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Life Cycle Analysis of Bioethanol Production from Fermentation of Pyrolysis Gas

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Abstract

As the effects of climate change continue to intensify and the need for clean energy sources grows, the production of bioethanol from synthesis gas is presented as a common solution. Synthesis gas is composed of a mixture of gases such as CO, CO2, H2, and NOx, which contribute to air pollution, and certain Clostridium species can metabolize these gases for bioethanol production. Bioethanol is a highly important biofuel among renewable energy sources due to the advantage of being directly usable when mixed with gasoline. The pyrolysis process offers a significant alternative to the costly pretreatment methods used for utilizing waste and lignocellulosic raw materials in bioethanol production. In this study, the environmental impacts of bioethanol production from pyrolysis gas using pure Clostridium ragsdalei culture and mixed species will be compared through a life cycle analysis. The functional unit of the study has been defined as the production of 1 g of bioethanol. The impact categories to be examined in the study are climate change impact (carbon footprint), acidification, eutrophication, and ozone depletion.

Keywords: renewable energy, climate change, carbon footprint, synthesis gas, bioethanol

1. Introduction

Growing concerns about climate change have spurred research into sustainable, and renewable alternatives to fossil fuels. The demand for clean, environmentally friendly energy sources is becoming increasingly urgent, emphasizing the need to develop effective and long-term solutions. Biofuels represent one of the most promising sustainable alternatives to fossil fuels. The development of next-generation biofuel technologies has focused on enhancing production yield and process efficiency while minimizing waste generation (Sikuru et al., 2024). Biofuels can be produced through biochemical or thermochemical processes, each leading to different forms of energy. Biochemical processes have drawn significant attention due to their potential for sustainable biofuel production (Okoro et al., 2022). Bioethanol is the most widely utilized biofuel (Jayakumar et al., 2023), which is typically produced through the microbial fermentation of sugars derived from lignocellulosic biomass. Prior to the fermentation process, lignocellulosic biomass requires pretreatment methods such as hydrolysis, which break down complex structural components and significantly enhance fermentation efficiency. However, even with proper pretreatment, conversion of lignocellulosic biomass is not fully completed; a huge amount of residual waste - consisting of recalcitrant components such as lignin- remains, resulting in an environmental challenge. Apart from the biochemical routes, one of the most widely applied thermochemical conversion methods for lignocellulosic biomass is pyrolysis, which generates biochar as a solid product, with liquid and pyrolysis gas as byproducts. The aqueous phase of liquid product, commonly known as wood vinegar, possesses potential in agricultural uses (Zhang et al., 2020). The gaseous phase, referred to as pyrolysis gas, mostly consists of CO_2, CO, and trace quantities of hydrocarbons, with its composition varying according to the process conditions. Pyrolysis gas can be further employed in syngas fermentation. Syngas fermentation an innovative microbial process that transforms CO, CO_2, and H_2 into bioethanol. Recent studies focus on the utilization of waste gas streams such as industrial flue gases, synthesis gas derived from biomass or municipal solid waste, and steel mill off-gases as sustainable feedstocks for syngas fermentation (Khanongnuch et al., 2022). Pyrolysis gas can be also converted into ethanol (and other alcohols) and acetates by pure culture such as *Acetobacterium woodie* and the clostridial strains such as *Clostiridium ljungdahlii, Clostridium autoethanogenum, Clostridium ragsdalei* (Manna et al., 2024 Abubackar et al., 2011) or mixed culture such as wastewater sludge (Owoade et al., 2023). Since clostridial microorganisms are strictly anaerobic, pyrolysis gas may be a better alternative to gasification derived syngas, as pyrolysis-gas lacks oxygen (Manna et al., 2024).

The integration of pyrolysis and syngas fermentation provides a sustainable route for the simultaneous production of biochar and bioethanol, minimizing residual waste and improving overall process efficiency. Nevertheless, only a few studies have explored syngas fermentation using pyrolysis gas (Keskin and Duman, 2020; Manna et al., 2024). In our previous work, pyrolysis gas was converted into acetate and bioethanol in presence of mixed culture and found that preheating of mixed culture enhanced the bioethanol production.

