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Evaluating ecosystem impacts of biogas pathways using life cycle assessment and ecosystem service models

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ABSTRACT

The regional energy transition from fossil fuels to alternatives with lesser environmental impact has become significant in recent years. The UN and the Sustainable Development Goals (SDGs) emphasize the importance of cleaner, safer, and more modern energy production to support environmental and climate protection. Renewable energy-based agricultural feedstock is considered a better substitute; however, its increasing share among alternative technologies powered by biomass sources still requires comprehensive environmental impact assessments. This study employs Life Cycle Assessment (LCA) modeling to evaluate the environmental impacts of biogas pathways, focusing on maize silage production for biogas in Alberta, Canada. Using openLCA software and Eco-invent data, the analysis covers the entire supply chain from upstream to downstream, assessing emissions, land use, and climate change impacts. The methodology involved consulting literature reviews, utilizing databases such as Eco-Indicator 99, ReCiPe, and the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). Key findings indicate that nitrogen fertilizer use (above 120 kg/ha in the maize farm) significantly contributes to eutrophication. Additionally, drying maize silage with natural gas poses a high climate change potential. These insights suggest that while biogas from maize silage is not entirely environmentally benign, improvements are achievable through optimized practices.

Contribution/Originality: This study uniquely integrates Life Cycle Impact Assessment with the InVEST ecosystem service model to spatially evaluate maize silage biogas pathways in Alberta, Canada. It highlights eutrophication and land-use impacts while proposing a hybrid drying method and optimized fertilizer strategies. This approach, which is rarely applied in Canadian biogas sustainability assessments, provides a comprehensive framework for evaluating environmental impacts and optimizing biogas production processes.

1. INTRODUCTION

Assessing the environmental impacts of renewable energy technologies has become more critical due to climate change, population growth, eutrophication, and land-use change, among other human-induced environmental challenges. Moreover, issues surrounding sustainable global energy transition cannot be overemphasized. The climate conference held in Paris in 2015 and Scotland (COP) in 2021, COP27 in Egypt in 2022, and now, more recently, COP28 in Dubai (Arora, 2024) emphasized the reduction of global temperature to an average of below 2 degrees Celsius, ideally at 1.5 degrees Celsius. This reduction is necessary even as demand for energy increases globally. To cut down on global emissions of CO_2, renewable energy-based agricultural feedstock is considered a better substitute with lesser environmental impact (Filippa, Panara, Leonardi, Arcioni, & Calderini, 2020). Biogas and fuels from biomass sources will help improve the security of energy systems both now and in the future because of their renewability features (Karp & Shield, 2008). While reducing climate change, ecotoxicity, and eutrophication impacts, over 85% of the total primary and secondary energy use in Alberta alone is supplied by fossil fuels (Statistics Canada, 2013). The same is applicable in several countries around the world, especially in oil-producing nations.

However, Canada depends mainly on fossil fuels for their energy generation and use because they are one of the world's oil-producing countries with cheap/affordable natural gas prices. The Canadian government, like many other nations of the world, still supports bioenergy activities through an ecoENERGY initiative that granted about 1.5 billion dollars for 9 years starting from 2008 for renewable energy production. Also, another eco-agriculture Biofuel Capital program in 2011 allocated about 200 million dollars in support of agricultural production for bioenergy in response to the energy transition call. A similar offer was announced in 2021 for the Agricultural Climate Solution to help farmers tackle climate change as mentioned in (Government of Canada, 2021; Whitman, Yanni, & Whalen, 2011). In Canada, Alberta has the fourth-largest biomass resources after Quebec, Ontario, and British Columbia provinces, according to Alberta Innovates Bio Solutions (2014) and Alberta Innovates Bio Solutions (2025). However, bioenergy development is still slow in the country at large. It is established by some scholars that bioenergy feedstocks are carbon-neutral (Chauhan et al., 2025) feedstock such as maize is not carbon neutral and not without environmental impacts, because energy is being used during the cultivation, processing, and transportation periods. The potential of CO_2-neutral fuels derived from renewable sources to minimally impact climate change strongly supports the use of renewable energy though (Jury, Smith, & Horton, 2010). Nonetheless, the anticipated reduction in impact may be lessened by the energy and materials required for crop cultivation (e.g., maize silage, grass silage, whole wheat plant silage) and the transportation of these materials. Moreover, biogas plants contribute additional emissions during their operation, the use of the biogas produced, and the transport and disposal of leftover materials, known as digestate. These considerations are crucial in the pursuit of environmentally friendly and sustainable biogas energy production (Poeschl, Ward, & Owende, 2012). Furthermore, achieving a positive energy balance in the production and use of biogas, including the employment of the anaerobic digestion (AD) process for waste management, further bolsters the environmental sustainability of biogas as a renewable resource, as highlighted by Pöschl, Ward, and Owende (2010).

Conversely, Shapouri, Duffield, and Wang (2002), referenced in Whitman et al. (2011), suggested that it is still debatable whether bioenergy is emission-free or not. Increased use of bioenergy technologies should not be at the expense of environmental protection and prosperity, so all impacts arising from biogas production have to be assessed from the onset and made known, as this study revealed. When applying the life cycle impacts assessment as in this study, an integrated efficiency of the complete process that considers initial input and the final output is determined (Abu-Rayash & Ibrahim, 2019). The Eco-indicator impact assessment method has been applied in this study to carry out the life cycle impact assessment (LCIA), which reports the environmental impact value in numbers or scores known as eco points. Eco points are represented as an environmental load of an average European for production and consumption undertaken in an economy annually, according to (Goedkoop, 1999; PRé Consultants, 2017), who proposed an oriented method for life cycle impacts assessment in Eco-Indicator 99; 1999). On the other hand, impact on ecosystem quality includes, but is not limited to, eutrophication, which occurs when fertilizers and plant protective chemicals are used on farms. The nutrients easily wash down to nearby rivers, causing an accumulation of substances that suffocate or kill aquatic creatures, as reported in Pal (2020). Also, land use change impacts on species diversity and acidification, among others. When a land ecosystem is damaged (loss of naturalness and loss of potential carbon sink), it changes the quality from acting as a resistance to erosion and flooding. This can affect the groundwater protection ability, filtering and buffering capacity functions as mentioned in Lakhani, Martinsen, Nielsen, and Stranddorf (2014). However, there is an increasing need to develop a more bio-based economy with modern and cleaner energy systems to reduce greenhouse gas emissions from fossil fuel use (Goglio et al., 2018). Baumgärtner et al. (2021) presented a holistic national energy model that includes high-emission sectors and LCA. Their model provides detailed environmental impacts for electricity, heat, and transport processes in Germany for meeting the climate targets up to 2050. Baumgärtner et al. (2021) study found that renewable energy and storage are key technologies for decarbonized energy systems. Furthermore, sector coupling is crucial and doubles electricity demand. Our LCA shows that environmental impacts shift from operation to infrastructure, highlighting the importance of an impact assessment over the full life cycle. Decarbonization leads to many environmental benefits; however, it also increases freshwater ecotoxicity and depletion of metal and mineral resources. Thus, holistic planning of decarbonization strategies should also consider other environmental impacts. Although the use of biomass sources as a renewable energy feedstock has been seen as more sustainable compared to the use of fossil fuel sources such as natural gas, there have also been concerns about land occupation and conversion, issues of fertilizer application, and movement of its debris to water bodies. Furthermore, it is essential to consider the machinery and transportation used in maize cultivation, as highlighted by Reid, Ali, and Field (2020) due to the potential loss of ecosystem services and species. This consideration is crucial during the development and deployment of bioenergy, which can result from deforestation and land use changes, to ensure early mitigation strategies are in place (Vohra et al., 2021). Table 1 below presents the selected unit process, the input material and output necessary for running the 3 different LCIA models This introduction now clearly states the research gap and objectives. It emphasizes the need for comprehensive environmental assessments of biogas production which positions this study as addressing these gaps.

1.1. Hypothesis and Research Questions

1.1.1. Aim and Objectives

The purpose of this study is to explore the environmental impacts of biogas production to support the future ambitions of the Canadian renewable heat and gas market sustainably, using LCA tools with the following objectives.

1. To assess the environmental impacts of alternative or renewable energy on air, land use, water, and nutrient delivery to avoid or reduce eutrophication and CO_2 problems.
2. To investigate the environmental impacts of the entire life cycle stages of biogas pathways and compare them with natural production influences on climate change and land use change.

The research answers the following hypothetical questions:

Will the modeling of ecosystem services with the OpenLCA software provide robust data that will help to reduce the environmental impacts of biogas production in support of energy transitions?

Which of the flow or impact categories contributes more to the environmental burden when maize silage is produced, considering the biogas pathways (cultivation, digestion, or conversion)?

How can this study's LCIA result be incorporated into an ecosystem services model to provide spatially resolved insights (i.e., a measure of the smallest ecological impact) and details?

Table 1. Presents the models' input and output data necessary for performing the life cycle impact assessment, including the selected unit processes required to produce the modeled maize silage biogas pathways.

