereas 75% of the steel is assumed to be recycled and the rest landfilled (Mahbub et al. 2017; Spath et al. 2005; Spath and Mann 2000). At the plant, 500 dry tonnes of biomass/day are fed into the gasifier, where produced ash will be collected and dumped 50 km from the plant. The produced syngas is then cleaned and the tar reduced through thermal cracking and reforming (Li et al. 2004; Zhang et al. 2016). High hydrogen content in the syngas is required for high methanol yield and therefore the ratio of H_2 and CO in the syngas is adjusted using the water-gas shift (WGS) reaction and the conversion rate varied until the ratio is 2:1. Methanol is then synthesized from the adjusted syngas at a temperature of 300 °C and formaldehyde (FA) produced from methanol at a conversion rate of 60%. OMEs are then produced from methanol and FA using a continuous stirred-tank reactor (CSTR) reactor with a reactor volume of 1 L at a temperature of 60 °C and pressure of 1 bar through a series of reaction chains in the presence of the heterogeneous catalyst Dowex50Wx2, which is an acidic ion exchange resin (Deutsch et al. 2017; Oestreich et al. 2017; Zhang et al. 2016).

This study considers OME combustion to be carbon neutral, as is (Mahbub et al. 2017) commonly understood in biomass combustion assessments (Agbor et al. 2016; Shahrukh et al. 2015, 2016b). After OME is produced, it is assumed to be transported 300 km from the plant for blending.

2.2 Sustainability indicators

Following a comprehensive review of published sustainability assessments and in discussion with the experts and decision-makers, we selected eight indicators to assess environmental, economic, and social sustainability (Table 2).

Environmental indicators Greenhouse gas (GHG) emissions, soot emissions, and water use (waster footprint) are used to assess environmental sustainability. GHG emissions are a universal environmental impact indicator used to assess the global warming potential of materials, processes, and systems (Sarkar and Kumar 2009). The measure of GHG emissions is carbon dioxide equivalent (CO_2eq) with a GWP conversion factor of 34 for methane and 298 for nitrous oxide (Myhre et al. 2013). In this study, GHG emission factors for energy and material use in unit operations were selected from several studies (Pellegrini et al. 2013); (Rahman et al. 2015). Soot (or black carbon) emissions are generated from transportation fuel combustion and are considered an air pollutant (Bond et al. 2013). The amount of soot in particulate matter (PM) emissions from OME combustion is estimated to be 33% and from conventional diesel 77% (Pellegrini et al. 2013). The combustion emissions (both the GHG and soot emissions) for 100% OME were taken from experimental results by Pellegrini et al. (2013). Pellegrini et al. investigated the emission performance of an old light duty diesel engine Euro 2 car fueled with 100% OME and 100% diesel over the NEDC driving cycle and found that soot emissions from old vehicles can be reduced without any engine modification or using any diesel particulate filter. We have considered the average soot/GHG emissions for OME 1–8 in this analysis.

Water footprint as a measure of the total amount of freshwater consumed to produce a particular good or service is another important indicator in assessing life cycle sustainability (Dominguez-Faus et al. 2009; Hoekstra et al. 2011; Singh and Kumar 2011; Singh et al. 2014; Wong 2015; Yang et al. 2011) because water availability varies with region, weather, and plant location. In the OME production life cycle, water is consumed in processes such as biomass growing (Wong et al. 2016). The chemical conversion (OME synthesis) process, however, does not require any additional water because the steam used for syngas cleaning can be recovered from the moisture content of biomass during drying. In addition, water use in ash disposal and plant construction, subunit operations of chemical conversion, is so negligible water use in chemical conversion is considered to be zero (Singh and Kumar 2011; Singh et al. 2014).

Two aspects of water consumption are considered in the study, direct and indirect water use. Direct water use refers to the water required for biomass growth (Singh and Kumar 2011; Wong 2015) and indirect water use refers to water required in the production of energy inputs to the system such as diesel (Singh and Kumar 2011; Wong 2015). The average annual precipitation (rainfall) in the western province of Alberta, Canada (480 mm/year), time required to harvest forest biomass (100 years of rotation is required for whole tree harvest whereas forest residues are harvested every year [Kumar et al. 2003]), and biomass yield extracted from Wong et al. (2016) are used to calculate the water use factor for biomass growth and are 5714.3 L H_2O/kg dry wood for the whole tree and 3886.6 L H_2O/kg dry wood for the forest residue pathway (Wong et al. 2016). The equation to calculate the water use factor for biomass growth is illustrated in Appendix B (Electronic Supplementary Material). Water is also used in diesel production processes such as extraction and refining. A water use factor of 2.2 L H_2O/L diesel (King and Webber 2008) is considered in this study. Thus, the amount of water required in unit operations like biomass growth, biomass harvesting, biomass transportation, and road construction is estimated by using the water use factor and the amount of material (or biomass) used (or harvested) in the operations.

Economic indicators Economical sustainability is measured through three cost indicators, capital cost, operational cost, and overall cost. In general, overall cost is the sum of capital cost and operational cost. The capital cost is an indicator of the competitiveness of a company or an investment on capital markets and is the base for calculating the equity yield rate. Potential investors use the information provided by the capital cost to determine if the technology yield rate compete with an alternative. The operating cost is an implicit indicator of short-term market risks. It comprises all costs that depend on short-term upstream market developments, e.g., raw material costs. The overall cost is an indicator of the general competitiveness of a product as well as its long-term sustainability.

