

ENVIRONMENTAL SUSTAINABILITY OF BIOFUELS IN INDIA: AN LCA APPROACH

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by

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*Dedicated with love and gratitude to my parents,
Prof. Ramnarayan Patel and Mrs. Lata Patel*

*Your support, encouragement, and faith in me have
made this achievement possible.*

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ABSTRACT

The increasing global demand for energy, coupled with the environmental consequences of prolonged reliance on fossil fuels, has intensified the search for sustainable, renewable energy alternatives. Among these, biofuels have emerged as a promising solution due to their potential to reduce greenhouse gas emissions, enhance energy security, and support rural economies. In the Indian context, rapid industrialization, urbanization, and population growth have further increased energy demand, making the transition to cleaner fuels both an environmental necessity and a strategic priority. Bioethanol and biodiesel, as liquid biofuels compatible with existing infrastructure, have gained significant attention; however, their environmental sustainability varies considerably depending on feedstock selection, production processes, and regional conditions. Therefore, a comprehensive evaluation from a life-cycle perspective is essential to ensure that hidden burdens across the different stages of production and use do not offset their perceived environmental benefits. This research systematically evaluates the environmental sustainability of bioethanol and biodiesel production in India using a Life Cycle Assessment (LCA) framework. For bioethanol production, diverse feedstocks, including molasses, broken grains, agricultural residues (rice straw, corn stover, cassava straw), and municipal solid waste, are assessed. At the same time, biodiesel pathways include edible oil-based (rapeseed, palm oil, palm stearin), non-edible oil-based (jatropha), waste-derived (used cooking oil), and third-generation (microalgae) feedstocks. A cradle-to-gate approach is adopted to quantify impacts across multiple categories, such as global warming potential, resource depletion, water consumption, toxicity, and ecosystem damage, using ReCiPe 2016, IMPACT 2002+, and IMPACT World+ methods, complemented by cumulative energy demand analysis and Monte Carlo simulation to ensure statistical robustness and uncertainty characterization. The results demonstrate that environmental performance is strongly feedstock-dependent across both biofuel systems. In bioethanol production, global warming impacts range from 3.3 to 3.8 kg CO₂ eq, with significant contributions from ecotoxicity categories (up to 7.21 kg 1,4-DCB eq), largely driven by energy-intensive stages such as pre-treatment, enzymatic

hydrolysis, and distillation. First-generation pathways, such as molasses and grain, exhibit moderate impacts but are heavily influenced by electricity and steam consumption, whereas second-generation feedstocks, such as agricultural residues, demonstrate comparatively lower impacts and improved resource efficiency due to waste valorization. However, MSW-based bioethanol exhibits poor energy performance ($NER = 0.48$, $NEV = -47.39$ MJ, $NRnEV = -23.63$ MJ) despite its circular-economy advantages. In biodiesel systems, substantial variation is observed across feedstocks, with palm oil and microalgae exhibiting the highest environmental burdens (5.92 and 5.89 kg CO₂ eq, respectively), primarily due to intensive agricultural inputs and energy consumption during cultivation and processing. In contrast, waste-derived biodiesel from used cooking oil demonstrates the lowest impacts and minimal fossil resource use (0.15 kg oil eq), indicating strong environmental and circularity benefits. Non-edible feedstocks such as jatropha have moderate impacts, whereas rapeseed biodiesel has relatively higher burdens due to fertilizer-intensive cultivation practices. These findings highlight that feedstock selection is a critical determinant of sustainability outcomes in biodiesel production. Energy analysis further reveals that most agricultural residue-based bioethanol systems are energy-positive, with NER values up to 4.19 and NEV values around 32–33 MJ, indicating favorable net energy gains and reduced dependence on fossil fuels. Similarly, biodiesel from UCO demonstrates superior energy efficiency ($NER = 5.49$) and a lower cumulative energy demand than conventional feedstocks. Across both biofuel systems, key environmental hotspots include electricity consumption, steam generation, fertilizer use, and chemical inputs, emphasizing the need for process optimization and integration of renewable energy sources. Uncertainty analysis indicates low to moderate variability across most impact categories, with coefficients of variation generally between 4% and 10%, confirming the robustness and reliability of the model outputs. The probabilistic distributions follow near-lognormal behavior with well-defined confidence intervals, although higher variability is observed in toxicity-related categories, reflecting sensitivity to input parameters and underlying assumptions. The comparative assessment highlights that second-generation and waste-derived biofuels consistently outperform first-generation systems in environmental and energy performance, whereas third-generation pathways, such as microalgae, require further

technological advancements to reduce their energy and nutrient intensity. From a policy perspective, the findings support the promotion of non-edible and waste-based feedstocks, improved process efficiency, and the integration of renewable energy within biofuel production systems. In conclusion, this study provides a comprehensive, quantitative evaluation of the sustainability of bioethanol and biodiesel in India, demonstrating that their environmental performance is shaped by a complex interplay of feedstock characteristics, production technologies, and energy inputs. The integration of LCA, energy analysis, and uncertainty assessment provides a robust decision-support framework for identifying critical hotspots and guiding the development of sustainable biofuel systems aligned with climate mitigation, resource efficiency, and circular-economy objectives.

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List of Abbreviations

1G	–	first generation
2G	–	second generation
3G	–	third generation
AGTP	–	absolute global temperature change potential
AGWP	–	absolute global warming potential
CED	–	cumulative energy demand
CGTP	–	cumulative global temperature change potential
CoV	–	coefficient of variation
DALY	–	disability-adjusted life years
EBP	–	ethanol blended program
f.u.	–	functional unit
FAME	–	fatty acid methyl esters
FEP	–	freshwater eutrophication potential
FExP	–	freshwater ecotoxicity potential
FFA	–	free fatty acid
FPMF	–	fine particulate matter formation
FRS	–	fossil resource scarcity
GHG	–	greenhouse gas
GTP	–	global temperature change potential
GWP	–	global warming potential
HCT	–	human carcinogenic toxicity
HNCT	–	human non-carcinogenic toxicity
IPCC	–	intergovernmental panel on climate change
IRP	–	ionizing radiation potential
ISO	–	international organization for standardization
LCA	–	life cycle assessment
LCI	–	life cycle inventory

LCIA	–	life cycle impact assessment
LU	–	land use
MCS	–	monte carlo simulation
MEP	–	marine eutrophication potential
MExP	–	marine ecotoxicity potential
MJ	–	megajoules
MRS	–	mineral resource scarcity
MSW	–	municipal solid waste
NER	–	net energy ratio
NEV	–	net energy value
NRnEV	–	net renewable energy value
ODP	–	ozone depletion potential
PDF	–	potential disappeared fraction
Rn	–	renewability
SD	–	standard deviation
SDGs	–	sustainable development goals
SEM	–	standard error of the mean
SETAC	–	society of environmental toxicology and chemistry
TAP	–	terrestrial acidification potential
TExP	–	terrestrial ecotoxicity potential
UCO	–	used cooking oil
WC	–	water consumption

CHAPTER 1

INTRODUCTION

The environment is a shared heritage connecting all of humanity, transcending boundaries and generations. Reflecting our actions and aspirations, it serves as a testament to progress and a reminder of our responsibilities. Protecting this fragile balance is imperative to ensure the resources and beauty we enjoy today remain for future generations. Biofuels offer a unique opportunity to align growth with ecological care, reinforcing a commitment to a future where development and environmental stewardship go hand in hand. However, the journey toward sustainable biofuel adoption presents challenges. From feedstock cultivation to production, distribution, and use, the environmental impact must be holistically assessed. A Life Cycle Assessment provides a vital lens to identify areas for improvement and ensure true sustainability. In India, with its diverse resources and socio-economic complexities, such an approach is crucial for balancing energy needs with environmental preservation. By doing so, we can foster a future where innovation, inclusivity, and ecological harmony converge. This not only supports India's energy transition but also empowers rural economies, strengthens energy security, and addresses global challenges like climate change. Ultimately, sustainable biofuel systems can set a global precedent for harmonizing development with environmental integrity.

1.1 Energy challenges and sustainable alternatives

Energy production and use have been related to urbanization, modernization, and industrialization in various economic, scientific, and social fields. The depletion of non-renewable fuels and the subsequent rise in greenhouse gas (GHG) emissions have become a critical problem (Fawzy et al., 2020; Osman et al., 2021). Economic development is accelerating, particularly in developing nations like India and China. These nations have now reached the stage of economic development when energy use is at its highest due to industrialization. Meeting the rising energy demand while having sustainable energy supplies for the future is thus a significant problem (Yazan et al., 2017). Between 1971 and 2024, the total energy supply worldwide increased 2.6 times, from 230 to 650 EJ. The primary energy sources for power generation in 2019 were still oil and coal, which accounted for 31% and 27% of global energy production, respectively (IEA, 2025). In 2024, the pace of energy demand growth in emerging market and developing economies declined to under 3%, compared to nearly 4% in 2023. This drop was primarily driven by a sharp slowdown in China, where demand growth was cut in half, partly due to the fading impact of its post-Covid economic rebound seen in early 2023 (IEA, 2025). India also experienced a slowdown, with growth dipping below 5%. Despite this moderation, emerging markets and developing countries still accounted for 80% of the global increase in energy demand, with Developing Asia contributing 60% of that total. Remarkably, India's energy demand growth alone exceeded the combined increase seen across all advanced economies, shown in Figure 1.1. The Intergovernmental Panel on Climate Change (IPCC) Working Group III (WG3) has identified energy systems, industry, buildings, transportation, and AFOLU (agriculture, forestry, and other land uses) as the five primary sectors responsible for global greenhouse gas emissions (Lamb et al., 2021). GHG emissions from transportation have been growing faster compared to other industries. The leading cause of GHG emissions related to transportation is the burning of fossil fuels in various modes of transport. The fuel used for transportation mainly consists of petroleum, which makes up over 90% of gasoline and diesel. Globally, transportation accounts for 15% of total GHG emissions and 23% of CO₂ emissions associated with energy consumption (Jeswani et al., 2020; Sims and Schaeffer, 2014;

Uusitalo et al., 2014), shown in Figure 1.2. Biofuels are commonly recognized as possible substitute fuels for transportation that can decrease reliance on fuels made from petroleum and help address the problem of climate change. As an alternative to conventional fuels, several feedstocks and conversion methods for biofuel have been proposed.

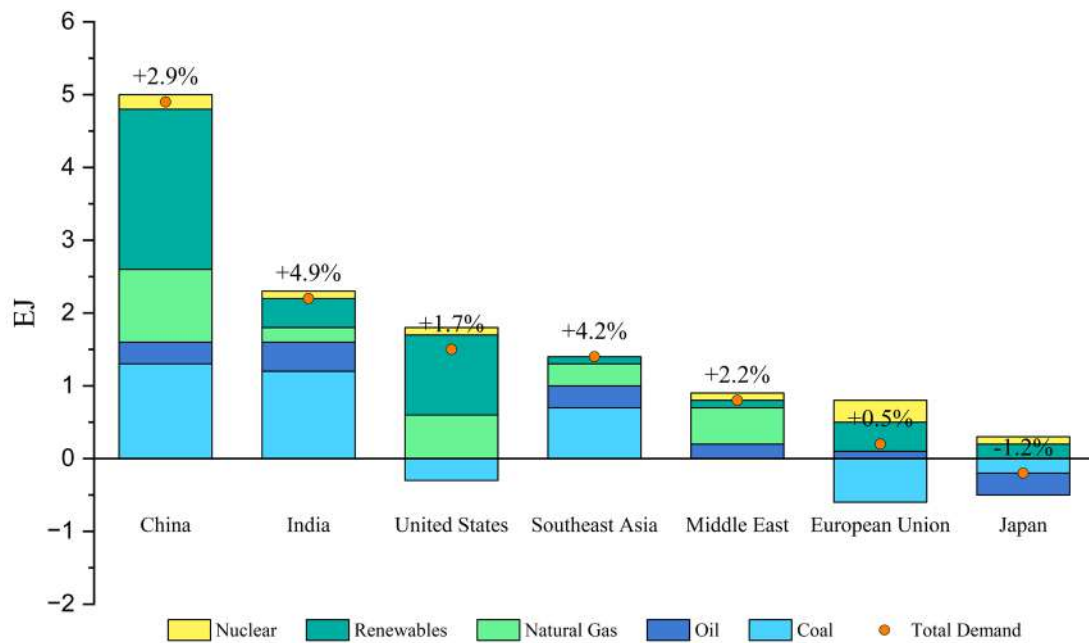


Figure 1.1 Change in energy demand in selected regions, 2023-2024 (IEA, 2025)

Biofuels refer to energy-enriched compounds derived from biomass, such as biodegradable waste or residue from forestry, agriculture, fishing, or biodegradable urban or industrial waste. The kind of feedstock, the conversion method, the technical specifications of the fuel, and its intended application are a few distinguishing factors that may be used to categorize biofuels. Different definitions for different biofuel types are in use due to the vast number of potential differences (Bharti et al., 2021). Biofuel sources are categorized into three generations of feedstock: edible energy and oil-

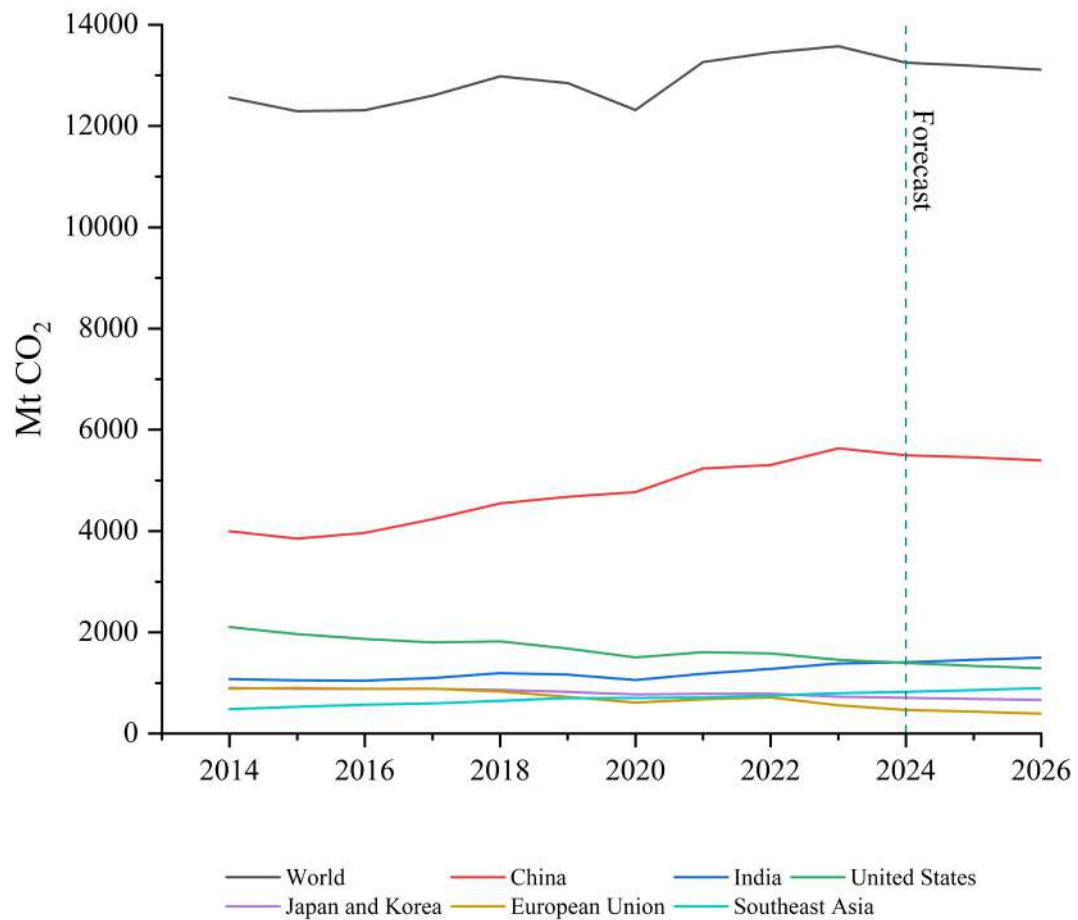


Figure 1.2 CO₂ emissions from electricity generation, 2014-2026 (IEA, 2024)

based crops (first-generation (1G)), lignocellulose-based (second-generation (2G)) (Chen et al., 2019), and algae-based (third-generation (3G)) (Kumar Sharma et al., 2021; Ocreto et al., 2021). First-generation biofuels are primarily derived from food crops through fermentation (UN Report, 2007). However, this approach faced significant criticism, particularly regarding using food crops for fuel production when food shortages were prevalent, leading to societal discontent (Ahlgren and Di Lucia, 2014). In response to these challenges, second-generation biofuels were developed, aiming to overcome the limitations of the first generation. These biofuels were produced from non-food organic sources such as crop residues, wood, municipal solid waste (MSW), and other biomass materials, thus mitigating the primary drawback (Liska et al., 2009). The third generation of biofuels explores novel biomass sources

for biofuel synthesis, including unique energy crops or species like algae (Chisti, 2007). Among renewable energy sources, bioenergy, mainly derived from lignocellulosic biomass such as wheat straw, corn stover, rice straw, and MSW, has garnered significant attention for its potential to reduce global GHG emissions (Jiang et al., 2020; Liu et al., 2022). These renewable resources hold promise as eco-friendly alternatives to environmentally harmful fossil fuels, potentially leading to the development of sustainable products (Deshmukh and Pathan, 2023; Kaparaju et al., 2009).

1.2 Current status of biofuel in India

India is now the world's third-largest producer and consumer of ethanol, with production tripling over the past five years. This rapid growth shows the country's strong potential to expand even further—provided it maintains supportive policies, keeps production costs under control, and ensures a steady, sustainable supply of feedstocks (IEA, 2024). In 2018, the Government of India introduced the National Policy on Biofuels, which set a blending target for ethanol (20% blending by 2030) and biodiesel (5% by 2030), feedstock requirements for different fuels, and laid out the responsibilities of 11 ministries to coordinate government actions (GOI, 2018). To support these targets, the government implemented several measures, including guaranteed ethanol pricing, long-term supply contracts, and the development of technical standards and regulations. Financial incentives were also introduced to help build new production facilities and upgrade existing ones. Buoyed by its success, the government revised its goals in 2022, pushing the ethanol blending target of 20% ahead by five years—now aiming to achieve it by 2025–26 under an updated version of the National Policy on Biofuels. As of March 2025, India has already achieved 20% ethanol blending with petrol, with the blend currently available at 1,350 fuel outlets across the country (ChiniMandi, 2025). The government now aims to make this blend available nationwide by October 2025. Building on this momentum, India has now set a more ambitious target of achieving a 30% ethanol blend by 2030. However, progress on biodiesel blending remains modest, with the current blend level at only 0.6%. To reach the interim goal of 5% biodiesel blending by 2023, the government estimates a

financial requirement of ₹25 billion, highlighting the need for stronger investment and policy support in this segment (BioEnergyTimes, 2025). Non-edible industrial oils like used cooking oil (UCO), animal fats, and tallows are key biodiesel feedstocks, but their supply varies, causing production fluctuations. To stabilize supply and reduce health risks from reused cooking oil, India's FSSAI launched the RUCO initiative in 2018, promoting UCO collection and conversion into biodiesel. The government supports collection centers and incentives to ensure steady biodiesel production from these feedstocks (USDA, 20225).

To achieve the 20% ethanol blending target, a diversified approach to sourcing feedstock has been critical. The current composition of feedstock supplied to Oil Marketing Companies reflects this strategy, with maize accounting for the largest share at 48.52%. This is followed by sugarcane juice, which contributes 25.56%, and B-heavy molasses at 13.61%. Additionally, damaged food grains make up 11.22% of the feedstock share, while C-heavy molasses contributes a smaller portion at 1.09%. To further enhance the sustainability and self-reliance of India's biofuel program, the government is increasingly focusing on 2G biofuels. These advanced biofuels are produced from non-food biomass such as agricultural residues, helping to avoid competition with food crops and offering a more environmentally friendly alternative. The Indian government is actively promoting 2G biofuels through the "Pradhan Mantri JI-VAN (Jaiv Indhan- Vatavaran Anukool fasal awashesh Nivaran) Yojana", which provides financial assistance and incentives for 2G bio-ethanol projects. This scheme aims to encourage the development of 2G ethanol capacity and attract investment in this sector. The government also plans to establish 2G ethanol bio-refineries and supports initiatives like off-take assurance by OMCs, ensuring a stable market for producers and boosting investor confidence. As part of these efforts, the Indian government has already established a 2G bio-refinery in Panipat, Haryana (MoP&NG, 2024). This facility utilizes cellulosic and lignocellulosic biomass, along with petrochemical routes and other feedstocks, to produce ethanol. It has a production capacity of 100 kilolitres per day. In addition, five more 2G bio-refineries are in advanced stages of construction, marking a significant step toward scaling up advanced biofuel infrastructure across the country.

1.3 Importance of environmental sustainability in biofuels

Systems for producing, converting, and supplying sustainable renewable energy must be effective and environmentally, economically, and socially sustainable for both the present and the future. Identifying biofuel sources can potentially lessen the environmental impact of fossil fuels (Balajii and Niju, 2019; Gunarathne et al., 2019). Biofuels can also help mitigate the rising fossil fuel usage and relieve dependence on non-renewable resources (Hassan et al., 2020; Peng et al., 2020). How to define sustainable biomass production is a topic of debate on the national and international levels (Kaloudas et al., 2021). First and foremost, biofuel should reduce energy use and improve energy security by relying less on petroleum-based products. Second, it must be advantageous for the environment by lowering greenhouse gas emissions, conserving diverse land uses, protecting soil productivity, water quality and quantity, and biodiversity. Third, it should not unnecessarily affect food availability and other resources while improving ecosystem functions. It should also be competitive economically and contribute more energy than it uses in production (BRDI, 2008; Munagala et al., 2022). Bioethanol and biodiesel are popular biofuels for blending with Petro-diesel to lessen reliance on traditional diesel. Bioethanol production involves converting starch or high-sugar biomass (such as sugar cane or grains) into sugar, which is then fermented and distilled. Another method for producing bioethanol or bio-oil is the hydrolysis of lignocellulosic biomass, followed by fermentation and distillation, also referred to as biomass-to-liquid (BTL). Alternatively, biodiesel can be produced by using alcohol to extract and esterify vegetable oils, discarded cooking oils, and animal fats (Foteinis et al., 2020; Sinha et al., 2013). India is attempting to embrace renewable energy sources, including biofuel, to reduce its reliance on conventional energy. Since utilizing green fuels like biodiesel and ethanol instead of traditional transportation fuels helps reduce greenhouse gas emissions, these renewable fuels are being advocated globally. Brazil is the global leader with a fleet of vehicles that uses gasoline-ethanol blends with a 27% content (USDA, 2021a). Across its fleet, the United States now uses roughly 7.1% biofuels, while the European Union (EU) has a bold ambition to use 10% renewable fuels by 2020 (EASAC, 2012). India has stepped up its efforts to achieve its objective of being

in the E-20 by Ethanol Supply Year (ESY) 2025. While maintaining its immediate objective of E-10 by ESY 2022, the Indian government stated its E-20 target year of ESY 2025 instead of 2030 (USDA, 2021b).

Building on these developments, the assessment of environmental sustainability in biofuels increasingly requires a holistic, life-cycle-based perspective to ensure that perceived benefits are not offset by hidden environmental burdens (Patel and Singh, 2023). In this context, Life Cycle Assessment (LCA) has emerged as a critical tool for evaluating the overall environmental performance of biofuels, from feedstock cultivation and processing to distribution and end use. Such evaluations help identify trade-offs between greenhouse gas mitigation and other impact categories, such as land-use change, water consumption, and eutrophication potential (Jeswani et al., 2020). Moreover, the sustainability of biofuels is strongly influenced by feedstock selection, agricultural practices, and technological efficiency, which vary significantly across regions (Pfister and Scherer, 2015). Therefore, integrating sustainability criteria into policy frameworks, technological advancements, and resource management strategies is essential to ensure that biofuel production effectively contributes to climate change mitigation, energy security, and sustainable development goals without compromising ecological integrity or socio-economic stability.

1.4 Overview of life cycle assessment for biofuels

The sustainability and benefits of biofuels are impacted by the emissions and energy used in their manufacturing process. Therefore, to accurately assess the advantages of using biofuels instead of traditional fossil fuels, it is essential to use reliable, practical, and scientific evaluation methods (Chamkalani et al., 2020; Kargbo et al., 2021). To evaluate the reductions in emissions by utilizing biofuels in India, an LCA must be performed. The LCA evaluates the complete life cycle of a product or process, including the acquisition of raw material through manufacturing, usage, and disposal, to measure its environmental impact by creating a comprehensive inventory of all the material inputs, energy consumption, and emissions associated with the product or process. The ultimate goal of LCA is to provide policymakers with a better understanding of the environmental impact by analyzing the assessment results (Soam

et al., 2015). The life cycle assessment method will light India's energy and environmental advantages of biofuel production. Understanding the GHG emission reduction that biofuels may achieve compared to their fossil fuel counterparts is crucial for guiding policy development and selecting optimal fuel choices (RAE, 2017). By calculating their carbon footprint, several studies have examined the biofuel's potential to reduce GHG emissions. However, their conclusions are sometimes contradictory because of the vast range of estimations. In order to influence future policy, the primary goal of this study is to increase clarity and knowledge of the environmental footprints of various liquid biofuels. The study evaluates the techniques and environmental sustainability of biofuels by examining the prior LCA studies, highlighting significant methodological approaches, and presenting critical conclusions.

Despite its comprehensive framework, the application of LCA to biofuels is often associated with several methodological challenges and uncertainties that can significantly influence the outcomes of the assessment (Patel and Singh, 2023; Yin et al., 2024). These include the selection of system boundaries, functional units, and allocation methods for co-products, all of which can lead to variations in results across studies (Gaffey et al., 2024). In addition, differences in data quality, availability, and regional specificity, as well as assumptions related to energy inputs, emission factors, and technological efficiencies, further contribute to inconsistencies in reported outcomes. Such variability highlights the importance of adopting transparent, consistent, and well-documented methodological approaches (Reijnders, 2021; Salas et al., 2024). Furthermore, incorporating sensitivity and uncertainty analyses within LCA studies is essential to evaluate the robustness of results and to identify key parameters that drive environmental impacts. Strengthening methodological rigor and improving data reliability can enhance the credibility and comparability of LCA findings, thereby supporting more informed and effective decision-making in the development and deployment of biofuels. In this regard, the harmonization of methodological choices and the use of standardized databases and guidelines can further improve the consistency of LCA studies (Patel and Singh, 2024). This will ultimately facilitate more reliable comparisons and strengthen the scientific basis for policy and technological advancements in the biofuel sector.

1.5 Objective of the study

Since biofuels have the potential to address India's growing energy needs while reducing environmental impacts, this study aims to assess their environmental sustainability through life cycle assessment approach. To achieve this, the following objectives have been devised.

Objective 1: To analyse the environmental performance of biofuel production in India by life cycle assessment methodology.

Within this research objective, three overall research questions are formulated:

- (i) What are the key environmental impacts associated with bioethanol and biodiesel production pathways in India?
- (ii) How do different feedstocks influence the environmental performance of biofuels?
- (iii) Which stages of the biofuel life cycle (cultivation, processing, etc.) contribute most to overall environmental burdens?

Objective 2: To compare the environmental impacts of utilizing the biofuels produced.

The questions relevant to this objective are:

- (i) How do the life cycle environmental impacts of bioethanol and biodiesel compare with those of conventional fossil fuels?
- (ii) Do second-generation biofuels offer significantly lower environmental footprints than first-generation alternatives?

Objective 3: To determine the energy efficiency of biofuel production using life cycle energy analysis.

The questions raised in this objective are:

- (i) What is the net energy ratio for major biofuel production pathways in India?
- (ii) How much fossil energy is required per unit of biofuel energy output, and how does this vary by feedstock and technology?
- (iii) What are the main sources of energy input in the biofuel life cycle, and how do they affect overall energy efficiency?

Objective 4: To perform the sensitivity analysis to investigate the effect of an individual input parameter.

The questions relevant to this objective are:

- (i) How do uncertainties in key input parameters influence the environmental impact outcomes of biofuel life cycle assessments in India?
- (ii) To what extent does uncertainty affect the interpretation and comparability of LCA results across different biofuel production scenarios?