To better understand the potential of an integrated pyrolysis - syngas fermentation system, it's important to carefully assess how efficiently the pyrolysis gas can be used in the fermentation process. This insight is key to improving the overall system. Life cycle assessment (LCA) is a helpful tool in this context, as it allows for an objective comparison of the environmental impact and sustainability of the integrated approach.

2. Material and Method

This research employed the Life Cycle Assessment (LCA) methodology as outlined by ISO 14040. The key phases of this approach are as follows:

(a) Goal and scope
(b) LCI (Life Cycle Inventory)
(c) Impact assessment
(d) Interpretation

2.1 Goal and Scope

The goal of this study was to use the life cycle analysis approach to compare the environmental effects of environmental impacts of bioethanol production from pyrolysis gas using pure *Clostridium ragsdalei* and mixed species. The system boundaries of this study start from pyrolysis and end with ethanol fermentation (Figure 1). The functional unit of the study is 1 g bio-ethanol production.

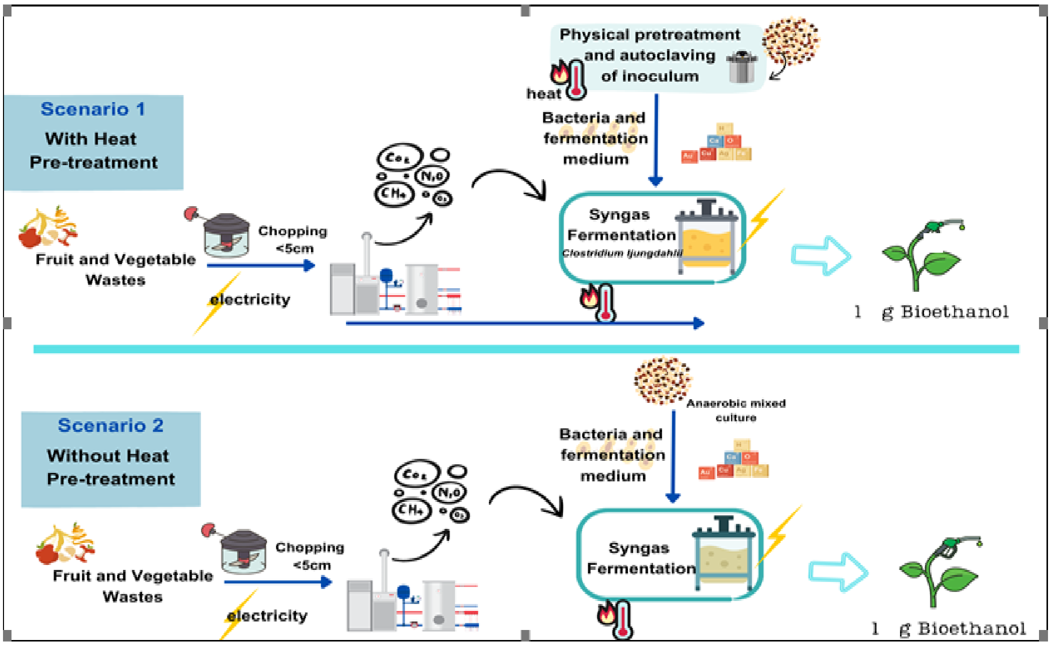

Figure 1. System boundaries

2.2 Life Cycle Inventory (LCI)

The data employed in this study were sourced from Keskin and Duman (2019). Inputs and outputs were established based on the mass balance of the products discussed in this research. In calculating the total energy consumption, both the equipment utilized for energy consumption and the duration of its use were considered. Table 1 illustrates the inputs and outputs for the various scenarios.

Table 1. LCI of the study

Pyrolysis	
Electricity	0,015 kWh
Temperature	500 °C
Heating rate	10 °C/min
Residence time	1 hour
Yield (% w/w)	
Biochar	31.2 %
Liquid (considered as wood vinegar)	39.7%
Gas (total)	39.1%
CO_2	30.7 %
CO	4.4 %
H_2	0.02%
Fermentation	
Electricity	0.025 kWh
Heat pre-treatment for inoculum	2kWh
Fermentation	