Unit process	Inputs	Outputs
Cultivation/tilling	Farm machines	GHG emissions
Fertilization	N, P, Fertilizer	Nitrates
Pesticide	Agrochemicals	Atrazine
Transportation, freight	t*Km distance travelled	CO_2/Fuel emission
Land transformation and occupation	Land use change	Heavy metal (lead), erosion
Drying	Agro machine	CO_2/GHG emissions

Table 1 outlines the input and output parameters for each unit process involved in maize silage biogas production. It details the cultivation, fertilization, pesticide application, transportation, land transformation, and drying stages, specifying the associated material or energy inputs and the resulting emissions, pollutants, or environmental changes.

2. CONTRIBUTION TO RELEVANT LCIA STUDIES

This study contributes to the existing literature and beyond by analyzing the environmental impact of maize silage biogas pathways exceptionally and offering new knowledge. In the literature review of related studies previously carried out by other scholars, details of what authors have done in this field of study and about the model result are presented. Also, a few works of literature have been used to calibrate and validate this study, such as Jaroslav et al. (2021); Dressler, Loewen, and Nelles (2012); Filippa et al. (2020); Aracil, Haro, Vidal-Barrero, Ollero, and Cano (2017); Jayasundara, Wagner-Riddle, Dias, and Kariyapperuma (2014) and Kalu et al. (2021). The selected inventory data is in the supplementary data section.

This study has been examined in a more comparative and comprehensive manner for the environmental performance of products and services throughout their lifetime while presenting its results in a standardized form following the ISO 14040 and 14044 (ISO, 2018a and ISO, 2018b) standard. It is an important tool for identifying trade-offs that will help in making environmentally friendly decisions on renewable energy projects.

In this study, transportation distance, medium (freight road transport), fertilizers/chemicals, energy use, and emissions into the land, air, and water (L.A.W) has been assessed within the supply chain. One of the features of energy systems LCA explored in this study requires the complete analysis to determine the integrated efficiency that considers the input and output as mentioned in Abu-Rayash, Azzam and Ibrahim Dincer, 2019; Ibrahim Dincer and Yusuf Bicer, 2018). Lakhani, R. et al., 2014 argued that damaging the land ecosystem will affect its natural state that acts as carbon sink. They added that it can change land quality and the ability to act as a resistance to erosion and flood. This can affect the groundwater protection capacity, filtering and buffering functions.

Still, there is an increasing need to develop a more bio-based economy with cleaner energy systems to reduce greenhouse gas emissions from fossil fuel use, Goglio et al. (2018).

Huang et al. (2022) conducted a comparative analysis of the life-cycle outcomes of biodiesel generation from wet microalgae, revealing that the primary contributor to systemic energy usage and environmental burdens was the organic solvent. In a study by Xiao, Zhang, Xiong, Yang, and Yang (2020), the life-cycle of biogas production from microalgae biomass was assessed, indicating that the utilization of hydrothermal pretreatment (HTP) led to a substantial increase in biogas production compared to the energy consumption of the HTP process. Sun, Liu, Zhang, and Chen (2019) undertook a life-cycle assessment (LCA) of biogas production through two-stage fermentation utilizing microalgae biomass and food waste, demonstrating that the elevated carbon-to-nitrogen ratio of food waste notably enhanced biogas output while reducing the net energy ratio to 0.24. Sinsuw, Chartchalerm, Bunnak, Limtong, and Kiatkittipong (2024) carried out an LCA to compare the environmental impact potential of commercial and pilot-scale anaerobic biogas plants, highlighting both systems' relatively low environmental footprint, with the commercial plant exhibiting lower impacts than the pilot-scale facility. The most significant impacts were observed in terms of photochemical ozone creation potential for commercial plants and eutrophication for pilot-scale plants. The integration of digesters resulted in a considerable reduction in environmental impacts, underscoring the viability of regional sustainability strategies in managing livestock waste through anaerobic biogas plants. Shinde, Bhosale, and Thombre (2021) performed an LCA to evaluate the environmental repercussions of two utilization pathways for biogas derived from organic household waste, grease trap removal sludge, and ley crops as vehicle fuels in Västerås, Sweden. The Swedish study revealed that while both biomethane and biogas-based electricity diminished environmental impacts compared to conventional fuels, biomethane buses exhibited a higher global warming potential (0.26 kg CO_2-eq/VKT) than electric buses (0.11 kg CO_2-eq/VKT). Electric buses also mitigated the impact of acidification and eutrophication in contrast to biomethane buses. They concluded that the utilization of biogas was environmentally viable and represented a competitive option among alternative choices.

Hosseini, Ugursal, and Kumar (2022) conducted an evaluation of the environmental ramifications of electricity production in Alberta, Canada, with the aim of providing insights to policymakers regarding the integration of sustainable technologies. The investigation demonstrated that coal and lignite-based power facilities exhibited the most significant potential for harm to both human health and ecosystems compared to other non-renewable options. Power plants utilizing natural gas displayed a lower damage potential but showcased increased resource utilization. Conversely, hydropower and wind energy facilities emerged as the most environmentally friendly within the realm of renewable energy sources. In contrast, biogas-powered plants demonstrated relatively higher impacts, surpassing even coal-based plants in terms of ecosystem damage potential. Achieving the 30% renewable energy target could lead to a reduction in fossil fuel consumption and a decrease in global warming potential by approximately 9.5–27.7% and 41–49%, respectively. Muradin, Popławski, and Piersa (2023) examined the environmental implications associated with the operation of two agricultural biogas plants employing different feedstock supply methods. Their assessment of environmental impacts throughout the life cycle was conducted from the initial stages to the point of entry into the system, utilizing SimaPro software in conjunction with the ILCD 2011 Midpoint+ method. The system boundaries included maize cultivation, feedstock delivery to the plants, energy generation, as well as the storage and transportation of digestate. The findings highlighted that the transportation of liquid manure resulted in the most substantial environmental repercussions.

This paper reviewed almost 100 studies across all the chapters in a unique manner, while maintaining its originality. Considering the existing school of thoughts and body of knowledge, the importance of life cycle impact assessment for maize silage biogas pathways has not been over-emphasized still both globally, regionally, and locally.

3. METHODOLOGY AND DATA

The study utilizes openLCA software and Eco-invent data to simulate the environmental impacts of maize silage production, digestion, and conversion. Impact categories such as climate change, eutrophication, and land use change were selected based on their relevance to biogas production processes. The LCIA methods employed include Eco Indicator 99, ReCiPe, and TRACI, ensuring a comprehensive assessment.

As every study has a laid-down procedure followed to achieve the set goals and objectives, the method of this study includes the use of open software and Eco-invent data to simulate the impacts of maize production, digestion, and conversion. Additionally, relevant websites were surveyed, and some literature values were adopted. An open search on the topic was carried out on Google Scholar, Web of Science, and government websites such as Agri-Food Canada, Statistics Canada, Environment Canada, and the Canadian Center for Energy Information 2020. A careful selection of the most relevant and recent studies followed the three mandatory elements of LCIA selection, classification, and characterization. A quality assurance and quality control (QAQC) assessment was conducted to determine the origin of individual literature values and whether they meet and align with the overall scope of this study before applying them. Some literature values were harmonized; for example, (Titaporn, Cha-um, & Paoin, 2020). Part of the harmonization involved converting different measuring units used in various literature into kilograms to match this study. The main focus of the simulation is on climate change, GHGs, GWP, CO2, acidification/eutrophication, nitrates, ammonia, atrazine, and land use change, all of which constitute the flows and impact categories of this study. The selected literature used mass-based functional units for easy conversion from tons to kilograms for more accurate comparison. Subsequently, the model was run iteratively using the Eco-indicator, Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), and ReCiPe methods, which were compared to the inventory results from the contribution tree. A comparison of the different life cycle stages was also conducted to identify the most impactful stage among maize production, digestion, and conversion processes.

3.1. Study Area Description and Bioenergy in Canada

With a total area of approximately 661,848 sq. km, Alberta is situated in the west-central region of Canada, sharing a boundary with British Columbia. The highest elevation point in Alberta is Mount Columbia, at 3,747 meters. Significant rivers in the province include the Peace, Slave, Milk, Red Deer, and Hay River. The lowest elevation point is 175 meters, located in the northeastern area near the Slave River valley. The land is predominantly flat and covered with prairies, where maize silage production occurs (Awada, Cecil, & Peter, 2021; Guyader, Baron, & Beauchemin, 2018). Alberta's southern and eastern regions are characterized by these prairies. As an oil-producing province, Alberta primarily relies on natural gas and other fossil fuels for energy. In 2011, coal accounted for nearly 87.4% of the province's energy consumption, as reported by various sources, Statistics Canada (2013). The province generated around 36% of the country's fossil CO_2 emissions according to Environment Canada (2013) as, Alberta and Ontario have been the most significant emitters since 2005, resulting from oil and gas expansion as reported in the National Inventory Report 1990-2019 as submitted to the United Nations framework convention on climate change, (Environment Canada, 2021). Increasing the share of renewable energy from biomass can reduce air emissions as the region has a substantial amount of untapped feedstock that can support energy transition (Weldemichael & Assefa, 2016). Nonetheless, only about 0.04% of the biomass sources are harvested annually until 2014 (Statistics Canada, 2013).