Bioethanol and biodiesel were selected as the focal biofuels in this study due to their widespread use, established production technologies, and significant relevance in the Indian context. Both fuels are currently among the most commercially established liquid biofuels globally and in India, supported by active government policies such as the Ethanol Blending Program (EBP) and National Biodiesel Mission. These fuels are an important part of India's biofuel strategy, aimed at reducing dependence on fossil fuels, improving energy security, and addressing environmental concerns such as GHG emissions and air pollution. Although India is rapidly expanding electric mobility and renewable electricity, liquid biofuels can complement electrification, particularly in transport applications that are relatively difficult to electrify due to high energy requirements, long operating ranges, payload constraints, or refuelling requirements. Therefore, biofuels are considered in this study as complementary options rather than alternatives to electric mobility.

From a technological perspective, bioethanol and biodiesel are well-researched, yet their environmental performance varies significantly depending on feedstock type, production methods, and regional conditions. LCA has been widely applied to both fuels, offering rich literature for comparative analysis and critical evaluation. Additionally, both fuels can be produced from a diverse range of first- and second-generation feedstocks, allowing the study to cover a spectrum of sustainability implications, from food-versus-fuel debates to waste valorization. Other biofuels, such as biogas, biomethane, sustainable aviation fuel, and biohydrogen, were not included because they involve different production technologies, infrastructure requirements, end-use applications, and sustainability considerations. Including these pathways would substantially broaden the scope of the study and introduce comparisons among fundamentally different fuel systems. Focusing on bioethanol and biodiesel therefore enables a more detailed and policy-relevant assessment of liquid biofuel sustainability in India, while providing a focused analysis of established road-transport fuel pathways. The future role of these fuels will depend on technological development, sustainable feedstock availability, and the pace of electrification across different transport sectors.

1.6 Scope and relevance of the study

The study on the environmental sustainability of biofuels in India through an LCA approach holds significant scope and relevance in addressing pressing global and national challenges. As the world transitions toward cleaner energy solutions, biofuels emerge as a promising alternative to fossil fuels, offering the potential to reduce greenhouse gas emissions, enhance energy security, and support rural economies.

India's leadership in establishing the Global Biofuel Alliance at the G20 Summit underscores the nation's commitment to advancing sustainable biofuel adoption globally. This initiative aims to foster international collaboration, facilitate technology transfer, and promote the production and use of biofuels to achieve a more sustainable energy landscape.

Moreover, this study aligns directly with the objectives of several **United Nations Sustainable Development Goals (SDGs)**. Promoting biofuels contributes to **SDG 7 (Affordable and Clean Energy)** through renewable energy advocacy, **SDG 12 (Responsible Consumption and Production)** by emphasizing resource efficiency and sustainable practices, and **SDG 13 (Climate Action)** by addressing carbon emissions. These linkages underscore the broad relevance of biofuels in addressing energy, environmental, and developmental challenges, while also connecting with **SDG 9 (Industry, Innovation, and Infrastructure)** by encouraging technological advancements and resilient energy systems and **SDG 15 (Life on Land)** through the sustainable management of forests and agricultural resources (Figure 1.3).

By focusing on the environmental impacts of biofuels, this research contributes to policy formulation, identifies opportunities for sustainable practices, and addresses critical challenges, including land use, water consumption, and biodiversity conservation. The findings of this study are not only relevant to India's energy transition but also provide insights for global efforts to achieve a balanced approach to economic growth and environmental protection. Building on this scope, the present study adopts a systematic, comprehensive life-cycle-based framework to evaluate multiple biofuel pathways under Indian conditions. It emphasizes identifying key environmental impact hotspots across different stages of production and supply chains, enabling a clearer understanding of where improvements can be made. The study also

compares alternative feedstocks and conversion technologies to highlight more sustainable options, thereby supporting evidence-based decision-making. By integrating robust methodological approaches with region-specific data, this research aims to provide practical insights to optimize biofuel systems and enhance their overall environmental performance, aligning with national and global sustainability targets.

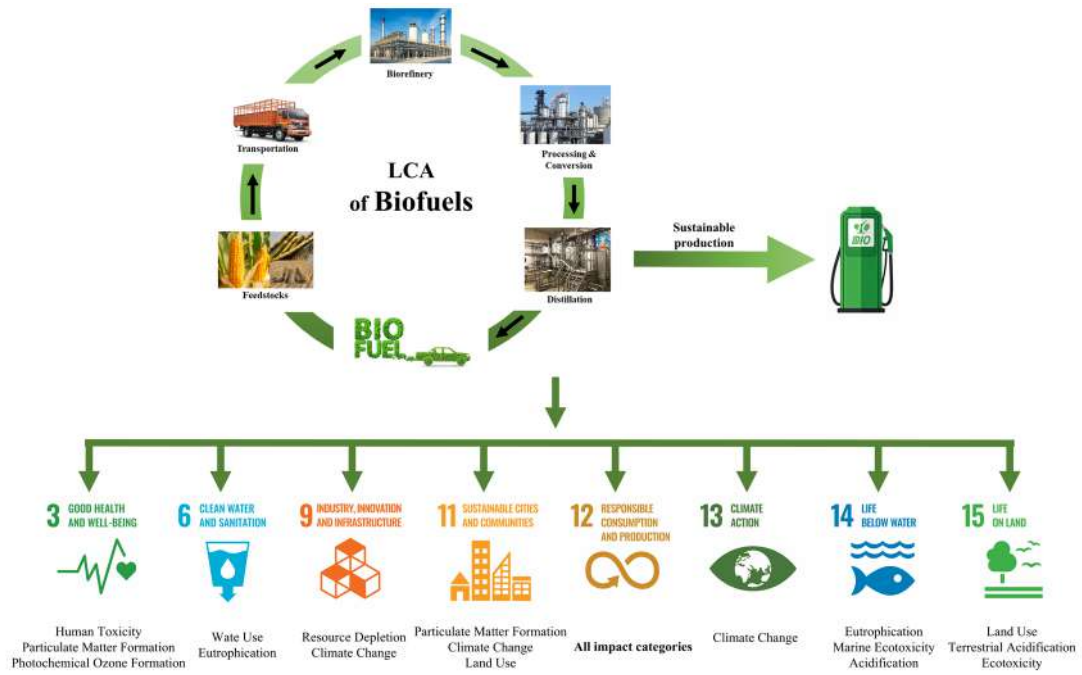


Figure 1.3 Life Cycle Assessment of Biofuels: Environmental Impacts and Contributions to Sustainable Development Goals

1.7 Structure of the thesis

This thesis is organized into five chapters. A brief description of each chapter is given below.

Chapter 1 provides an overview of the significance of biofuels as a sustainable energy alternative and their relevance in addressing environmental and energy challenges in India. This chapter outlines the importance of the research, states the objectives of the study, and discusses the scope of the present work in the context of biofuel sustainability and life cycle assessment.

Chapter 2 provides a literature review of LCA studies conducted in several countries on first-, second-, and third-generation biofuels, focusing on key aspects such as production processes, environmental impacts, and policy considerations. The chapter also identifies critical research gaps and uncertainties in existing studies, providing a foundation for future research.

Chapter 3 explains how LCA was carried out, following the guidelines set by the International Organization for Standardization (ISO). It includes the key steps in the research process: defining the goal and scope, setting system boundaries, and choosing a functional unit. The chapter also covers the development of the life cycle inventory, the life cycle impact assessment, and how the results were interpreted to support the study's objectives.

Chapter 4 presents a comprehensive life-cycle assessment of both bioethanol and biodiesel production pathways derived from multiple first- and second-generation feedstocks. For bioethanol, the analysis evaluates systems based on molasses, grains, agricultural residues, and municipal solid waste, comparing their environmental impacts in terms of emissions, resource consumption, and energy use to identify key trade-offs and more sustainable production routes. In parallel, biodiesel pathways derived from feedstocks such as jatropha, rapeseed, palm oil, used cooking oil, and microalgae are assessed using a similar LCA framework. The chapter systematically compares greenhouse gas emissions, cumulative energy demand, and land and water use across these systems, highlighting the influence of feedstock type, process efficiency, and by-product utilization. Overall, the chapter provides an integrated comparative evaluation of bioethanol and biodiesel systems, emphasizing trade-offs and identifying comparatively sustainable biofuel pathways.

Chapter 5 concludes by integrating the overall findings on biofuels in India, emphasizing their role in energy security and emission reduction while noting significant variability across feedstocks and technologies. It highlights future research needs, social implications, and policy alignment to ensure that biofuel development supports sustainable, inclusive growth alongside national renewable energy goals.

CHAPTER 2

REVIEW OF LITERATURE

The transition to renewable energy sources has become imperative in the face of climate change, resource depletion, and energy security concerns. Among the various renewable alternatives, biofuels have emerged as a promising solution to reduce dependence on fossil fuels and mitigate environmental pollution. In India, biofuels play a critical role in the government's energy strategy, particularly through the utilization of agricultural residues, municipal solid waste, and non-food biomass. However, the sustainability of biofuels remains a subject of extensive research, as factors such as water footprint and energy balance influence their overall environmental impact. To systematically evaluate these aspects, LCA has become an essential tool, providing a comprehensive framework for assessing the environmental impacts of biofuel production. This chapter presents a detailed review of the existing literature on biofuels, their environmental sustainability, and the application of LCA to evaluate their long-term feasibility.

Publication out of this chapter:

1. Patel, K., Singh, S.K. Environmental sustainability analysis of biofuels: a critical review of LCA studies. *Clean Techn Environ Policy* 25, 2489–2510 (2023).
<https://doi.org/10.1007/s10098-023-02596-y>

2.1 Biofuel feedstock and availability

Biofuels can be categorized based on the type of feedstock used for production, broadly classified into first-, second-, and third-generation biofuels. First-generation (1G) biofuels are derived from food crops containing sugar or starch, such as sugarcane, sugarcane molasses, corn, palm oil, rapeseed oil, damaged grains, sugar beet, etc., as shown in Figure 2.1. In India, corn- and sugarcane-based bioethanol is mainly used, while non-edible oils like jatropha and pongamia have been promoted for biodiesel production. However, large-scale jatropha cultivation has faced several setbacks due to poor yields and high maintenance requirements. Also, the reliance on food crops raises the food-versus-fuel debate, particularly in developing countries where food security remains a critical concern.

Second-generation (2G) biofuels use lignocellulosic biomass such as agricultural residues (rice straw, corn stover, cassava straw, bagasse), forestry waste, municipal solid waste, and energy crops like switchgrass for bioethanol, while used cooking oil (UCO) is promoted for biodiesel. These feedstocks are more sustainable because they do not directly compete with food crops and use waste biomass. In India, with its abundant agricultural residues and UCO, 2G technologies have the potential to significantly reduce environmental impacts while enhancing rural incomes through value addition to waste. According to the Ministry of New and Renewable Energy, approximately 500 million metric tons of crop residues are generated annually (FAO, 2022; Gatkhal et al., 2024), providing a substantial feedstock for biofuel production. This abundance of agricultural residue underscores its potential for sustainable biofuel production, further enhancing its appeal as a renewable energy source. Also, India generates around 3.4 million tons of UCO (IMARC, 2025), which can be effectively used as a sustainable feedstock for biodiesel production, thereby reducing environmental pollution, promoting circular economy practices, and decreasing dependence on imported crude oil. The National Policy on Biofuel 2018 also focuses on second-generation biofuels, which offer various advantages over first-generation biofuels (GOI, 2018), especially for municipal solid waste due to its low cost, consistent supply, and existing collection infrastructure. This offers the advantage of

reducing the environmental impacts of waste disposal by displacing fossil fuels. However, the adoption of 2G biofuel is low in India due to its high capital cost.

Third-generation (3G) biofuels are primarily derived from microalgae and other advanced biomass sources because of their ability to grow on non-arable land using saline or wastewater, their high photosynthetic efficiency, and their fast growth rates. However, the commercial viability of algal biofuels remains constrained by high production costs and energy inputs. Nevertheless, ongoing research explores genetically enhanced strains and integrated biorefinery models to make algal biofuels more sustainable and economically viable.

India's biofuel policy emphasizes the use of indigenous feedstocks to minimize imports and promote energy security. However, the availability, seasonality, and logistics of biomass feedstock collection continue to pose challenges. A comprehensive assessment of feedstock sustainability—considering yield, land and water use, emissions, and socioeconomic impacts—is essential for scaling up biofuel production in an environmentally and economically responsible manner.

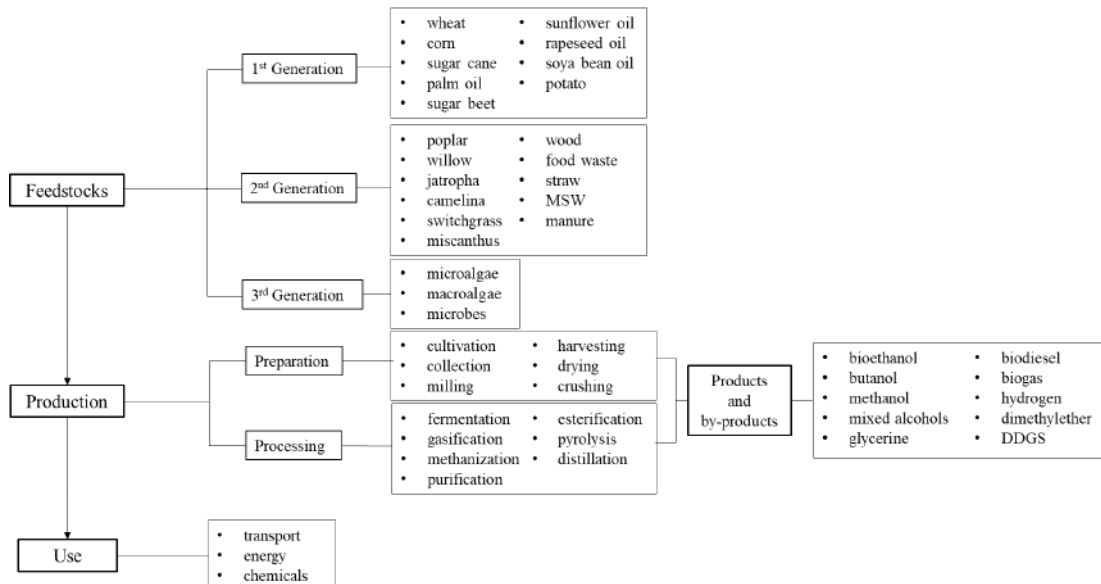


Figure 2.1 Feedstock and production processes for different biofuels

2.2 Biofuel production processes

The production of biofuels involves a series of chemical, biochemical, or thermochemical processes. Among the most commonly produced liquid biofuels are bioethanol and biodiesel, each requiring distinct technological pathways depending on the nature of the feedstock. Understanding these pathways is essential for evaluating environmental performance, energy efficiency, and overall sustainability. The choice of process technology significantly affects life-cycle emissions, resource consumption, and the feasibility of large-scale production, especially in a diverse, resource-constrained context like India.

The production processes of bioethanol and biodiesel differ significantly due to the distinct nature of their feedstocks. Each involves multiple stages, from feedstock pretreatment to conversion and purification, and has unique environmental and energy impacts that are crucial for life-cycle assessment. Bioethanol production involves converting sugar- or starch-based feedstock via biochemical pathways. For sugar-rich materials, like sugarcane or molasses, the process begins with dilution and fermentation, where yeast (commonly *Saccharomyces cerevisiae*) converts the sugar into bioethanol, as shown in Figure 2.2a. The yeast contains invertase, which converts sucrose (a disaccharide) into glucose and fructose (monosaccharides), and a complex enzyme group called zymase, which converts glucose and fructose into ethanol and carbon dioxide. For starch-based feedstocks such as corn, damaged rice, and wheat, after slurry preparation, an additional liquefaction step is required to break down the starch (a complex carbohydrate) into shorter dextrins, which are then fermented into fermentable sugars (glucose) before fermentation, as shown in Figure 2.2b. Enzymes such as alpha-amylase and Glucoamylase are used for liquefaction. In the case of lignocellulosic biomass, pre-treatment is crucial to break the lignin content from the biomass and expose the cellulose and hemicellulose to the enzymes for hydrolysis, which can either be enzymatic (using cellulase or hemicellulase) or acid hydrolysis, to break down the complex carbohydrates into simple fermentable sugars (glucose and pentose), followed by fermentation, as shown in Figure 2.2c. The final step is

distillation and dehydration to get fuel-grade ethanol, usually 99.5% purity, using a 3A molecular sieve (0.3nm pore size) or azeotropic distillation in the dehydration unit.

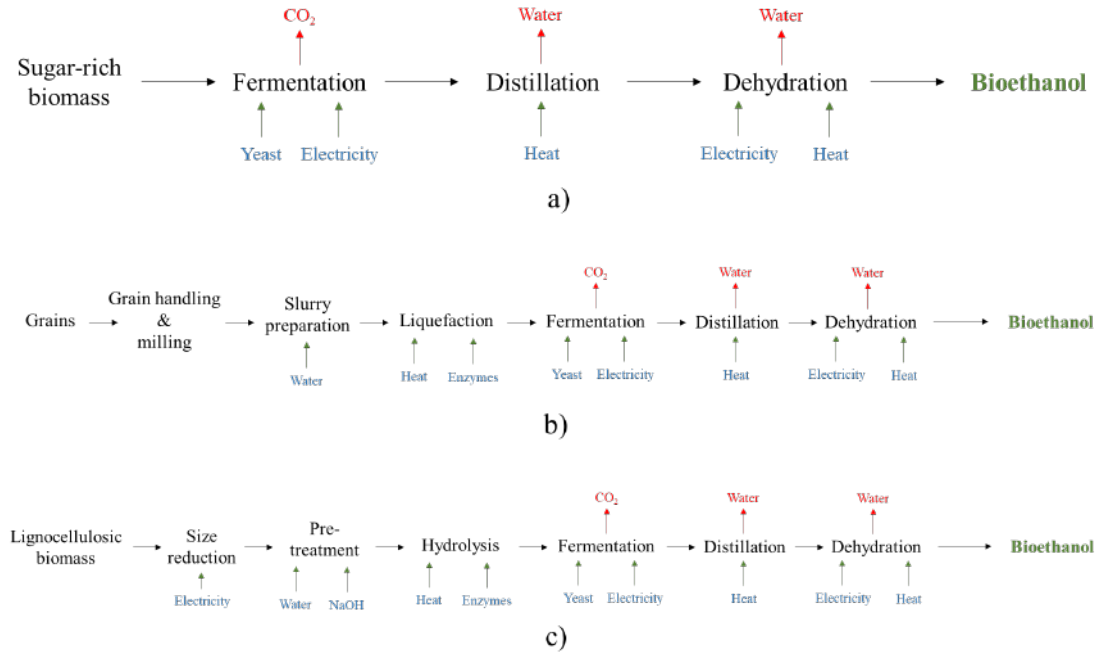


Figure 2.2 General process flow diagram for bioethanol production from a) Sugar crops based, b) grains, and c) lignocellulosic biomass

Biodiesel production, on the other hand, is primarily a chemical process involving the transesterification of triglycerides found in oils or fats. The triglycerides react with alcohol (commonly methanol) in the presence of a catalyst, commonly sodium hydroxide or potassium hydroxide, to produce fatty acid methyl esters (FAME) – a chemical name of biodiesel, and glycerol as a by-product. The chemical reaction is shown in Figure 2.3. If a high content of free fatty acid (FFA) is present in the oil, it

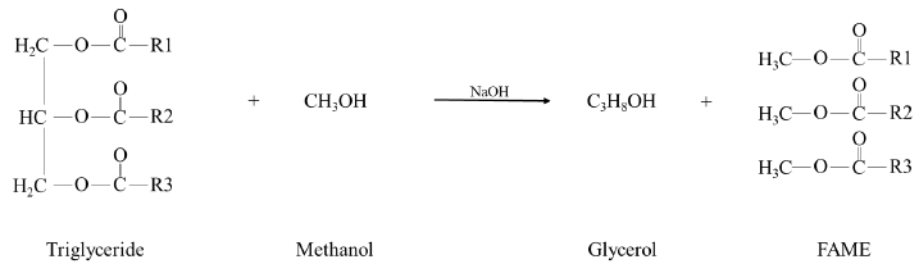


Figure 2.3 Transesterification of a triglyceride for biodiesel production

reacts with the catalyst to form soap instead of undergoing transesterification, which reduces biodiesel yield and creates emulsions that make product separation (biodiesel, glycerol, and water) very difficult. It is removed by acid esterification, which converts FFA into esters, as shown in Figure 2.4. After transesterification, the biodiesel is separated, washed to remove residual catalyst and impurities, and dried for use as a fuel.

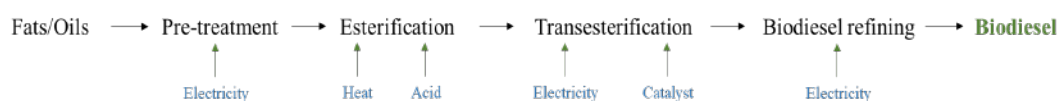


Figure 2.4 General process flow diagram for biodiesel

2.3 Life cycle assessment of biofuels and environmental impacts

Life Cycle Assessment is a widely recognized tool for quantifying the environmental impacts of a product, process, or service throughout its life cycle. In the context of biofuels, LCA plays a crucial role in evaluating sustainability by accounting for resource use, energy inputs, emissions, and environmental effects from feedstock cultivation to fuel combustion. While the detailed methodological framework is discussed in Chapter 3, this section reviews how LCA has been applied in existing research to analyze the environmental implications of biofuel production.

A wide range of studies have utilized LCA to assess both bioethanol and biodiesel across different geographical contexts and feedstock types. For example, Alengebawy et al. (Alengebawy et al., 2022) performed an LCA of rice straw-based bioenergy in China, using a cradle-to-gate system boundary, and demonstrated that syngas-based pathways offered the lowest marine ecotoxicity impacts. In India, Bhonsle et al. (Bhonsle et al., 2022) examined biodiesel production from used cooking oil and reported favorable outcomes in terms of greenhouse gas emissions and energy efficiency compared to petroleum diesel. Similarly, Pradhan et al. (Pradhan et al., 2022) conducted an LCA of rice bran oil methyl ester and highlighted the contribution

of electricity and chemical use to overall environmental burdens. Table 2.1 presents the characteristics of the various LCA studies on biofuel production.

The estimated GHG emission of first-generation bioethanol ranges from 0.006 to 167 g CO₂ eq. / MJ, and that for biodiesel varies from – 7.3 to 329 g CO₂ eq. / MJ, as shown in Figure 2.5a and Figure 2.6a, respectively. When the average values are taken into account, the global warming potential (GWP) of most first-generation

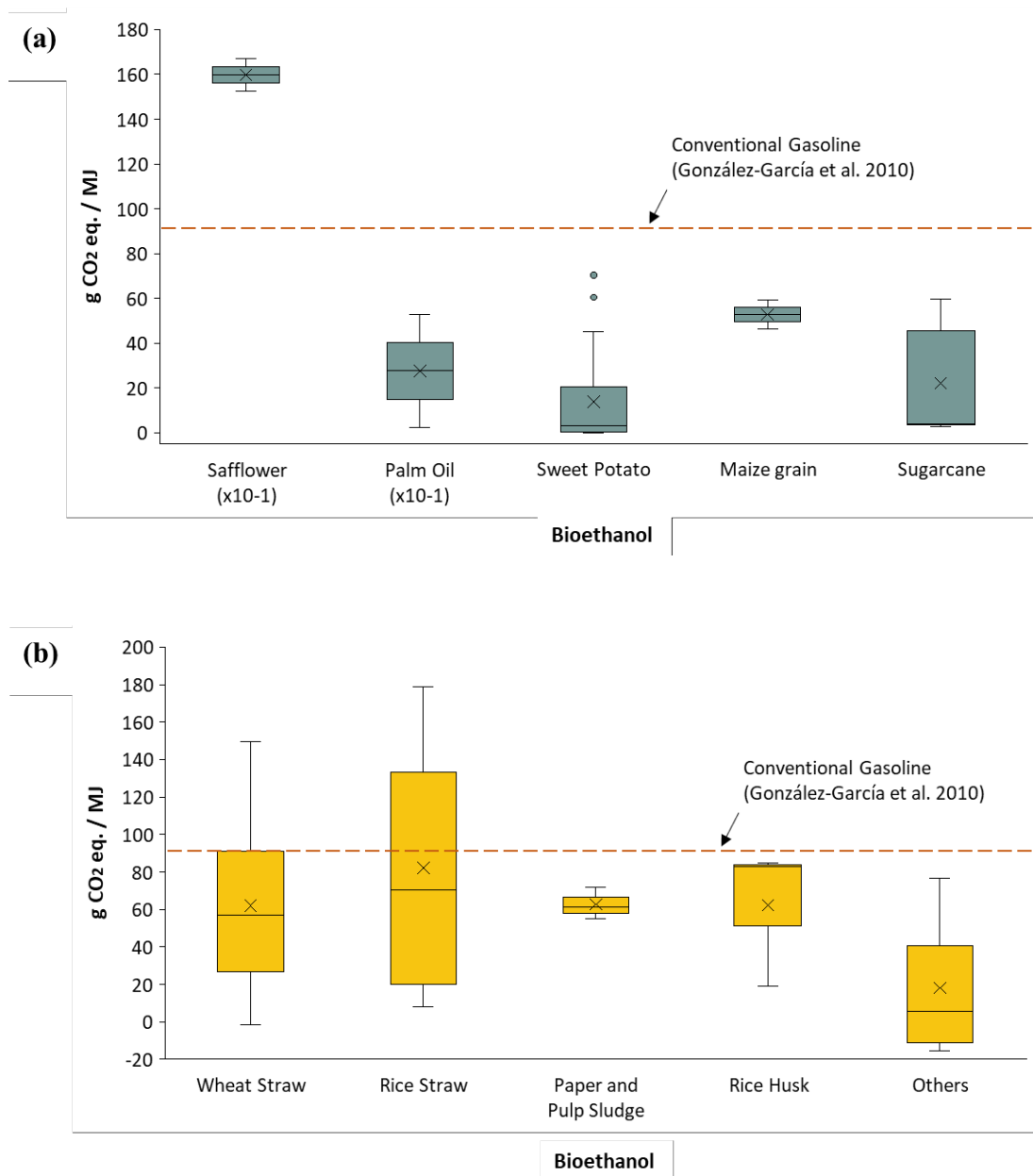


Figure 2.5 GHG emissions from a) first-generation and b) second-generation bioethanol

biofuels is lower than that of conventional gasoline (72.8 to 96 g CO₂ eq. / MJ (González-García et al., 2010a, 2010b; Ou et al., 2009) and diesel (80 to 120 g CO₂ eq. / MJ (Ou et al., 2009; Passell et al., 2013; Shirvani et al., 2011), except for rapeseed biodiesel. Some LCA studies analyzed show that rapeseed biodiesel emits 2.8 to 350 g CO₂ eq. / MJ of energy (González-García et al., 2013; Gupta et al., 2022; Uusitalo et al., 2014). Compared to fertilizer application in the agricultural stage (which consumes 70% more energy and 80% more GWP) (Gallejones et al., 2015), the contribution from the phases of seed drying and cooling, oil extraction, and refining was minimal. According to the study by Arguelles-Arguelles et al. (2021), GHG emissions were negative for biodiesel production from palm oil because the amount of carbon dioxide captured during the cultivation phase was more than the biofuel's GHG emissions. Most studies on palm oil, soybeans, and sugarcane (Arpornpong et al., 2015; Fernández-Tirado et al., 2016; Lee and Ofori-Boateng, 2013; Munagala et al., 2022; Rocha et al., 2014) reported lower GHG emissions than those of conventional fuels. The growing and harvesting phase of biofuel LCA is critical for biofuel generation. As a result, the quantity of fertilizer, pesticides, and fuel used during the agricultural phase plays a critical role in determining the outcomes and environmental effects of the biofuel, as shown in Table 2.2. Most reviewed studies show that first-generation biofuels reduce GHG emissions compared to conventional diesel and gasoline.