Fermentation medium	10 mL (1 L); 0.9 g NaCl, 0.4 g $MgCl_2.6H_2O$, 0.75 g KH_2PO_4, 1.5 g K_2HPO_4, 0.5 g yeast, 0.0025 g $FeCl_3.6H_2O$, 20 g bacterial pepton, 0.1 g $MnCl_2.4H_2O$, 0.006 g H_3BO_3, 0.19 g $CoCl_2.2H_2O$, 0.002 g, $CuCl_2.2H_2O$, 0.024 g $NiCl_2.6H_2O$, $NaMoO_4.2.H_2O$, 0.75 g cystein-HCl)
Bacteria	40 mL mixed culture
Water	50 ml
Heat	1,5 kwh
Electricity	0,025 kwh

2.3 Life cycle impact assessment (LCIA)

The impact categories analyzed in this study included carbon footprint, eutrophication, and acidification. The classification, characterization of effects, and the results of category changes were performed using the SimaPro 8.9.3.4 software, along with the weighting of the results. The impact analysis was integrated with the ReCiPe methodology. The selection of this software and methodology was justified by its extensive use in the life cycle assessment (LCA) of bioethanol production.

2.4 Interpretation

In this phase, the impact categories and the resulting damages were analyzed, and the primary factors contributing to the increase in impacts and damages were identified. Recommendations for enhancing or modifying the situation from a life cycle assessment (LCA) perspective were also presented in discussion.

3. Results and Discussion

A detailed understanding of the processes involved in the production of bioethanol from syngas and their environmental effects is essential. The transition to bioethanol as a sustainable energy source is primarily motivated by the necessity of decreasing carbon emissions and combating climate change. Syngas, mostly composed of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), and minor nitrogen oxides (NOx), demonstrates significant promise as a feedstock for bioethanol production via fermentation processes (Wang et al. 2023).

The research conducted by Safarian et al. (2021) highlights the success of combining biomass gasification with syngas fermentation, emphasizing the significant impact of factors such as cell recycling rate, gas flow rate, and hydrogen content on ethanol yield and gas conversion efficiency. The findings indicate that addressing these factors using system engineering principles could substantially improve the sustainability and operational efficiency of biofuel production systems.

In this study the syngas obtained from pyrolysis of fruit and vegetable wastes was used as a substrate to compare bioethanol production through mixed culture and *Clostridium ragsdalei* culture using Life Cycle Assessment (LCA). The LCA results indicated that the mixed culture yielded more environmentally friendly outcomes in the impact categories of climate change, ozone depletion, terrestrial acidification, and freshwater eutrophication (Table 2).

Table 2. The comparison of the Life Cycle Assessments of mixed culture and *Clostridium ragsdalei* culture

Impact category	**Unit**	***Clostridium ragsdalei***	**Mixed Culture**
Climate change	kg CO_2eq	0,435	0,175
Terrestrial acidification	kg SO_2eq	0,00219	0,00088
Ozone depletion	kgCFC-11eq	8,32E-09	3,36E-09
Freshwater eutrophication	kg Peq	0,000453	0,000183

In the climate change category, under laboratory conditions, 1 g bioethanol production from pyrolysis gas using mixed culture has a carbon footprint of 0.175 kg CO_2eq, whereas using *Clostridium ragsdalei* has a carbon footprint of 0.435 kg CO_2eq. In the terrestrial acidification impact category, syngas fermentation by *Clostridium ragsdalei* has an impact of 0.00219 kg SO_2eq, while syngas fermentation by mixed culture has an impact of 0.00088 kg SO2eq. In the ozone depletion impact category, the values using *Clostridium ragsdalei* and mixed culture are 8.32E-09 and 3.36E-09 kgCFC-11eq, respectively. For freshwater eutrophication, the values are 0.000453 kg Peq for using *Clostridium ragsdalei* and 0.000183 kg Peq for using mixed culture. The reason for using mixed culture being more environmentally friendly under laboratory conditions is interpreted as the higher yield produced compared to using *Clostridium ragsdalei*. Using mixed culture, 5.4 g of bioethanol was produced with 5 mL of syngas feeding, while 2.5 g of ethanol was produced with 10 mL of syngas feeding under the same energy consumption.