Cost indicators are calculated based on available data and process modeling. The biomass delivery cost, which refers to the total cost of delivering biomass to the OME plant, is the sum of the biomass point of origin cost and transportation cost. The point of origin costs include biomass harvesting costs (i.e., costs of felling, chipping, forwarding, skidding), biomass field costs (royalties paid to the crown), nutrient replacement costs, silviculture costs, and road construction costs. The biomass transportation costs include the costs of loading and unloading the biomass feedstock and transporting the biomass from the forest/field to the OME plant (Kumar et al. 2003). Road construction cost is not considered for forest residues since they are transported on existing roads used for logging operation. Likewise, silviculture cost is not considered for forest residues since they are assumed to be available in the forests. Capital costs consist of costs for the construction and installation of the OME plant. The costs are estimated over a 20-year plant lifetime. Developed process models using the Aspen software (Aspen-Icarus 2014) were used to estimate the capital costs. The equipment is mapped and sized before costs are estimated. Before the costs were analyzed in the process model, the mass and energy balance for each piece of equipment used in OME production in process model were calculated. An overall installation factor of 3.02 is used for all the purchased equipment, as suggested in the literature (Peters et al. 2003). The total purchased equipment costs (TPEC) are estimated from the process model and the total installed cost (TIC) calculated after factoring the installation factor of 3.02 (Peters et al. 2003; Swanson et al. 2010). The indirect costs (IC) are estimated as 89% of TPEC (construction expenses [34% of TPEC], engineering and supervision [32% of TPEC], and legal and contractors' fees [23% of TPEC]) (Kumar et al. 2017; Peters et al. 2003). The total direct and indirect cost (TDIC) is the sum of TIC and IC. The project contingency is calculated as 20% of TDIC. The capital cost for the whole tree pathway includes an extra 5% of the other costs to account for camping costs (Kumar et al. 2003). All costs are given in US dollars ($) and based on the year 2016. The conversion rate of US$ to Canadian dollars (C$) is considered to be 0.7459 based on the Bank of Canada's rates on March 3, 2016.

Operational costs refer to raw material cost, maintenance cost, utilities (e.g., electricity) cost, plant overhead cost, operating charges, operating employee wage and benefit, and general and administrative (G&A) cost. Plant overhead is considered to be 50% of the total operating labor and maintenance costs and consists of costs during production for services, facilities, and payroll. Operating charges are 25% of the operating labor costs, and the general and administrative expenses (G&A) are specified as 8% of the total operating costs. The G&A costs are the costs incurred during production such as administrative salaries/expenses, research and development, product distribution, and sales costs. A discounted cash flow analysis model was developed to estimate the unit price of OME based on a 10% IRR on investment over 20 years of plant life. While 10% IRR was considered in this study, a sensitivity analysis (in a techno-economic study) was also done to see the impacts of IRR on the unit price of OME (Oyedun et al. 2018).

The life cycle costs of diesel include the costs of both oil extraction and refining diesel from fossil oil. The cost of refining diesel is assumed to be 30% more than the oil price (Van Vliet et al. 2009). King and Weber have assumed a price of $44.75/barrel for petroleum oil; thus, the cost of refining fossil diesel from petroleum oil is $58.18/barrel (Van Vliet et al. 2009). That value was used in this study.

Social indicators Employment potential and employee wages and benefits are used to assess social sustainability.

Employment potential is considered a relevant social impact assessment indicator because the newly emerging OME production technology can affect local employment both directly and indirectly (Benoît Norris et al. 2013). In this study, employment potential for a particular unit operation can be assessed by dividing a ratio of operation time by the biomass volume (m^3) involved in the operation (Valente et al. 2011). Employment potential is assessed for biomass harvesting, biomass transportation, chemical conversion, and OME transportation.

Wages and benefits are widely used in corporate social responsibility assessments because income is employees' primary concern and directly affects their well-being (Benoît Norris et al. 2013). In this study, employee wages and benefits for chemical conversion are determined based on the required working skill, plant scale, and typical employee wage in similar plants. For the harvesting and transportation operations, employee wages were calculated based on hours of operation and hourly labor rates (details in Appendix D, Electronic Supplementary Material).

2.3 Multi-criteria decision analysis

PROMETHEE was used to compare the sustainability of the two OME production pathways (Brans and Mareschal 2005; Brans and Vincke 1985; Brans et al. 1986). PROMETHEE is one of the most commonly used alternative ranking methods for a wide range of applications, including energy systems

(Behzadian et al. 2010; Kumar et al. 2006; Luk et al. 2010; Mohamadabadi et al. 2009; Sultana and Kumar 2012; Zhang and Haapala 2015). PROMETHEE compares different alternatives based on both quantitative and qualitative criteria, and its application and interpretation of results can be easily understood by decision-makers (Sultana and Kumar 2012).

In this analysis, alternatives are compared through several criteria and the alternative with the higher preference is selected as a preferred solution. This work studied two pathways of OME production, whole tree (WT) and forest residue (FR). The variable *i* denotes the criterion of the pathways, as in WT_i and FR_i. If the objective of a criterion is to maximize its value, the pathway with the higher criterion value is preferred over others and vice versa. In this study, all the environmental, economic, and social indicators are minimized except employee wages and benefits and employment potential.

2.3.1 Step 1: define preference function

The two pathways are first compared by criterion (indicator), and the difference between the estimates of the two pathways on a specific indicator is converted to a degree of preference quantified from 0 to 1 (0 being not preferred at all and 1 being strictly preferred) by using a preference function (Fülöp 2005; Mohamadabadi et al. 2009). For example, Eq. (1) shows the preference function of the whole tree pathway (WT) over the forest residue pathway (FR) on a particular criterion *i* as

$$P_i(\mathrm{WT},\mathrm{FR}) = p_i(\mathrm{WT}_i\text{–}\mathrm{FR}_i) \tag{1}$$

where p_i is a non-decreasing function, and $p_i(\mathrm{WT}_i - \mathrm{FR}_i) = 0$ when $(\mathrm{WT}_i - \mathrm{FR}_i) \leq 0$ and $0 \leq p_i(\mathrm{WT}_i - \mathrm{FR}_i) \leq 1$ when $(\mathrm{WT}_i - \mathrm{FR}_i) > 0$.

Usual and linear preference functions are used in this study. For usual preference functions, indifference occurs when the deviation between the evaluations of the two pathways on a specific indicator is 0 (the evaluations are equal). When the deviation is not 0, the pathway with a higher value is strictly preferred over the lower value one (Brans and Vincke 1985). No threshold is required for the usual preference function. Linear preference functions require two threshold types, indifference (*Q*) and preference thresholds (*P*), to make a preference decision. The indifference threshold (*Q*) for a specific indicator is determined by the largest difference between the estimates of the two pathways on that indicator. The pathways have no preference over one another below *Q*. The preference threshold (*P*) is determined by the smallest deviation between the estimates of the two pathways, above which the alternatives have strict preference over one another (Mohamadabadi et al. 2009; Sultana and Kumar 2012). In linear preference, indifference occurs when the deviation between evaluations exceeds the indifference threshold, and above this, the threshold preference increases progressively until the deviation equals the sum of the indifference and preference thresholds (Brans and Vincke 1985). Detailed mathematical equations of preference functions are given in Appendix C (Electronic Supplementary Material). The preference and indifference thresholds are usually determined based on the decision-maker's assumed choices. In this study, preference and indifference thresholds are assumed to be 10% and 5% of average estimates, respectively, based on literature reviews (Kumar et al. 2006; Mohamadabadi et al. 2009); (Sultana and Kumar 2012).