The GHG emissions of second-generation biofuels range from -15.4 to 178.7 g CO₂ eq. / MJ for bioethanol and -0.21 to 113.8 g CO₂ eq. / MJ for biodiesel, as shown in Figure 2.5b and Figure 2.6b, respectively. These discrepancies result from various factors, such as the feedstock used, production routes, technological assumptions, and differences in analytical methodologies. It should be noted that technological uncertainties are particularly important when evaluating their potential, as advanced biofuels have not yet reached full commercialization. As a result, the quality of the information now accessible is not as strong as for the well-known first-generation biofuels (Kovacs et al., 2022; Mohd YUSOF et al., 2019). The GWP of lignocellulosic biofuel produced from agricultural and forestry wastes is often lower than that of biofuel produced from energy crops (Gandam et al., 2022). This is mainly caused by N₂O emissions from fertilizers used during the cultivation of energy crops (Jeswani et

al., 2020; Olukoya et al., 2014). Assuming that residues have no environmental effects and are solely linked to the primary crop from which they are generated, then the adverse effects associated with that crop can be avoided by using the residues instead. The production of lignocellulosic bioethanol involves the assumption that the leftover lignin will generate heat and power to meet the energy needs of the process. Any excess electricity produced is then supplied to the grid (Sawatdeenarunat et al., 2015). This results in the biofuel production system being acknowledged for preventing GHG emissions from a specific amount of grid power (Jiang et al., 2022). In some instances, such as with feedstocks like spent coffee grounds, forest residue, and rice straw, the benefits from generating power and other byproducts outweigh the emissions from producing biofuels. Some of the reviewed studies show negative GHG emissions from biofuel production. Jeswani et al. (Jeswani et al., 2015) analyzed the LCA of ethanol production from lignocellulosic biomass and compared the bioethanol production from wheat straw, miscanthus, poplar, and forest residue. The analysis shows that the GWP of bioethanol production is negative for all four feedstocks, mainly due to the production of co-products. The study by Schmidt Rivera et al. (Schmidt Rivera et al., 2020) compares the different valorization routes of spent coffee grounds for the production of value-added products such as biodiesel. The method of incineration was found to be the most sustainable option because it had a total of 14 net negative environmental impacts, including greenhouse gas emissions ($-0.212 \text{ g CO}_2 \text{ eq. per MJ}$). The high energy output of waste-to-energy conversion technologies and credits for replacing a fossil-fuel-dominated electricity mix mitigate the negative impacts of these valorization routes. Pradhan et al. (Pradhan et al., 2022) analyzed biodiesel production from used rice bran oil via through esterification and transesterification. The GHG emissions were found to be very high ($831.5 \text{ to } 1138.4 \text{ g CO}_2 \text{ eq. / MJ}$) compared with conventional diesel ($102 \text{ g CO}_2 \text{ eq. / MJ}$) (Ou et al., 2009), which has similar results to the study by (Sun et al., 2022). However, the analysis shows that the vanadium-impregnated solid catalyst results in a 26.96% reduction in GWP compared to a commercial hydroxyapatite-supported catalyst, shown in Figure 2.6b.

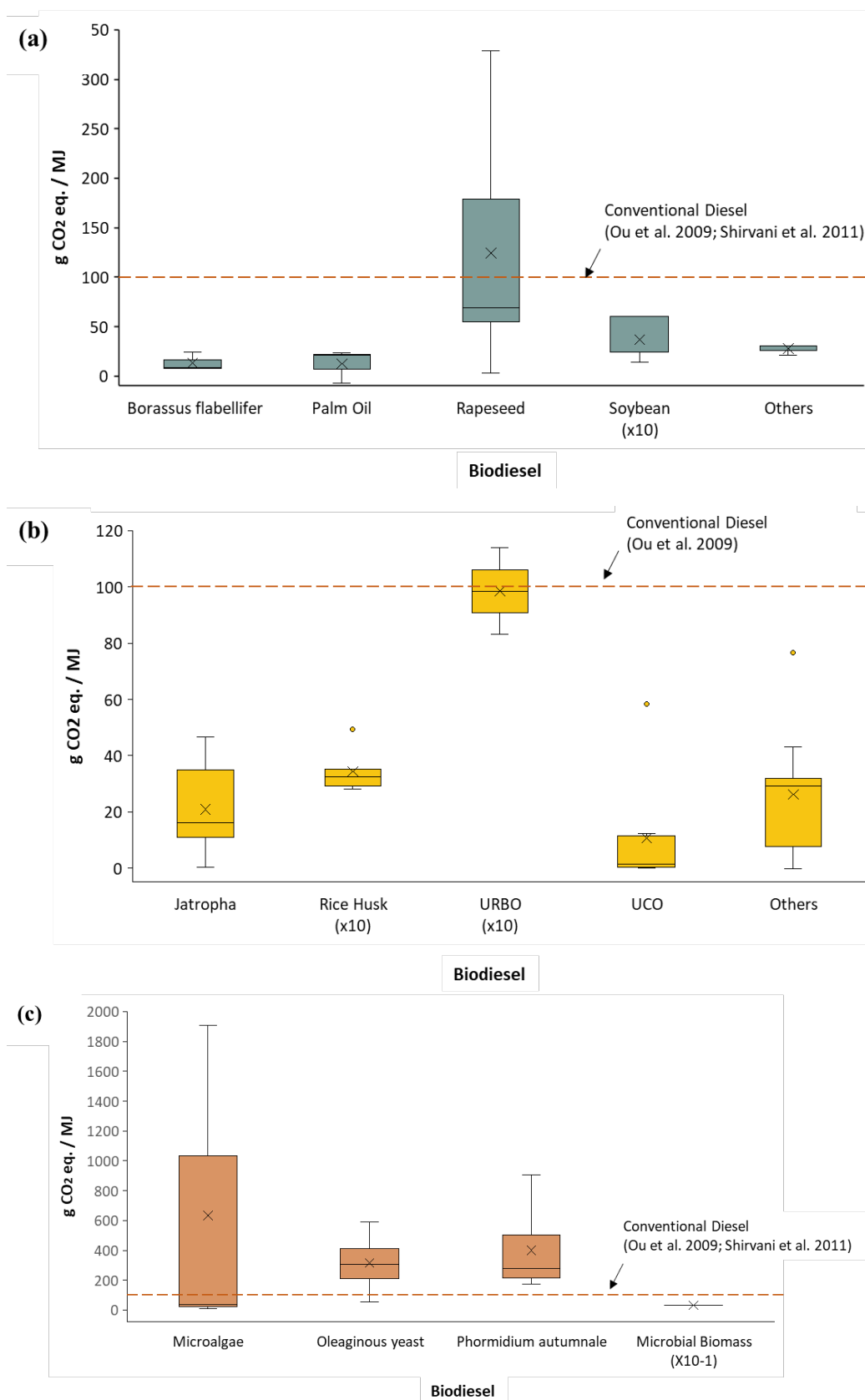


Figure 2.6 GHG emissions from a) first-generation, b) second-generation, and c) third-generation biodiesel

Table 2.1 Characteristics of LCA research analyzed in the study

Biomass Source	Location	System Boundary	Functional Unit	Software	LCIA Method	Database	Year	Reference
Jatropha, Rapeseed Oil	India	CTG	1 MJ of energy	OpenLCA	ReCiPe 2016	Ecoinvent 3.8	2025	(Shrees et al., 2025)
Corn stover, Wheat Straw, Rice Husk	n/i	CTGa	1 kg of bioethanol	GaBi	ReCiPe 2016	GaBi database	2025	(Sajid et al., 2025)
Switchgrass	USA	CTGa	1 MJ of ethanol	n/i	IPCC	GREET model, Ecoinvent	2024	(Kim et al., 2024)
Jatropha	Thailand	WTW	1000 megajoules (MJ) of biodiesel	SimaPro	IPCC 100-year GWP	Ecoinvent	2024	(Rattanaphra et al., 2023)
Reed Straw	China	CTGa	1000 kg of biodiesel	SimaPro	CML-IA baseline, ReCiPe 2016, IPCC 2021 GWP100	Ecoinvent 3	2024	(Wang et al., 2024)
Sugarcane Bagasse	Mexico	CTGa, CTG	1,000 liters of bioethanol	Aspen Plus, SimaPro	CML 2001	Ecoinvent	2023	(Santoyo-Castelazo et al., 2023)
Moringa oleifera oilseeds	Algeria	WTW	1 ton of biodiesel	SimaPro	CML-IA baseline	Ecoinvent 3.1	2023	(Amouri et al., 2023)
Microalgae Species	Portugal	WTW	Combustion of 1 MJ of algal biodiesel	GaBi	ReCiPe 2016, IPCC AR5	Ecoinvent 3.2	2023	(Bradley et al., 2023)

Biomass Source	Location	System Boundary	Functional Unit	Software	LCIA Method	Database	Year	Reference
Used Rice Bran Oil (URBO)	India	CTGa	1 kg biodiesel production	OpenLCA	CML 2001	Ecoinvent 3.5	2022	(Pradhan et al., 2022)
Safflower	Turkey	CTGa	Using a new medium-sized car for 100 km	SimaPro	Eco-Indicator 99; IPCC	Ecoinvent	2022	(Isler-Kaya and Karaosmanoglu, 2022)
Rapeseed Oil	UK	CTGa	1-ton biodiesel production	n/i	CML 2001	n/i	2022	(Gupta et al., 2022)
Used cooking oil	India	CTGa	1 ton of Biodiesel	SimaPro	ReCiPe 2016	Ecoinvent	2022	(Bhonsle et al., 2022)
Sugarcane Bagasse	India	CTGa	1 kg of Bio-CNG	OpenLCA	ReCiPe 2016	n/i	2022	(Munagala et al., 2022)
Safflower	Malaysia	CTGa	1 MJ bioethanol produced	SimaPro	IMPACT 2002+	Ecoinvent 3.0	2022	(Hosseinzadeh-Bandbafha et al., 2022)
Rice Straw	China	FTGa	1 metric ton dry rice straw	OpenLCA	CML 2001	Ecoinvent 3.7	2022	(Alengebawy et al., 2022)
Date Seed Oil	Oman	CTGa	1000 kg of biodiesel produced	n/i	CML-IA baseline V3.06; ReCiPe 2016	n/i	2021	(Al-Mawali et al., 2021)
Date Palm Waste	Tunisia	CTGa	1 GJ synthetic diesel and gasoline	SimaPro	ReCiPe 2016	Ecoinvent; PSILCA	2021	(ben Hnich et al., 2021)

Biomass Source	Location	System Boundary	Functional Unit	Software	LCIA Method	Database	Year	Reference
Palm Oil	Mexico	CTG	1.6×10^{-2} m ³ (13.13 kg) of renewable diesel	CCalC2 V1.1	n/i	CCalC2 database	2021	(Arguelles-Arguelles et al., 2021)
Waste loquat seed oil	Oman	CTGa	1000 kg of biodiesel produced	SimaPro	CML-IA baseline V3.06, ReCiPe 2016	SimaPro 8.0 database	2021	(Al-Multaseb et al., 2021)
Borassus flabellifer	India	CTGa	1 kg biodiesel	SimaPro v9.0	IMPACT 2002+	Ecoinvent 3.0	2021	(Mukhopadhyay and Chakraborty, 2021)
Crop Residues	China	CTG	1t of crop residues	Gabi	CML2001	GaBi database	2021	(Yang et al., 2021)
Estuarine Microalgae	India	CTGa	one-hectare area	OpenLCA	CML – IA	Ecoinvent 3.6	2020	(Saranya and Ramachandra, 2020)
Spent Coffee Grounds	United Kingdom	CTG	treatment of 1 tonne of SCG	Gabi	ReCiPe 2016	Ecoinvent 3.3	2020	(Schmidt Rivera et al., 2020)
Used Cooking Oil	Greece	CTGa	production of 1 ton biodiesel	SimaPro 8	ReCiPe	Ecoinvent 3	2020	(Foteinis et al., 2020)
Pine Residues; Switchgrass	Southeastern United States	CTGa	1 MJ of biofuel produced	GREET	n/i	Ecoinvent; USLCA; GREET 1.8	2020	(Lan et al., 2020)
Rice Husk	Southeast Asia	GaTGa	1 kg of biohydrogen produced	OpenLCA	CML 2001	Ecoinvent 3.5	2020	(Reaño, 2020)

Biomass Source	Location	System Boundary	Functional Unit	Software	LCIA Method	Database	Year	Reference
Rice Straw	India	CTGa	1 L of ethanol	OpenLCA	ILCD 2011 midpoint	Ecoinvent 3.3	2020	(Sreekumar et al., 2020)
Forest Residues	USA	CTGa	1 MJ of renewable diesel	Gabi	n/i	Ecoinvent; GaBi 9 database	2020	(Spatari et al., 2020)
Oleaginous yeast	India	CTGa	300 L biodiesel	SimaPro v8.0	ReCiPe End-Point (H); IMPACT 2002+	Ecoinvent 3.1	2020	(Chopra et al., 2020)
Desmodemus	China	CTGa	1 kg microalgae	n/i	n/i	n/i	2020	(Li et al., 2020)
Waste Cooking Oil	Malaysia	CTGa	1000 kg of biodiesel production	SimaPro	CML 2001 and Eco-indicator 99	Agribalyse; NEEDS	2019	(Chung et al., 2019)
Microalgae	Taiwan	CTGa	100 MJ petrofuel produced; 1 kg biofuel produced	SimaPro	ReCiPe	Ecoinvent 3.5	2019	(Wu et al., 2019)
Microalgal biomass	India	CTGa	mass of CO ₂ equivalent released per MJ of fuel produced	Gabi	n/i	GaBi 7 database	2019	(Banerjee et al., 2019)
Biowaste	EU-27	CTGa	1 MW of Biomethane	SimaPro	IMPACT 2002+	Ecoinvent 3.2	2019	(Ardolino and Arena, 2019)

Biomass Source	Location	System Boundary	Functional Unit	Software	LCIA Method	Database	Year	Reference
Residual wood	Spain	CTGa	1 th-1 of hardwood chips	SimaPeo	ReCiPe 1.12	Ecoinvent	2018	(Bello et al., 2018)
Sweet Potato	Brazil	CTGa	1 MJ of bioethanol produced	SimaPro	CML IA Baseline	Ecoinvent 3.1	2018	(Costa et al., 2018)
Sweet Potato	China	CTGa	1000 L of 99.5% bioethanol production	Microsoft Excel 2013	CML - IA 2000	CML Database	2017	(Zhang et al., 2017)
Wheat Straw	n/i	CTGa	1 kg of n-butanol	n/i	IMPACT 2002+	Ecoinvent 3.0	2017	(Brito and Martins, 2017)
Microalgae	India	WTT; TTW	1 kg biodiesel	SimaPro	ReCiPe midpoint(E)	SimaPro Database	2016	(Gnansounou and Kenthorai, 2016)
Sugarcane	Brazil	WTT; TTW	1 ton of sugarcane; 1 km of car operation	SimaPro	ReCiPe midpoint(E)	Ecoinvent 3.0	2015	(Gnansounou, 2015)
Multi feedstock	n/i	CTGa	1 kg of ethanol	SimaPro	ReCiPe	SimaPro Database	2014	(Muñoz et al., 2014)

Cradle to Gate (CTGa), Field to Gate (FTGa), Farm to Gate (FaTGa), Cradle to Grave (CTG), Gate to Gate (GaTGa), Well to Wheel (WTTW), Well to Tank (WTT), Tank to Wheel (TTW), Well to Gate (WTGa), n/i: not included

Among the studies evaluated, only 7 LCA studies reported GHG emissions for third-generation biofuels. However, these studies used different approaches, methods, and assumptions when managing feedstocks, nutrients, and co-products, as well as when setting system boundaries and designing processes. Consequently, the GHG emissions have varied significantly, as indicated in Figure 2.6c, ranging from 10.2 to 1910 g CO₂ eq. / MJ. These findings suggest that, depending on the assumptions, microalgae diesel can significantly reduce or increase GHG emissions compared to diesel (Soratana et al., 2014). Despite being in its present development stage, many research works have concluded that algal biodiesel generates more GHGs throughout its lifespan than fossil fuels (Banerjee et al., 2019). This is mainly due to the low algal yield and the substantial energy consumption during the cultivation, harvesting, and drying stages (Banerjee et al., 2019; Mu et al., 2014). A study by (Saranya and Ramachandra, 2020) evaluated the LCA of estuarine microalgae for biodiesel production. The analysis shows that the scenario using wastewater as a nutrient has lower GHG emissions of 0.85 kg CO₂ eq. per kg of biodiesel (22.4 g CO₂ eq. / MJ) than other scenarios. There was a 67.9 to 85.4% reduction in GHG emissions when microalgal biodiesel was used instead of fossil diesel. However, the study by Soratana et al. (Soratana et al., 2012) shows that none of the four conditions considered for biodiesel production meet the Renewable Fuel Standard, which requires a 50% reduction in GHG emissions for advanced biofuels. The analysis shows GHG emissions range from 854 to 1910 g CO₂ eq. / MJ. Another research by (Chopra et al., 2020) examined the environmental impact of producing biodiesel and bio-crude from oleaginous yeast and found GHG emissions ranging from 56 to 600 g CO₂ eq. / MJ. Therefore, more investigation is needed to ensure the sustainability of the process.

Besides carbon footprint, the environmental impact categories examined in biofuel LCA studies include acidification, eutrophication, toxicity, impacts on human health and ecosystems, and resource depletion. Since the reviewed LCA studies employed various methodologies to assess other environmental impacts, comparing them and providing meaningful ranges of impacts across different biofuels is difficult (Kalaivani et al., 2014). Furthermore, there is variability in the scope of the studies reviewed. Some studies focus primarily on assessing the environmental impacts of biofuels within a cradle-to-gate system boundary, which considers the stages from raw

material extraction to the point of leaving the production facility. On the other hand, certain studies adopt a broader cradle-to-grave system boundary, encompassing the entire life cycle of the biofuel, including additional stages such as use, maintenance, and end-of-life considerations. This variation in system boundaries leads to differences in the extent and depth of assessments, affecting the comprehensiveness and breadth of the environmental impact analysis (Jolliet et al., 2003). The results of the research are also influenced by assumptions about the type of vehicle in which biofuels are used (Arpornpong et al., 2015). Some studies indicate that reducing GHG emissions by using biofuels instead of fossil fuels can have negative consequences on the environment, such as increasing acidification, eutrophication, respiratory issues caused by organic and inorganic pollutants, and ecotoxicity (Arguelles-Arguelles et al., 2021; Borrión et al., 2012; Yang et al., 2021).

2.4 Bibliometric analysis of biofuel LCA

To locate pertinent publications and pinpoint gaps in research on the environmental effects of biofuel production, a Boolean search strategy was used across databases, including Web of Science (WoS), Scopus, ScienceDirect, and PubMed, to identify peer-reviewed studies on the sustainability of biofuels. The bibliometric mapping data shown in Figure 2.7 were visualized using VOSviewer software to show the co-occurrence of keywords in the literature from 2014 to 2024. Bibliometric research methodology: TOPIC: “life cycle assessment” AND TOPIC: ‘Biofuels’ OR TOPIC: ‘Bioethanol’ OR TOPIC: ‘Biodiesel’. The publications in this study were selected if they (1) revealed that LCA was performed, (2) had well-defined system boundaries, and (3) examined a set of impact (midpoint or damage) categories. A qualitative analysis was conducted once all pertinent research had been considered. The selected articles include life-cycle analysis of biofuels, geographic location, functional unit, feedstock used, impact assessment methodology, system boundaries, and findings. The review covers various biofuels from different feedstocks, classified into first-, second-, and third-generation categories, with over 25 feedstocks used. Among the selected articles, 26% evaluated first-generation biofuels, 57% evaluated second-generation biofuels, and 17% evaluated third-generation biofuels.

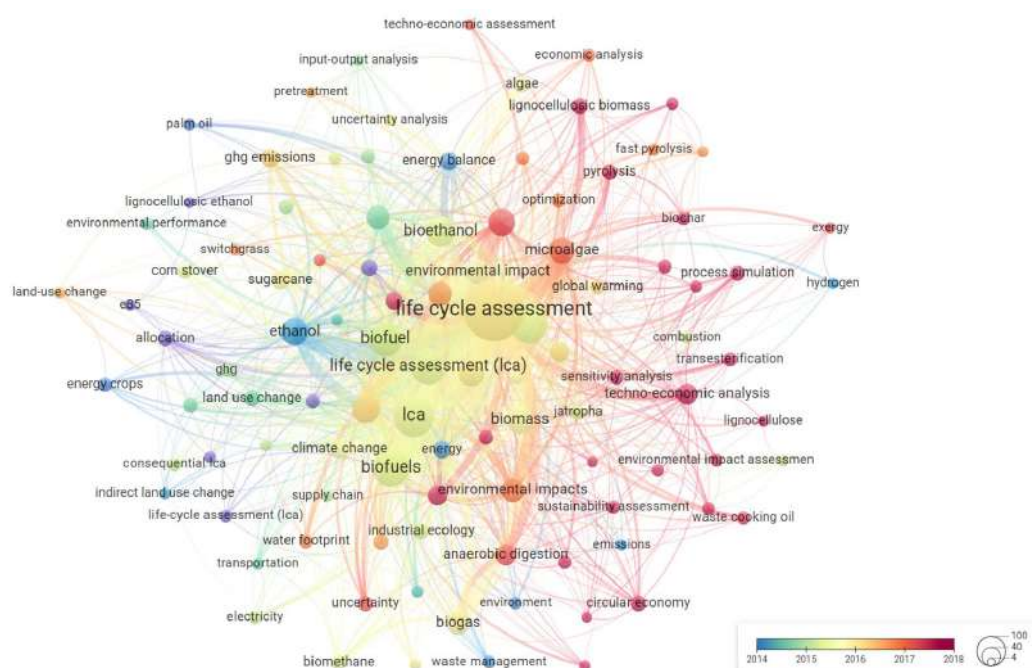


Figure 2.7 VOSviewer analysis on network visualization of prominent keywords in the literature

Over ten years (2014–2024), bibliometric mapping shows that terms such as life cycle assessment, environmental impacts, biofuel, carbon dioxide, and greenhouse effect dominate the literature. The density visualization mapping shown in Figure 2.8 shows that the literature focused on environmental impacts. The darker region indicates the focused area, and the lighter region shows the research gap in the study area that needs further research in the near future. For example, further research is needed on social life-cycle assessment, water footprint, waste management, bioeconomy, land-use change, and techno-economic analysis. The bibliometric analysis shows a diverse geographical distribution of research. The United States leads, accounting for 24% of the studies, followed by China at 12%. Europe also emerges as a significant contributor, with notable contributions from countries such as the UK (8%), Italy (6%), Spain (6%), Germany (5%), and France (3%). Moreover, emerging economies such as Brazil (8%) and India (7%) are demonstrating growing interest in this field, with significant research efforts. These findings highlight the global reach and interest in LCA studies of biofuels across different regions.

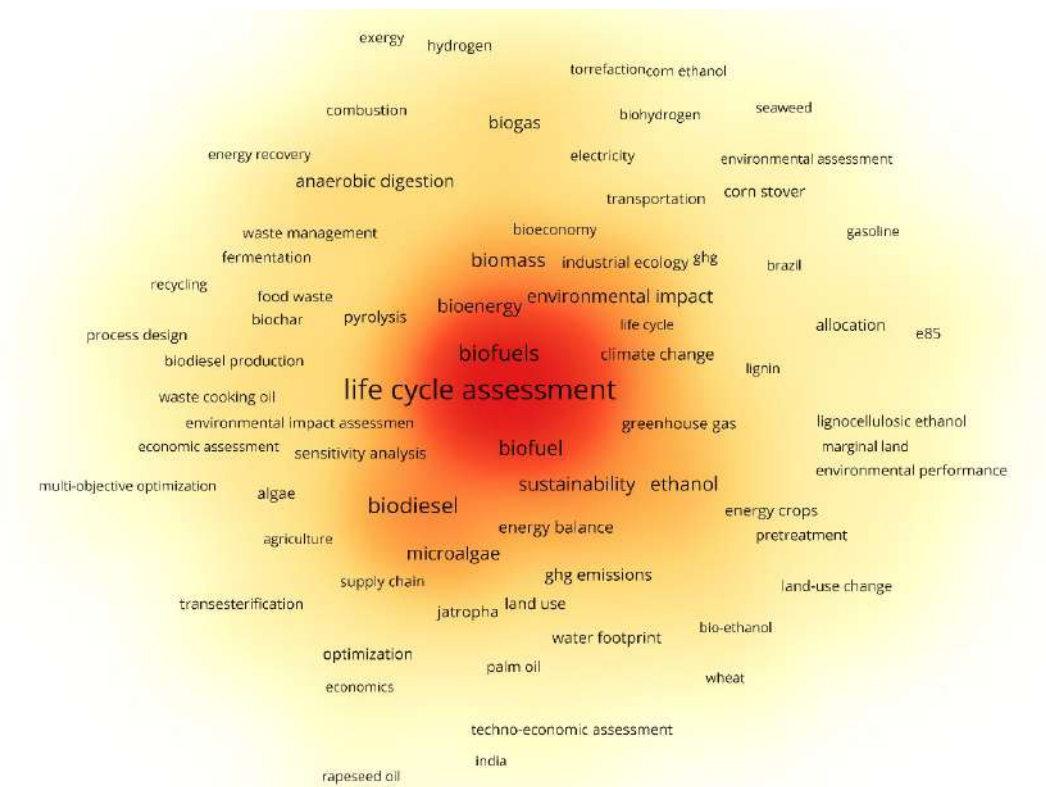


Figure 2.8 VOSviewer analysis on network visualization of prominent keywords in the literature

2.5 Challenges in biofuel LCA: Uncertainty and research gaps

Life Cycle Assessment has emerged as one of the most widely used tools for evaluating the environmental sustainability of biofuels. However, the reliability and comparability of LCA results are often influenced by uncertainties associated with methodological choices, data quality, and system assumptions. Significant variations in reported environmental impacts are observed across studies due to differences in system boundaries, functional units, allocation methods, impact assessment methodologies, and geographical conditions (Patel and Singh, 2024). For instance, studies employing cradle-to-gate boundaries may produce substantially different results from those adopting cradle-to-grave or well-to-wheel approaches, thereby affecting the overall interpretation of biofuel sustainability. Similarly, the selection of

functional units such as per MJ of energy, per litre of fuel, or per kilogram of feedstock further complicates the comparison of results across studies.

The geographical and temporal representativeness of life cycle inventory data is another important limitation affecting the reliability and comparability of biofuel LCA studies. Agricultural practices, feedstock yields, fertilizer and pesticide application rates, irrigation requirements, and energy consumption vary considerably across geographical regions due to differences in climatic conditions, soil characteristics, resource availability, and farming practices. For instance, variations in fertilizer application and crop yields can substantially influence the environmental impacts associated with feedstock cultivation, particularly global warming potential, acidification, and eutrophication. Similarly, differences in electricity generation mixes and processing technologies across regions can significantly affect the environmental performance of biofuel production systems. Temporal representativeness is equally important, as changes in agricultural productivity, energy efficiency, electricity mixes, and industrial processing technologies over time may lead to differences in estimated environmental impacts. The use of inventory data from different years or geographical regions may therefore introduce additional uncertainty, particularly when generic or global databases are used to represent region-specific production systems. Consequently, the use of geographically and temporally appropriate inventory data, along with transparent documentation of data sources and their limitations, is essential for improving the reliability, consistency, and applicability of biofuel LCA results.

The review of previous studies also indicates that the majority of biofuel LCAs primarily focus on greenhouse gas emissions as the main indicator of environmental performance. While global warming potential remains an important sustainability metric, other environmental impact categories such as acidification, eutrophication, ecotoxicity, resource depletion, and water consumption are comparatively less explored. Furthermore, growing concerns about land-use change, resource utilization, and environmental trade-offs highlight the need for a more comprehensive sustainability assessment framework.

A critical review of the literature reveals that most studies evaluate individual biofuel pathways or specific feedstocks in isolation. Comparative assessments involving multiple bioethanol and biodiesel feedstocks under a consistent

methodological framework remain limited, especially under Indian conditions. In addition, considerable variability exists in the reported environmental performance of first-, second-, and third-generation biofuels due to differences in feedstock characteristics, technological assumptions, co-product management, and energy requirements. These variations make it difficult to identify environmentally preferable biofuel pathways and support evidence-based policy decisions.

Another important gap identified in the literature is the limited application of uncertainty and sensitivity analyses. Although uncertainty arising from data variability, modeling assumptions, and inventory limitations can significantly influence LCA outcomes, only a small proportion (19%) of studies have incorporated formal approaches such as scenario analysis or Monte Carlo simulation to evaluate the robustness of their results (Patel and Singh, 2023). The absence of such analyses reduces confidence in sustainability assessments and may affect the reliability of recommendations derived from LCA studies.

Based on the reviewed literature, there is a need for a comprehensive and India-specific life cycle assessment of biofuel production pathways that integrates environmental impact assessment, energy performance evaluation, and sensitivity analysis within a unified methodological framework. Such an approach would enable a more reliable comparison of selected bioethanol and biodiesel feedstocks and contribute to the development of sustainable biofuel strategies aligned with national energy and environmental objectives.