The production of maize silage in the Canadian prairies has increased to about 383,879 hectares as of 2016, and this is due to maize's high yield potential compared to other feedstocks. However, the long cold seasons affect its ability to yield more than 320-380 g kg of whole plant dry matter content necessary for ensiling, as cited in Guyader et al. (2018). In the year 2019 alone, Canadian energy consumption was approximately 8,882,020 terajoules, of which 2,282,309 terajoules were Albertans' share, according to the Canadian Centre for Energy Information (2020). As the production of crops contributes about 6.5 per cent of the country's emissions (Awada et al., 2021), many scholars have assessed the impacts of bioenergy production in Alberta, Canada. They include (Bell & Weis, 2009; James & Ben, 2014; Weldemichael & Assefa, 2016). Nevertheless, evaluating the environmental impacts of maize silage production for biogas use, with a focus on health, ecosystems, and resources, by applying the Eco-indicator method across the life cycle pathways, still has increased demand. There is no doubt that bioenergy deployment in the Canadian province of Alberta will significantly decarbonize its electricity grid emissions, as the GHG emission category by sector is elaborated more in Table 2.

Table 2. Presents Canadian GHG emissions by the Intergovernmental Panel on Climate Change (IPCC), focusing on selected sectors as measured in metric tons of CO_2 equivalent from 2005 to 2019.

Sector	Year 2005	Year 2015	Year 2017	Year 2019
Oil & gas extraction	63 Mt CO_2 eq.	97 Mt CO_2 eq.	97 Mt CO_2 eq.	105 Mt CO_2 eq.
Transport	190 Mt CO_2 eq.	201 Mt CO_2 eq.	207 Mt CO_2 eq.	217 Mt CO_2 eq.
Agriculture	60 Mt CO_2 eq.	58 Mt CO_2 eq.	58 Mt CO_2 eq.	59 Mt CO_2 eq.
Land use change & forestry	8.2 Mt CO_2 eq.	4.0 Mt CO_2 eq.	0.70 Mt CO_2 eq.	9.9 Mt CO_2 eq.

Recall that Alberta is one of the largest oil-producing provinces or jurisdictions globally, with over 83% of its electricity approximately coming from non-renewables (Giesy, 2010; Jiaao, Kumar, & Sahinidis, 2020; Olmstead & Ayres, 2014). However, Canada accounts for about 60% of its total primary energy supply from biomass, hydropower, solar, wind, and geothermal. Nonetheless, power generation from bioenergy still varies significantly across different municipalities and provinces, Natural Resources Canada (2021). A recent paper published in January 2022 suggests that Canada needs to step up more renewable energy policies, plants, and incentives to be able to match up with the biogas front-runners such as Germany, China, the UK, Italy, and Japan, to mention but a few. The anaerobic digestion system has proven to be a suitable method for converting both energy crops and waste to renewable energy (Omid & Anime, 2022).

3.2. Life Cycle Impact Assessment (LCIA) Model

Impact analysis is where the inventory results are translated into new information related to impacts coming from the flows to assess their significance on humans, ecosystems, and resources (H.E.R.). In LCIA, a series of factors are applied to the inventory results while generating the impact estimates. A key difference between life cycle impact assessment and other frameworks is its link to a particular functional unit (and, of course, the entire life cycle as a boundary). LCA and LCIA have two unique features and objectives compared to other models. Firstly, it evaluates the environmental performance of maize silage production in this study, considering raw material production, transportation, machine manufacturing, and so on, following ISO 14040 and 14044 (ISO, 2018). A similar process is seen in (Pieragostini, Aguirre, & Mussati, 2014). The second major benefit is that decision-makers can make environmentally friendly choices on bioenergy projects while selecting from alternative processes.

Additionally, LCIA results can serve as a basis for making potential improvements in a product system's environmental performance. This method has informed and derived several activities within a product/service supply chain. The LCIA carried out in this study considers the actual adverse effects of biogas processes on health, ecosystems, and resources, not merely tracking quantities such as tons of emissions or liters of fuel consumed during production but also the real environmental effects. The final LCIA results are presented as indicators (Minu, 2018). An indicator is a generic term that refers to a clear pointer or signal. For instance, fish dying in a water body could be an indication of eutrophication. Global warming could also be an indication of greenhouse gas emissions.

This study applied Eco-indicator 99, ReCiPe, and TRACI (Tool for the Reduction and Assessment of Chemicals and Other Environmental Impacts), developed primarily for use in the U.S. and North America to guide LCIA studies (Bare, 2011; Bare, 2012). The egalitarian assessment category is chosen to fulfill the study's scope, as this method deals with the endpoint results and has been widely used for similar studies (Cavalett, Chagas, Seabra, & Bonomi, 2013; Homagain, Shahi, Luckai, & Sharma, 2015). In this project, some of the input data and production procedures were adapted from the widely used databank. This databank has a publicly open and non-open access database; the US Life Cycle Inventory (LCI) databank is regulated by the National Renewable Energy Laboratory (NREL) (2012). Eco-invent paid database is provided by the Center for Life Cycle Inventories Swiss, eco-invent.

3.2.1. Goal and Scope Definition

The primary objective of this case study is to evaluate the environmental impacts associated with the cultivation of corn (maize silage) and its processing for biogas-electricity and heat generation. The secondary input data utilized for the analysis are sourced from the EcoInvent database (paid) and simulated using the openLCA tool, employing the Eco-indicator 99 life cycle environmental impact assessment (LCIA) method, as well as TRACI and ReCiPe methods (Goedkoop et al., 2013). The primary environmental mediums assessed include water (for eutrophication due to nitrate emissions), air (for CO_2 emissions related to climate change and respiratory issues), land (for acidification and land use change/land conversion), and resources (energy consumption).

3.2.1.1. The System Boundary

Every LCA study has a developed scope and system boundary that guides it. This study's system boundary is considered cradle-to-gate since it covers maize cultivation, fertilizing, harvesting, drying, transportation, and processing (digestion and conversion into CHP). Furthermore, the final emissions to land, air, and water arising from the process supply chain (maize production and conversion processes) were assessed. The system boundary diagram in Figure 1 shows the inputs and outputs used in this analysis. This boundary is sufficient for this study as it showcases what was implemented and other literature, such as Bacenetti, Lovarelli, and Fiala (2016), has also used a similar boundary.

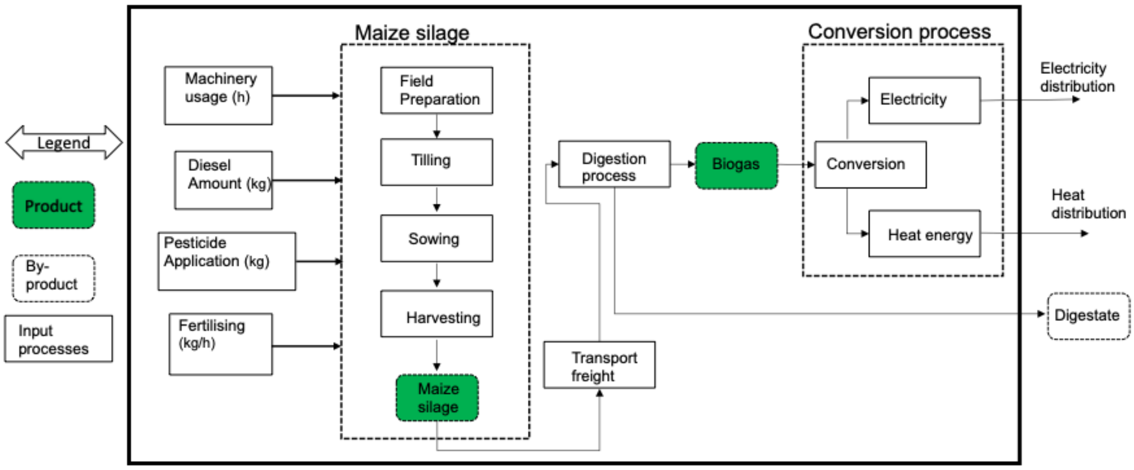

Figure 1. System boundary showing the products, processes, and inputs.

3.2.1.2. The Functional Unit (FU)

There are different units for this type of assessment, and 1 kg of maize silage (mass-based FU) has been chosen as recommended for this project and has also been used previously by Boone et al. (2016) and Król-Badziak, Pishgar-Komleh, Rozakis, and Księżak (2021). Some other studies use energy-based functional units such as a 1-meter cube of biogas for convenience's sake, as seen in Wang, Li, Gao, and Li (2016).

3.2.2. Life Cycle Inventory

The inventory considers the number of agricultural machines and sheds, including the quantity of diesel fuel consumed. In addition, it considers the quantity of air emissions from combustion, noise pollution, and emissions to the soil from tyre abrasion during farming activities and processes. Some preliminary agricultural activities include clearing a parcel of land, say 1 ha surface, attaching the adequate machine to the tractor, and uncoupling it at the end of use. This dataset was generated following the Eco-invent quality guidelines, which are available via the Eco-invent website (http://www.ecoinvent.org/database/ecoinvent-version-3/reports-of-changes/).