2.3.2 Step 2: weighing the indicators and multi-criteria preference index

Weights are assigned to the criteria based on their relative importance in the decision-making process (Luk et al. 2010; Mohamadabadi et al. 2009; Sultana and Kumar 2012). Weight is usually decided by the decision-maker's preference for a criterion and the contribution of the criterion towards sustainability (Luk et al. 2010; Mohamadabadi et al. 2009; Sultana and Kumar 2012). Each alternative is compared pairwise with other alternatives and the weighted sum of the preference functions is calculated. This weighted sum is known as the multi-criteria preference index (Mohamadabadi et al. 2009) and is a value between 0 and 1, indicating the preference of one alternative over the others considering all the weighted criteria (indicators). For example, the multi-criteria preference index for WT over FR is defined in Eq. (2) as:

$$\pi(\mathrm{WT},\mathrm{FR}) = \textstyle\sum_{i=1}^{m} w_i \qquad P_i(\mathrm{WT},\mathrm{FR}) \tag{2}$$

Table 2 Selected sustainability indicators

Environmental		Economic		Social	
Indicator	Measurement	Indicator	Measurement	Indicator	Measurement
GHG emissions	Gram CO_2eq	Capital cost	US dollar ($)	Employment potential	Hours
Soot emissions	Gram soot	Operational cost	US dollar ($)	Employee wage and benefit	US dollar ($)
Water depletion	L H_2O	Overall cost	US dollar ($)		

Table 3 Environmental impacts of whole tree and forest residue pathways

Unit operation	Pathway	Energy consumption GJ /MJ	GHG emissions gCO_2eq/MJ	Soot emissions g/MJ	Water depletion L H_2O/MJ
Biomass growth	Whole tree	0.001	0.22	0[a]	1238
	Forest residue[b]	0[b]	0[b]	0[b]	842
Biomass harvest	Whole tree	0.17	13.01	0.001	0.008
	Forest residue	0.09	7.13	0.001	0.004
Biomass transportation	Whole tree	0.017	2.96	0.0002	0.001
	Forest residue	0.022	1.69	0.0002	0.001
Chemical conversion	Whole tree	1.04	4.02	0[a]	0[a]
	Forest residue	1.04	4.06	0[a]	0[a]
OME transportation	Whole tree	0.01	0.49	0[a]	0.0003
	Forest residue	0.01	0.49	0[a]	0.0003
Vehicle operation	Whole tree	N/A	0(89.55)[c]	0.0011	N/A
	Forest residue	N/A	0(89.55)[c]	0.0011	N/A

[a] Impact values from these unit operations were found to be negligible and so assigned a value of zero

[b] Forest residues are assumed to be readily available in the forests and are harvested on the logging roads; hence, the impact values of energy consumption, GHG emissions, and soot emissions from the biomass growth operation in the forest residue pathway are considered to be zero

[c] Combustion emissions from vehicle operations are considered to be carbon neutral or zero as the CO_2 emitted during combustion of OME is same as taken up by the plants during its growth

where $w_i > 0$ is a normalized weight assigned to criterion i and m is the number of indicators; $m = 9$.

2.3.3 Step 3: partial and complete ranking of alternatives

Two types of outranking flows are calculated to rank the alternative pathways: positive outranking flow (leaving flow) and negative outranking flow (entering flow). For a particular pathway, these flows are calculated using the multi-criteria preference index (Luk et al. 2010). The positive outranking flow $\varnothing^{+}(\mathrm{WT})$ determines how much the WT pathway outranks or dominates the other pathway (FR). A higher $\varnothing^{+}(\mathrm{WT})$ value indicates that WT is more favorable than FR. The calculation for positive outranking flow is given by Eq. (3) (Fülöp 2005):

$$\varnothing^{+}(\mathrm{WT}) = \frac{1}{n-1}\sum_{k=1}^{n}\pi(\mathrm{WT},\mathrm{FR}) \tag{3}$$

where n is the number of pathways and for this study $n = 2$.

The negative outranking flow $\varnothing^{-}(\mathrm{WT})$ shows how much the WT pathway is outranked or dominated by the other pathway (FR). A lower $\varnothing^{-}(WT)$ value indicates a more favorable selection. Equation (4) shows the calculation for a negative outranking flow.

$$\varnothing^{-}(\mathrm{WT}) = \frac{1}{n-1}\sum_{k=1}^{n}\pi(\mathrm{WT},\mathrm{FR}) \tag{4}$$

Both the PROMETHEE I partial ranking and the PROMETHEE II complete ranking were conducted to rank the alternatives. In the PROMETHEE I partial ranking, the WT is preferred over the FR pathway if $\varnothing^{+}(\mathrm{WT}) \geq \varnothing^{+}(\mathrm{FR})$, $\varnothing^{-}(\mathrm{WT}) \leq \varnothing^{-}(\mathrm{FR})$, and one of them is a strict inequality. The WT and FR pathways are indifferent if $\varnothing^{+}(\mathrm{WT}) = \varnothing^{+}(\mathrm{FR})$ and $\varnothing^{-}(\mathrm{WT}) = \varnothing^{-}(\mathrm{FR})$. Otherwise, the WT and FR pathways are incomparable (Fülöp 2005). In the PROMETHEE II complete ranking, the net outranking flows $\varnothing(\mathrm{WT})$ and $\varnothing(\mathrm{FR})$ are determined by adding the