2.6 Policy and sustainability considerations for biofuels

Biofuels are increasingly viewed as a promising solution to reduce our dependence on fossil fuels and cut down greenhouse gas emissions. But realizing their full potential requires more than just technological breakthroughs—it demands thoughtful policy frameworks and a deep understanding of their broader environmental impacts. While biofuels offer several advantages, including waste reduction and energy diversification, their sustainability depends heavily on how they are produced and managed. The shift from traditional, food-based biofuels to second-generation options—like those derived from agricultural residues or municipal waste—is a significant step forward. These sources don't compete with food supply

and help address pressing waste management challenges. For example, using rice straw or municipal solid waste not only diverts these materials from burning or landfill disposal but also helps generate clean energy. However, producing biofuels from these feedstocks still involves notable energy and water inputs. Electricity, chemical treatments, and fermentation processes can carry a considerable environmental footprint, depending on the specific methods and materials used.

Policy plays a crucial role in steering the biofuel sector toward sustainability. Effective regulations must ensure that biofuel production does not cause unintended consequences such as deforestation, biodiversity loss, or increased water stress. They should also promote the use of genuine waste materials over food crops, support research and infrastructure development, and encourage innovation in cleaner production technologies. Water usage is another critical concern. Some biofuel production processes consume far more water than fossil fuel production, raising important questions about resource sustainability, especially in water-scarce regions. Alongside water, the energy required to produce biofuels—measured through cumulative energy demand—can vary widely. While some processes are energy-efficient and yield more energy than they consume, others still depend heavily on fossil energy for processing and transport.

To make sound decisions, it's essential to use tools like life cycle assessment, which evaluate environmental impacts from start to finish. These assessments help identify 'hotspots' in the production chain where improvements can be made, such as reducing electricity use or improving enzyme production efficiency. They also bring transparency to the process, showing where policies can have the most impact. Another key element is dealing with uncertainty. Real-world conditions rarely conform to idealized models, so it's important to account for variables such as climate, feedstock availability, and changes in production efficiency. Including uncertainty analysis in environmental assessments strengthens their reliability and ensures that decisions are based on realistic expectations rather than optimistic assumptions.

Ultimately, the promise of biofuels lies in their ability to turn waste into energy while supporting climate goals and reducing environmental harm. But fulfilling that promise requires clear-eyed policies, robust sustainability assessments, and a

willingness to balance benefits against potential trade-offs. When managed wisely, biofuels can be a powerful tool in building a cleaner, more resilient energy future.

2.7 Summary

This chapter reviewed the current state of knowledge on biofuel production and its environmental sustainability from a life cycle perspective. The review covered first-, second-, and third-generation biofuels, highlighting their feedstocks, production pathways, and sustainability implications. A comprehensive assessment of previous LCA studies revealed substantial variation in environmental performance due to differences in feedstocks, system boundaries, functional units, databases, and impact assessment methodologies. The review further demonstrated that while biofuels have significant potential to reduce dependence on fossil fuels and mitigate greenhouse gas emissions, their overall sustainability depends on several factors, including feedstock selection, cultivation practices, processing technologies, resource consumption, and co-product management. The bibliometric analysis showed increasing global research interest in biofuel sustainability and identified major research themes related to life cycle assessment, environmental impacts, greenhouse gas emissions, and renewable energy systems.

The chapter also highlighted several challenges and research gaps in existing biofuel LCA studies. Although numerous investigations have evaluated individual biofuel pathways, comparative assessments of multiple bioethanol and biodiesel feedstocks using a consistent methodological framework remain limited, particularly under Indian conditions. Furthermore, most studies focus primarily on greenhouse gas emissions, while other environmental impacts, energy performance indicators, and uncertainty considerations receive comparatively less attention. Variability in methodological assumptions, data quality, and inventory databases further contributes to uncertainty in LCA results. These findings emphasize the need for a comprehensive and India-specific assessment of biofuel production pathways that integrates environmental impact evaluation, energy analysis, and sensitivity assessment. Accordingly, the subsequent chapters present the methodology and analytical framework adopted to evaluate the environmental sustainability of selected bioethanol and biodiesel pathways in India through life cycle assessment.

CHAPTER 3

METHODOLOGY

In order to achieve the goals of sustainable development, it is essential to employ robust and holistic analytical tools that support informed decision-making. Such decisions must be grounded in a systems perspective that considers the entire life cycle of a product or process, thereby accounting for all upstream and downstream environmental implications. Life Cycle Assessment is one such comprehensive tool that aligns with this approach. It evaluates environmental impacts associated with all stages of a product's life—from raw material extraction through production, use, and final disposal—making it particularly valuable for assessing sustainability in biofuel systems. This chapter outlines the methodology adopted in the present study and introduces the core ideas, frameworks, and analytical tools, particularly focusing on the use of LCA software. It sets the foundation for evaluating the environmental performance of biofuel production systems and identifying key environmental hotspots to support sustainability-oriented improvements.

Publications out of this chapter:

1. Patel, K., Singh, S.K. Environmental sustainability analysis of biofuels: a critical review of LCA studies. *Clean Techn Environ Policy* 25, 2489–2510 (2023). <https://doi.org/10.1007/s10098-023-02596-y>
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3.1 Introduction

To promote sustainable development, it is essential to use comprehensive tools that facilitate informed, system-oriented decision-making. Life Cycle Assessment is one such tool that evaluates the environmental impacts associated with all stages of a product's life—from the extraction of raw materials through processing, distribution, use, and disposal (Patel and Singh, 2024a). The LCA framework is designed to estimate several environmental impacts and identify opportunities to reduce them, while considering multiple environmental indicators such as energy consumption, land use, water use, and impacts on biodiversity. It enables the identification of potential trade-offs and environmental burdens by considering the complete life cycle rather than focusing on a single stage or process. Particularly in the context of energy systems and biofuel production, LCA provides a structured means to assess emissions, resource use, and environmental performance, making it a valuable methodology for evaluating renewable energy alternatives and supporting cleaner production pathways (Patel and Singh, 2022).

The LCA methodology follows the ISO 14040 and 14044 standards (ISO, 2006a, 2006b), which outlines a four-phase process: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. Defining the system boundary and functional unit is essential to ensure consistency and comparability across scenarios. A life cycle inventory involves compiling data on energy and material inputs and the associated environmental releases. The impact assessment stage then translates these flows into indicators representing environmental issues such as climate change, resource depletion, and ecosystem impacts. Interpretation is carried out in conjunction with each phase, ensuring that assumptions, limitations, and uncertainties are considered. This structured approach allows for transparent, reproducible, and policy-relevant sustainability analysis (Weidema et al., 2013). To strengthen the findings, uncertainty analysis using techniques such as Monte Carlo simulation and sensitivity analysis is incorporated, enabling the identification of key influencing parameters and data variability.

This chapter presents the methodological approach used to assess the sustainability of biofuel production systems in India. Figure 3.1 shows the integrated

methodological framework for assessing the environmental sustainability of biofuels in India. It outlines the tools, datasets, and analytical techniques applied to address the objectives of the study. The methodology described herein serves as the foundation for identifying environmental hotspots, guiding optimization strategies, and supporting policy and technological interventions for a more sustainable bioenergy future.

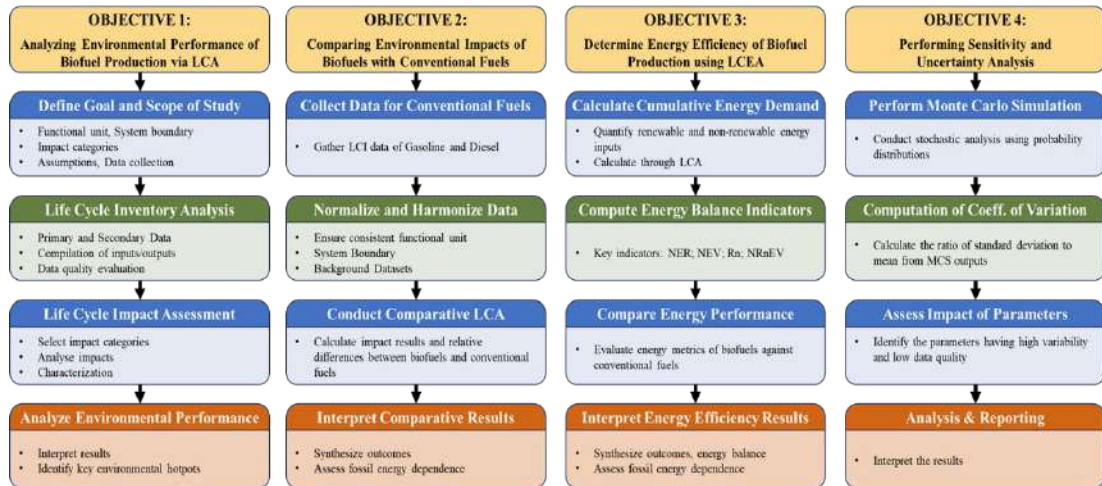


Figure 3.1 Methodological flowcharts for LCA-based biofuel sustainability assessment.

3.2 Environmental assessment using LCA

The analysis is conducted to quantify environmental impacts across different stages of the biofuel life cycle and to enable a comparative assessment of multiple feedstocks and production pathways. By applying a standardized LCA methodology, the study identifies key environmental hotspots and examines the trade-offs associated with the utilization of biofuels. The approach ensures a systematic and consistent evaluation of environmental burdens, thereby supporting informed decision-making for sustainable biofuel development.

3.2.1 Goal and scope definition

Every life cycle assessment begins by defining its goal and scope. The goal explains what the study aims to achieve, while the scope outlines what parts of the system will be included in the analysis and where its boundaries are set. This has an

important impact on the LCA, since decisions taken in subsequent LCA stages must be compatible with the target specification. Several aspects are usually considered during LCA, such as the results application and methodological choices limits, the reason for conducting the study, the target audience, comparative studies to be revealed to the public, and the commissioner of the study and other significant actors. The scope description, together with the aim definition, provides strong guidance on how the subsequent LCA phases should be conducted and how the LCA should be reported.

Goal of the study

The goal of this research is to comprehensively assess the environmental sustainability of biofuels in the Indian context using a life-cycle assessment framework, with a focus on identifying key processes and parameters that influence overall environmental impacts. The study aims to evaluate the environmental performance of multiple biofuel production pathways by quantifying impacts across the life cycle, from feedstock acquisition to fuel production. In addition, it seeks to compare the environmental implications of various feedstocks and technologies to determine more sustainable alternatives. Particular emphasis is placed on identifying environmental hotspots and understanding the contribution of critical inputs such as energy use, raw materials, and process efficiencies. This approach enables a systematic and transparent evaluation of biofuel systems, providing insights that can support sustainable development and policy decision-making in the Indian bioenergy sector.

Scope definition

The scope of this study is defined to ensure a consistent and transparent assessment of the environmental sustainability of biofuel production systems in India. A process-based life cycle assessment approach is adopted, incorporating both foreground processes (feedstock collection, transportation, and conversion) and background processes obtained from established databases. The analysis focuses on selected first-, second-, and third-generation feedstocks relevant to the Indian context. A cradle-to-gate system boundary is considered, covering all stages from raw material acquisition to biofuel production, while excluding downstream processes such as distribution and end-use. The study includes appropriate impact categories, data

sources, and modeling assumptions to ensure methodological consistency and comparability of results.

Selection of feedstocks

In selecting feedstocks for bioethanol and biodiesel production in the Indian context, a combination of technical viability, economic feasibility, environmental sustainability, and resource availability guided decision-making. For bioethanol, the first-generation feedstocks are broken rice, a byproduct of rice milling with high starch content that is suitable for fermentation without directly affecting the edible rice supply, and sugarcane molasses, a residual syrup from sugar production rich in fermentable sugars, making it an efficient and economical substrate for ethanol production. Second-generation feedstocks include agricultural residues such as rice straw, corn stover, and cassava straw—abundantly available in Indian agricultural systems and representing an opportunity to convert waste into valuable fuel. Municipal solid waste (MSW), also classified as a second-generation feedstock, was selected for its high organic content and potential to support urban waste reduction and circular economy initiatives.

For biodiesel, the first-generation feedstocks include rapeseed, palm oil, and palm stearin. While rapeseed is an edible oil crop, its cultivation is widespread in India, and its oil content makes it suitable for biodiesel production under controlled usage to avoid food-fuel conflict. Palm oil, derived from oil palm fruit, is one of the highest-yielding vegetable oils globally and provides a cost-effective, efficient raw material for biodiesel production due to its high oil productivity per hectare. Palm stearin, a solid byproduct of palm oil refining, is non-edible and offers industrial-scale potential without expanding palm cultivation. The second-generation feedstocks include jatropha and used cooking oil (UCO). Jatropha is a non-edible oilseed that can thrive on marginal lands and is well-suited to India's diverse climates. At the same time, UCO represents a valuable waste stream from urban areas, reducing disposal issues and enabling low-cost biodiesel production. Microalgae, chosen as a third-generation feedstock, stand out for their high lipid content, rapid growth, and minimal land or freshwater requirements, making them a promising long-term solution for biodiesel sustainability. This tiered selection strategy ensures the use of underutilized or waste

materials, minimizes competition with food production, and supports India's goals for renewable energy and resource efficiency. Feedstocks were selected with a clear focus on minimizing environmental impacts across the biofuel life cycle. Emphasis was placed on non-edible, waste-based, and low-input resources to limit land-use change, water use, and emissions, ensuring the LCA reflects realistic, scalable, and environmentally sustainable options for biofuel production in India.

Functional unit

The functional unit provides a reference basis for quantifying and comparing environmental impacts across different biofuel production systems. In this study, the functional unit is defined as the production of 1 kg of biofuel. This ensures consistency and enables a direct comparison of environmental impacts among different feedstocks and production pathways.

System boundary

A system boundary is essential for capturing the full scope of environmental impacts, including land-use changes, cultivation, harvesting, processing, transportation, and combustion. These boundary choices significantly influence the outcomes of biofuel LCAs and must be aligned with the study's objective to ensure transparency and relevance. In this study, the system boundary is defined as cradle-to-gate. Post-gate stages, such as distribution, storage, and combustion, are excluded due to variability in usage conditions and end-use technologies, which fall outside the production-focused scope of this analysis.

3.2.2 Life cycle inventory

Life Cycle Inventory analysis plays a foundational role within the broader Life Cycle Assessment framework, serving as the quantitative backbone that accounts for all relevant energy and material flows associated with a product system. LCI involves systematically compiling and evaluating inputs (such as resources and energy) and outputs (such as emissions and waste) for each unit process in a product's life cycle. These data are scaled to a functional unit, which represents the specific performance of a product system, ensuring comparability across different studies. The

quality of LCI results hinges on two key components: the system model used to represent the product system and the inventory data. Robust LCI data are typically transparent, comprehensive, consistent, timely, and third-party verified, enabling reliable downstream impact assessment (Arvidsson and Ciroth, 2021). In this study, the inventory data were sourced from operational distilleries and supplemented with information from published literature. Background data, including upstream processes and broader system flows, were obtained from the ecoinvent database to ensure consistency, completeness, and alignment with standard LCI practices. Table 3.1 presents the inventory data sources used for each selected bioethanol and biodiesel feedstock.

Table 3.1 Inventory data sources for the selected bioethanol and biodiesel feedstocks.

Feedstock	Inventory data source
Bioethanol	
Molasses	Published papers: (Rathnayake et al., 2018; Sujata et al., 2021); Ecoinvent database (Wernet et al., 2016)
Broken Rice	Primary data; Published reports: (Monceaux and Kuehner, 2009; Paramarsh, 2022; RBBPL, 2020); Ecoinvent database (Wernet et al., 2016)
Rice Straw	Published papers: (Hassan et al., 2021; Peng et al., 2023; Soam et al., 2016); Ecoinvent database (Wernet et al., 2016)
Corn Stover	Published papers: (Daylan and Ciliz, 2016; Mata et al., 2022; Zhao et al., 2019); Ecoinvent database (Wernet et al., 2016)
Cassava Straw	Published papers: (Lyu et al., 2020; Rathnayake et al., 2018); Ecoinvent database (Wernet et al., 2016)
MSW	Published papers: (Gunarathne et al., 2019; Shakelly et al., 2023); Ecoinvent database (Wernet et al., 2016)
Biodiesel	
Rapeseed	Published report: (IEA, 2021); Published paper: (Gupta et al., 2022); Ecoinvent database (Wernet et al., 2016)
Palm Oil	Primary data; Published papers: (Gheewala et al., 2022; Yung et al., 2020; Zulqarnain et al., 2021); Ecoinvent database (Wernet et al., 2016)
Palm Stearin	Primary data; Published papers: (Gheewala et al., 2022; Yung et al., 2020; Zulqarnain et al., 2021); Ecoinvent database (Wernet et al., 2016)
Jatropha	Published report: (IEA, 2021); Published paper: (Ajayebi et al., 2013); Ecoinvent database (Wernet et al., 2016)
UCO	Published paper: (Foteinis et al., 2020; Talens Peiró et al., 2010); Ecoinvent database (Wernet et al., 2016)
Microalgae	Published papers: (Bradley et al., 2023; Gnansounou and Kenthorai Raman, 2016; Nazloo et al., 2022); Ecoinvent database (Wernet et al., 2016)

The process of LCI analysis includes constructing a flow chart of the product system, gathering data for each process, conducting calculations to quantify flows, and interpreting the results (Ciroth and Burhan, 2021). Despite its complexity, LCI remains crucial in identifying environmental hotspots and informing improvements in product design and policy. As such, LCI analysis is not just a technical exercise but a strategic tool to guide decision-making toward more sustainable systems.

3.2.3 Life cycle impact assessment

Life Cycle Impact Assessment is a pivotal phase within the broader methodology of LCA, serving to translate complex life cycle inventory data into understandable environmental impact indicators. Developed through decades of scientific advancement and standardization efforts by bodies such as ISO and SETAC, LCIA encompasses both quantitative modeling and value-based interpretation. Its foundation lies in the careful selection of relevant impact categories—such as climate change, acidification, or human toxicity—and the classification of inventory flows (like emissions or resource use) into these categories based on their environmental relevance (Hauschild and Huijbregts, 2015). Characterization models are then applied to convert raw data into impact scores using scientifically derived factors, enabling a meaningful assessment of a product or process's environmental footprint.

In this study, the ReCiPe 2016 method is used to perform impact assessment in order to quantify the potential environmental impacts associated with the system under investigation. ReCiPe 2016 is a widely accepted impact assessment framework that translates life cycle inventory data into a comprehensive set of midpoint and endpoint impact indicators, enabling a robust and scientifically grounded evaluation of environmental burdens. The method integrates both problem-oriented (midpoint) and damage-oriented (endpoint) approaches, allowing for detailed analysis at different levels of environmental cause-and-effect chains. Figure 3.2 provides an overview of the impact categories covered in the ReCiPe2016 methodology and their relation to the areas of protection. The selection of impact categories in this study was based on their relevance to the major environmental burdens associated with biofuel production and use, their applicability to the feedstocks and conversion processes considered, and the availability of reliable inventory data and established characterization factors.

Particular emphasis was placed on impact categories that can capture the environmental effects of feedstock cultivation, fertilizer and agrochemical use, energy consumption, processing, transportation, and fuel utilization. This selection also enables the identification of potential environmental trade-offs among the different biofuel pathways rather than evaluating their performance based on a single impact category.

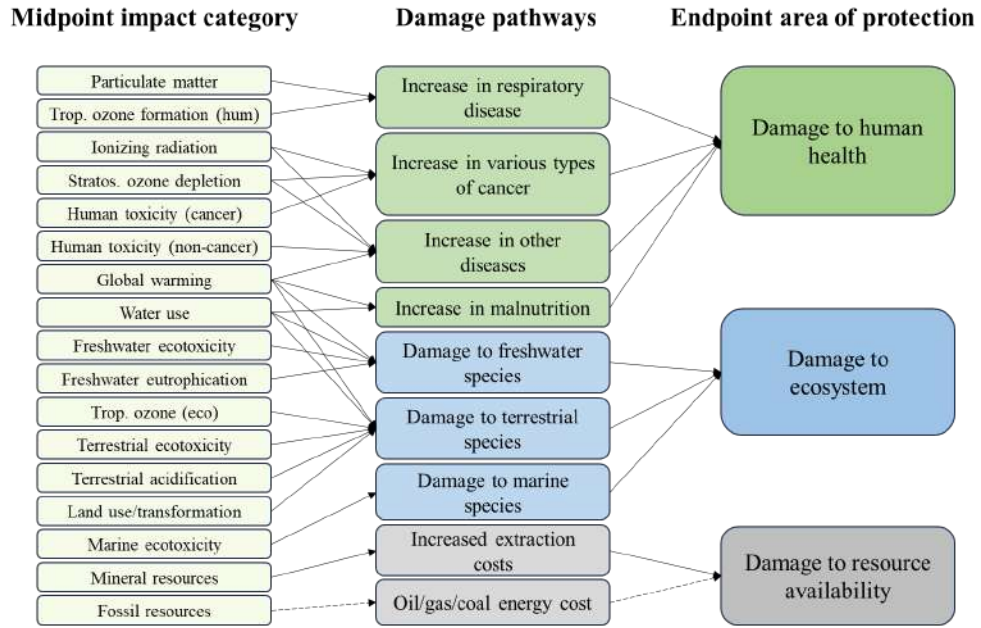


Figure 3.2 ReCiPe 2016 LCIA framework

In the ReCiPe 2016 environmental impacts are quantified by converting life cycle inventory flows into midpoint impact indicators using characterization factors specific to the method. The impact score for a given category k is:

$$I_k = \sum_{i=1}^n (LCI_i \times CF_{i,k}) \quad (1)$$

Where:

- I_k = Impact score for impact category k
- LCI_i = Life Cycle Inventory flow i (e.g., emissions, resource use)
- $CF_{i,k}$ = Characterization factor of flow i for category k
- n = Total number of inventory flows

At the midpoint level, environmental impacts are characterized into specific categories such as climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine ecotoxicity, human toxicity, and fossil resource scarcity. These categories were considered because the investigated biofuel pathways can influence climate change through GHG emissions, acidification and eutrophication through agricultural and process-related emissions, toxicity-related impacts through chemical and pollutant releases, and resource scarcity through fossil-energy and material requirements. Thus, the selected categories are directly linked to the major emission and resource-use pathways within the defined system boundary. These indicators provide a detailed understanding of how individual emissions and resource extraction contribute to distinct environmental problems. At the endpoint level, these midpoint impacts are further aggregated into damage categories, namely human health, ecosystem quality, and resource availability, thereby offering a more interpretable representation of overall environmental consequences. Categories that were outside the defined system boundary or for which sufficiently robust and comparable inventory information was not available were not given additional emphasis. Therefore, the final selection represents a balance between environmental relevance, methodological consistency, and data availability. A summary of the ReCiPe 2016 midpoint impact categories, along with their corresponding units and descriptions, is presented in Table 3.2.

These midpoint results can be further aggregated into endpoint damage categories, such as human health, ecosystem quality, and resource scarcity, providing an integrated assessment of environmental burdens.

$$D_j = \sum_{k=1}^m (I_k \times DF_{k,j}) \quad (2)$$

Where:

- D_j = Damage indicator (e.g. human health, ecosystem quality)
- $DF_{k,j}$ = Damage factor linking midpoint category k to endpoint j

Table 3.2 ReCiPe 2016 midpoint impact categories with units and descriptions.

Midpoint Impact Category	Unit	Description
Climate Change	kg CO ₂ eq	Quantifies the radiative forcing effects of greenhouse gas emissions over a specified time horizon (typically 100 years), contributing to global temperature increase and associated climatic changes.
Ozone Depletion	kg CFC-11 eq	Assesses the potential of emitted substances to degrade the stratospheric ozone layer, thereby increasing ultraviolet (UV-B) radiation reaching the Earth's surface.
Ionizing Radiation	kBq Co-60 eq	Evaluates the potential human exposure to ionizing radiation from radionuclide releases, considering long-term radiological impacts on health.
Fine Particulate Matter Formation	kg PM2.5 eq	Represents the formation of secondary particulate matter (PM2.5) from precursor emissions, which are associated with adverse respiratory and cardiovascular health outcomes.
Photochemical Ozone Formation (Human Health)	kg NOx eq	Quantifies the formation of ground-level ozone due to precursor emissions (e.g., NOx and VOCs), contributing to photochemical smog and its impacts on human health.
Photochemical Ozone Formation (Terrestrial Ecosystems)	kg NOx eq	Assesses ozone formation and its phytotoxic effects on vegetation, including reduced crop yields and ecosystem productivity.
Terrestrial Acidification	kg SO ₂ eq	Measures the deposition of acidifying substances leading to soil acidification, nutrient leaching, and adverse impacts on terrestrial biodiversity.
Freshwater Eutrophication	kg P eq	Evaluates the contribution of phosphorus-based emissions to nutrient enrichment in freshwater bodies, promoting algal blooms and subsequent ecological imbalance.

Midpoint Impact Category	Unit	Description
Terrestrial Ecotoxicity	kg 1,4-DCB eq	Assesses the potential toxic effects of chemical emissions on terrestrial organisms, considering fate, exposure, and species sensitivity.
Freshwater Ecotoxicity	kg 1,4-DCB eq	Evaluates the ecotoxicological impacts of pollutants on freshwater ecosystems, incorporating bioavailability and species-specific toxicity responses.
Marine Ecotoxicity	kg 1,4-DCB eq	Quantifies toxic impacts of chemical substances on marine biota, accounting for transport, dilution, and persistence in marine environments.
Human Carcinogenic Toxicity	kg 1,4-DCB eq	Represents the potential increase in lifetime cancer risk in humans due to exposure to carcinogenic substances released throughout the life cycle.
Human Non-Carcinogenic Toxicity	kg 1,4-DCB eq	Assesses the potential for non-cancer health effects in humans resulting from chronic exposure to toxic substances.
Fossil Resource Scarcity	kg oil eq	Measures the depletion of fossil energy carriers by assessing the marginal increase in extraction costs associated with resource consumption.
Water Consumption	m ³	Accounts for net freshwater consumption, considering regional water scarcity and its implications for ecosystem integrity and human water availability.

Normalization

To support better comparison and interpretation of impact results, LCIA also includes optional steps such as normalization. Normalization contextualizes the magnitude of each impact by comparing it to a reference system, often the average environmental load of a region or population, providing insight into the relative importance of different categories (Guinée, 2015). This converts results into dimensionless values, allowing comparison across different impact categories and helping identify the most significant environmental issues. Table 3.3 shows the normalization factors used in ReCiPe 2016 to express impact category results relative to a defined reference system, thereby improving interpretation. Following normalization, the normalized impact scores are calculated by dividing each category indicator by its corresponding reference value, as expressed below:

$$I_k^{norm} = \frac{I_k}{N_k} \quad (3)$$

Where:

- I_k = Impact score for impact category k
- N_k = Normalization reference

In addition to the ReCiPe 2016 method, the IMPACT 2002+ or IMPACT World+ method was also applied to evaluate environmental impacts in selected cases. This was done to enable cross-method comparison and to capture endpoint-oriented impact categories, particularly those related to human health and ecosystem quality.

Table 3.3 Normalization factors for midpoint impact categories as per ReCiPe 2016.

Impact Category	Normalization
Water consumption	0.00375
Terrestrial ecotoxicity	6.58E-5
Terrestrial acidification	0.0244
Stratospheric ozone depletion	16.7
Ozone formation, Terrestrial ecosystems	0.0563
Ozone formation, Human health	0.0486
Marine ecotoxicity	0.023
Ionizing radiation	0.00208
Human non-carcinogenic toxicity	3.20E-5
Human carcinogenic toxicity	0.0971
Global warming	0.000125
Freshwater eutrophication	1.54
Freshwater ecotoxicity	0.0397
Fossil resource scarcity	0.00102
Fine particulate matter formation	0.0391

3.3 Energy analysis

Energy analysis is a core component of LCA for biofuels, offering critical insight into the sustainability and efficiency of alternative fuel systems. It involves the evaluation of all energy inputs and outputs across the production chain—from raw material acquisition through processing, distribution, and use (Wahyono et al., 2023). The goal is to determine whether the energy delivered by the biofuel exceeds the energy invested in its production, a concept often quantified using indicators such as Net Energy Ratio (NER), Cumulative Energy Demand (CED), and Net Energy Value (NEV).