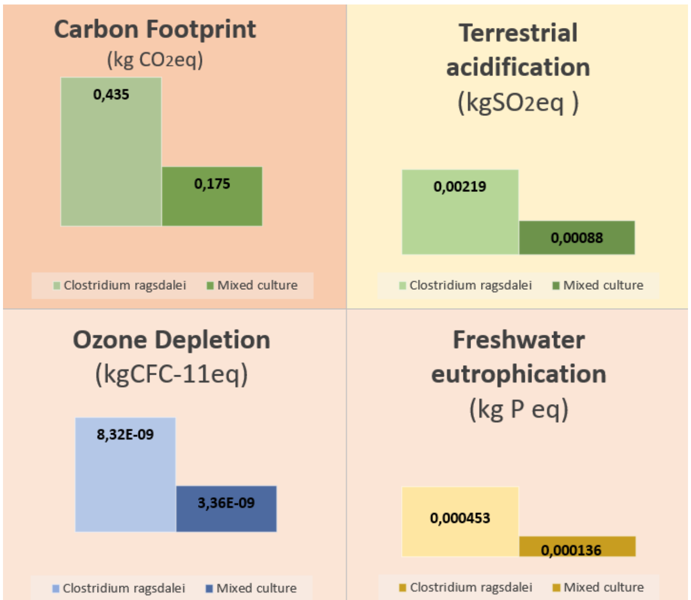

Figure 2. Comparison of Environmental Impact Categories between Mixed Culture and *Clostridium ragsdalei* Culture

Within the system boundaries, the process, starting with pyrolysis and the use of syngas as a substrate for bioethanol production, identified the fermentation phase as the point of highest emissions. In the case of bioethanol production with *Clostridium ragsdalei*, 85% of the emissions were attributed to the incubation heating process, while 90% of the emissions from using mixed culture were due to the heating process during ethanol production. The study conducted by LanzaTech, they analyzed the total greenhouse gas emissions resulting from ethanol production. GHG emissions for the first waste gas option were quantified as 0.0314 kg CO_2-eq/MJ, while for corn stover, switchgrass, and forest residues, emissions were estimated as 0.008, 0.012, and 0.015 kg CO_2-eq/MJ, respectively. According to the results of the study, service consumption (electricity and steam) accounted for a large portion of the greenhouse gas emissions in the ethanol life cycle, while other inputs to the process (nutrients, chemicals, water) contributed relatively little. The total emissions presented in this study resulted in a 67% reduction in emissions compared to the life cycle greenhouse gas emissions of petroleum gasoline (Handler et al., 2016). The energy requirements show the importance of energy input choices in the LCA framework; managing these factors can significantly reduce ecological footprints. Studies on energy consumption patterns in bioethanol production is needed for innovative processes that reduce energy input without reducing output quality (Biró & Csete, 2023). Furthermore, the selection of materials, energy sources, and operational methodologies has been shown to significantly influence LCA outcomes across various production contexts (Biró & Csete, 2023).

As can be seen from Figure 2, the fermentation efficiency of varying microbial cultures significantly influences greenhouse gas emissions, which aligns with findings from LCA studies that evaluate biofuels derived from various biomass sources (Angili et al., 2021). Moreover, optimizing microbial selection could broaden ecological and health impact assessments, leading to improved biotechnological approaches in bioethanol production (Nikolić et al., 2019). Long and Liu (2023), used machine mearning (ML) models for the prediction and optimization of bioethanol production. The optimization models showed an 18% improvement compared to the highest yield (0.41 g/g) in the dataset. ML models (prediction and optimization algorithms) were further integrated with the LCA model (GREET1) to increase ethanol yield and reduce greenhouse gas (GHG) emissions for target feedstocks. This resulted in a 6% and 19% improvement in ethanol yield and a reduction of approximately 8% and 14% in GHG emissions for grass and corn stover, respectively (Long and Liu). These data demonstrate that by modeling the yield parameter using machine learning in future studies, the environmental impacts of the processes can be reduced.