Table 4 Economic indicators for the whole tree and forest residue pathways

Cost components	Units	Whole tree	Forest residue
Unit cost of OME	$/L	1.92	1.71
Capital cost	$/dry tonne	55.30	43.65
Biomass harvesting cost	$/dry tonne	31.14	29.94
Biomass transportation cost	$/dry tonne	11.10	14.83
Silviculture cost	$/dry tonne	1.75	N/A
Total raw materials cost	$/dry tonne	45.16	47.26
Maintenance cost	$/dry tonne	33.18	26.19
Utilities cost	$/dry tonne	80.05	70.33
Plant overhead	$/dry tonne	34.04	30.55
Operating charges	$/dry tonne	8.73	8.73
Employee wage and benefit	$/dry tonne	62.58	67.26
G and A cost	$/dry tonne	18.88	17.44
Total operating cost	$/dry tonne	254.95	235.41
Overall cost	$/dry tonne	310.25	279.06

respective positive and negative outranking flows given by Eqs. (5) and (6). The net outranking flow determines the final preference of the two alternatives (Fülöp 2005).

$$\varnothing(\mathrm{WT}) = \varnothing^{+}(\mathrm{WT}) - \varnothing^{-}(\mathrm{WT}) \tag{5}$$

$$\varnothing(\mathrm{FR}) = \varnothing^{+}(\mathrm{FR}) - \varnothing^{-}(\mathrm{FR}) \tag{6}$$

If $\varnothing(\mathrm{WT}) > \varnothing(\mathrm{FR})$, WT is preferred to the FR pathway and the pathways are indifferent if $\varnothing(\mathrm{WT}) = \varnothing(\mathrm{FR})$. The pathway with the largest net outranking flow value ($\varnothing$) is considered to be the best sustainable pathway.

3 Results and discussion

The results are discussed in two sections. We developed a base case to select the most sustainable pathway of OME production from two types of biomass, and, with the base case results, we developed a scenario in order to select the most sustainable OME-diesel blend ratio from the preferred pathway. Sections 3.1, 3.2, and 3.3 present the assessment results and Section 3.4 presents the multi-criteria decision analysis for the two cases.

3.1 Environmental impact assessment

Table 3 presents the environmental impact assessment results for the two pathways. The emission values are given in the unit of per MJ heat produced from OME. Around 80% of total GHG emissions were found to come from vehicle operation (combustion of OME in vehicles) for both pathways (shown in parentheses in Table 3). However, biomass combustion in vehicles and in chemical conversion is considered to be carbon neutral because the amount of CO_2 released during combustion is compensated by the amount of CO_2 taken by the tree during its growth (Chum and Overend 2001; Mahbub et al. 2017; Sultana and Kumar 2011). Hence, the GHG emissions from vehicle operation (combustion of OME in vehicles) for both pathways are shown as 0 in Table 3. Here, it is worth mentioning that the carbon and climate neutrality of bioenergy production from forest residue is beyond the above-mentioned simplified assumption. The carbon stock capacity of the residue and the temporal dynamics of the emissions and their consequent climate change effect are important aspects that need to be considered in the assumptions. Forest residues normally act as carbon stock, and harvesting them and using them as a source of energy release CO_2 emissions that would otherwise have been stored for a long time, depending on their decomposition rate. The potential climate change effect due to forest biomass removal should be compensated by increasing tree growth rate and carbon sequestration.

Within the chemical conversion system, 4% (≈ 4 g CO_2eq/MJ) of total life cycle GHGs are emitted, and these mainly come from ash disposal and the use of a fossil source. A very small amount of natural gas (around 5.65% of total life cycle energy consumption) that is used during the chemical conversion process contributes to these emissions. Biomass transportation emissions are relatively low in the forest residue pathway (1.69 gCO_2eq/MJ) compared to the whole tree pathway (2.96 gCO_2eq/MJ) as there is no road construction involved in harvesting forest residues. The whole tree pathway has more energy-intensive harvesting unit operations, resulting in higher GHG emissions (13.01 gCO_2eq/MJ) than the forest residue pathway (7.13 gCO_2eq/MJ). Soot emissions from OME combustion in vehicles are the same for both pathways. However, total life cycle soot emissions are higher

Fig. 3 Breakdown of operational costs for the whole tree and forest residue pathways

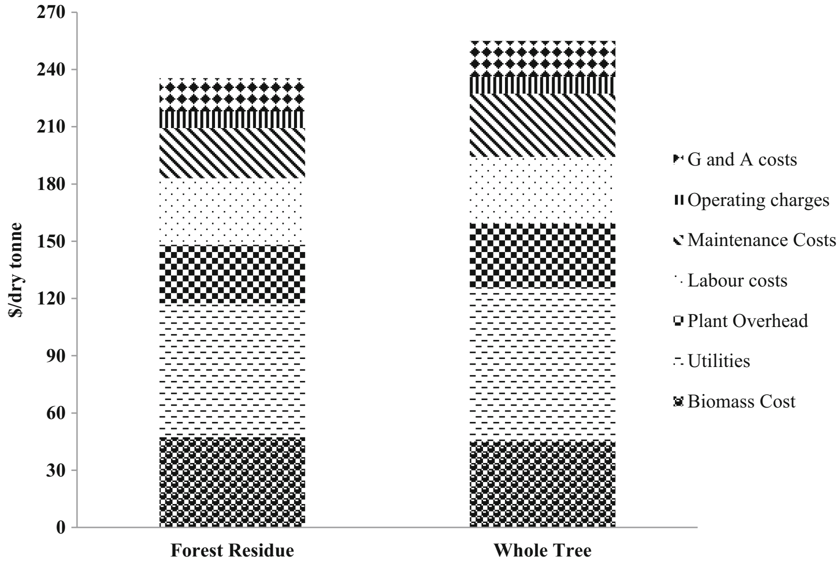

Table 5 Social impact for whole tree and forest residue pathways

Unit operations	Pathways	Employment potential h/m^3	Employee wage and benefit $/dry tonne
Biomass growth	Whole tree	0.04	8.17
	Forest residue	0.05	8.17
Biomass harvest	Whole tree	0.04	7.33
	Forest residue	0.03	5.06
Biomass transportation	Whole tree	0.03	6.27
	Forest residue	0.14	21.40
Chemical conversion	Whole tree	0.01	34.91
	Forest residue	0.01	34.91
OME transportation	Whole tree	0.03	5.89
	Forest residue	0.04	5.89
Vehicle operation	Whole tree	N/A	N/A
	Forest residue	N/A	N/A