3.3.1 Cumulative energy demand

In this study, the CED method has been employed to perform the life cycle energy analysis of biofuel production from various feedstocks. The CED approach quantifies the total amount of primary energy required throughout the entire production chain, from raw material acquisition to final fuel output. By applying this method, we captured both direct and indirect energy inputs at each stage of the biofuel life cycle, enabling a comprehensive assessment of the energy intensity of different

feedstock pathways. This analysis serves as a foundation for identifying energy hotspots and evaluating the overall efficiency and sustainability of biofuel production systems (Dasan et al., 2019; Patel and Singh, 2024a). It distinguishes between different energy sources such as renewable (e.g., biomass, solar) and non-renewable (e.g., fossil fuels, nuclear), providing insight into resource depletion and environmental impacts. A summary of CED indicators and their meanings is provided in Table 3.4 to clarify the significance of each energy category assessed.

Table 3.4 Cumulative Energy Demand indicators and their significance in Life Cycle Assessment

CED Indicator	Significance / Meaning
Non-renewable, fossil energy	- Represents energy from fossil fuels such as coal, oil, and natural gas - Indicates dependency on depleting resources - Major contributor to greenhouse gas emissions and environmental impacts
Non-renewable, nuclear energy	- Energy derived from uranium and nuclear processes - Reflects reliance on finite nuclear resources - Associated with radioactive waste and long-term environmental concerns
Non-renewable, biomass energy	- Refers to biomass used at a rate faster than its natural regeneration (unsustainable use) - Indicates depletion of biological resources such as forests - Associated with land-use change, biodiversity loss, and ecological imbalance
Renewable, biomass energy	- Energy obtained from organic materials like wood, crop residues, and agricultural biomass - Considered sustainable if managed properly - Can reduce dependence on fossil fuels
Renewable, water energy	- Energy generated from water sources such as rivers and reservoirs - Indicates use of hydropower in the system - Sensitive to climate variability and water availability
Renewable, wind/solar/geothermal energy	- Combined category of clean energy sources including wind, solar, and geothermal - Low environmental impact and low emissions - Wind and solar are intermittent, while geothermal is more stable - Represents transition toward sustainable energy systems

A high CED can be a red flag, especially if the energy comes from non-renewable sources, thus diminishing the environmental benefits of biofuels (Firrisa et al., 2014). Despite the appeal of biofuels as renewable alternatives, energy analysis frequently reveals systemic inefficiencies in their production. High energy demands in stages such as cultivation, processing, and refining can erode the environmental benefits they aim to deliver. Furthermore, the type and source of energy used during production play a pivotal role. For instance, reliance on fossil-derived inputs can significantly offset the reductions in greenhouse gas emissions achieved through biofuel use (Patel and Singh, 2023).

3.3.2 Energy performance indicators

Assessing the energy balance in LCA of biofuel production commonly involves considering four factors: renewability (Rn), net energy ratio, net renewable energy value (NRnEV), and net energy value (Wahyono et al., 2023). Table 3.5 shows the methods for calculating energy balance. The energy input value corresponds to the cumulative energy demand, and the energy output value corresponds to the energy content of biofuel and its co-products (Frischknecht et al., 2015).

Table 3.5 Energy balance parameters.

Parameter	Formula	Reference
NEV	Energy content of biofuel (and its co-products) – Net energy input	Silalertruksa et al. (2012); Wahyono et al. (2023); Gheewala et al. (2022)
NRnEV	Energy content of biofuel (and its co-products) – Fossil energy inputs	
NER	Net energy outputs / Net energy inputs	
Rn	Net energy outputs / Net fossil energy inputs	

Energy analysis within LCA frameworks is indispensable for evaluating the technical and environmental viability of biofuel systems. It allows stakeholders to identify energy-intensive hotspots, compare production pathways, and make informed decisions to optimize energy performance while minimizing ecological footprints. Integrating energy analysis with economic and environmental assessments thus provides a comprehensive approach to developing truly sustainable biofuel technologies.

3.4 Sensitivity and uncertainty analysis

In life cycle assessment studies of biofuels, sensitivity analysis plays a crucial role in evaluating the robustness and reliability of environmental impact results. Among the various approaches, Monte Carlo Simulation (MCS) is widely employed as a probabilistic sensitivity analysis tool (Hughes et al., 2013). It systematically accounts for variability and uncertainty in input data by running the LCA model multiple times using randomly sampled inputs drawn from specified distributions. This allows researchers to capture the range and distribution of potential outcomes, rather than relying on single-point estimates. The application of MCS in LCA enhances the credibility of the results by quantifying the confidence level in impact categories such as global warming potential, human toxicity, or cumulative energy demand. Thus, it provides valuable insights into how uncertainties in inventory data might influence the overall environmental performance of biofuel systems (Patel and Singh, 2024a). The MCS incorporated a pedigree matrix. The overall uncertainty was determined by combining both basic and additional uncertainties. Initially, data quality indicators were assigned based on the characteristics of the data inventory. Each input parameter was given an uncertainty value between 1 (highest quality) and 5 (lowest quality) based on its pedigree, reflecting the data quality of that parameter. This method was applied not only to the background data from Ecoinvent but also to the inventories, including literature data on biofuel production processes. This approach was used to assign uncertainty levels based on critical data quality indicators such as reliability, completeness, and alignment with the study's time frame to ensure variability and uncertainty. The variance of total uncertainty was calculated using the following formula by (Frischknecht et al., 2005).

$$\sigma_t^2 = \exp^{\sqrt{\ln(U_1)^2 + \ln(U_2)^2 + \ln(U_3)^2 + \ln(U_4)^2 + \ln(U_5)^2 + \ln(U_b)^2}} \quad (4)$$

where: σ_t^2 = variance for total uncertainty

U_1 = uncertainty factor of reliability

U_2 = uncertainty factor of completeness

U_3 = uncertainty factor of temporal correlation

U_4 = uncertainty factor of geographic correlation

U_5 = uncertainty factor of other technological correlation

U_b = basic uncertainty factor

Lognormal distribution was employed for MCS as it was commonly found in actual populations (Weidema et al., 2013). This reflects the fact that environmental systems typically exhibit multiplicative rather than additive effects, leading to a lognormal distribution (Sonnemann et al., 2003). Uncertainty in each impact category is typically quantified by the ratio of the standard deviation to the mean. The IPCC suggests a ratio greater than 0.3 indicates considerable uncertainty (Sharma et al., 2019).

Apart from probabilistic methods, another important approach in sensitivity analysis involves extending the system boundary of the LCA. This method assesses how changes in the inclusion or exclusion of life-cycle stages or co-products affect overall environmental outcomes. For example, incorporating avoided products—those displaced by the use of biofuels—into the analysis can significantly alter the interpretation of net impacts (Patel and Singh, 2024b). This extended boundary approach is particularly useful for highlighting the environmental benefits of waste-derived biofuels, where the substitution of conventional waste disposal or fossil energy sources improves the system's sustainability profile. Together, Monte Carlo simulation and boundary extension methods offer a comprehensive and multifaceted view of sensitivity in biofuel LCA, aiding more informed and resilient decision-making.

The results of the Monte Carlo simulation are commonly presented using probability distribution plots to effectively visualize the variability and uncertainty associated with impact categories in Life Cycle Assessment. These figures typically combine histograms with fitted probability distribution curves (e.g., normal or lognormal) and cumulative probability functions to provide a comprehensive representation of the data. The histogram illustrates the frequency of simulated outcomes, while the distribution curve highlights the central tendency and spread of results. In addition, cumulative probability curves help assess the likelihood that results fall within a specific range. Key statistical indicators such as mean, standard deviation, and percentile ranges (e.g., 5th and 95th percentiles) are often included to define confidence intervals and quantify uncertainty. Figure 3.3 illustrates the probability distribution of impact results obtained from a Monte Carlo simulation, highlighting the uncertainty and variability within the LCA.

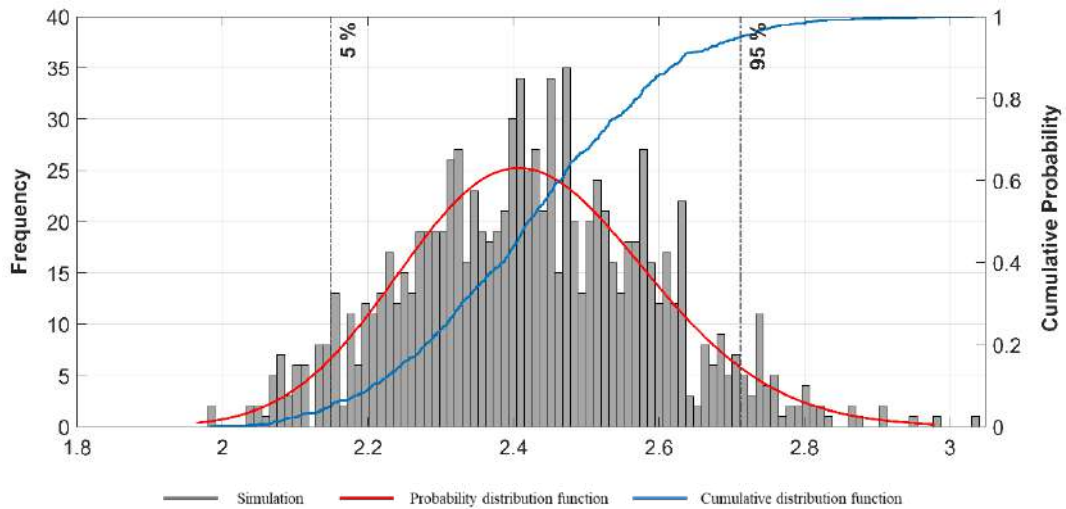


Figure 3.3 Probability distribution of life cycle impact results obtained from MCS, illustrating variability, cumulative probability, and uncertainty range (5th–95th percentile) in LCA.

3.5 Data analysis and visualization

Data analysis and visualization are essential for converting complex datasets into clear, actionable insights. Tools such as SimaPro and openLCA are used to conduct detailed life-cycle assessments, enabling systematic evaluation of environmental impacts. MATLAB is specifically used for Monte Carlo Simulation, supporting uncertainty analysis and probabilistic modeling to better understand data variability. For visualization, OriginPro is used to create high-quality graphs and plots that effectively communicate results. This combination of analytical and visualization tools ensures both rigorous data processing and clear presentation of findings.

3.5.1 SimaPro

SimaPro 9.4 plays a central role in enabling comprehensive life cycle assessment of systems and processes (Figure 3.4). It allows modeling complex product systems by defining detailed inputs, outputs, and interconnected process chains, and facilitates the evaluation of environmental impacts across multiple categories, such as global warming potential, resource depletion, and human health effects (Figure 3.5). It also supports the comparison of alternative scenarios and identification of environmental hotspots, contributing to more informed decision-making and

alignment with internationally recognized LCA methodologies. The details of the software will be available in <https://simapro.com/wp-content/uploads/2022/07/FullUpdateInstructionsToSimaPro940.pdf>.

File

Edit

Calculate

Tools

Window

Help

A=B

D+A 42

Documentation

Input/output

Parameters

System description

Products

Outputs to technosphere: Products and co-products

Amount

Unit

Quantity

Waste type

Allocation

Category

Comment

Bioethanol_Molasses

1

ton

Mass

not defined

100 %

Others[Mol...

Add line

Outputs to technosphere: Avoided products

Amount

Unit

Distribution

SD2 or 2SD

Min

Max

Comment

Add line

Inputs

Inputs from nature

Subcompartment

Amount

Unit

Distribution

SD2 or 2SD

Min

Max

Comment

Chlorine

(unspecified)

0.38

kg

Undefined

Water, unspecified natural origin[m3]

(unspecified)

11000

l

Undefined

Add line

Inputs from technosphere: materials/fuels

Amount

Unit

Distribution

SD2 or 2SD

Min

Max

Comment

Sulfuric acid (RoW) market for sulfuric acid | Cut-off, U

0.41

kg

Undefined

Magnesium sulfate (GLO) market for magnesium sulfate | Cut-off, U

0.11

kg

Undefined

Urea, as N (GLO) market for urea, as N | Cut-off, U

1.3

kg

Undefined

Phosphoric acid, industrial grade, without water, in 85% solution state (GLO) market for phosph...

0.14

kg

Undefined

Soda ash, light (GLO) market for soda ash, light | Cut-off, U

0.06

kg

Undefined

Sodium hydroxide, without water, in 50% solution state (GLO) market for sodium hydroxide, wit...

0.6

kg

Undefined

Fodder yeast (GLO) market for fodder yeast | Cut-off, U

2

kg

Undefined

Enzymes (GLO) market for enzymes | Cut-off, U

0.22

kg

Undefined

Add line

Inputs from technosphere: electricity/heat

Amount

Unit

Distribution

SD2 or 2SD

Min

Max

Comment

Steam, in chemical industry (RoW) market for steam, in chemical industry | Cut-off, U

2.5

ton

Undefined

Electricity, medium voltage [IN-Northern grid] market for electricity, medium voltage | Cut-off, U

990

kWh

Undefined

Add line

Outputs

Emissions to air

Subcompartment

Amount

Unit

Distribution

SD2 or 2SD

Min

Max

Comment

Carbon dioxide

(unspecified)

180

kg

Undefined

Add line

Emissions to water

Subcompartment

Amount

Unit

Distribution

SD2 or 2SD

Min

Max

Comment

Figure 3.4 Picture of SimaPro software platform.

Select	Impact category	Unit	Total	Bioethanol, Molasses	Sulfuric acid (RoW)	Magnesium sulfate (GLO)	Urea, as N (GLO)	Phosphoric acid, industrial grade	Soda ash, light (GLO)	Sodium hydroxide, without water	Fodder yeast (GLO)	Enzymes (GLO)	Steam, in chemical industry	Electricity, medium voltage
☒	Global warming	kg CO2 eq	2.4	0.18	6.91E-5	9.9E-5	0.00613	0.000197	2.65E-5	0.000807	0.00596	0.00237	0.886	1.32
☒	Stratospheric ozone depletion	kg CFC11 eq	4.57E-7	x	3.66E-11	4.21E-11	8.05E-10	5.59E-11	6.95E-12	3.75E-10	2.79E-8	1E-8	9.72E-8	3.2E-7
☒	Ionizing radiation	kBq Co-60 eq	0.0388	x	3.68E-6	1.68E-6	8.76E-5	8.11E-6	1.01E-6	8.09E-5	0.000125	0.000282	0.00588	0.0323
☒	Ozone formation, Human health	kg NOx eq	0.00409	x	4.01E-7	5.46E-7	8.65E-6	6.25E-7	8.33E-8	2.14E-6	1.05E-5	7.84E-6	0.00124	0.00282
☒	Fine particulate matter formation	kg PM2.5 eq	0.00402	x	1.06E-6	2.26E-7	6.69E-6	1.13E-6	7.22E-8	1.64E-6	8.55E-6	4.09E-6	0.000784	0.00321
☒	Ozone formation, Terrestrial ecosystems	kg NOx eq	0.00421	x	4.12E-7	5.6E-7	9.22E-6	6.48E-7	8.51E-8	2.19E-6	1.1E-5	8.09E-6	0.00134	0.00285
☒	Terrestrial acidification	kg SO2 eq	0.00612	x	3.42E-6	4.47E-7	2E-5	3.43E-6	2.39E-7	2.93E-6	3.56E-5	1.95E-5	0.00205	0.00398
☒	Freshwater eutrophication	kg P eq	0.0016	x	1.14E-7	3.49E-8	1.57E-6	2.43E-7	1.58E-8	4.99E-7	1.75E-6	1.6E-6	0.000132	0.00146
☒	Marine eutrophication	kg N eq	9.44E-5	x	3.04E-9	5.39E-9	2.05E-7	7.41E-9	8.11E-10	3.68E-8	4.93E-6	3.4E-6	7.81E-6	7.8E-5
☒	Terrestrial ecotoxicity	kg 1,4-DCB eq	3.81	x	0.00351	0.000267	0.000964	0.0022	0.000125	0.00213	0.0126	0.0111	2.93	0.838
☒	Freshwater ecotoxicity	kg 1,4-DCB eq	0.0504	x	8.23E-5	8.82E-6	0.000228	6.04E-5	3.45E-6	5.08E-5	0.000193	0.00019	0.00612	0.0434
☒	Marine ecotoxicity	kg 1,4-DCB eq	0.0703	x	0.000105	1.14E-5	0.000298	8.05E-5	4.47E-6	6.68E-5	0.000248	0.000189	0.00973	0.0596
☒	Human carcinogenic toxicity	kg 1,4-DCB eq	0.218	x	4.36E-5	1.69E-5	0.000714	0.000613	8.99E-6	0.00018	0.000736	0.000447	0.0495	0.166
☒	Human non-carcinogenic toxicity	kg 1,4-DCB eq	2.14	x	0.00164	0.000273	0.00516	0.00122	7.66E-5	0.00132	0.00408	0.00534	0.267	1.85
☒	Land use	m2a crop eq	0.054	x	7.09E-6	2.61E-6	0.00011	5.32E-5	2E-6	2.25E-5	0.0201	0.00162	0.00647	0.0256
☒	Mineral resource scarcity	kg Cu eq	0.00093	x	5.45E-6	3.64E-6	1.75E-5	9.18E-6	2.38E-7	2.94E-6	1.71E-5	1.18E-5	0.000393	0.00047
☒	Fossil resource scarcity	kg oil eq	0.589	x	1.94E-5	2.67E-5	0.00173	4.72E-5	5.85E-6	0.00021	0.000866	0.00058	0.261	0.325
☒	Water consumption	m3	0.019	0.011	5.65E-6	4.37E-7	0.000239	1.69E-5	9.48E-7	1.22E-5	8.86E-5	0.000279	0.000807	0.00652

Figure 3.5 SimaPro data output.

3.5.2 openLCA

openLCA 1.11.0 provides a flexible and transparent platform for conducting life cycle assessments (Figure 3.6). It is particularly useful for working with diverse databases and impact assessment methods, allowing models to be tailored to specific study requirements. It is also effectively used in conjunction with Monte Carlo Simulation approaches, supporting the generation and analysis of multiple MCS iterations to better capture uncertainty and variability in life cycle impact results (Figure 3.7). The details of the software will be available in <https://www.openlca.org/about/>.

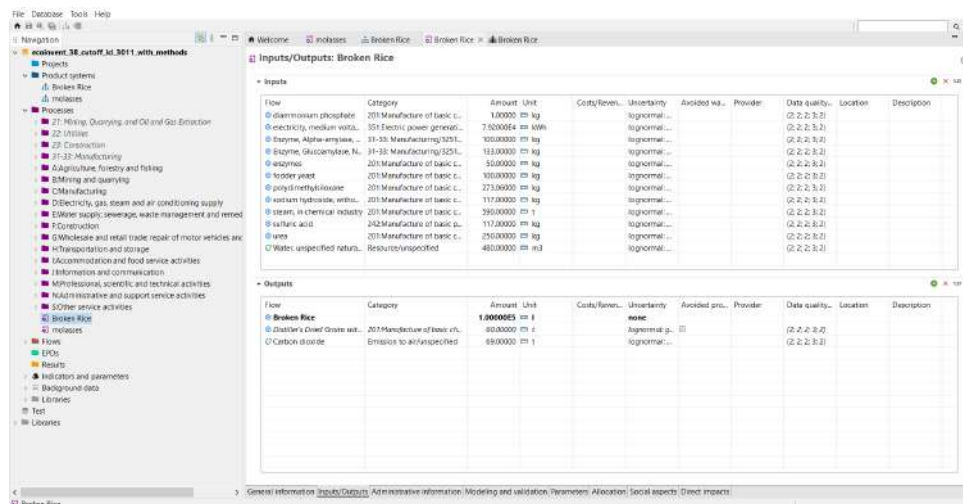


Figure 3.6 Data feeding in openLCA software

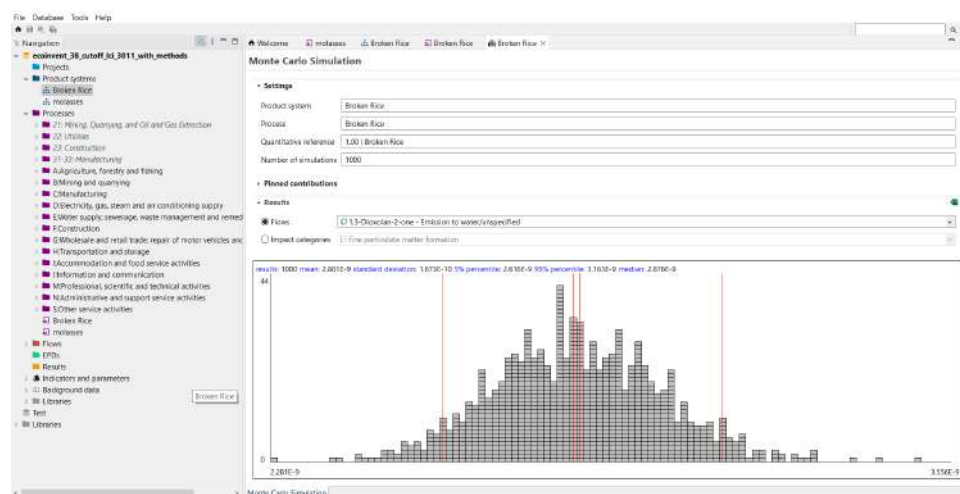


Figure 3.7 MCS output in openLCA

3.5.3 MATLAB

MATLAB is widely recognized for its broad range of applications in numerical computing, data analysis, modeling, and visualization (Figure 3.8). In this context, it is used in MCS, particularly to generate the large number of iterations required for uncertainty analysis. This approach enhances the robustness of the results by moving beyond single-point estimates and enabling detailed sensitivity analysis (Figure 3.9), while also supporting efficient handling of complex, large-scale data. The details of the software will be available in

https://www.mathworks.com/products/new_products/release2022b.html.

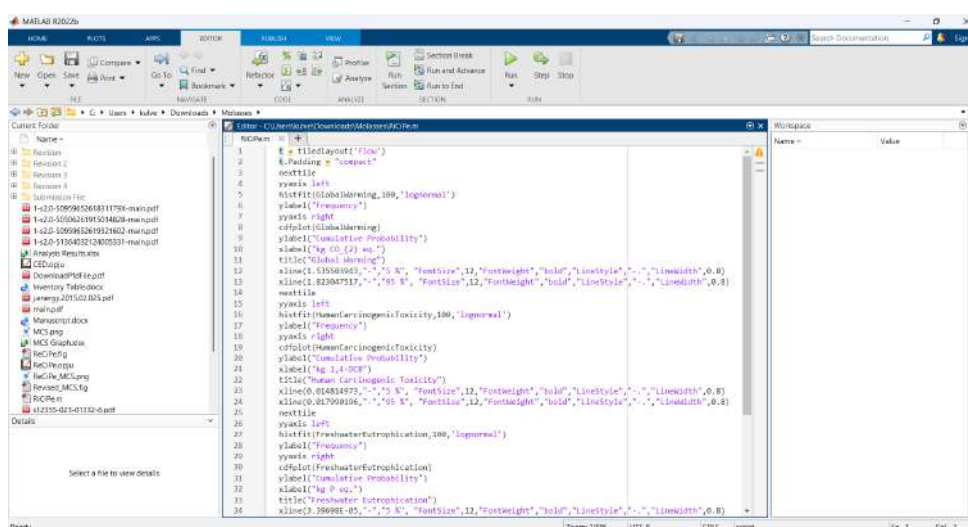


Figure 3.8 Picture of MATLAB software platform.

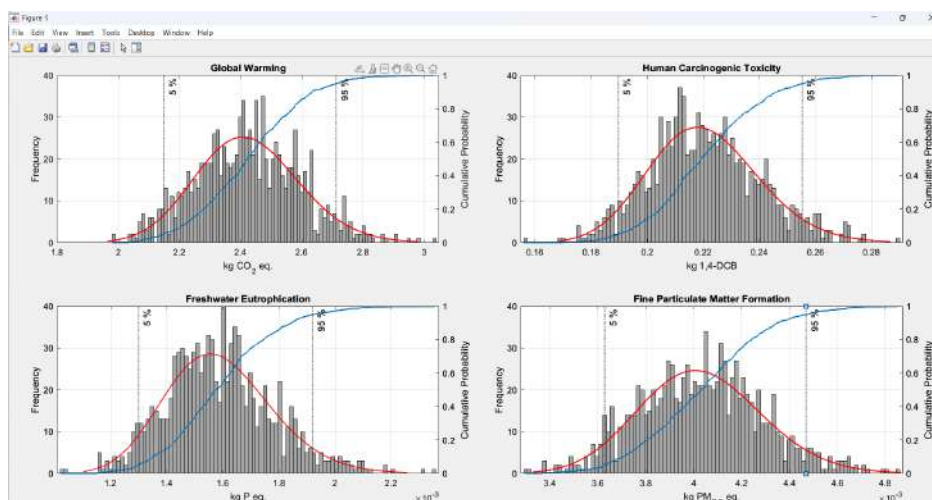


Figure 3.9 MATLAB data output

3.5.4 OriginPro

OriginPro significantly supports data visualization and interpretation by enabling the creation of high-quality, publication-ready graphs and figures. It offers a wide range of plotting options, curve-fitting tools, and statistical analysis features that help present results in a clear, structured manner (Figure 3.10). Complex datasets can be transformed into visually intuitive charts, making it easier to highlight trends, comparisons, and key findings, thereby improving clarity and overall impact in technical documentation and presentations (Figure 3.11). The details of the software will be available in <https://www.originlab.com/getstarted>.

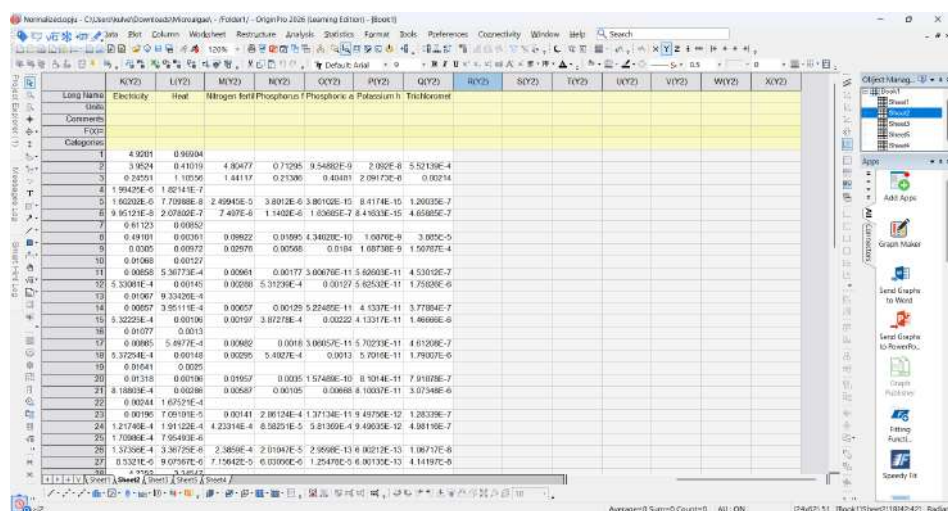


Figure 3.10 Picture of data feeding platform in the OriginPro software.

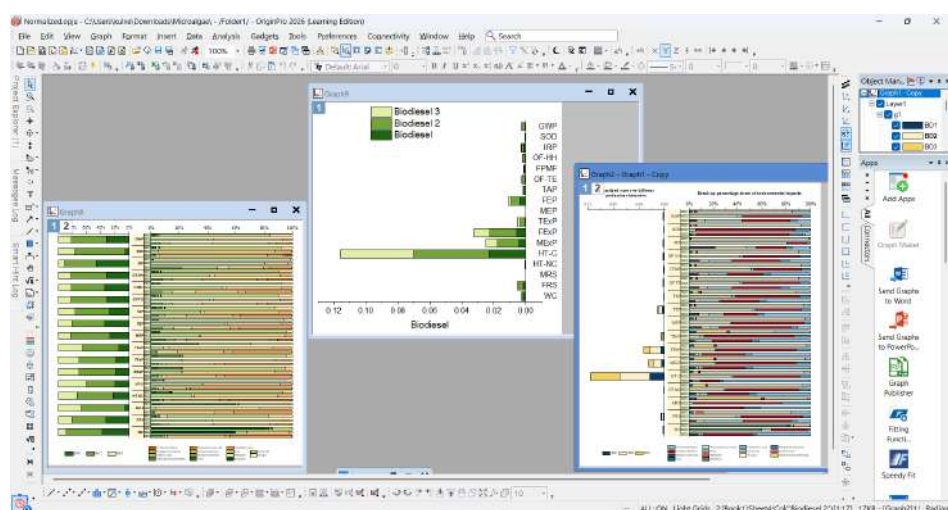


Figure 3.11 Output of the data visualization in the OriginPro software.