Eco-invent background data is crucial, as it is the largest transparent Life Cycle Inventory database globally, according to Gregor, Bauer, Cox, and Mutel (2016), as referenced in Aleksandra, Ivona, and Antonija (2021). Also, diesel consumption is calculated from primary data and models from the American Society of Agricultural and Biological Engineers (ASABE) published in ASABE Technical Library (2006). The dataset includes transfer to the field; fieldwork for an area of land of about 1 ha, including turning, idling, and overlapping processes Quebec Reference Center for Agriculture and Agri-food (CRAAQ) (2011). In general, maize production datasets have been extrapolated to include the land-use change for the Canadian region with the emissions according to the second edition of the Quantis-modified tool developed by Blonk Consultants (2014), World Food Life Cycle Assessment Database (WFLDB) - adapted Blonk (2014) direct land-use change assessment tool Sebastien (2014). The size of the accounted emission depends mainly on the country-specific land transformations and the relative crop expansion in all other countries where the crop has grown during the last 20 years. Additionally, the current results are based on the average Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) data from the year 2011 harvested area, as cited in Food and Agriculture Organization of the United Nations (FAO) (2018).

3.2.3. Life Cycle Impact Assessment

The life cycle assessment method followed the LCA series of the ISO standard principle of goal and scope, inventory, impact assessment, and interpretation, Figure 2. The Eco indicator 99 method openly developed by Dutch Pre (Product Ecology Consultants) for the Dutch Ministry of Environment (Filippa et al., 2020), is used majorly to carry out this cradle-to-gate (Titaporn et al., 2020) assessment of maize silage production. It allows and shows environmental impacts/scores (mile points) of a product or service in numbers called eco points. The digestion and conversion stages were also simulated. The Eco indicator (damage-oriented method) unit of measurement called mile-point (eco-point) can be described as the conventional annual load of an average citizen, considering the production and consumption capacity in the economy (Goedkoop & Spriensma, 1999).

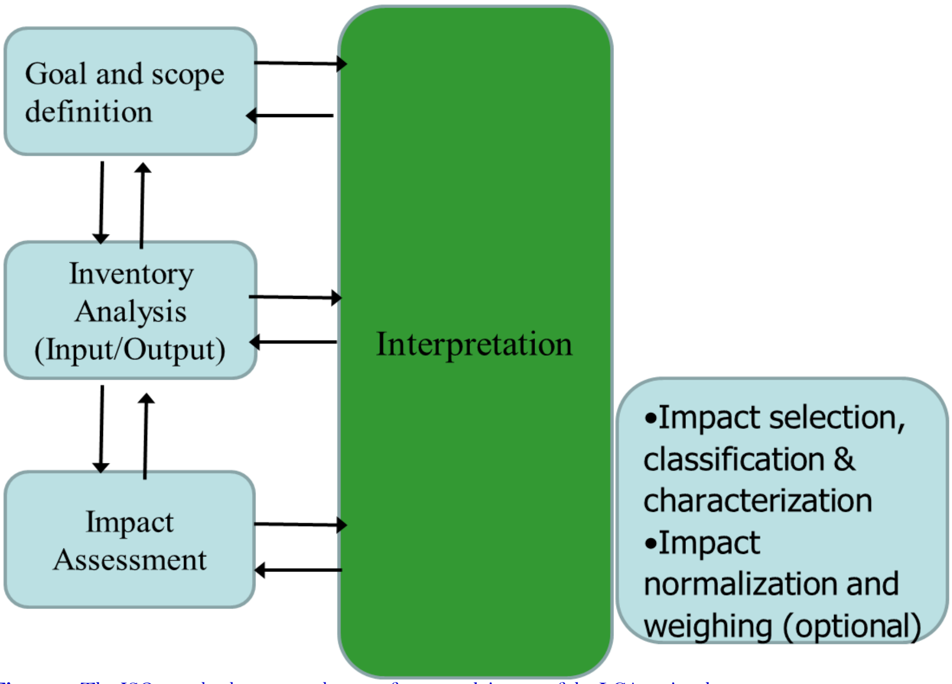

Figure 2. The ISO standard 14040 and 14044 framework is part of the LCA series that promotes transparency in reporting product emissions, as demonstrated in this research (ISO, 2018).

4. RESULT, ANALYSIS AND INTERPRETATION

This analysis illustrates the model's buildup, simulation, and the arrival of the desired result with a specified outlook/interpretation of each figure. The flows & impacts categories were analyzed considering the individual LCA stages or biogas pathways; others were compared with natural gas or literature. To perform this LCIA practically with a key interest in health, ecosystem, and resources (H.E.R), climate change, and respiratory effects for the health impact category are analyzed, and acidification/eutrophication and land occupation for the ecosystem impact category were assessed. Additionally, fossil fuels and mineral extraction for the resources category were also evaluated and compared across the biogas LCA stages. The flows and impact categories were populated using the LCA selection method from the three impact assessment methods. Averages from each impact were chosen from the three methods used (Eco-indicator, ReCiPe, and TRACI). Some of the results were compared with the harmonized papers (part of the harmonization was carried out by converting the different measuring units used in different literature into kg to match this study's goal). The most significant maize silage production impact category contributor depicted in Figure 3 gives an idea of all the results at a glance. The result shows that excessive drying, manufacturing, and the use of farm chemicals such as fertilizer greatly affect the water ecosystem through eutrophication, which releases nitrogen and its oxides into the environment. The analysis reveals that the drying process is the largest contributor to CO_2 emissions during maize silage production (Figure 3). Comparative assessments with natural gas indicate that while biogas production has higher eutrophication potentials, it offers lower overall global warming potential. Subsections detail the impacts on climate change, eutrophication, and land use.

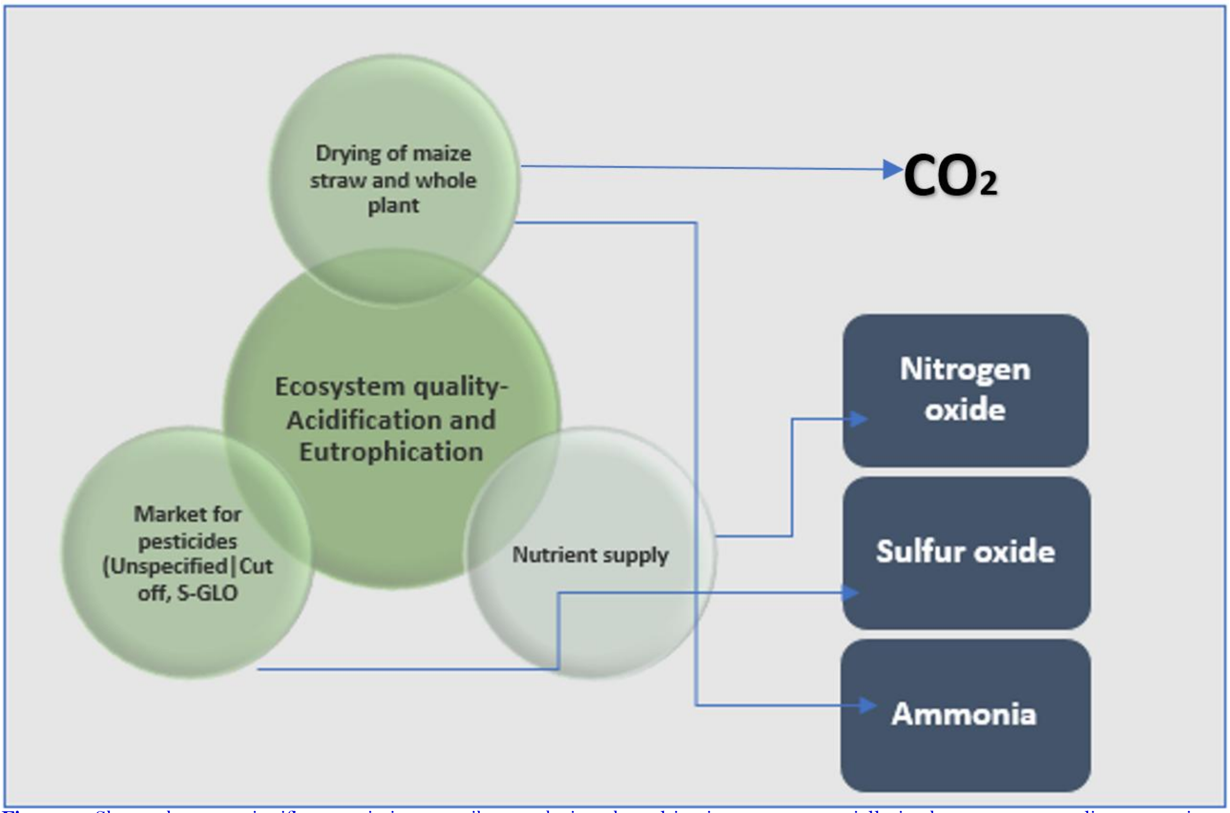

Figure 3. Shows the most significant emission contributors during the cultivation stages, especially in the ecosystem quality categories of acidification and eutrophication. Emissions from drying are leading during the maize production stage.