in the forest residue pathway (0.004 g/MJ) than the whole tree pathway (0.003 g/MJ) due to the higher diesel requirement throughout in forest residue pathway. Soot emissions from OME transportation and chemical conversion for both pathways are negligible (Table 3). Water is primarily consumed in biomass growth (almost 99.99%) for both pathways. Water consumption is almost negligible in all other unit operations compared to water consumption in biomass growth (Table 3). Water consumption in biomass transportation for the forest residue pathway is 0.001 L H_2O/MJ, much higher than that of whole tree pathway, which uses only around 0.0003 L H_2O/MJ water for biomass collection and road construction. This is mainly due to the longer transportation distance for biomass collection in the forest residue pathway (36.17 km) compared to the whole tree pathway (8.65 km). Since the moisture content of biomass serves as a source of steam in the chemical conversion process, no extra water is needed (Zhang et al. 2016). Thus, water consumption in the chemical conversion process of OME from biomass mainly comes from water required for ash disposal and is almost negligible for both pathways.

3.2 Economic impact assessment

Table 4 lists the economic indicators along with all other cost components considered in this study for both pathways. The unit cost of producing OME from the whole tree pathway (1.92 $/L) is significantly higher than that of forest residue (1.71 $/L). The base year for all cost figures in this study is 2016 and the US$ is used. The initial moisture content of the biomass plays a significant role in the final unit cost of producing OME. Capital and operational costs are higher for the whole tree pathway than the forest residue pathway. Biomass yield has a large impact on biomass transportation cost since biomass yield is inversely proportional to harvest area, which is directly related to transportation distance. The higher the yield, the shorter the transportation distance, resulting in lower transportation cost. The higher yield of whole trees, around 84 dry tonnes/hectare, compared to that of forest residue (0.247 dry tonne/hectare), results in a biomass transportation cost of the forest residue pathway ($14.83/dry tonne forest residue) that is significantly higher than that of the whole tree pathway ($11.10/dry tonne whole tree). In spite of higher costs on the

Table 6 Preference functions, threshold values, objectives, and weights for selected sustainability indicators

Criteria	Unit	Obj	Preference function	WT	FR	Weight	Preference threshold *P*	Indifference threshold *Q*
GHG emissions	gCO_2eq/MJ	Min	Linear	20.70	13.38	0.125	1.70	0.85
Water depletion	L H_2O/MJ	Min	Linear	1238.05	842.06	0.125	104.01	52
Soot emissions	g/MJ	Min	Linear	3.72	4.21	0.125	0.25	0.13
Employment potential	h/m^3	Max	Usual	0.15	0.27	0.125	N/A	N/A
Employee wage and benefit	$/dry tonne	Max	Usual	62.58	67.26	0.125	N/A	N/A
Capital cost	$/dry tonne	Min	Usual	55.30	43.65	0.125	N/A	N/A
Operating cost	$/dry tonne	Min	Usual	254.95	235.41	0.125	N/A	N/A
Overall cost	$/dry tonne	Min	Usual	310.25	279.06	0.125	N/A	N/A

WT whole tree, *FR* forest residue, *Obj* objective, *Min* minimize, *Max* maximize

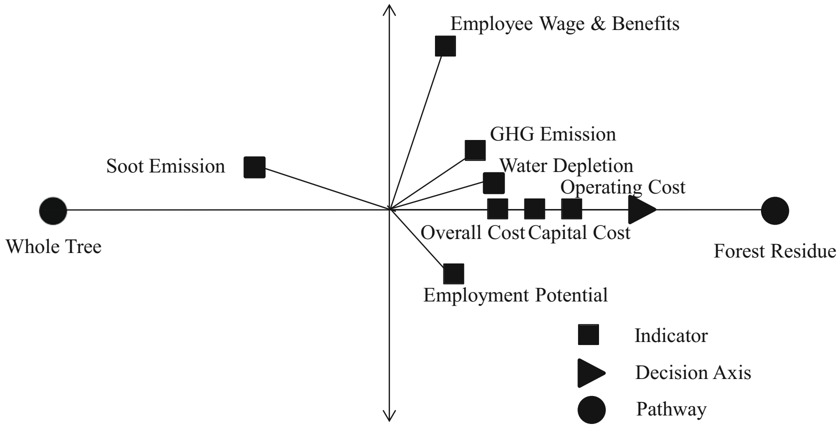

Fig. 4 PROMETHEE ranking results for the two pathways

upstream side, due to the lower capital and operating costs, the forest residue pathway has a lower overall cost than the WT ($279.06/dry tonne compared to around $310.25/dry tonne).

Figure 3 presents the breakdown of the operational costs for the two pathways. The major cost components are raw material costs, utilities, and labor costs.

3.3 Social impact assessment

Table 5 shows the social impact assessment results of the two OME production pathways.

Employment potential is higher in the forest residue pathway (around 0.27 h/m^3 of woody biomass or 0.0004 h/MJ of OME) than the whole tree (0.15 h/m^3 biomass or 0.0003 h/MJ). Thus, the forest residue pathway leads to more jobs than the whole tree pathway. As for wages and benefits, from the employees' perspective, a higher number means a more secure life situation and a higher living standard. Employee wages and benefits overall are higher for the forest residue pathway ($67.26/dry tonne) than the whole tree ($62.58/dry tonne). Wages and benefits for each unit operation can be found in Table 5. The wages and benefits for the harvesting and transportation operations are estimated to be $26.11/h (Canada-Visa 2014), equivalent to the required skill level of the job.

3.4 Multi-criteria decision analysis for the comparison of the whole tree and forest residue pathways

The PROMETHEE outranking method is used to compare the alternatives and select the most sustainable pathway. A base case was developed as a starting point to compare the two pathways. Based on the selected pathway, a second case was developed to compare different ratios of OME as a diesel additive. Preference function selection is based on the decision-maker's judgment. This study uses a combination of linear and usual preference functions. For GHG emissions, water depletion, and soot emissions indicators, linear preference function are used because the deviations among these indicators can be sensitive to a decision-maker's judgment. For cost indicators and employment potential indicators, the usual preference function is used because lower cost and higher job creation potential are always preferred. In the base case, all indicators are given an equal weight. We conducted a separate sensitivity analysis to examine outcomes from different decision-making scenarios based on changes of weights. Table 6 shows the nine sustainability indicators, values, weights, and corresponding objectives to meet sustainability, preference functions, and respective threshold values for the chosen functions.