Qian et al. (2024) performed a comprehensive life cycle assessment and techno-economic study focused on wood-based biorefineries to produce cellulosic ethanol. Their findings demonstrate the need to comprehend both the environmental effects, including greenhouse gas emissions and resource utilization, and the economic feasibility of different bioethanol production methods. Such studies are crucial for determining policy decisions and investment plans in renewable energy sectors (Qian et al., 2024). Following on these points of view, the study by Wang et al. (2023) examines the broader implications of life cycle effects related to greenhouse gas emissions from bioethanol-derived jet fuel. They offered insights into energy consumption patterns and emissions along the production cycle, emphasizing that bioethanol, when incorporated into more complex fuel production processes, can substantially reduce the carbon footprints linked to fossil fuels. This strategy effectively corresponds with international goals to shift towards cleaner energy sources while addressing urgent climate issues (Wang et al., 2023). Pati et al. (2023) performs an integrated techno-economic evaluation, assess investment risks, and do a life cycle study of lignocellulosic biomass valorization using co-gasification and syngas fermentation processes. They highlighted the economic viability and scalability of syngas fermentation with agricultural waste, demonstrating how localized approaches can enhance energy independence and address climate change mitigation (Pati et al., 2023). In this study, bioethanol production was not directly obtained from waste products. Production was achieved using syngas generated from the pyrolysis of waste fruits and vegetables. This approach actually avoided the need for enzyme pre-treatment or acid-base pre-treatments, which could have contributed a significant GHG burden. The studies have shown that enzymatic pre-treatments in bioethanol production result in different GHG emissions depending on the enzyme used (Konti et al. 2020).

González-García et al. (2019) reported that 20% of the greenhouse gas emissions produced throughout the entire life cycle of bioethanol from a brewery waste-based biorefinery were attributed to the enzymes and chemicals required (González-García et al 2019). In another study it was reported that the enzyme contribution to the Global Warming Impact (GWI) of ethanol-producing biorefineries varied between 11% and 62%, due to the high variability in the reported GWI of enzymes, different enzyme loadings, and ethanol yield Papadaskalopoulou et al 2019).

It has been observed that most studies focus on Global Warming Potential (GWP). However, there are fewer studies on the other three impact categories. Approximately 80% of the reviewed articles reported that, despite the reduction in global warming potential, bioethanol production increases the impact on acidification, eutrophication, and photochemical oxidant formation (Angili et al., 2021). In a study where bioethanol was produced from cattle manure, 18 different impact categories were examined. Accordingly, the following results were found: freshwater eutrophication 7.72E-04 kg P eq, climate change 1.51E+00 kg CO_2 eq, terrestrial acidification −2.11E-01 kg SO_2 eq, and ozone depletion −7.77E-07 kg CFC-11 eq. When compared to results in this study, it was observed that in the climate change and freshwater eutrophication categories, the impact values for *Clostridium* and mixed culture were higher compared to the study, whereas in the terrestrial acidification and ozone depletion categories, *Clostridium* and mixed culture showed more environmental impacts. This was attributed to the different steps in the process and the use of different substrates. In this study, the most significant emission source for each category was found to be electricity usage during fermentation, whereas in the study with cattle manure, the most significant emission points were the drying step for the climate change category, phase separation for ozone depletion, acid pre-treatment for terrestrial acidification, and enzymatic hydrolysis for freshwater eutrophication (Azevedo et al., 2017). In summary the selection of the correct microbial culture and substrate to maximize bioethanol production from syngas is of considerable importance. In this study using mixed culture showed promising results for bioethanol production. Life Cycle Assessment (LCA) results can also be used for evaluating the environmental impact of syngas fermentation using different microbial cultures. The choice between pure and mixed cultures significantly influences emissions profiles, necessitating thorough analysis within the context of when (Heijungs et al., 2012).

4. Conclusion

In conclusion, Life Cycle Assessment serves a critical role as analytical frameworks to quantify the environmental impacts of bioethanol production to facilitate the identification of processes and choices that reduce ecological footprints and enhance the overall sustainability of renewable energy systems. The incorporation of modern techniques, optimum operational parameters, and comprehensive environmental evaluations establishes syngas fermentation as a significant competitor in the renewable energy sector, but the type of microorganism is a very important factor. Selecting the correct type of microorganism will be directly related to the energy needs of the process. Moreover, since the demand for effective renewable energy solutions increases, further refinement of these technologies will be crucial. Increasing production efficiency or reducing the energy needs of syngas fermentation process will reduce the environmental impacts and will help to reach objectives of sustainability and climate resilience.

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