Outlook: What decision-makers should do to maintain environmental protection while switching to biogas in Alberta is to regulate the use of farm chemical inputs. This study recommends about 120 kg of nitrogen fertilizer per hectare (Jaroslav et al., 2021; Jayasundara et al., 2014). Since nutrients from farm chemicals and drying for ecosystem quality category are the major contributors, as shown in Figure 3, it is recommended that maize silage drying should be carried out with a hybrid system (biogas and natural gas) to reduce nitrogen, sulfur dioxide, and ammonia emissions.

4.1. Maize Silage Production Flow Categories Analysis

4.1.1. GHG (CO_2)

The CO_2 emissions arising from the maize production alone were contributed mainly from the drying process, the market for pesticide & farm chemicals production and their applications with farm machines, as also shown in Whitman et al. (2011) with 0,320 $kgCO_2$ eq/kg of maize produced in Quebec. Freight transport is the third main CO_2 contributor in this LCA stage. This result is expected considering the study location, where fossil electricity is used for drying and other major farm activities. Canada also has long cold periods, which causes the excessive use of electricity for drying. Large amounts of CO_2 are emitted into the air during this drying process. The obtained result has been compared with other studies, as Figure 4 depicts, to gain more confidence, which helps to provide accurate policy recommendations for Alberta in the outlook. While analysing from the most significant impact to the smallest, considering the study's assumptions, the research carried out by Titaporn et al. (2020) has the most significant value of 0,351 $kgCO_2$ eq/kg of maize silage produced in a small county of Thailand. While our study on the contrary reports 0,132 $kgCO_2$ eq/kg Figure 4. To reduce emissions, we have assumed that biogas and natural gas (hybrid gas) will be used to dry the maize silage instead of natural gas alone, which is commonly used now. This change will significantly reduce the drying emissions in the form of GHGs.

Additionally, following a comparative analysis of CO_2, it was found that Jayasundara et al. (2014), who studied the GHG intensity of corn production in Ontario, reported in the range of 0.243 – 0.353 $kgCO_2$eq/kg. In this acidification impacts category, drying is the major contributor as the inventory data includes the energy demand (supplied by burning light fuel oil and consumption of electricity). The infrastructure, including the drying machine for the maize plant, starting at about 110-120 degrees Celsius, was inventoried as they have climate warming potential.

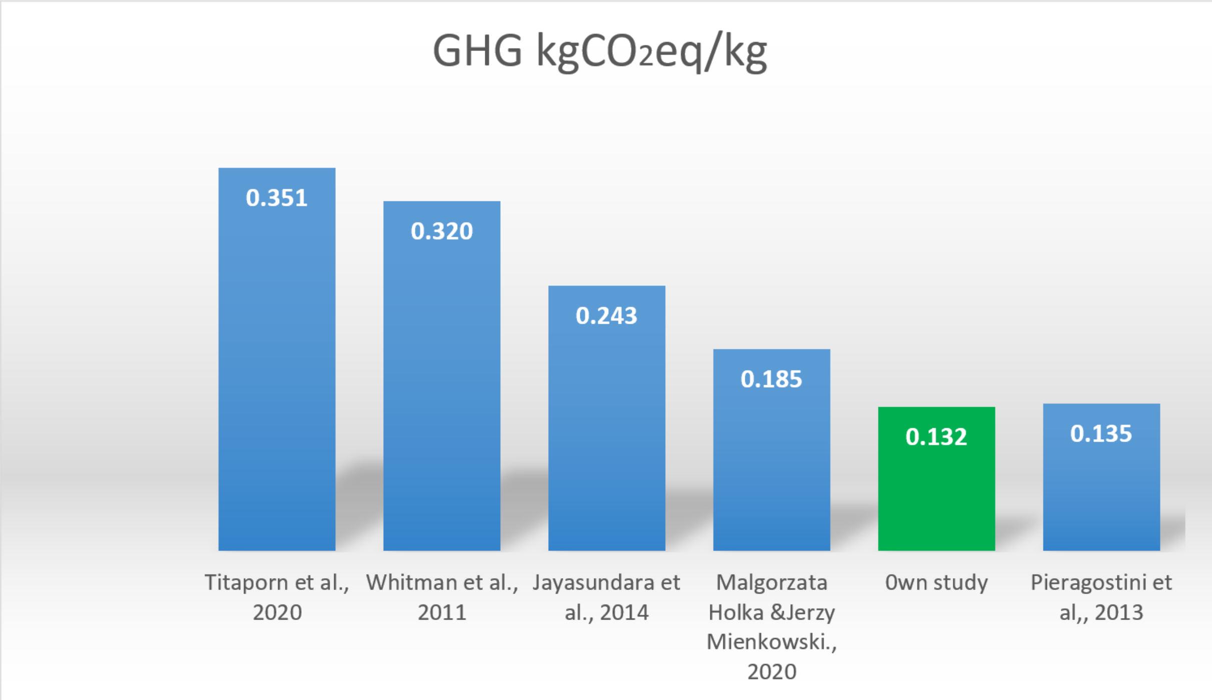

Figure 4. CO_2 comparative LCIA assessment for the production of 1 kg of maize silage in Alberta measured in GHG kg CO_2eq/kg.
Source: Titaporn et al. (2020); Whitman et al. (2011); Jayasundara et al. (2014); Małgorzata and Jerzy (2020) and Pieragostini et al. (2014).

Further CO_2 analysis shows that the maize silage cultivation process has the highest GHG emission, as reflected in other study's results as well. For example, Adams, Mezzullo, and McManus (2015) evaluated the GHG produced in the United Kingdom biogas facilities and found that cultivation activities for 4 different maize scenarios have higher emissions than the upgrading and other processes involved in getting the biogas. Whitman et al. (2011) report the total GHG impact of between 40 and 61%, which is caused mainly by the loss of soil organic content during cultivation in Quebec. At the same time, the nitrate emission is at 31% for the same paper. This study reports 0.132 kg CO_2eq/kg as compared to 0.135 and 0.185 kg CO_2eq/kg reported by Pieragostini et al. (2014), which is the closest to our result and Małgorzata and Jerzy (2020), respectively. Also, 1 ton of maize silage can generate 650 m^3 of biogas, according to Filippa et al. (2020) experiments. In their study, the maize cultivation stage has the highest impact compared to other processes, and the majority (63%) of the impact comes from fertilization. Another impact originates from drying and nutrients released into the environment during the cultivation stage.

Outlook: Alberta can reduce CO_2 emissions by modeling this LCA result in an ecosystem services model capable of showing the most impacted point explicitly. When this is done, then drying can be carried out during the summer period to reduce the use of fossil gas.

4.2. Flow Analysis (Nitrates, Atrazine, Ammonia) For Maize Cultivation Compared to Other Life Cycle Stages

For the selected flow categories (nitrate, ammonia, and atrazine), the most significant contributors during the cultivation stage are nitrates at 0.117 kg/kg of maize silage produced, followed by ammonia at 0.018 kg/kg, and atrazine at 0.028 kg/kg. This result from the cultivation process alone has been compared with other life cycle assessment (LCA) stages (i.e., digestion and conversion processes), as depicted in Figure 5. The emissions from nitrate at 0.117 kg/kg represent the highest flow category, primarily originating from drying and farm nutrients or chemicals production and use. Additionally, atrazine, the second-highest contributor from maize production, results from the production and farm application of herbicides used to protect maize from pests, which adversely affect the water ecosystem. Ammonia emissions stem from various agricultural activities, such as machinery use, which releases emissions into the air and water bodies. Nitrate emissions continue to be a significant impact during the maize production stage. It is important to note that the major pollutants released into the environment from farm chemicals and drying processes are nitrogen oxides and sulfur dioxides. In this flow analysis across the life cycle pathways, ammonia emissions from the digestion stage are notable compared to other stages. The model accounts for potential impacts, such as digestate (slurry) produced during digestion, which may cause environmental issues when used as farm manure or if digestate leaks from the anaerobic digestion plant, leading to high eutrophication potential. Consequently, the lowest impact in this LCA flow analysis emanates from the digestion and conversion stages concerning atrazine emissions, as shown in Figure 5. Since atrazine content is not directly involved in other life cycle pathways except during maize cultivation, it is justifiable that atrazine's impact is insignificant during anaerobic digestion and the subsequent conversion into electricity and heat stages.