3.6 Assumptions and limitations

The life cycle assessment of biofuels in this study is based on several key assumptions that guide the scope and interpretation of the results. A cradle-to-gate system boundary is adopted, encompassing processes from biomass collection to the production of bioethanol or biodiesel, but excluding the use and disposal phases. Agricultural residues and municipal waste are considered burden-free inputs, meaning no environmental impacts from cultivation or generation are assigned to them (Patel and Singh, 2024c, 2022). This approach is common in LCA studies involving waste-based feedstocks. The analysis uses a standardized functional unit (e.g., per liter of bioethanol or per kg of biodiesel) to enable comparability between different biofuel systems. Inventory data are primarily sourced from established databases and prior literature, with the assumption that they accurately represent the environmental and energy profiles of local conditions. Uncertainty in model inputs is addressed through techniques such as Monte Carlo simulation.

Despite these structured assumptions, the study has some limitations. Key environmental factors such as land use change, infrastructure development, and end-use combustion emissions are excluded from the system boundaries, which may underestimate the full life cycle impact (Patel and Singh, 2024a). The reliance on secondary data introduces uncertainty, particularly when applied to region-specific conditions with limited availability of primary data. Additionally, some environmental impact categories—such as biodiversity loss, long-term soil degradation, or social impacts—are either simplified or omitted. These limitations underscore the importance of interpreting LCA results within the context of methodological choices and data constraints.

By examining variations in energy use, emissions, and resource consumption across multiple biomass sources, the study will highlight how these methodological constraints influence the comparative sustainability outcomes. This deeper investigation will provide a more nuanced understanding of the environmental trade-offs associated with each feedstock, helping inform more accurate, context-specific assessments of biofuel viability.

3.7 Summary

This study evaluates the sustainability of biofuel production systems in India through a comprehensive life cycle assessment. The methodology integrates multiple components—goal and scope definition, inventory analysis, impact assessment, energy evaluation, and sensitivity analysis—that are aligned with internationally recognized standards. A cradle-to-gate system boundary was adopted, using a standardized functional unit to ensure comparability across different feedstocks. The inventory phase combined primary and secondary data, while the impact assessment applied midpoint and endpoint methods to evaluate a broad range of environmental categories. Energy analysis was conducted using cumulative energy demand and net energy ratio metrics, offering insights into the efficiency of each production pathway. Sensitivity and uncertainty analyses were conducted to assess the robustness of the outcomes and the influence of key input parameters.

By adopting this structured, data-driven approach, the study ensures a consistent, transparent evaluation of environmental performance and energy efficiency across diverse biofuel systems. The integration of sensitivity analysis enhances the reliability of the findings by quantifying data variability and identifying critical factors influencing impact results. Collectively, these methods provide a robust platform for comparing biofuel alternatives and assessing their potential trade-offs, limitations, and areas for improvement. The following chapters build on this framework to present and analyze the environmental and energy outcomes associated with different feedstocks, offering a deeper understanding of their viability within India's renewable energy landscape.

The study delivers a detailed comparison of the environmental impacts and energy performance of biofuels produced from a range of feedstocks, including agricultural residues, municipal waste, and non-edible oils. It identifies key environmental hotspots, assesses trade-offs among different production pathways, and highlights the most efficient and sustainable options for large-scale biofuel implementation. By integrating impact assessment, energy analysis, and sensitivity testing, the study aims to provide data-driven insights to support informed decision-making by policymakers, researchers, and industry stakeholders. The findings will

contribute to advancing sustainable bioenergy strategies by identifying pathways that minimize environmental burdens while maximizing resource efficiency. In addition, the study offers a critical evaluation of the methodological choices and data uncertainties that influence life-cycle results, thereby enhancing the transparency and credibility of the conclusions. By exploring region-specific conditions and feedstock characteristics, it also provides context-sensitive insights applicable to India's energy and environmental goals. The outcomes can serve as a scientific foundation for guiding policy development, improving production technologies, and promoting the adoption of cleaner, more sustainable biofuel alternatives. Ultimately, the study aims to contribute meaningfully to the broader discourse on renewable energy transitions and circular economy practices.

CHAPTER 4

RESULTS AND DISCUSSION

In the context of growing concerns about climate change and fossil fuel depletion, biofuels have gained prominence as renewable, cleaner alternatives to conventional fossil fuels. Produced from a wide range of feedstocks, biofuels offer potential environmental benefits, including reduced greenhouse gas emissions, improved waste management, and enhanced energy sustainability. However, the overall environmental performance of biofuel production can vary significantly depending on the type of feedstock, the conversion technologies used, and the supply chain processes involved. LCA provides a comprehensive framework for systematically evaluating environmental and energy impacts across the entire production pathway. This chapter, therefore, examines the life cycle implications of biofuels derived from diverse feedstocks, analyzing key environmental indicators, trade-offs, and uncertainties to support the development of more sustainable biofuel systems.

Publications out of this chapter:

1. Patel K, Singh SK, Clean energy from algae: Tracing the sustainable biodiesel pathway through environmental impact, energy demand, and uncertainty assessment. *Renewable Energy*, 274 (2026). <https://doi.org/10.1016/j.renene.2026.126212>
2. Patel K, Singh SK, Advancing Uncertainty Decomposition in Environmental Assessment: The LMDI Method in Life Cycle Analysis of Bioethanol. *ASCE - Journal of Environ Engg*, 152 (5) (2026). <https://doi.org/10.1061/JOEEDU/EEENG-8423>
3. Patel K, Singh SK, Comprehensive Life Cycle Analysis of Bioethanol from Molasses: Addressing Energy Use and Uncertainty. *BioEnergy Research*, 19:65 (2026). <https://doi.org/10.1007/s12155-026-11003-5>
4. Patel K, Singh SK, Sustainable biodiesel from used cooking oil: a comparative life cycle, energy, and uncertainty analysis. *Environ Dev Sustain* 27, 14755–14780 (2025). <https://doi.org/10.1007/s10668-024-05692-1>
5. Patel K, Singh SK, Environmental sustainability, energy efficiency and uncertainty analysis of agricultural residue-based bioethanol production: A comprehensive life cycle assessment study. *Biomass Bioenergy* 191:107439 (2024). <https://doi.org/10.1016/j.biombioe.2024.107439>
6. Patel K, Singh SK, Sustainable waste management: a comprehensive life cycle assessment of bioethanol production from agricultural and municipal waste. *Environ Sci Pollut Res* 31, 51431–51446 (2024). <https://doi.org/10.1007/s11356-024-34612-z>

4.1 Introduction

The continued reliance on fossil fuels has been a primary driver of global environmental issues, particularly GHG emissions and climate change, thereby necessitating a transition to more sustainable, renewable energy systems. Escalating energy demands, along with rapid industrialization, urban expansion, and population growth, have further intensified the strain on conventional energy resources and amplified environmental degradation (Gheewala, 2023; Patel and Singh, 2024). In this context, biomass has emerged as a viable renewable resource due to its widespread availability and capacity to support sustainable energy production. It can be converted into biofuels using a variety of feedstocks, including agricultural and forest residues, dedicated energy crops, and the organic fraction of municipal solid waste (Kaparaju et al., 2009; Mahmoodi et al., 2018). The growing concerns surrounding the greenhouse effect and global warming have accelerated interest in biofuels as substitutes for petroleum-based fuels, given their potential to reduce reliance on fossil resources and contribute to climate change mitigation (Guo et al., 2015). Biofuels are generally regarded as more sustainable alternatives because they originate from renewable biological materials that can be replenished, and they offer the possibility of lowering GHG emissions compared to conventional fuels (Ajayebi et al., 2013; Rathore et al., 2013). Among these, bioethanol and biodiesel have gained considerable importance as transportation fuels; bioethanol can be blended with gasoline for use in existing engines with reduced emissions (Gheewala et al., 2022), while biodiesel can be synthesized from diverse lipid-based sources such as jatropha oil, rapeseed oil, palm oil, palm stearin, used cooking oil, and microalgal oil. Furthermore, both first- and second-generation biofuels can be derived from sugars, starch-rich materials, lignocellulosic biomass, and organic wastes, thus encouraging the productive use of underutilized and waste resources (Cheali et al., 2015; Patel and Singh, 2024).

Despite these advantages, the environmental benefits of biofuels are not uniform and are strongly influenced by factors such as the nature of the feedstock, agricultural practices, conversion technologies, and distribution systems (Lardon et al., 2009). Biofuels derived from low-impact or waste-based feedstocks tend to offer greater environmental advantages, as they reduce the burden on land resources and

minimize additional energy inputs. For example, the utilization of used cooking oil and agricultural residues can contribute to emission reductions by diverting waste streams from disposal pathways and decreasing dependence on fossil fuels (Santoyo-Castelazo et al., 2023). Similarly, replacing conventional fuels in the transportation sector with biofuels can lead to a net reduction in carbon emissions (Liu et al., 2018; Stamford; Laurence, 2020). Feedstocks such as broken rice, molasses, agricultural residues, and MSW are particularly attractive for bioethanol production due to their availability and limited current utilization. Broken rice and molasses serve as efficient substrates for fermentation, while agricultural residues help mitigate environmental issues such as open-field burning. The use of MSW additionally supports integrated waste management strategies. However, not all biofuel pathways yield positive outcomes; the cultivation of certain feedstocks, including palm oil, soybean, and corn, has been associated with adverse effects such as deforestation, land-use change, water consumption, and emissions from agrochemical inputs (Davis et al., 2009; Gandam et al., 2022; Liska et al., 2009). Moreover, energy-intensive processing steps and transportation requirements can offset the potential environmental gains, underscoring the importance of comprehensive evaluation.

To systematically assess these complexities, LCA has been widely adopted as an analytical framework for quantifying the environmental impacts of biofuel systems across their life cycles, from resource extraction to end use. This approach facilitates the evaluation of multiple environmental indicators, including GHG emissions, energy demand, land and water use, and other ecological impacts, enabling a more comprehensive comparison of alternative fuel pathways (Li et al., 2021; Lyu et al., 2020; Patel and Singh, 2024a). Numerous studies have employed LCA to investigate the sustainability of biofuels (Santoyo-Castelazo et al., 2023), with earlier research on biodiesel largely emphasizing fossil energy use and GHG emissions (DanDan et al., 2008; Hu et al., 2008; Lardon et al., 2009; Santoyo-Castelazo et al., 2023). However, limiting the assessment to these indicators does not capture the full spectrum of environmental impacts. Therefore, the present chapter undertakes a comparative LCA of biofuels produced from a broad range of feedstocks, including biodiesel derived from jatropha oil, rapeseed oil, palm oil, palm stearin, used cooking oil, and microalgal oil, as well as bioethanol produced from broken rice, molasses, agricultural residues,

and MSW. By incorporating feedstocks that span food-processing by-products, lignocellulosic materials, and waste-derived resources, this study enables a detailed evaluation of environmental trade-offs across diverse biofuel pathways. The objective is to identify the critical contributors to impact and assess the relative sustainability of these systems. Although LCA provides valuable insights, its outcomes are influenced by methodological assumptions, system boundaries, and data selection; therefore, careful interpretation is essential to ensure robust conclusions that can inform the development of environmentally sustainable biofuel production strategies (Plevin et al., 2014; Sreekumar et al., 2020).

4.2 Environmental impacts of bioethanol feedstocks

Bioethanol has gained attention as a renewable alternative to fossil fuels, but its environmental impacts depend strongly on the type of feedstock used and the overall production chain. First-generation bioethanol, derived from sugar- and starch-based feedstocks such as molasses, corn, and wheat, can reduce greenhouse gas emissions; however, its sustainability is often constrained by intensive land use, high water consumption, and reliance on fertilizers and pesticides, which contribute to soil degradation, water pollution, and biodiversity loss (Sujata et al., 2021; Sumisha and Shastri, 2025). In contrast, second-generation bioethanol utilizes lignocellulosic biomass such as agricultural residues and waste materials, offering lower environmental burdens by avoiding direct competition with food crops and reducing waste streams (Li et al., 2019). Nevertheless, 2G processes are more energy-intensive and technologically complex. LCA studies highlight that feedstock cultivation and energy use are key contributors to overall environmental impacts, emphasizing the importance of feedstock diversification and efficient resource management for improving the sustainability of bioethanol systems (Rohit Kumar et al., 2024).

4.2.1 Molasses-based bioethanol

Bioethanol production from molasses offers a solution to both agricultural waste utilization and energy diversification while supporting national targets for ethanol blending in transportation fuels. The process enables the valorization of surplus molasses, potentially minimizing both waste and GHG emissions relative to

gasoline. However, the pathway is not devoid of environmental concerns: agricultural inputs (such as fertilizers), cane trash management, energy-intensive conversion steps, and transportation logistics can substantially influence the overall energy balance and environmental footprint of the process. Studies from India, Indonesia, and Ethiopia consistently identify sugarcane cultivation and transport as the dominant contributors to GHG emissions across the bioethanol lifecycle, and sensitivity analyses highlight that factors such as crop yield, molasses price, and fossil energy inputs can shift the sustainability balance (Patel and Singh, 2026a).

4.2.1.1 Environmental assessment

Life Cycle Assessment provides a systematic, ISO-standardized framework for evaluating the environmental impacts and resource use across the entire value chain of bioethanol production—from sugarcane cultivation through processing, transport, and final use (Patel and Singh, 2024a). LCA enables the quantification of global warming potential, acidification, eutrophication, toxicity, and resource depletion, supporting decision-makers with a holistic perspective that incorporates trade-offs and hotspots. By clarifying the direct and indirect environmental consequences, LCA also informs improvements in process design, infrastructure investment, and sustainability policy.

Goal and scope. The study aims to analyze the environmental footprint of bioethanol production from molasses. The analysis was conducted using a cradle-to-gate system boundary that reflects current industrial practices and technologies for bioethanol production, as shown in Figure 4.1. To ensure comparability of results, the functional unit (f.u.) selected was based on the scope of the study and defined as per kg of ethanol (99.8%) on a mass basis at the refinery gate.

Inventory analysis. A list of the data sources utilized in this study is presented in Table 4.1. Background processes relied on secondary data sources obtained from published materials such as industry reports, peer-reviewed journal articles (Rathnayake et al., 2018; Sujata et al., 2021), information from the environmental impact assessment reports, and Ecoinvent databases (Wernet et al., 2016).

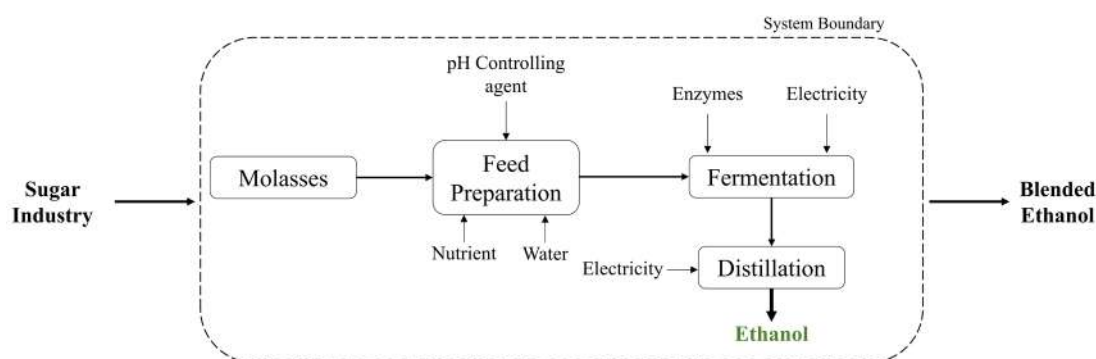


Figure 4.1 System boundary for bioethanol production from molasses

Table 4.1 Inventory of the material and energy inputs involved in the production of bioethanol from molasses

Inputs	Unit	Quantity
Molasses	kg	4500
Water	L	6000
Sulphuric acid	kg	0.4
Magnesium sulphate	kg	0.1
Urea	kg	1.3
Phosphoric acid	kg	0.14
Sodium hydroxide	kg	0.6
Chlorine	kg	0.4
Soda	kg	0.1
Yeast	kg	2
Enzymes	kg	0.22
Steam	kg	2500
Electricity	MJ	3564

Impact assessment. In this study, the ReCiPe 2016 method was used, which provides a comprehensive evaluation of environmental impacts, as described in Chapter 3. Alongside ReCiPe 2016, the cumulative energy demand method was integrated to assess total energy consumption throughout the life cycle of bioethanol production from molasses. Furthermore, an uncertainty analysis using Monte Carlo simulation was conducted to assess the robustness and reliability of the life-cycle results, accounting for data variability and methodological assumptions.

Interpretation. The ReCiPe method was selected for this study because it enables the conversion of complex environmental impacts into both midpoint and endpoint indicators, thereby providing a robust evaluation of potential ecological consequences and human health risks (Patel and Singh, 2024b). This comprehensive approach enables a more nuanced analysis of sustainability performance across the bioethanol production lifecycle, facilitating clearer interpretation and communication of results to stakeholders and decision-makers. Table 4.2 presents comparative results for midpoint and endpoint impacts associated with bioethanol production from molasses.

Table 4.2 Environmental impacts of molasses-based bioethanol

Impact Category	Unit	Impact score
Endpoint Categories		
Human health	DALY	6.0E-06
Ecosystem	species.yr	1.04E-08
Resources	USD2013	0.114
Midpoint Categories		
Global warming (GW)	kg CO ₂ eq	2.40
Stratospheric ozone depletion (SOD)	kg CFC11 eq	4.6E-07
Ionizing radiation (IR)	kBq Co-60 eq	3.9E-02
Ozone formation, Human health (OF-HH)	kg NO _x eq	4.1E-03
Fine particulate matter formation (FPMF)	kg PM _{2.5} eq	4.0E-03
Ozone formation, Terrestrial ecosystems (OF-TE)	kg NO _x eq	4.2E-03
Terrestrial acidification (TA)	kg SO ₂ eq	6.1E-03
Freshwater eutrophication (FE)	kg P eq	1.6E-03
Marine eutrophication (ME)	kg N eq	9.4E-05
Terrestrial ecotoxicity (TEx)	kg 1,4-DCB	3.81
Freshwater ecotoxicity (FEx)	kg 1,4-DCB	5.0E-02
Marine ecotoxicity (MEx)	kg 1,4-DCB	7.0E-02
Human carcinogenic toxicity (HCT)	kg 1,4-DCB	2.2E-01
Human non-carcinogenic toxicity (HNCT)	kg 1,4-DCB	2.14
Land use (LU)	m ² a crop eq	5.4E-02
Mineral resource scarcity (MRS)	kg Cu eq	9.3E-04
Fossil resource scarcity (FRS)	kg oil eq	5.9E-01
Water consumption (WC)	m ³	1.9E-02

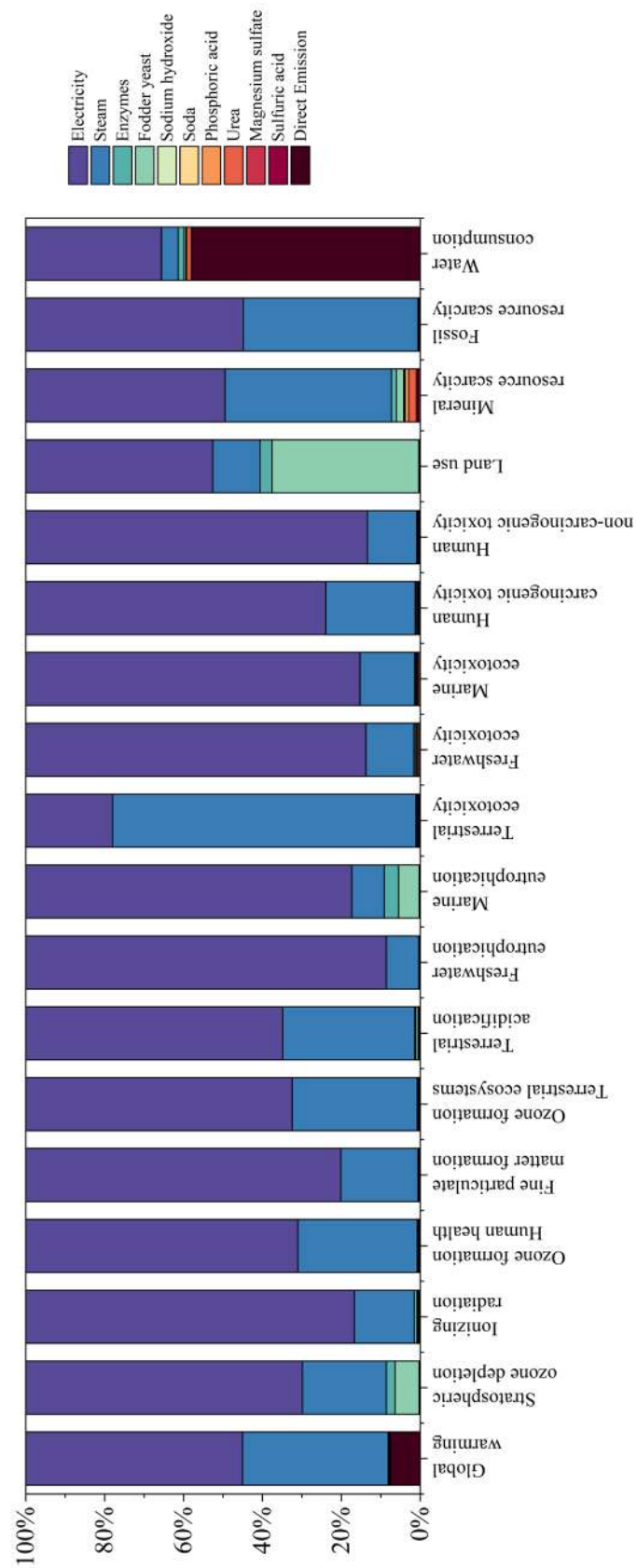


Figure 4.2 Environmental midpoint impact category of molasses-based bioethanol production

Climate and atmospheric impacts. Climate and atmospheric impacts refer to environmental issues related to emissions and their influence on both global and regional atmospheric systems. These impacts include global warming potential, depletion of the stratospheric ozone layer, effects of ionizing radiation, and the formation of ozone that adversely affects human health and terrestrial ecosystems. Molasses-derived bioethanol generates 2.4 kg CO₂ eq. per functional unit (shown in Table 4.2), with the main contribution from electricity use (54.9%), followed by steam generation (36.9%), direct fermentation emissions (7.5%), and minor contributions from other inputs (0.7%), as shown in Figure 4.2. For stratospheric ozone depletion (SOD), electricity accounted for the largest share (70.1%), followed by steam (21.3%), enzyme production (2.2%), and other inputs (6.4%). These impacts mainly stemmed from emissions of dinitrogen monoxide (97.2%), bromotrifluoromethane (2.1%), and other air pollutants (0.7%). For ionizing radiation potential, the dominant contributors were emissions of Radon-222 (88.5%), carbon-14 (8.7%), and other trace emissions (2.8%), arising primarily from electricity consumption (83.3%), steam (15.1%), and other inputs (1.6%). In the case of ozone formation—human health (OF-HH), nitrogen oxides were the primary contributors (95%), followed by non-methane volatile organic compounds (NMVOCs) (4.8%) and other minor emissions (0.2%), mainly associated with electricity (69%), steam (30.3%), and other inputs (0.7%). Similarly, for ozone formation—terrestrial ecosystems (OF-TE), electricity (67.5%), steam (31.7%), and other inputs (0.8%) were the major sources, resulting in emissions of nitrogen oxides (92.1%), NMVOCs (7.4%), and other pollutants (0.5%).

Air and water quality impacts. Air and water quality impacts refer to environmental consequences arising from emissions and discharges that degrade atmospheric and aquatic systems. These impacts include fine particulate matter formation, terrestrial acidification potential, freshwater eutrophication potential, and marine eutrophication potential, all of which influence ecosystem health, biodiversity, and human well-being through changes in air composition and nutrient loading in water bodies. For the FPMF impact, molasses-based bioethanol production results in 4.02 kg PM_{2.5} equivalent, as presented in Table 4.2. This impact primarily from PM_{2.5} emissions (56%) generated during electricity production, followed by sulfur dioxide (32.9%), nitrogen oxides

(10.6%), and other minor emissions (0.5%), as shown in Figure 4.2. Regarding ME and FE, electricity was the dominant contributor, accounting for 82.6% and 91.4% of the impacts, respectively, while steam contributed 8.27% and 8.24%, and other inputs 9.23% and 0.36%. The major sources of these impacts were nitrate emissions (97%) for ME and phosphate emissions (85%) for FE. Similarly, for TA, bioethanol production leads to $6.12\text{E-}3$ kg SO₂ eq. emissions, primarily attributed to electricity (65%), steam (33.5%), enzymes (0.3%), yeast (0.6%), and other inputs (0.6%). The associated emissions include sulfur dioxide (74.4%), nitrogen oxides (22.8%), ammonia (2.6%), and other minor air pollutants (0.1%).

Toxicity impacts. Toxicity impacts refer to the adverse effects of chemical substances and pollutants on both ecosystems and human health. These impacts include terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity, each quantified in kilograms of 1,4-dichlorobenzene (kg 1,4-DCB) to represent their relative potential for causing harm to living organisms in soil, freshwater, and marine environments. Beyond ecological effects, toxicity impacts also encompass human health concerns, including carcinogenic and non-carcinogenic toxicity, which evaluate the potential of pollutants to cause cancer or other chronic health conditions. Assessing these toxicity impacts is crucial for understanding how chemical emissions and pollutants interact with biological systems, influencing ecosystem stability, biodiversity, and long-term human well-being. The analysis shows that the TE exhibits the highest ecosystem toxicity impacts, amounting to 3.81 kg 1,4-DCB emissions, primarily driven by the release of copper (74%), zinc (10%), vanadium (4%), nickel (4%), mercury (2%), and other minor emissions (6%) into the air originating mainly from steam (77%), electricity (22%), and other minor inputs (1%). In the case of human toxicity, however, the HNCT shows the highest impact, as presented in Table 4.2, primarily due to the emission of zinc (47.4%), arsenic (45.3%), and other pollutants (7.3%) into water, predominantly from electricity (86.6%), steam (12.5%), and other inputs (0.9%).

Resource depletion and water scarcity. Resource depletion and water scarcity represent significant environmental concerns associated with the intensive extraction and utilization of natural resources. These impacts include mineral resource scarcity, which denotes the exhaustion of vital mineral reserves; fossil resource scarcity, which

emphasizes the reliance on and depletion of non-renewable fossil fuels; and water consumption, which measures the total volume of water used, indicating pressures on freshwater availability and ecosystem balance. Together, these factors illustrate the growing strain on Earth's natural systems resulting from human activities, underscoring the urgent need for sustainable resource management and conservation practices. As shown in Table 4.2, the bioethanol production causes moderate environmental impact concerning resource depletion and water consumption, mainly caused by use of resources like iron (43.8%), nickel (16.1%), copper (10.8%), molybdenum (7.2%), aluminium (4.8%), uranium (3.2%), and other mineral resources (14.1%) from the use of electricity (50.5%), steam (42.2%), yeast (1.8%), enzymes (1.2%), and other inputs (5.5%). Similarly, for WC, the utilization of water in processes such as the dilution of molasses, fermentation, distillation, and purification contributes to a total of 0.019 m³ of water used.

The life cycle assessment results clearly indicate that molasses-based bioethanol production exerts diverse environmental pressures across multiple impact categories. Electricity and steam use dominate most midpoint and endpoint contributions, influencing climate change, atmospheric emissions, and aquatic nutrient loading. Toxicity assessments reveal significant ecological and human health risks, mainly due to trace metal emissions associated with process energy inputs. Resource depletion and water consumption are moderate but highlight the dependence on non-renewable inputs and freshwater use throughout the production chain. Overall, the findings emphasize that while molasses-based bioethanol demonstrates potential for reduced fossil fuel dependency, its sustainability performance is strongly tied to improvements in energy efficiency and emission control within key operational stages.

4.2.1.2 Energy analysis

Table 4.3 shows the CED of bioethanol production from sugarcane molasses. It shows that the production relies heavily on fossil resources, causing 93% of resource use from fossil energy, of the total 27 MJ of energy use. This energy use is from the use of electricity (55.6%) during the entire production process, steam use (44%), and other inputs (0.4%), as shown in Figure 4.3.