The alternative ranking is generated from the Visual PROMETHEE software (Visual-PROMETHEE 2015). Figure 4 shows the base case ranking results in a GAIA (geometrical analysis for interactive assistance) plane where a preferred pathway is determined on the decision axis by using the position of the pathways and the orientation of the indicator axes towards the pathways. By comparing GHG emissions from both pathways, for example, we can see that forest residue outranks whole tree, as the GHG emission indicator sign is located in the same direction as the decision axis. However, in Fig. 4, the soot emissions indicator axis is in the opposite direction of the decision axis (shown by the triangle bullet in Fig. 4). This implies that all the indicators except soot emissions are in accordance with the obtained ranking (Mareschal 2013; Mohamadabadi et al. 2009). The position of the pathway relative to any indicator reflects the performance of the pathway on this particular indicator and the closer the distance, the better the performance (Mohamadabadi et al. 2009). Figure 4 shows that forest residue performs better than whole tree in all areas except soot emissions. Having seven indicators in its favor, the forest residue pathway outranks the

Table 7 Ranking results for the whole tree and forest residue pathways

Pathways	$\varnothing^+$ (positive flow)	$\varnothing^-$ (negative flow)	$\varnothing$ (net flow)
Whole tree	0.13	0.88	− 0.75
Forest residue	0.88	0.13	0.75

Table 8 Sustainability impacts for different OME and diesel blends

Ratio of OME in diesel	GHG emissions gCO_2eq/MJ	Water consumption L H_2O/MJ	Soot emissions g/MJ	Overall cost \$/MJ
10%	120.36	1576.85	0.33	0.018
20%	113.53	3151.49	0.30	0.023
30%	105.92	4726.14	0.26	0.028
40%	97.42	6300.79	0.23	0.034
50%	87.84	7875.43	0.19	0.040
60%	76.96	9450.08	0.16	0.048
70%	64.51	11,024.73	0.12	0.056
80%	50.13	12,599.38	0.09	0.066
90%	33.31	14,174.02	0.06	0.078
100%	13.38	15,748.67	0.02	0.091

whole tree pathway. It is worth noting that the decision axis does not represent the optimum solution; rather, it indicates the preferred compromise based on the assigned weights of the indicators (Mareschal 2013; Mohamadabadi et al. 2009). Thus, forest residue is the preferred pathway based on the current weights of the indicators.

Positive, negative, and net outranking flows for the two pathways are shown in Table 7. For the forest residue pathway, the positive outranking flow (0.88) is higher than that of the whole tree (0.13) and the negative outranking flow (0.13) is less than that of the whole tree (0.88). Hence, based on the PROMETHEE I partial ranking, the forest residue pathway outranks the whole tree pathway. Nevertheless, the net outranking flow is higher for the forest residue (0.75) than that of the whole tree (− 0.75). Hence, the PROMETHEE II complete ranking also shows a preference for the forest residue pathway over the whole tree.

3.5 Multi-criteria decision analysis for the comparison of different OME-diesel blending ratios

Pellegrini et al. recommended that OME be used as a diesel additive in vehicles. They investigated the particulate matter (PM) emissions from different OME blends with fossil diesel and found that 18–77% emissions reduction is possible compared to neat diesel (Pellegrini et al. 2013, 2014). Zhang et al. found that a blend of 20% forest biomass-based OME in 80% fossil diesel can decrease PM emissions by 50% from old used cars (Zhang et al. 2014). The life cycle GHG emissions and soot emissions of OME derived from forest biomass were investigated by Mahbub et al. (2017). The authors compared the life cycle GHG and soot emissions of OME and diesel. Diesel life cycle emissions include emissions from crude extraction, crude refining, and the combustion of diesel in vehicles. Mahbub et al. found that 79–86% life cycle GHG emissions can be reduced using OME as a transportation fuel rather than diesel and life cycle soot emissions can be reduced by 89% compared to using 100% diesel. The authors also compared the performance of 10% OME blended with 90% diesel and found that life cycle GHG emissions can be reduced by up to 5.35% and the life cycle soot emissions can be reduced even more, 30% compared to neat diesel (Mahbub et al. 2017).

Therefore, in this study a second case was developed based on the selected forest residue pathway to examine the sustainability performance of different OME-diesel blend ratios. Ten different ratios of OME blends were compared in this study: 10% OME and 90% diesel, 20% OME and 80% diesel, 30% OME and 70% diesel, 40% OME and 60% diesel, 50% OME and 50% diesel, 60% OME and 40% diesel, 70% OME and 30% diesel, 80% OME and 20% diesel, 90% OME and 10% diesel, and 100% OME. The sustainability of each blend was examined with respect to four indicators: GHG emissions, soot emissions, water consumption, and overall cost. These indicators were selected because they are considered to be the

Table 9 Preference functions, objectives, weights, and thresholds used to compare OME blends

Criteria	Objective	Preference function	Weights	Preference threshold *P*	Indifference threshold *Q*
GHG emissions	Minimize	Linear	16.67	7.63	3.82
Water consumption	Minimize	Linear	16.67	866.28	433.14
Soot emissions	Minimize	Linear	16.67	0.02	0.01
Overall cost	Minimize	Usual	50	0.01	0.002

Table 10 Alternative ranking of different OME blends with diesel

Ranking of OME blends with diesel	$\varnothing^{+}$(positive flow)	$\varnothing^{-}$ (negative flow)	$\varnothing$ (net flow)
10%	0.67	0.33	0.34
20%	0.63	0.37	0.26
30%	0.59	0.41	0.18
40%	0.56	0.44	0.11
50%	0.52	0.48	0.04
60%	0.48	0.52	−0.04
70%	0.44	0.56	−0.11
80%	0.41	0.59	−0.19
90%	0.37	0.63	−0.26
100%	0.33	0.67	−0.33

main sustainability contributors. Table 8 shows the impact values of all the OME blends. The environmental, economic, and social impacts for different OME blends are calculated on a volume basis. The GHG emissions from the two fuels, diesel and OME, are first converted to volume-based emissions (g CO_2eq/L of fuel). For example, GHG emissions from 90% diesel on a volume basis are added to the GHG emissions coming from 10% OME on a volume basis. Equal weights are assigned to each impact areas assessed: 50% for environmental impact, and 50% for economic impact. For the environmental impact assessment, the 50% weight is divided further: 16.67% for GHG emissions, 16.67% for soot emissions, and 16.67% for water depletion. Table 9 shows the weights, preference functions, and thresholds for the indicators used to compare different OME blends.