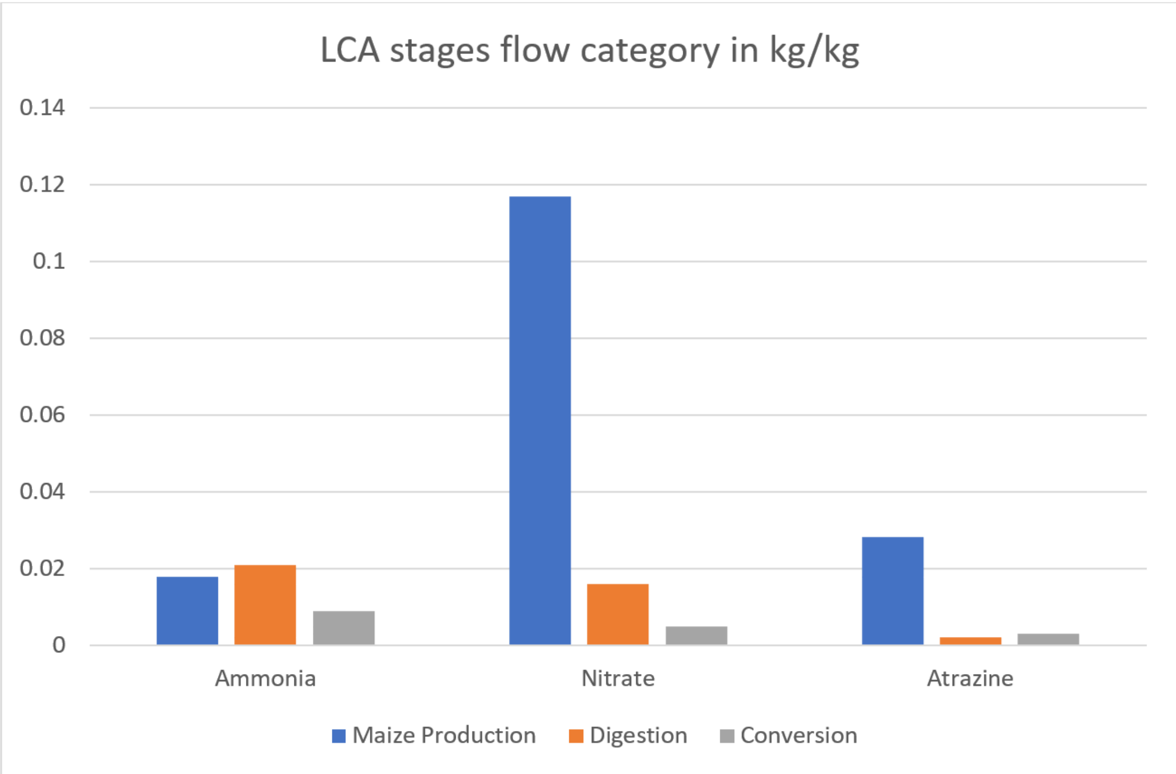

Figure 5. Flow category analysis for the production of maize compared with other LCA stages (digestion and conversion LCA stages) in kg/kg of maize silage produced.

4.3. Comparing Natural Gas Production Against the LCA Stages Impact Categories, GWP and Climate Change, and Eutrophication/Acidification

The study observed that eutrophication has the lowest impact on natural gas production, followed by acidification impacts because only the cultivation process has significant eutrophication potential compared to other biogas pathways and natural gas, respectively. Nitrate emissions are also low for the natural gas impact in this analysis compared to the biogas LCA stages. Conversely, the global warming potential (GWP) is significant across all pathways, which is an agent of climate change and automatically increases the climate potential for both biogas and natural gas processes. Natural gas production has the most significant climate change potential, followed by the maize cultivation phase in this study. The maize production stage has the lowest GWP, followed by the conversion and digestion stage processes, as natural gas production has the highest GWP and climate impact, as evidenced in Figure

6. The comparison of biogas impacts with their fossil fuel counterpart is observed in a recent study (Jan, Khan, Tahir, & Ali, 2020) where the fossil reference scored higher in the GWP than it is in this study. They also observed the same pattern in Wagner, Majer, and Wurster (2019) and Kiesel, Wagner, and Lewandowski (2017). This is an indication that fossil fuel still has more air emission environmental impacts than biogas in general, despite the high eutrophication impacts biogas has recorded. This makes biogas a better option for environmental protection.

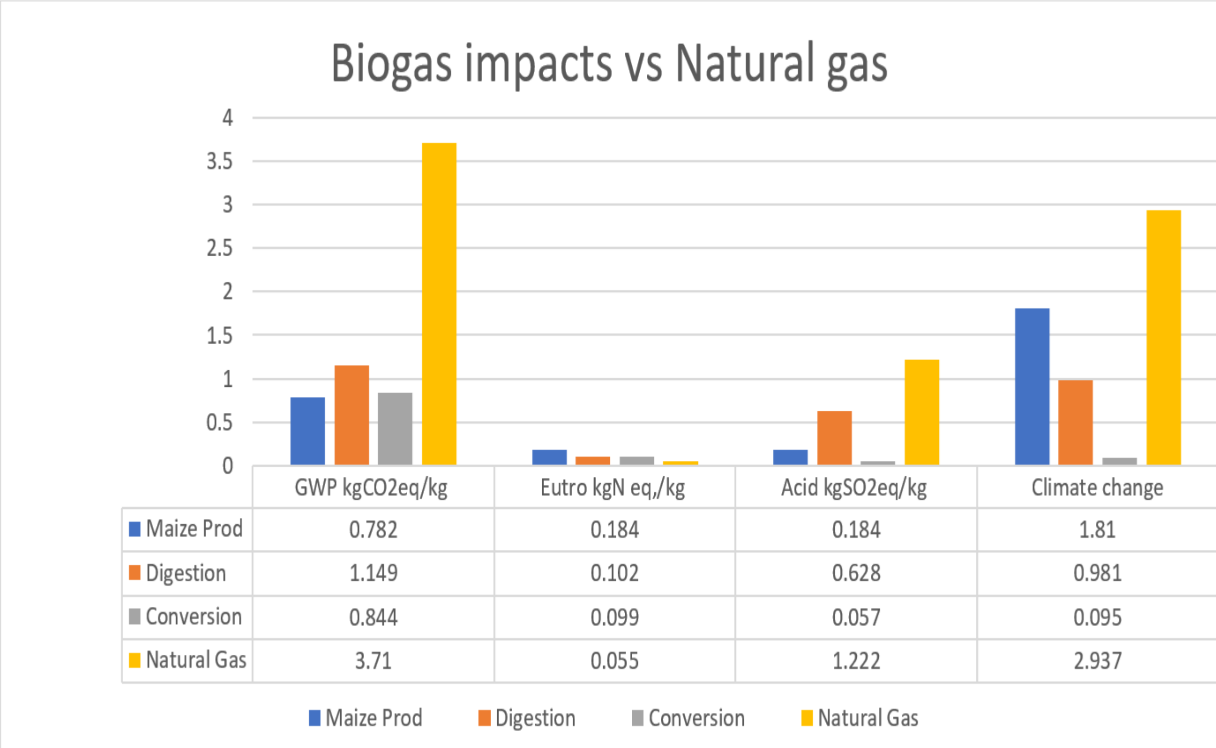

Figure 6. Impact category analysis of the three LCA stages (biogas pathway) compared to the natural gas processes.

Outlook: How are the land, air, and water ecosystems affected when switching from natural gas to biogas in Alberta?

Natural gas has a higher impact on GWP, with 3.71 kg CO_2eq/kg, and significantly contributes to climate change with a value of 2.93, as well as acidification at 1.22. It records a lesser impact on eutrophication potential, at 0.05, as seen in Figure 6, for known reasons. The production of natural gas presents the most substantial climate change potential, followed by the maize cultivation phase in this study. Conversely, the maize production stage exhibits the lowest GWP, followed by conversion and digestion processes. Generally, during the energy transition, impacts are expected to shift; air emissions will decrease, while water pollution through eutrophication may increase. However, moderate use of farm chemicals, such as 120 kg of N fertilizer per hectare, can help balance biogas production with environmental protection. Other contributors to environmental impact include emissions from methane gas leakages, which contribute to high GHG emissions and climate change impacts, as well as acidification processes that affect ecosystem services.

4.4. Land Occupation and Transformation Analysis

Due to the complexity of gathering land-use change data for LCA and its complications, many studies do not consider land-use change when assessing the environmental impacts of maize production in LCA (Changqi, Xiaoxia, & Zhenglong, 2018). However, this study finds it very important, as land occupation, transformation, and conversion have their associated challenges that can negate the positivity in bioenergy production and the entire energy transition goal (González-García, Bacenetti, Negri, Fiala, & Arroja, 2013). This study's initial results from the Eco-indicator and ReCiPe assessment methods for the land occupation impact category indicate 0.124 and 0.186 milipoints, respectively, while the third assessment method used (TRACI) does not account for a land-use impact category. The above result corresponds well with Filippa et al. (2020), Whose total single-year land-use impact from maize cultivation scored 0.155 milipoints. The percentage contribution shows that the sowing stage, tilling, and harvesting have the highest scores for both methods (Eco-indicator and ReCiPe) at 57% and 78%. This study's initial model run assumes the average of 68% for the land occupation impact category, which is in line with other studies such as Pieragostini et al. (2014), whose impact from corn seed production contributed 67% to the land use category, which is attributed to conventional tillage.

Figure 7 depicts the land use percentage contribution of maize production (cultivation) and the impact from other life cycle stages (digestion and conversion) compared to the natural gas production land transformation and occupation. The production of maize is also the most relevant process among other stages here when analyzing land-use change impact. This research adopted about 0.124 points or 68% out of 100% land use impact for the maize production stage. Meanwhile, the digestion stage scored 18% (0.019), and conversion is at 14% (0.015), using the following conversion formula: 68 of 0.155 is 0.68 multiplied by 0.155 = 0.1054; 18 of 0.019 is 0.18 multiplied by 0.1054 = 0.019; and 14 of 0.015 is 0.14 multiplied by 0.1054 = 0.015. To reduce or evade the competition between food and energy, as noted in literature (Carlsson, Mårtensson, Prade, Svensson, & Jensen, 2017; Filippa et al., 2020; Mehmood et al., 2017), scholars concluded that it is better to grow maize on abandoned land that is degraded than to acquire or cultivate new land.