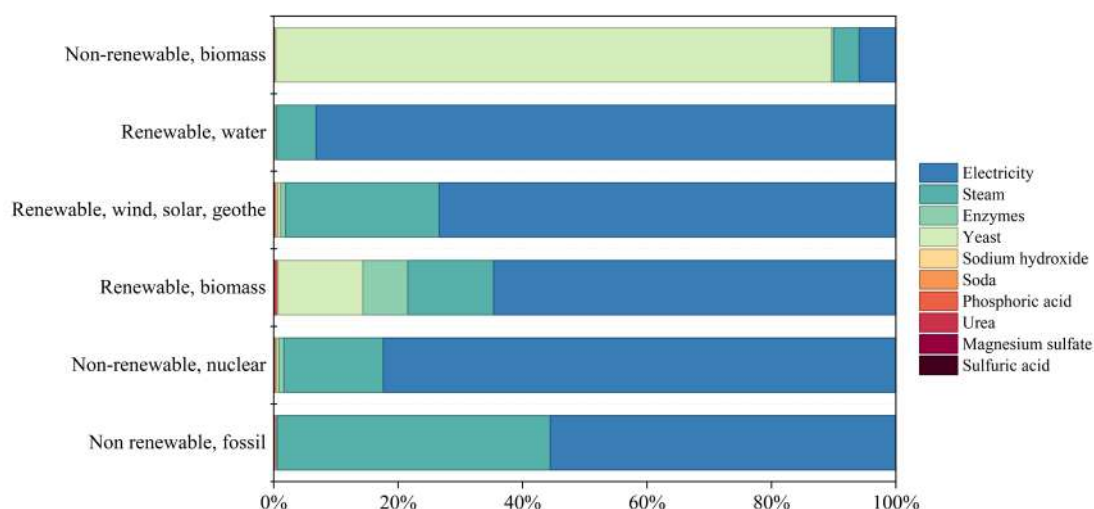


Figure 4.3 Cumulative energy demand profile showing contributions of various inputs to renewable and non-renewable energy sources in molasses-based bioethanol production.

Table 4.3 Cumulative energy demand and energy balance analysis of molasses-based bioethanol production

Impact category	Unit	Value
Non-renewable, fossil	MJ	25.01
Non-renewable, nuclear	MJ	6.8E-01
Renewable, biomass	MJ	2.1E-01
Renewable, wind, solar, geothermal	MJ	1.4E-01
Renewable, water	MJ	9.4E-01
Non-renewable, biomass	MJ	1.1E-03
Total	MJ	26.98
NER		1.04
NEV		1.02
Rn		1.12
NRnEV		2.99

The given energy balance indicators for molasses-based bioethanol, as shown in Table 4.3, shows that the process is energetically efficient and slightly positive in net energy output. A net energy ratio greater than 1 indicates that ethanol production yields about 3.8% more energy than it consumes, while the net energy value shows a

small overall energy gain. The renewability index above 1 indicates that renewable energy output exceeds fossil energy input, signifying good fossil fuel displacement. The high net renewable energy value further emphasizes a substantial surplus of renewable energy after accounting for fossil inputs. Together, these values suggest that molasses-based bioethanol production in India is marginally energy-positive, environmentally favorable, and contributes to reducing fossil fuel dependence.

4.2.1.3 Sensitivity and uncertainty analysis

The bioethanol production process involves several unit operations (Figure 4.1), which introduce uncertainties in the data. To evaluate these uncertainties, each input parameter is assigned an uncertainty value, and a Monte Carlo Simulation with 1000 iterations is conducted to estimate uncertainty in the midpoint impact categories. To calculate the overall uncertainty variance, the uncertainties derived from the pedigree matrix and the basic uncertainty are combined using the equation (4) described in Section 3.4 of Chapter 3. The result of the MCS for bioethanol production from molasses is presented in Table 4.4. The analysis shows that the environmental impact results exhibit consistently low variability, with coefficients of variation ranging from 10.3% to 11.4% across all categories. This narrow range indicates a high degree of stability and reliability in the simulation outcomes, confirming that the model is robust with minimal uncertainty in the environmental performance estimates. Among the various categories, human non-carcinogenic toxicity (1.732 kg 1,4-DCB) and global warming potential (0.975 kg CO₂ eq) show the highest mean values, suggesting that these two impacts are the major contributors to the overall environmental footprint of bioethanol production from molasses. Other notable contributors include terrestrial ecotoxicity (0.627 kg 1,4-DCB) and fossil resource scarcity (0.193 kg oil eq), which also indicate moderate influence on the system. Conversely, categories such as stratospheric ozone depletion (2.4E-07 kg CFC11 eq) and marine eutrophication (1.1E-04 kg N eq) demonstrate relatively minor impacts, reflecting their limited contribution to the total environmental burden. Overall, the MCS results highlight that while the process shows good consistency, mitigation strategies should primarily target toxicity-related and carbon-emission-linked impacts to enhance environmental sustainability.

Table 4.4 Uncertainty analysis of the LCA of molasses-based bioethanol

Environmental Impact Category	Unit	Mean	SD	CoV (%)
Freshwater ecotoxicity	kg 1,4-DCB	0.044	0.005	11.3
Fine particulate matter formation	kg PM2.5 eq	4.5E-03	5.1E-04	11.4
Marine eutrophication	kg N eq	1.1E-04	1.2E-05	11.2
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.3E-03	1.4E-04	11.3
Land use	m2a crop eq	0.007	6.8E-04	10.3
Water consumption	m3	0.009	9.7E-04	11.1
Ionizing radiation	kBq Co-60 eq	0.076	8.7E-03	11.4
Freshwater eutrophication	kg P eq	0.002	1.9E-04	11.4
Human non-carcinogenic toxicity	kg 1,4-DCB	1.732	0.197	11.4
Marine ecotoxicity	kg 1,4-DCB	0.060	6.8E-03	11.3
Ozone formation, Human health	kg NOx eq	1.3E-03	1.4E-04	11.3
Terrestrial acidification	kg SO2 eq	4.3E-03	4.9E-04	11.4
Mineral resource scarcity	kg Cu eq	3.3E-04	3.4E-05	10.4
Terrestrial ecotoxicity	kg 1,4-DCB	0.627	0.068	10.8
Human carcinogenic toxicity	kg 1,4-DCB	0.099	0.011	10.7
Fossil resource scarcity	kg oil eq	0.193	0.022	11.4
Global warming	kg CO2 eq	0.975	0.103	10.5
Stratospheric ozone depletion	kg CFC11 eq	2.4E-07	2.6E-08	11.1

SD: standard deviation; CoV: coefficient of variation

Figure 4.4 shows the distribution of selected environmental impact categories obtained from the Monte Carlo simulation. The histograms and fitted curves indicate that most results follow a near lognormal distribution, while the cumulative curves illustrate probability trends. The 5% and 95% lines represent the uncertainty bounds, within which most values fall. Categories like global warming show narrower distributions, indicating lower variability, whereas others, such as human toxicity, exhibit wider spreads. Overall, the results suggest generally consistent outcomes with varying levels of uncertainty across impact categories. The results show that the sustainability performance of molasses-based bioethanol is not fixed but depends on multiple uncertain factors, such as feedstock characteristics, energy use, and process efficiency.

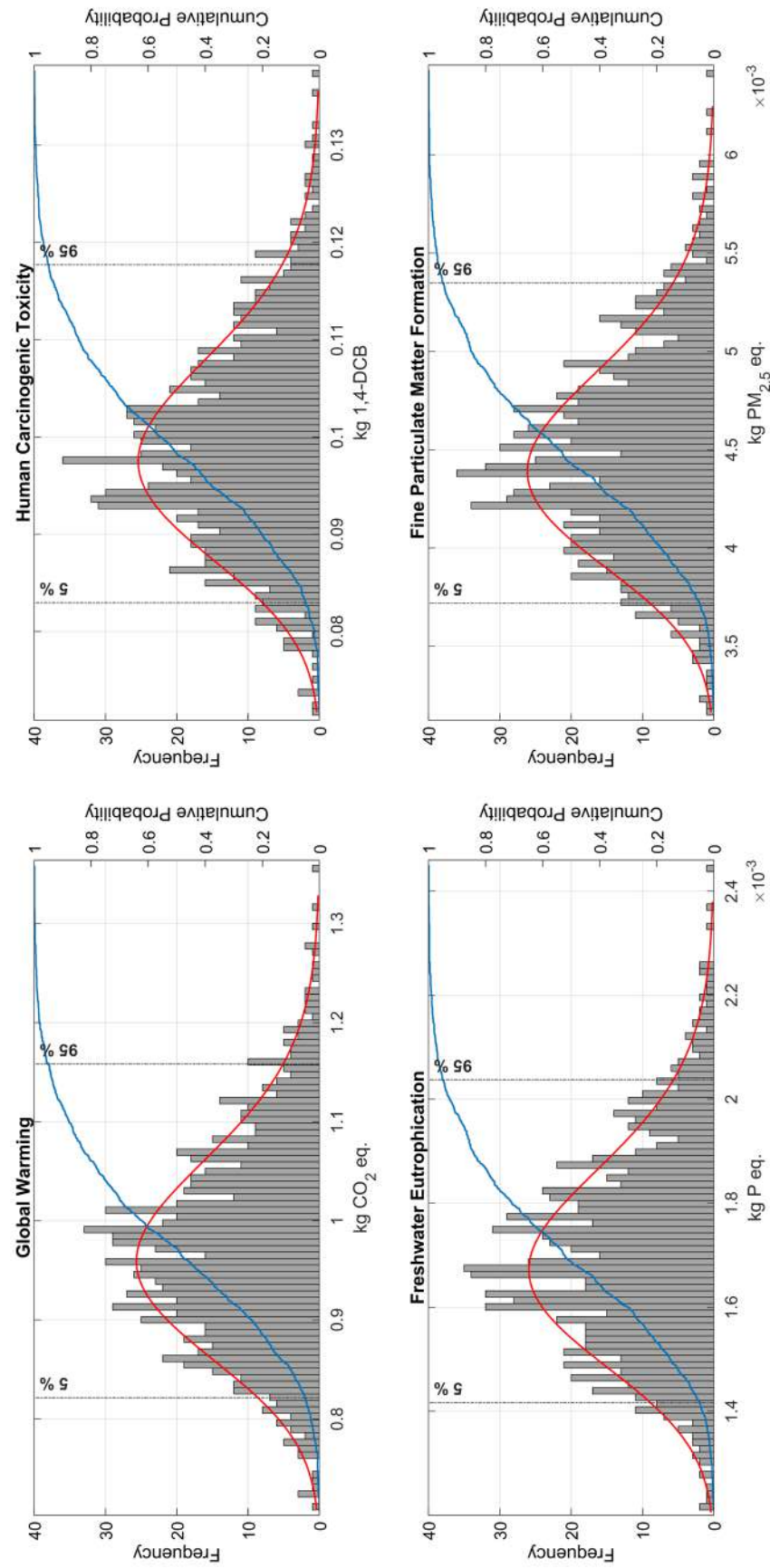


Figure 4.4 Uncertainty distributions of key environmental impacts from molasses-based bioethanol production obtained through Monte Carlo simulation.

4.2.2 Grain-based bioethanol

Grain-based bioethanol production offers a promising pathway for renewable energy generation while enabling the efficient utilization of surplus, damaged, or low-grade cereals such as broken wheat and rice. This approach not only supports energy diversification and national ethanol blending targets but also helps reduce post-harvest losses by converting underutilized agricultural resources into valuable fuel (Patel and Singh, 2026b). At the same time, the sustainability of this pathway depends on factors such as agricultural inputs, water use, and energy requirements during processing, which can significantly influence its overall environmental performance.

4.2.2.1 Environmental assessment

Life Cycle Assessment helps in evaluating the overall environmental impacts of a product across its entire life cycle. It supports the identification of key impact areas and enables informed decision-making for improving sustainability and resource efficiency.

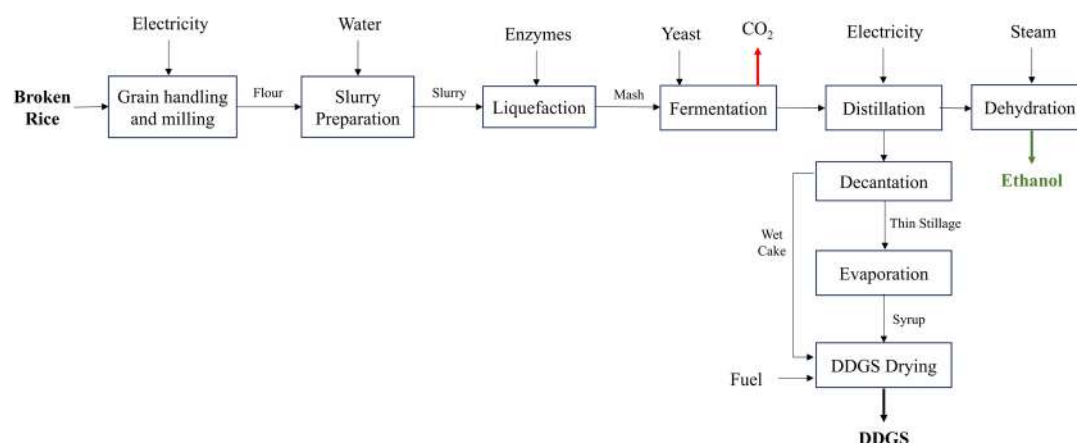


Figure 4.5 System boundary for bioethanol production from broken rice

Goal and scope. A case study on bioethanol production from broken rice is used, with a cradle-to-gate system boundary that begins with broken rice at the refinery and ends with the production of bioethanol and byproduct, which is distiller's dried grains with solubles (DDGS), shown in Figure 4.5. The functional unit (f.u.) used in this study is

per liter of bioethanol produced, but for the comparison purpose, results are converted into per kg bioethanol produced. Utilities, including electricity generation and steam production, are integral to the system, contributing significantly to emissions (SO_2 , NO_x , $\text{PM}_{2.5}$).

Inventory analysis. The inventory data for the study was based on the operational setup of a bioethanol distillery located in Chhattisgarh, India, given in Table 4.5. Background data, including upstream and supporting processes, were sourced from the Ecoinvent database, ensuring consistency and transparency in life cycle modeling.

Table 4.5 Inventory data related to bioethanol production for 100 KLPD distillery

Component	Unit	Amount
Input		
Broken Rice	MT/day	221
Alpha amylase	Kg/day	100
Glucosylase	Kg/day	133
Sulfuric acid	Kg/day	117
Urea	Kg/day	250
NaOH	Kg/day	117
Di-ammonium Phosphate	Kg/day	83
Antifoam agent (polydimethylsiloxane) density = 0.82 kg/l	L/day	333
Yeast	Kg/day	100
Water	M ³ /day	480
Steam	TPH	24.6 (590.4 TPD)
Electricity	kWh/day	79200
Neutrase	Kg/day	17
Viscozyme	Kg/day	33
Output		
Ethanol	KLPD	100
DDGS	MT/day	60
CO ₂	MT/day	69

Impact assessment. In this study, the ReCiPe 2016 method was used to assess the environmental impacts of bioethanol production from broken rice across its life cycle. Cumulative energy demand is used to analyze the energy demand as discussed in

Section 3.3 of Chapter 3, while uncertainty analysis using Monte Carlo simulation ensures the reliability of the results.

Interpretation. The deterministic results are based on aggregated inventory outputs generated by the modeled activity data. These flows were characterized and summed into impact category indicators using ReCiPe 2016, consistent with ISO 14040/44. Table 4.6 summarizes the results of the ReCiPe 2016 impact assessment method. The global warming score associated with bioethanol production accounted for 4.17 kg CO₂ eq. primarily contributed by steam (58.9%), emissions during fermentation (21.8%), electricity consumed (17.7%), and other minor sources comprising 1.6%, as shown in Figure 4.6. For FPMF, the largest contributors were steam at 56.7% and electricity at 40.5%, primarily due to emission of sulfur dioxide (52%), particulate matter <2.5 μ m (34.7%), nitrogen oxides (13.2%), and a small fraction of other air emissions (0.1%). Similarly, for TAP, the impacts were due to the emission of sulfur dioxide (80.2%), followed by nitrogen oxides (19.2%) and other air emissions (0.6%). In the case of FEP, the primary contributor was phosphate discharge into water (81%) from the electricity generation, with additional contributions from chemical oxygen demand (11.6%), biochemical oxygen demand (7%), and other emissions (0.4%).

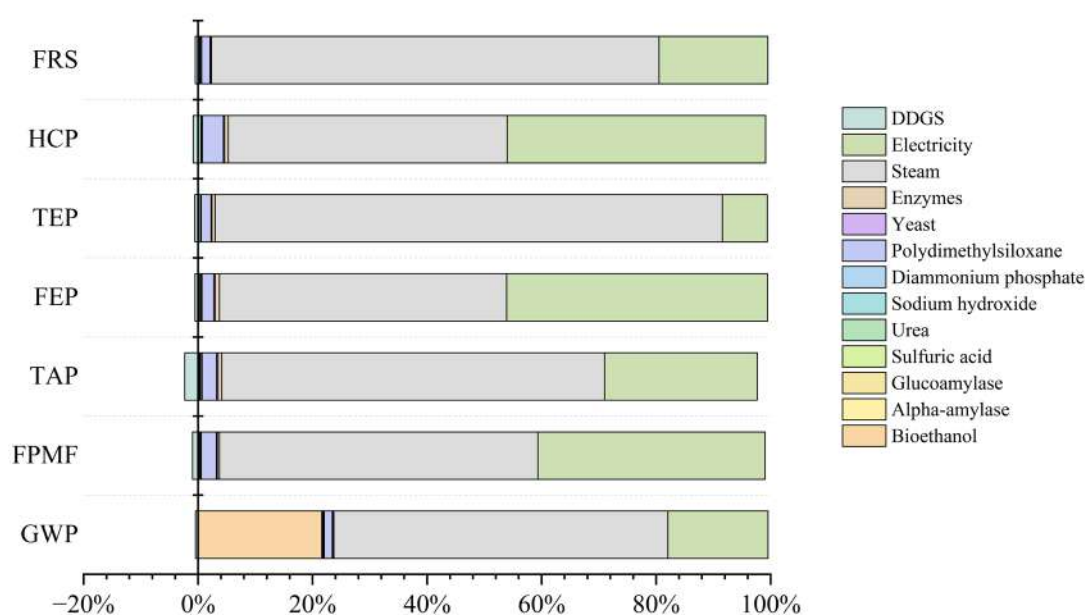


Figure 4.6 Contribution of each input to the environmental impact categories.

The HCP was mainly due to the discharge of hexavalent chromium (Cr VI), contributing 90.4% of the total, which primarily stemmed from steam use (44.4%) and electricity consumption (41.9%). Other contributors included arsenic (2.8%), nickel (2%), and various other emissions (4.8%). Additionally, FRS impact was driven by the consumption of natural gas (50.5%), coal (23.4%), and crude oil (23.3%), along with other fossil resources, all of which were used in generating the electricity and steam required for the bioethanol production process.

Table 4.6 Characterized results of environmental impacts for bioethanol production from broken rice

Impact Category	Unit	Total
Global warming potential (GWP)	kg CO ₂ eq	4.17
Ionizing radiation potential (IRP)	kBq Co-60 eq	1.1E-01
Ozone formation, Human health (OF-HH)	kg NO _x eq	5.0E-03
Fine particulate matter formation (FPMF)	kg PM _{2.5} eq	4.1E-03
Ozone formation, Terrestrial ecosystems (OF-TE)	kg NO _x eq	5.1E-03
Terrestrial acidification (TA)	kg SO ₂ eq	9.0E-03
Eutrophication potential (EUP)	kg P eq	8.1E-04
Terrestrial ecotoxicity potential (TExP)	kg 1,4-DCB	9.53
Freshwater ecotoxicity potential (FExP)	kg 1,4-DCB	3.5E-02
Marine ecotoxicity potential (MExP)	kg 1,4-DCB	5.1E-02
Human carcinogenic toxicity (HCT)	kg 1,4-DCB	6.4E-02
Human non-carcinogenic toxicity (HNCT)	kg 1,4-DCB	1.38
Fossil resource scarcity (FRS)	kg oil eq	9.4E-01
Water consumption (WC)	m ³	1.6E-02

The normalized result shown in Figure 4.7 indicates that human carcinogenic toxicity has the highest environmental impact, mainly due to steam and electricity generation during the production process, which also significantly influences other categories such as FEP and FRS, indicating their critical role in the environmental impact of the system. While using DDGS as an avoided product offers some environmental benefits, its positive effect is relatively minor (-0.8%) compared to the significant impacts associated with other input parameters. Minor but notable contributions from inputs such as enzymes, yeast, and process chemicals were also shown for specific categories in Figure 4.7. Normalization helps to identify the

environmental hotspots. HCP emerges as the major concern in bioethanol production from broken rice, highlighting the need for efficient methods to lower the impacts associated with steam and electricity to minimize the overall environmental impact throughout the process.

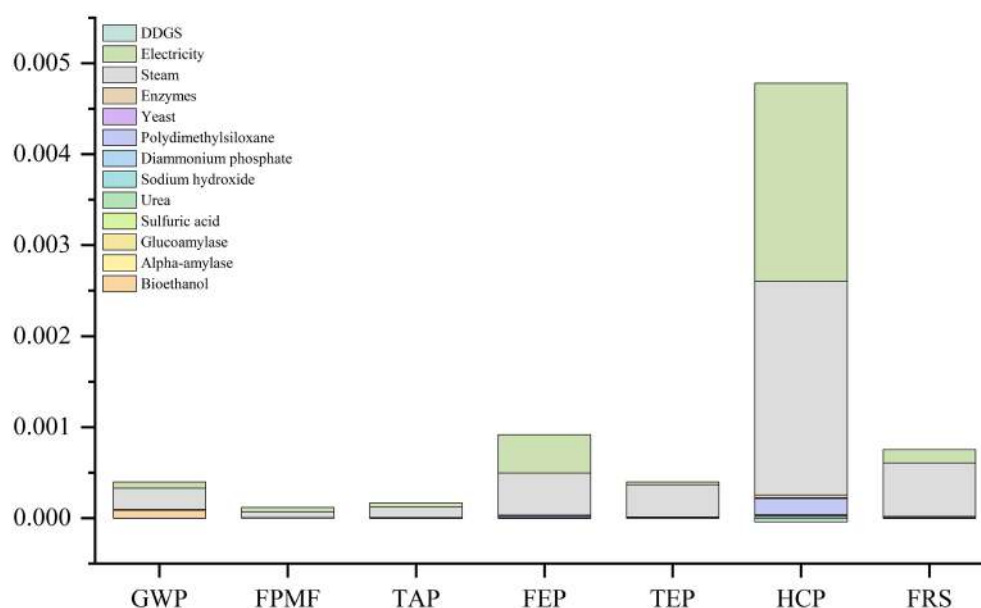


Figure 4.7 Normalized LCA score of bioethanol production.

4.2.2.2 Energy analysis

The energy analysis indicates that grain-based bioethanol production is predominantly dependent on non-renewable energy sources, particularly fossil fuels, which contribute the largest share (39.63 MJ), followed by a smaller contribution from nuclear energy, shown in Table 4.7. Major contributions are from the use of steam (79%), followed by electricity (19.2%), polydimethylsiloxane (1.5%), and other inputs (0.8%), as shown in Figure 4.8. However, the by-product DDGS causes a reduction in overall energy consumption (-0.5%) by considering the system expansion/avoided burden approach, where DDGS displaces conventional animal feed, thereby offsetting a portion of the energy demand. The negative value for renewable biomass ($-9.3\text{E-}02$ MJ) suggests a credit due to energy recovery or by-product utilization. The NER of

1.08 indicates that the system yields slightly more energy than it consumes, reflecting marginal energy efficiency. Similarly, the positive NEV of 3.44 MJ confirms a net energy gain from the process. The renewability factor of 2.68 highlights a moderate contribution of renewable energy within the system, while the NRnEV of 28.94 MJ suggests a significant potential for renewable energy benefits, despite the current reliance on non-renewable inputs.

Table 4.7 Cumulative energy demand and energy balance analysis of grain-based bioethanol production

Impact category	Unit	Grain
Non-renewable, fossil	MJ	39.63
Non-renewable, nuclear	MJ	2.02
Non-renewable, biomass	MJ	1.6E-03
Renewable, biomass	MJ	-9.3E-02
Renewable, wind, solar, geothermal	MJ	0.28
Renewable, water	MJ	0.92
NER		1.08
NEV		3.44
Rn		2.68
NRnEV		28.94

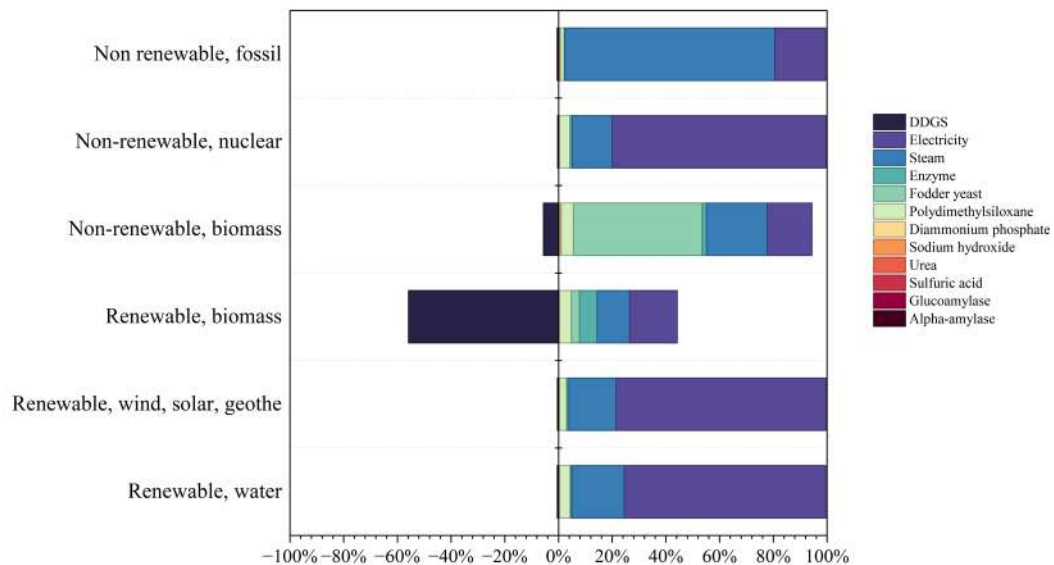


Figure 4.8 Cumulative energy demand profile showing contributions of various inputs in grain-based bioethanol production.

4.2.2.3 Sensitivity and uncertainty analysis

The Monte Carlo simulation (1000 iterations) indicates that the majority of environmental impact categories exhibit relatively low to moderate variability, with coefficients of variation generally ranging from approximately 10% to 45% for the more stable indicators, confirming a reasonable level of robustness in the model outcomes, as shown in Table 4.8. Impact categories such as global warming potential (3.38 kg CO₂ eq), fossil resource scarcity (0.774 kg oil eq), and fine particulate matter formation (0.00311 kg PM_{2.5} eq) show comparatively low variability (CoV $\approx$ 10–15%), indicating high confidence and stability in these estimates. Moderate variability is observed in categories including freshwater ecotoxicity (CoV 39.2%), freshwater eutrophication (44%), marine eutrophication (29.7%), and terrestrial acidification (18%), suggesting some sensitivity to input parameters but still within acceptable uncertainty bounds. The relatively narrow 95% confidence intervals for low-CoV categories further reinforce the reliability of the simulation results, shown in Figure 4.9. Overall, the findings suggest that while the model demonstrates good consistency for most impact categories, priority for mitigation should be given to high-magnitude impact categories, particularly those related to ecotoxicity and climate change, to improve the environmental performance of the biofuel production system.