Table 10 shows the positive, negative, and net outranking flows for the ten OME-diesel blends. According to the PROMETHEE I partial ranking and the PROMETHEE II complete ranking, the preference is highest for a 10% OME blended with 90% diesel fuel. For GHG and soot emissions, the preference increases with an increase of OME in diesel. However, for overall cost (economic impact indicator) and water depletion, the preference decreases with an increase of OME in diesel. Hence, with the indicator weights included, fuel blends with higher OME ratios are always less preferred over the lower ones, which also comply with the experimental results. Experimental results recommend that a maximum 10% of any oxygenated compound be added with petroleum-based fuels—in old vehicles with little or no engine alteration (Löfvenberg 2010; Pellegrini et al. 2013).

3.6 Sensitivity analysis

There are a number of variables with uncertainties in the model. These include but are not limited to indicator weights (which are based on decision-maker's preferences), threshold values, and the calculated indicator's impact values. Therefore, we conducted a sensitivity analysis to examine the impact of these variables and to represent different scenarios of decision-makers' preferences.

3.6.1 Weight sensitivity

A weight sensitivity analysis was conducted using the stability interval in Visual PROMETHEE. A stability interval determines the weight intervals for all the indicators, across which the ranking is not altered or the ranking remains stable (Genc 2014). If the stability interval is small on a particular indicator, the ranking becomes sensitive to the indicator's weight (Luk et al. 2010; Sultana and Kumar 2012) and even a small change beyond the interval can impact the ranking significantly. On the other hand, a large stability interval implies that the ranking is not affected by the change in weights within the interval (Safari et al. 2012; Sultana and Kumar 2012). For the base case, all the indicators except soot emissions have large stability intervals ranging from 0 to 100%. Soot emissions have a stability interval of 0 to 50%, which means that keeping all the other criteria equally weighted, the ranking will be altered (the whole tree pathway will be preferred) when the soot emission weight is assigned a value higher than 50%. Table 11 shows the weight stability intervals for the second case. The result shows that GHG and soot emissions have smaller sensitivity intervals. As an example, for GHG emissions, the preference rank will reverse (preference will increase with the rise of the OME ratio in the diesel blend) when the GHG emissions' weight is increased to over 36%. That means that if the decision-maker considers GHG emissions a key factor (with a value above 36%), the final rank will reverse.

Table 11 Sensitivity analysis of weights for the OME-diesel blend case

Indicators	Weights assigned	Stability interval
GHG emissions	16.67%	[0%, 36%]
Soot emissions	16.67%	[0%, 37%]
Water consumption	16.67%	[0%, 100%]
Overall cost	50%	[26%, 100%]

Table 12 Sensitivity analysis of sustainability impacts for the base case

	Rank	Pathways	$\varnothing$ (net flow)	$\varnothing^+$ (positive flow)	$\varnothing^-$ (negative flow)
Environmental scenario	1	Forest residue	0.60	0.80	0.20
	2	Whole tree	−0.60	0.20	0.80
Social scenario	1	Forest residue	0.87	0.93	0.07
	2	Whole tree	−0.87	0.07	0.93
Economic scenario	1	Forest residue	0.87	0.93	0.07
	2	Whole tree	−0.87	0.07	0.93

3.6.2 Sensitivity of environmental, economic, and social impacts

In order to study preference ranking for the sustainability factors (environmental, economic, and social), we developed three scenarios: environmental, economic, and social. In the environmental scenario, environmental impact is given a weight of 60% and the other two impacts 20% each. The other two scenarios are developed in the same way. Tables 12 and 13 show the sensitivity analysis results for the base case and the OME-diesel blend case, respectively. The ranking remains the same for the base case for all three scenarios. For the OME-diesel blend case, 80% of the weights are assigned to the preference scenario and the remaining 20% are assigned for the other scenario. As Table 13 shows, the ranking remains the same in the economic scenario. In the environmental scenario, however, the ranking pattern changes drastically, resulting in the 100% OME blend being the most preferred and the 10% OME the least. Hence, the environmental impact is sensitive to overall ranking in the OME-diesel blend case.

3.6.3 Sensitivity of preference and indifference thresholds

The preference and indifference threshold values are varied within a range of ± 10% and their impacts on the ranking of the alternatives are determined for both the base case and the OME-diesel blend case. Threshold values are changed in four ways: a 10% increase in both preference (*P*) and indifference (*Q*) thresholds, a 10% increase in the preference threshold and a 10% decrease in the indifference threshold, a 10% increase

Table 13 Sensitivity analysis of sustainability impacts for the OME-diesel blend case

	Rank	OME blends	$\varnothing$ (net flow)	$\varnothing^+$(positive flow)	$\varnothing^-$ (negative flow)
Environmental scenario	1	100% OME	0.07	0.53	0.47
	2	90% OME	0.05	0.53	0.47
	3	80% OME	0.04	0.52	0.48
	4	70% OME	0.02	0.51	0.49
	5	60% OME	0.01	0.50	0.50
	6	50% OME	−0.01	0.50	0.50
	7	40% OME	−0.02	0.49	0.51
	8	30% OME	−0.04	0.48	0.52
	9	20% OME	−0.05	0.47	0.52
	10	10% OME	−0.06	0.47	0.53
Economic scenario	1	10% OME	0.73	0.87	0.13
	2	20% OME	0.57	0.78	0.21
	3	30% OME	0.41	0.70	0.30
	4	40% OME	0.24	0.62	0.38
	5	50% OME	0.08	0.54	0.46
	6	60% OME	−0.08	0.46	0.54
	7	70% OME	−0.24	0.38	0.62
	8	80% OME	−0.41	0.30	0.70
	9	90% OME	−0.57	0.21	0.79
	10	100% OME	−0.73	0.13	0.87

Table 14 Sensitivity analysis rankings for the base case and the OME-diesel blend case