This approach has the potential to reduce carbon debt and loss of biodiversity resulting from the direct clearing of farmlands on a long-term basis, as in González-García et al. (2013). Another school of thought also noted that the arable land occupation for maize cultivation is responsible for the 94% contribution of the land competition; according to Jan et al. (2020), the intensification of land already in use has 65% of land transformed from other uses into cropland is at 34%. Malgorzata, Van Der Hilst, and Faaij (2017) analyzed land use for maize production in Poland and other EU countries.

They reported land-use indicators as 0.141 and 0.146 ha t per annum for the country (Poland) and the continent of Europe, respectively. Another researcher reported land use and climate change results as having a 100% impact on the environment and added that because the category results are expressed in different units, their results cannot be compared with each other. This 100% is the highest result in a given benchmark category. Chłopek and Samson-Bręk (2017) and Vera, Schippers, Hedrich, and Sand (2022) mentioned that using land to produce dedicated energy crops increases food prices, but it is difficult to determine all other impacts on both food supply and land use.

The average percentage obtained from the ReCiPe and Eco-indicator methods is compared with the digestion and conversion life cycle stages, as well as with the land occupation associated with natural gas production, to test the sensitivity of each stage in different model runs with varied input values.

Additionally, understanding the use of land for crops is very vital as population growth and increased demand for energy come with an inevitable need for more land occupation and transformation. The land-use change analysis comprises the environmental impacts of reshaping, occupying, transforming, and managing land that lead to its deterioration and degradation from its original naturalness. For the above reason, land use is at the heart of a few scholars focusing on energy crops for biogas systems, Hijazi, Munro, Zerhusen, and Effenberger (2016), as it is in this study too.

Outlook: Figure 7 depicts the land use percentage contribution of the biogas pathways compared to natural gas production land transformation and occupation. The cultivation stage recorded 68% or 0.124-0.186 milipoints, averaged to 0.155 milipoints, digestion at 18% (0.019), and conversion at 14% (0.015). To safeguard the Albertan land ecosystem and its services, and to reduce competition between food and energy systems that could occur in the future, decision-makers and stakeholders should encourage reusing already used land for cultivation. When this is achieved, the land use impact would reduce by half when switched to biogas as an energy source.

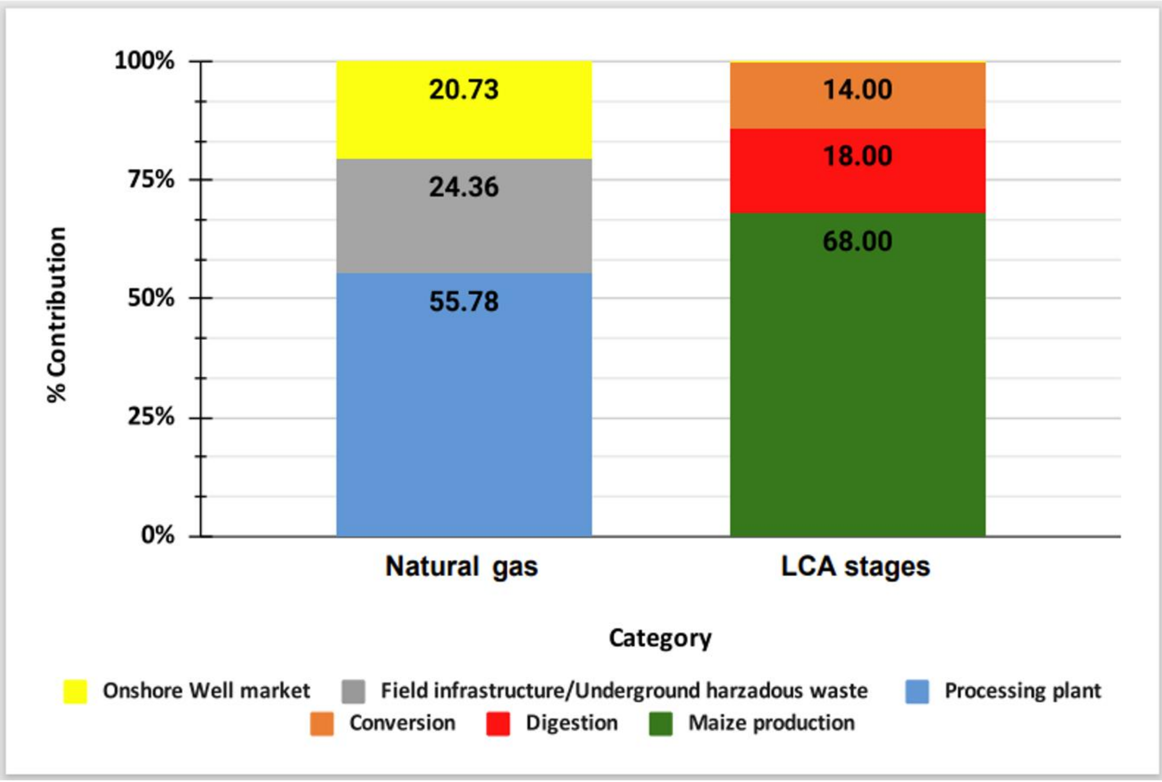

Figure 7. Land use percentage contributions for maize production, digestion and conversion compared with the natural gas processes.

For the digestion and conversion stages, the land occupation impacts are lesser than those of the maize cultivation stage, as seen from Figure 7 above, because, at this stage, the land is mostly used for building sheds and the anaerobic digestion/conversion plant construction, which is not land-intensive. In addition, the natural gas exploitation process and the building of the gas production plant (for sweetening and purification) after the exploration activities or (seismic operations) on the ground require land surface but not as much as maize cultivation does.

5. DISCUSSION AND LIFE CYCLE COSTING

This case study has examined the total supply chain impact of producing 1 kg of maize silage, processing it through anaerobic digestion, and converting it into heat and power for further use. The result is compared with the fossil natural gas emissions in Alberta, Canada. The final result shows that maize production has more impact during the cultivation stage compared to other life cycle stages assessed for land use and eutrophication potentials. Emissions from fertilizer and pesticide components are the major contributors to this analysis, especially emissions from drying CO_2 and other support activities (nutrient supply, market for pesticides) that consume fossil electricity as seen in the model output graph. To account for these quantifiable emissions, the mode of application, climatic conditions, and the ecosystem service of the cultivated area are considered. Although it is not very easy to get these data when conducting an LCA in detail (Fusi, Bacenetti, Fiala, & Azapagic, 2016). It is assumed that a good percentage of the applied farm chemicals components (fertilizer and pesticides) are retained in the soil. For instance, out of the 100% total quantity applied, the plants use up 45%, and the rest of the 55% is washed down to the nearby water body, which will have a more adverse effect. This assumption has also been made by other scholars, such as Fantin et al. (2015) and Falcone et al. (2015), as this has also been recommended by Curran (2012).

As mentioned above, this study estimated that the highest environmental impacts are experienced during the maize production process, especially for the nitrate being an agent of eutrophication, as illustrated in Figure 6 with the title (flow category analysis for the production of maize compared with other LCA stages). Also, similarly recorded by Abbas et al. (2021), who studied sustainable corn farming. The overall assessment and the sensitivity analysis result, as well as the input manipulations for the fertilizer, show that the largest impacts arise from its production and extreme use as reported in previous studies such as Sadeghi, Noorhosseini, and Damalas (2018) and Kiesel et al. (2017). However, drying of the maize silage plays a significant role in this study due to its excessive use of electricity during this operation, as compared to other studies such as Abbas et al. (2021), whose irrigation processes played a greater role in environmental damage when maize is used as an energy feedstock. Yeebiyo et al. (2016) estimated Alberta's biomass resources at 458 PJ, whereas agricultural biomass, of which maize silage is included, ranks as the most reliable for the energy transition. They added that about 39-40 percent of the province's heat supply from fossil fuels could be substituted with biomass resources, which can help in climate change mitigation and adaptation plans.

This study has assessed the overall (upstream and downstream) impact of feedstock production and the use of nitrogen fertilizer as one of the essential nutrients for plant growth. Additionally, the provision of this fertilizer and other plant-protective chemicals are energy-intensive, thus leading to fossil fuel emissions that decision-makers need to be aware of. This will facilitate proper energy transition legislation in favor of environmental protection and sustainability as introduced in the Brundtland report of 1987, cited in Marwa, Njalika, Ruganuza, Katabalo, and Kamugisha (2018). The high values from fossil emissions are expected in this research because Canada is an oil-rich country with a lot of oil exploration and exploitation activities going on in the boreal forest of the province of Alberta (Hebblewhite, 2017). The TRACI method, which was originally developed by the US Environmental Protection Agency to serve as a guide to sustainability practitioners, focuses more on US regulations and policies. TRACI is not sufficient to be used alone for this analysis since it lacks data on land transformation and occupation that exist in the eco-indicator method. Land resources are not only an important element for ecosystem impact assessment, but they are also one of the first requirements for the cultivation of bioenergy crops, in this case, maize. Eco-indicator is one of the widely used assessment methods in LCA, as mentioned in Homagain et al. (2015) and Cavalett et al. (2013), to evaluate endpoint results. This study made a valuable and useful highlight of some research gaps which have been fulfilled in this project and has proposed further steps for improvement and the integration of LCIA results into an ecosystem services valuation and tradeoffs model (InVEST) and vice versa. Moreover, the more the environmental impacts are assessed even before deployment (for instance, impact on human health or ecosystems), the more the benefits (Boschiero, Cherubini, Nati, & Zerbe, 2016; Gu & Bergman, 2017; Maier, Sowlati, & Salazar, 2019).