	Ranking of base case		Ranking of OME-diesel blend case									
Scenarios	WT	FR	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
+ 10% *P*, *Q*	2	1	10	9	8	7	6	5	4	3	2	1
+ 10% *P* − 10% *Q*	2	1	10	9	8	7	6	5	4	3	2	1
− 10% *P* + 10% *Q*	2	1	10	9	8	7	6	5	4	3	2	1
− 10% *P*, *Q*	2	1	10	9	8	7	6	5	4	3	2	1
+ 10% GHG emission	2	1	10	9	8	7	6	5	4	3	2	1
− 10% GHG emission	2	1	10	9	8	7	6	5	4	3	2	1
+ 10% soot emission	2	1	10	9	8	7	6	5	4	3	2	1
− 10% soot emission	2	1	10	9	8	7	6	5	4	3	2	1
+ 10% water depletion	2	1	10	9	8	7	6	5	4	3	2	1
+ 10% water depletion	2	1	10	9	8	7	6	5	4	3	2	1
+ 10% employment potential	2	1	10	9	8	7	6	5	4	3	2	1
− 10% employment potential	2	1	10	9	8	7	6	5	4	3	2	1
+ 10% employee wage and benefit	2	1	10	9	8	7	6	5	4	3	2	1
− 10% employee wage and benefit	2	1	10	9	8	7	6	5	4	3	2	1
+ 10% capital cost	2	1	10	9	8	7	6	5	4	3	2	1
− 10% capital cost	2	1	10	9	8	7	6	5	4	3	2	1
+ 10% operational cost	2	1	10	9	8	7	6	5	4	3	2	1
− 10% operational cost	2	1	10	9	8	7	6	5	4	3	2	1
+ 10% overall cost	2	1	10	9	8	7	6	5	4	3	2	1
− 10% overall cost	2	1	10	9	8	7	6	5	4	3	2	1

WT whole tree, *FR* forest residue, *OME-diesel blend case* % of OME in diesel, *P* preference threshold, *Q* indifference threshold

in the indifference threshold and a 10% decrease in the preference threshold, and, finally, a 10% decrease in both preference and indifference thresholds. In both the base case and the OME-diesel blend case, the ranking is not altered in any of the four above-mentioned scenarios (Table 14). Hence, it can be said that both the base case and OME-diesel blend case rankings are not sensitive to the assigned threshold values.

3.6.4 Impact values of indicators

As uncertainty may also exist in assessment impact values, we conducted a sensitivity analysis by changing the impact values by ± 10% for each indicator. The impacts on overall ranking are determined for both cases (see Table 14). One indicator is changed at a time. We found that rankings are not sensitive to

Table 15 Indicator values for OME as a transportation fuel scenario

		Whole tree		Forest residue	
		Base case transportation	OME as transportation fuel	Base case transportation	OME as transportation fuel
Energy consumption	GJ/MJ	0.017	0.013	0.022	0.010
GHG emissions	kg CO_2eq/MJ	2.96	2.49	1.69	0.109
Soot emissions	g/MJ	0.0002	0.0001	0.0002	0.00001
Water depletion	L H_2O/MJ	0.0003	0.0000006	0.001	0
Employment potential	h/m^3	0.033	0.033	0.135	0.135
Labor cost	$/MJ	0.002	0.002	0.007	0.007
Capital cost	S/MJ	0.013	0.013	0.010	0.010
Operational cost	S/MJ	0.061	0.061	0.056	0.056
Overall cost	S/MJ	0.074	0.074	0.067	0.067

changes in any indicator, that is, the rankings remain the same after the changes.

3.6.5 OME for biomass transportation

We developed a scenario assuming OME was the transportation fuel for biomass collection from the harvest area. It is expected that when the truck delivers biomass to the OME plant, it will be refilled with OME; thus, the truck does not use conventional fossil fuel for biomass transportation. Table 15 shows the impact values on transportation for this scenario. For the whole tree pathway, the changes are less than 2% for all the indicators. For the forest residue pathway, however, a 90–95% reduction in GHG and soot emissions is possible if OME is used for biomass transportation instead of diesel. Water consumption for biomass transportation in the whole tree pathway is negligible (0.0000006 L H_2O/MJ of OME from road construction), whereas in the forest residue pathway water required for biomass transportation is 0, as no external water is required for OME production from biomass. Indicators such as employment potential, labor cost, capital cost, and operational cost are not affected in this scenario. However, transportation costs increase by 5% and 1.62% in the forest residue and the whole tree pathways, respectively. The higher increase in the forest residue pathway is mainly due to the longer biomass collection distance compared to the other pathway. Change in overall cost is almost negligible for both pathways. Overall costs increase by 0.3% in the forest residue pathway and 0.07% in the whole tree pathway. As a result, the ranking remains the same as it is in the base case: the forest residue is preferred over the whole tree pathway.

4 Conclusions

The use of alternate fuels or fuel additives instead of fossil sources can improve environmental, economic, and social performances globally. This study developed a life cycle sustainability assessment (LCSA) framework for oxymethylene ether (OME) production from two types of forest biomass, whole tree and forest residue, to be used as a diesel additive by integrating the environmental, economic, and social impact assessments. Through the multi-criteria decision analysis method, the forest residue pathway was found to be strongly preferred over the whole tree pathway for OME synthesis in all sustainability impacts considered. The whole tree pathway is less preferred, as its GHG emissions were significantly higher (20.69 gCO_2eq/MJ) than in the forest residue pathway (13.37 gCO_2eq/MJ) due to energy-intensive road construction operations. All cost indicators are higher for the whole tree pathway, thus making it a less preferred pathway to produce OME from a cost perspective. From a social perspective, all the indicators also favor the forest residue pathway. A second case was developed to select the most sustainable blend of OME with diesel. Based on environmental, economic, and social assessments, a blend with a higher OME percentage is preferred. In this study, all the impacts were assigned equal weights for both cases. However, the sensitivity analysis of different model parameters (e.g., preference functions, threshold values, and weights) found that the variation in values is almost negligible. The developed LCSA framework can be used to assess different types of energy pathways to evaluate their environmental, economic, and social viability before commercialization. The framework can also be used to rank different energy pathways, thus assisting policy-makers to develop energy sector policies that are environmentally, economically, and socially sustainable.

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