Addition of life cycle costing (economics) to all the LCA stages to assess the monetary value of each.

For a more inclusive and holistic LCIA, it will be necessary to include a life cycle cost analysis (Whole-life costing) in the overall goal of achieving a comprehensive life cycle impact assessment, since renewable energy development cannot be completely isolated from the economic improvement of a nation. This is because economic activities play an important role in production (Neugebauer, Forin, & Finkbeiner, 2016) and, usage of goods and services of which biogas is one of them. The cost of each LCA stage will generate the economics involved, for example, the cultivation stage being the most impactful stage for eutrophication. Implementing a life cycle cost analysis will not only yield monetary value but will also trigger a culture of conserving the environment more independently by the heavy emitters. Additionally, suppose an individual knows the ecosystem services cost implication of using electricity from biogas beforehand. In that case, it will inform his decision on the actual cost of his energy demand, both environmentally and economically. The life cycle costing analysis can be carried out in the same way the environmental impact or endpoint analysis has been performed in this study. However, the LCA method to be chosen is the LCC (life cycle costing) instead of the Eco-indicator used as the life cycle impact assessment method in this open framework. This is after creating the flows, product system, and process, connecting them to the cost impact category result (Duyan & Ciroth, 2013). The findings suggest that optimizing fertilizer use and employing hybrid drying systems can significantly reduce environmental impacts. Policymakers should consider these strategies to enhance the sustainability of biogas production. Future research should focus on refining LCA models and incorporating comprehensive datasets to better capture the complexities of agricultural systems.

5. CONCLUSION AND RECOMMENDATIONS

This study's LCIA presents results from (Eco-indicator, ReCipe, and TRACI) combined methods using the openLCA tool. The analysis of maize silage production for biogas generation, compared to natural gas production, reveals several key findings. The stage of cultivation acts as a major contributor to emissions, especially in terms of eutrophication and ammonia release. Furthermore, the comparison with natural gas production showcases the environmental benefits of biogas despite higher eutrophication potentials. Biogas production is seen as a better sustainable option compared to fossil fuels, as it has lower overall global warming potential and climate change impacts. However, it is crucial to consider the complexities of land use change in the analysis, despite inherent limitations in data availability and modelling. Reusing already cultivated land and adopting sustainable land management practices can mitigate the environmental impact of energy crop cultivation.

However, despite the comprehensive analysis carried out in this study, data availability, especially regarding land use change, poses challenges to the accuracy of the results. Prospects for future research include refining modeling techniques to better capture the complexities of agricultural systems and land use dynamics. Incorporating more comprehensive datasets and conducting field studies to validate model outputs can enhance the reliability of LCA results. Overall, this study highlights the importance of considering the full lifecycle impacts of energy production and the need for holistic approaches to environmental management in energy transitions. By addressing these challenges and leveraging emerging technologies, we can move towards a more sustainable energy future while preserving critical ecosystems. Biogas production from maize silage presents a viable alternative to fossil fuels, with lower global warming potential despite higher eutrophication impacts. Sustainable practices, such as optimized fertilizer use and hybrid drying systems, are essential for maximizing environmental benefits. These findings support the integration of biogas into Alberta's renewable energy strategy

5.1. Recommendations

Since fertilizer production, its application, and the maize silage drying process contribute significantly to the assessed LCIA processes, (the maize silage is dried with electricity generated from natural gas in Alberta currently). Therefore, this study recommends that maize silage be dried in summer using a biogas and natural gas mix (hybrid) to reduce fossil fuel emissions from electricity. The use of bio-manures from waste products and/or forest residues is recommended instead of solely synthetic fertilizer during the planting stage to reduce environmental impacts associated with conventional fertilizer use as manure. Implementing a life cycle cost analysis to determine the monetary value of each emission and foster a culture of environmental conservation is highly recommended.

Moreover, the production of energy from alternative technologies powered by biomass sources is expected to play a major role both now and in future energy systems. Therefore, it is imperative to examine the environmental implications of alternative energy technologies, considering that the impacts vary depending on location, source, and type of technology, particularly regarding GHG emissions related to climate warming. To date, detailed assessments of the benefits and costs of alternative gas production technologies, with a focus on Albertan current and future biogas maize production, especially concerning eutrophication challenges, GHG emissions, and potential environmental (land-use) impacts, have remained scarce. This study addresses this knowledge gap by utilizing life cycle assessment as the modeling tool. The findings help quantify and inform public (stakeholder) perceptions and the heterogeneity of preferences for alternative energy generation pathways within the context of a sustainable environment. In conclusion, biogas systems can contribute to decarbonizing regional fossil energy grids, and drying of silage can be carried out in summer using a mix of biogas and natural gas to reduce CO_2 impacts. We propose the moderate use of farm chemicals to balance bioenergy development with environmental prosperity. The project is particularly unique as it explicitly states the environmental impacts of maize silage biogas production beyond CO_2 emissions, which is scarce in Alberta, Canada. It emphasizes the need to reduce excessive greenhouse gas emissions, land conversion, and nutrient runoff through biogas production and other energy transition activities that have the potential to increase global warming, damage water ecosystems, and land resources, especially in Alberta, which has not yet been thoroughly researched or published.

The research recommends the integration of the ecosystem services modelling tool (InVEST) and the LCIA to provide spatially explicit, resolved solutions in the following steps.

5.2. Integrating LCIA Output Data of This Study into the InVEST Ecosystem Services Model and or Vice Versa

Many scientists have recently used different scientific processes and diverse assessment methods, such as Cavalett et al. (2013) to solve ecological problems. In some cases, multiple models are used to arrive at more accurate and concrete results in solving environmental problems, such as in Chaplin-Kramer et al. (2017) and the study carried out by Souza, Teixeira, and Ostermann (2015). The former reports that spatially explicit data from InVEST on ecosystem services could be applied to LCA in large-scale predictive modelling in their new approach called Land-use Change Improved (LUCI)-LCA. Nonetheless, due to the complications and the problematic nature of this integration, authors mostly identify major gaps in analysing ecosystem services within the LCA framework and provide recommendations on how to tackle methodological challenges (Rugani et al., 2019) instead of performing the standard LCA with the ecosystem data or vice versa. This research found that LCIA outputs could be simulated in the InVEST nitrate delivery ratio (NDR) model, specifically for the eutrophication potential, which is a major ecological problem for water ecosystems pertinent to maize cultivation globally. The data needs to first appear in a spatially explicit form (e.g., vector, raster, shp, or tiff files readable in ArcGIS) to be able to work well in the ecosystem model (InVEST). One other possible and novel way would be to run OpenLCA with the NDR model details found in Kalu et al. (2021) for fertilizer, herbicide, and pesticide nutrients being the major farm chemicals that contribute to eutrophication during maize cultivation processes both in Alberta and globally. The output result of this simulation (in numbers) can now be fed into the InVEST NDR model for the Subsurface Critical Length (Nitrogen) and Subsurface Maximum Retention Efficiency (Nitrogen) inputs. By way of description, these two data show how critical and the maximum nitrate is delivered and retained in the water ecosystem at a particular time and area. This process of (integrating the LCA values into the InVEST NDR) will give an estimate and interpretation of the number of nutrients retained in water or underground water with its eutrophication potential when 1kg of maize silage is produced. The outcome will aid policy decision-making to reduce some farm chemicals' excessive use and maintain environmental sustainability. It is important to note that only the Subsurface Critical Length (Nitrogen) and the Subsurface Maximum Retention Efficiency (Nitrogen) data are not enough to perform the simulation in the InVEST NDR model. However, the following data (DEM, Land Use, Nutrient Runoff Proxy, Watersheds, Biophysical Table, Threshold Flow Accumulation, and Borselli K Parameter) are also needed, of which a default value for the study area of Alberta, Canada can also be obtained from the Natural Capital Project site directly (the developers of the InVEST model) and used for a start. For the InVEST sedimentary delivery ratio (SDR) model run, which will give the indication of the movement of soil and its debris down the slope (erosion) when maize is cultivated, the following data are needed: the land use land cover map of Alberta, which helps to determine different land use systems currently available in the area; rainfall erosivity index raster file (tiff); soil erodibility maximum SDR value; and the Borselli IC0 parameter. Once the data is obtained and inputted into the InVEST model, the result can now be viewed and arranged in the ArcGIS tool for visual presentation. The SDR data will indicate the extent to which land use has changed due to maize cultivation and can be reported as the land use impact category of the LCA. The implementation of the integration steps will provide spatially explicit data for better decision-making processes.

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Competing Interests: The author declares that there are no conflicts of interests regarding the publication of this paper.

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