Table 4.8 Uncertainty analysis of the LCA of grain-based bioethanol

Environmental Impact Category	Unit	Mean	SD	CoV (%)
Fine particulate matter formation	kg PM _{2.5} eq	0.00311	0.000438	14.1
Fossil resource scarcity	kg oil eq	0.774	0.112	14.4
Freshwater ecotoxicity	kg 1,4-DCB	0.0322	0.0126	39.2
Freshwater eutrophication	kg P eq	0.000702	0.000309	44
Global warming	kg CO ₂ eq	3.38	0.346	10.2
Ionizing radiation	kBq Co-60 eq	0.078	0.103	132
Land use	m ² a crop eq	0.0189	0.0114	60.4
Marine ecotoxicity	kg 1,4-DCB	0.0468	0.0175	37.5
Marine eutrophication	kg N eq	2.94E-05	8.73E-06	29.7
Mineral resource scarcity	kg Cu eq	0.00154	0.000304	19.7
Ozone formation (Human health)	kg NO _x eq	0.00434	0.000651	15
Ozone formation (Terrestrial ecosystems)	kg NO _x eq	0.00461	0.000693	15
Stratospheric ozone depletion	kg CFC11 eq	7.49E-06	1.06E-06	14.2
Terrestrial acidification	kg SO ₂ eq	0.00683	0.00123	18
Terrestrial ecotoxicity	kg 1,4-DCB	7.21	5.42	75.2

SD: standard deviation; CoV: coefficient of variation

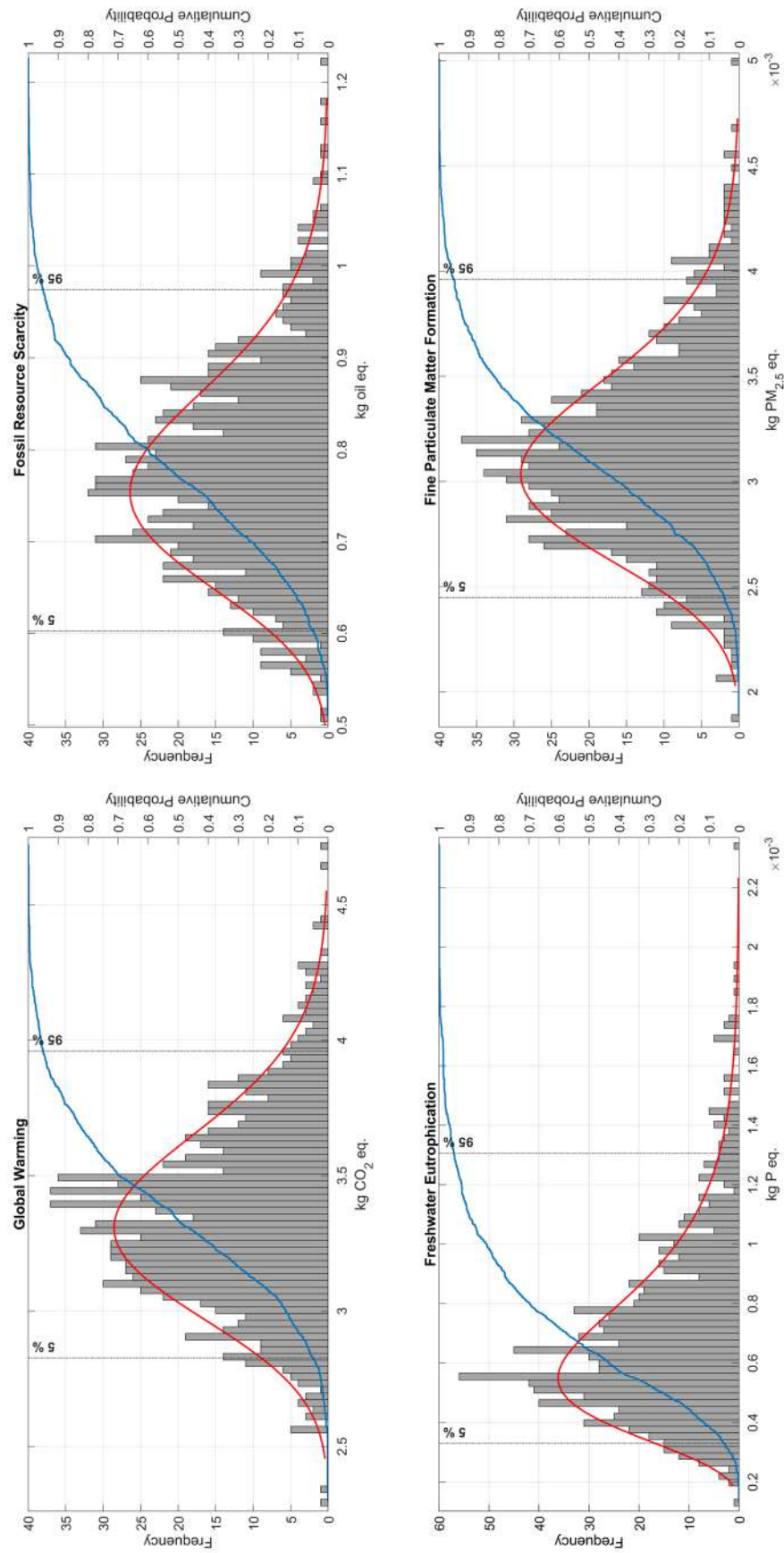


Figure 4.9 Uncertainty distributions of key environmental impacts from grain-based bioethanol production obtained through Monte Carlo simulation.

4.2.3 Agricultural residue-based bioethanol

Agriculture-based biofuels are crucial for addressing environmental issues, particularly by reducing greenhouse gas emissions and improving overall environmental performance. They offer a sustainable alternative to fossil fuels, helping mitigate the adverse impacts of climate change by reducing carbon dioxide and other harmful emissions. Using agricultural residues for biofuel production helps minimize waste while providing a sustainable energy source.

4.2.3.1 Environmental assessment

LCA is a tool for evaluating the environmental performance of agricultural-based biofuels. It allows for a comprehensive analysis of the entire life cycle of biofuel production, including the cultivation and harvesting, processing, distribution, and end-use stages (Patel and Singh, 2023a). LCA helps identify areas of improvement in biofuel production processes, guiding stakeholders in making informed decisions to enhance sustainability (Cheali et al., 2015; Li et al., 2021; Patel et al., 2024).

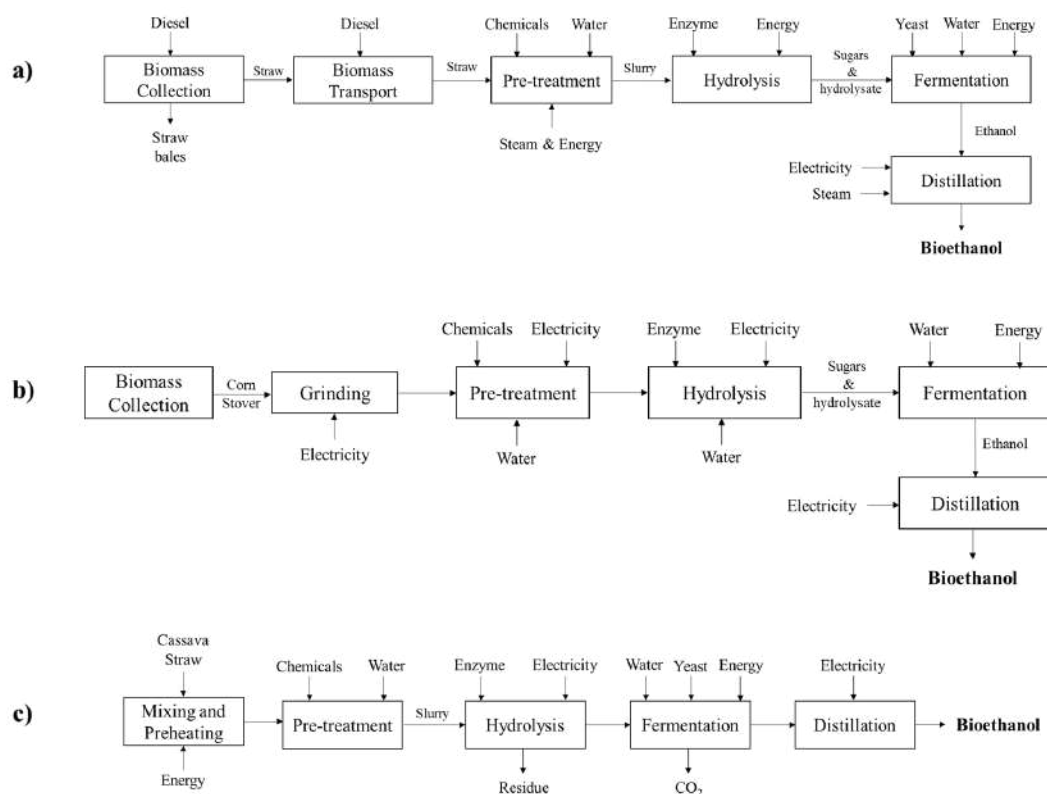


Figure 4.10 System boundary of cellulosic bioethanol from a) rice straw, b) corn stover, and c) cassava straw

Goal and scope. A “cradle-to-gate” LCA was applied to analyze the potential environmental impacts of agricultural residue-based bioethanol production. The study does not include the cultivation of feedstocks and does not account for any potential changes in land use in the results, as these are agricultural residues and not explicitly grown energy crops. The system boundary shown in Figure 4.10 includes processes for biomass collection, pretreatment, hydrolysis, fermentation, and distillation. Agro-residues are considered waste by-products, meaning they don’t carry any environmental burden from the cultivation of crops. This is a common approach in LCA when dealing with waste materials (Patel et al., 2025). Production of 1 liter of bioethanol is chosen as the functional unit (f.u.), but for comparison, results are converted to kg of bioethanol produced. Rice Straw, Corn Stover, and Cassava Straw were taken as agricultural residues for the comparative analysis. The study aims to identify the hotspot of agro-residue-based bioethanol production and to compare the environmental impacts of bioethanol production from different biomasses. The study also aims to evaluate the energy balance of producing bioethanol from several feedstocks using the LCA approach outlined in the ISO 14040/44: 2006 (ISO, 2006a, 2006b). Uncertainty analysis was also performed to account for variability and enhance the reliability of the impact assessment, thereby ensuring robust, accurate LCA results.

Inventory analysis. The inventory was carried out using the SimaPro 9.4 software with the Ecoinvent v3 database (Wernet et al., 2016) and published literature (Cherubini and Ulgiati, 2010; Daylan and Ciliz, 2016; Lyu et al., 2020; Patel and Singh, 2023b; Soam et al., 2016). The data source for rice straw, corn stover, and cassava straw is described in Table 3.1 of Chapter 3. Table 4.9 shows the inventory data for producing 1 liter of bioethanol from the different agricultural residues. The use of secondary data was primarily due to the current lack of comprehensive primary data available for bioethanol production processes in India. Using secondary data helps us identify key trends and environmental hotspots in bioethanol production, providing valuable insights into the sustainability of agro-residue use. The environmental impacts are mainly divided into direct and indirect impacts. Pollutant emissions from the production process lead to direct environmental impacts, while emissions from

other parts of the process account for indirect environmental impacts. The background processes data were chosen from the SimaPro Ecoinvent database (PRé Sustainability, 2022).

Table 4.9 Inventory data for the bioethanol production from agricultural residue

Materials	Unit	Rice Straw	Corn Stover	Cassava Straw
Inputs				
Biomass	kg	4.2	3.3	4.1
Electricity	kWh	0.57	1.05	0.92
Sulfuric acid	g	456	105	-
Vinyl Acetate	g	-	0.8	-
Sodium hydroxide	g	41.8	-	-
Yeast	g	-	-	0.2
Diammonium phosphate	g	10.9	5	7.3
Magnesium sulfate	g	0.42	-	-
Polydimethylsiloxane	g	1.67	-	-
Enzymes	g	80	30	84
Diesel	L	0.11	-	0.01
Water	L	0.6	-	-
Corn syrup	g	-	35	-
Ammonia	g	-	10	-
Lime	g	-	77	-
Coal	g	-	-	383
Urea	g	-	12.6	-
Outputs				
Carbon dioxide	g	335	-	745
Residue	kg	-	76	2.1
Electricity	kWh	1.07	1.05	0.92
Ethanol	L	1	1	1

Impact assessment. For this study, the IMPACT 2002+ impact assessment method is utilized to evaluate twelve midpoint impact categories, which include human toxicity (carcinogens and non-carcinogens), respiratory inorganics, ionizing radiation, global warming, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification, aquatic acidification, and aquatic eutrophication (Kumar et al., 2024). The energy profile is assessed using the cumulative energy demand methodology described by Frischknecht et al. (Frischknecht et al., 2015).

Interpretation. Table 4.10 summarizes the results from the twelve environmental impact categories of the IMPACT 2002+ method. Analyzing the environmental impacts of bioethanol production from cassava straw, corn stover, and rice straw reveals distinct differences across various categories. Rice straw bioethanol shows higher impacts across multiple midpoint impact categories than corn stover and cassava straw. On the other hand, corn stover and cassava straw exhibit lower environmental impacts in most categories, suggesting they may be more environmentally friendly options for bioethanol production, except for GWP.

Human toxicity potential (HTP). The HTP of rice straw bioethanol accounts for 0.0241 kg C₂H₃Cl eq. for carcinogens and 0.152 kg C₂H₃Cl eq. for non-carcinogens. The primary factors contributing to the HTP, as shown in Figure 4.11, are the enzymatic hydrolysis process (63% for carcinogens and 78% for non-carcinogens) and the use of acid (49% for carcinogens and 5% for non-carcinogens). However, electricity, as an avoided product, reduces environmental impacts by -24% and -5% for carcinogens and non-carcinogens, respectively. For cassava straw bioethanol, environmental impacts were primarily due to the use of diammonium phosphate during pre-treatment (95% and 96% for carcinogens and non-carcinogens, respectively). The enzymatic hydrolysis and pretreatment processes account for 50% and 24% of HTP in producing bioethanol from corn stover, respectively, for carcinogens and non-carcinogens. The environmental impacts of enzymatic hydrolysis result from emissions of hydrocarbons, benzo(a)pyrene, and arsenic, as well as energy consumption during enzyme production.

Respiratory inorganic potential (RIP). The cumulative RIP associated with bioethanol production was 1.52E-03 kg PM_{2.5} eq. for rice straw, 7.98E-04 kg PM_{2.5} eq. for corn stover, and 1.52E-04 kg PM_{2.5} eq. for cassava straw. Enzyme usage during hydrolysis accounts for 105%, 74%, and 82% of the RIP for rice straw, corn stover, and cassava straw, respectively. These impacts were primarily caused by emissions of nitrogen oxides (33%), sulfur dioxide (26%), and ammonia (23%) for rice straw; particulates < 2.5µm (35.2%), nitrogen oxides (26%), and sulfur dioxide (22%) for corn stover; and sulfur dioxide (89%), particulates <2.5µm (6.5%), and nitrogen oxides (4%) for cassava straw. However, electricity as an avoided product reduces

environmental impact by 49%. The use of sulfuric acid contributes to 26%, 11%, and 14% of the total RIP for rice straw, corn stover, and cassava straw, respectively.

Table 4.10 Characterized IMPACT 2002+ results of environmental impacts for bioethanol production from agricultural residues

Impact category	Unit	Rice Straw	Corn Stover	Cassava Straw
Aquatic ecotoxicity	kg TEG water	422	113	3.608
Global warming	kg CO ₂ eq	1.22	0.47	1.40
Terrestrial ecotoxicity	kg TEG soil	251.15	98.62	1.16
Ionizing radiation	Bq C-14 eq	12.73	6.91	0.23
Terrestrial acid/nutri	kg SO ₂ eq	0.071	0.0279	0.00253
Aquatic acidification	kg SO ₂ eq	1.39E-02	6.34E-03	1.27E-03
Non-carcinogens	kg C ₂ H ₃ Cl eq	0.15	0.05	1.52E-03
Aquatic eutrophication	kg PO ₄ P-lim	1.05E-03	4.06E-04	1.03E-03
Carcinogens	kg C ₂ H ₃ Cl eq	2.41E-02	1.12E-02	7.86E-04
Respiratory organics	kg C ₂ H ₄ eq	5.32E-04	1.52E-04	2.28E-04
Respiratory inorganics	kg PM _{2.5} eq	1.52E-03	7.98E-04	1.52E-04
Ozone layer depletion	kg CFC-11 eq	3.42E-06	4.94E-08	4.94E-09

Ionizing radiation potential (IRP). As shown in Figure 4.11, the total IRP for rice straw accounts for 12.734 Bq C-14 eq., of which 134% and 9% correspond to the hydrolysis and pre-treatment processes, respectively; however, electricity production reduced the impact by 53.5%. These impacts were mainly due to the emission of radon-222 (55.7%) and carbon-14 (42%) during enzyme production and energy usage. Enzymatic hydrolysis also has the greatest impact on corn stover (92%), and in cassava straw, using fuel and diammonium phosphate during pre-treatment yields 59% and 40% of total IRP. These impacts were due to radon-222 and carbon-14. Similar results were obtained by (Lyu et al., 2021), which analyzed the influence of the C5 cellulosic sugar from cassava straw on bioethanol production.

Global warming potential (GWP). Cassava straw has the highest GWP (1.4 kg CO₂ eq. per FU), primarily due to emissions from production (67%), the hydrolysis process (31%), and pre-treatment of feedstock (<2%), as shown in Figure 4.11. The findings of the study align with the conclusions drawn by (Rathnayake et al., 2018; Veiga et al., 2016). For rice straw and corn stover-based bioethanol, GWP was majorly due to hydrolysis (78% and 76%, respectively), as shown in Figure 4.11.

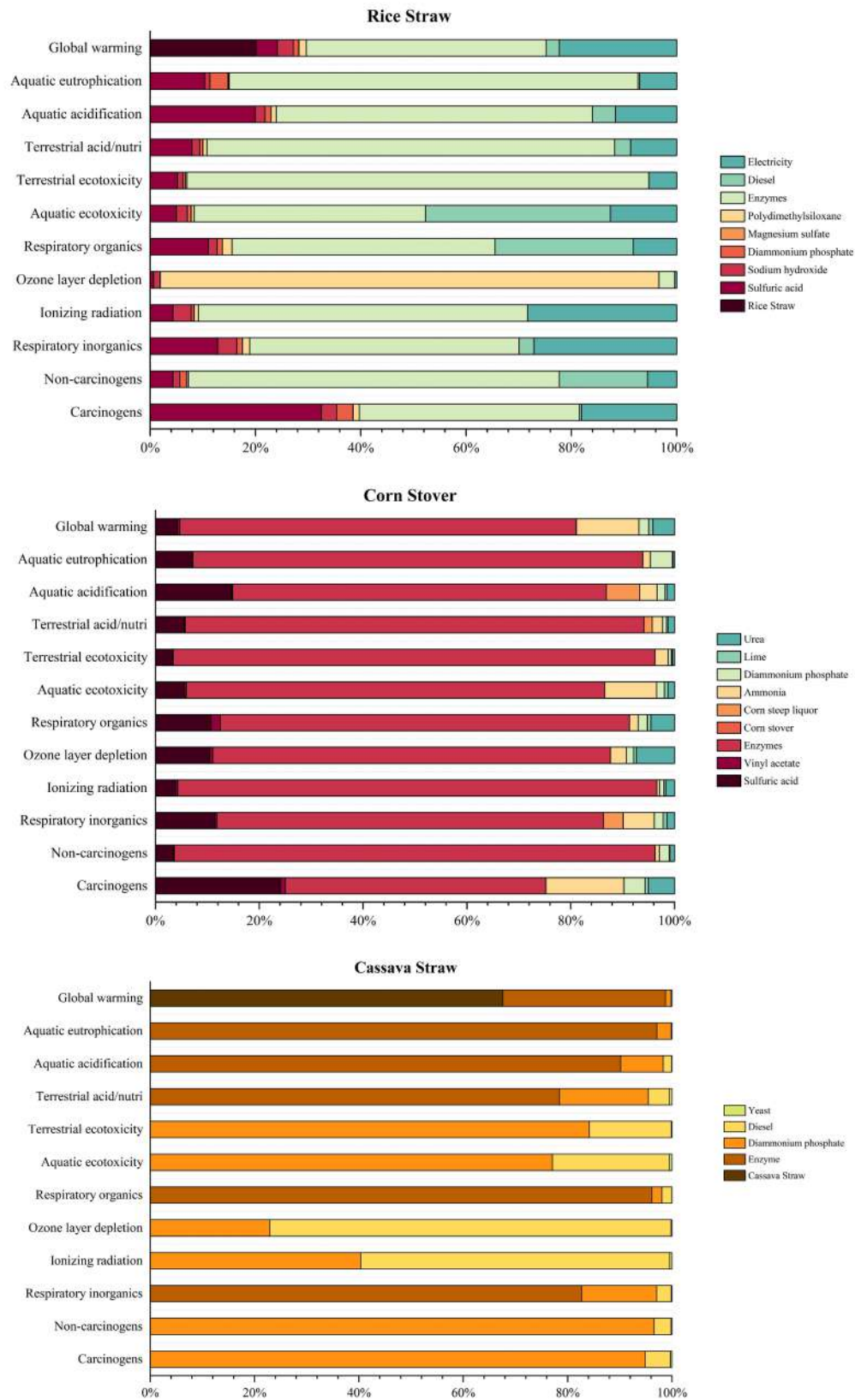


Figure 4.11 Midpoint category LCA results for bioethanol production from Rice Straw, Corn Stover, and Cassava Straw.

Ozone layer depletion potential (ODP). Regarding the ODP, the total estimated impact across the life cycle of rice straw bioethanol production was 3.42E-06 kg CFC-11 eq. (Table 4.10). This total impact mostly comes from the use of polydimethylsiloxane (95%). The primary contributor to the total ODP of cassava straw biofuel was the utilization of fuel (77%) and diammonium phosphate (23%) for pre-treatment. On the other hand, in the case of corn stover biofuel, enzymatic hydrolysis of biomass was identified as a significant factor, contributing to approximately 77% of the ODP. This impact category can contribute to the depletion of the stratospheric ozone layer, significantly affecting the amount of solar radiation reaching Earth's surface.

Ecotoxicity potential (EP). The primary contributors to rice straw-based bioethanol's aquatic and terrestrial ecotoxicity are the enzymatic hydrolysis process during biofuel production, which results in 422 kg of triethylene glycol (TEG) in water and 251.15 kg of TEG in soil. For cassava straw and corn stover, the utilization of diammonium phosphate and enzymatic hydrolysis, respectively, significantly reduces their aquatic and terrestrial ecotoxicity potential. Specifically, hydrolysis accounts for 81% and 93% of the impacts for corn stover, while pre-treatment accounts for 77% and 84% for cassava straw-based bioethanol, respectively. The primary cause of these impacts was the emission of aluminum in soil (26% and 35% for corn stover and cassava straw, respectively).

Respiratory organics potential (ROP). The primary reason for the high ROP of rice straw biofuel is enzymatic hydrolysis, accounting for 59% of the overall ROP, followed by diesel and acid utilization, which contribute 27% and 13%, respectively. These impacts were primarily caused by the emissions of non-methane volatile organic compounds (NMVOC; 89%), isoprene (1.5%), and aromatic hydrocarbons (0.9%) during enzyme production and energy use. However, electricity as an avoided product of rice-straw-based biofuel shows a reduction in ROP by -8.6% of the total impact. In the case of corn stover, the ROP is primarily influenced by the enzymatic hydrolysis process, which results in 86% NMVOC, 1.7% ethene, and 1.5% benzene emissions during its production. As for cassava, 96% of the ROP is attributed to enzymatic hydrolysis.

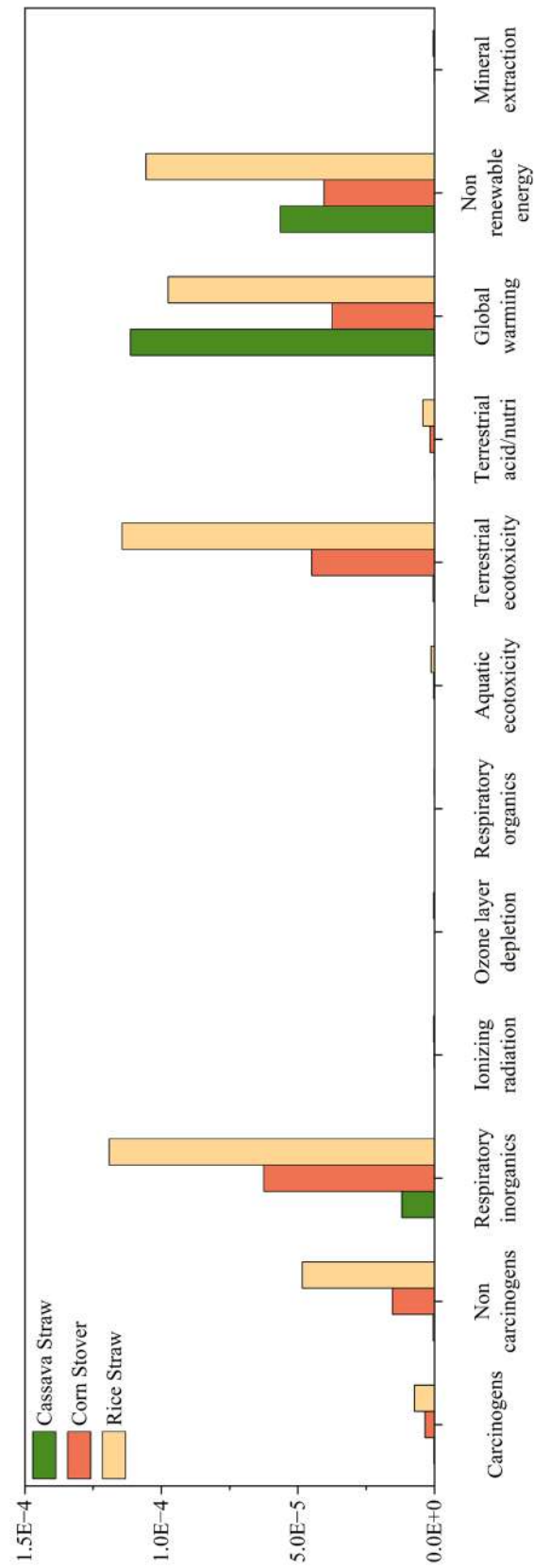


Figure 4.12 Normalization score of bioethanol production from agro-residues.

Eutrophication potential (EUP). The EUP for cassava and rice straw is the highest compared to corn stover. This high impact is mainly because of enzymatic hydrolysis (97% for cassava straw and 89% for rice straw), which is due to phosphate emission (97% and 46%, respectively), and phosphorus (0.1% and 47%, respectively), followed by consumption of diammonium phosphate (2% and 3%, respectively). In the case of corn stover, EUP is $4.06\text{E-}04$ kg PO₄ P-lim. These adverse effects are primarily the result of inorganic emissions caused by phosphates, total organic carbon, and NO_x compounds, as well as long-term emissions to freshwater resources.

Acidification potential (AP). Among the three biomasses compared, rice straw bioethanol exhibits the highest AP. Enzymatic hydrolysis contributes most to AP values, accounting for 79%, followed by acid use at 26% for aquatic acidification and 88% and 9% for terrestrial acidification (Figure 4.11).

Normalization. Normalization, as discussed in Chapter 3, helps to check inconsistencies, facilitate communication, and prepare for additional procedures, such as grouping and weighing. Figure 4.12 shows the normalized score of agro-residue-based bioethanol production. Normalization results showed that the environmental impact categories, like respiratory inorganics, terrestrial ecotoxicity, and global warming, are the dominating categories. In contrast, ozone layer depletion, respiratory organics, ionizing radiation, and aquatic ecotoxicity have the most negligible environmental impacts.

4.2.3.2 Energy analysis

The cumulative energy demand associated with fossil fuels, including hard coal, lignite, natural gas, and crude oil, was considered throughout the life cycle of bioethanol production. As shown in Table 4.11, rice straw-based bioethanol production consumes the most fossil fuel (17.62 MJ), mainly due to enzymatic hydrolysis (66%) followed by pre-treatment (30%). As observed in Figure 4.13, the energy sources required to produce bioethanol from agricultural biomass still rely on fossil fuels. Patel and Singh (Patel and Singh, 2024) reported similar results in their analysis of biofuel production from agricultural residue and municipal solid waste. The total CED for

producing bioethanol from corn stover was quantified as 10.93 MJ, which mainly comes from fossil fuel (~57%), followed by renewable biomass (29%), nuclear energy (~9%), hydro energy (~2.6%), renewable energy sources such as wind, solar and geothermal (~1.2%), and non-renewable biomass (<0.1%). For cassava straw-based bioethanol, the total CED was 10.31 MJ, mainly from fossil fuels (>99%), followed by renewable biomass, nuclear energy, and other sources, which together accounted for <1%. For cassava straw and corn stover, the CED was mainly due to the enzymatic hydrolysis during biofuel production.

Table 4.11 Environmental impact categories obtained from the cumulative energy demand in the bioethanol production from agricultural residues

Impact category	Unit	Rice Straw	Corn Stover	Cassava Straw
Non-renewable, fossil	MJ	17.26	6.29	10.29
Non-renewable, nuclear	MJ	1.8	1.0	8.5E-03
Non-renewable, biomass	MJ	3.0E-03	1.3E-03	1.1E-04
Renewable, biomass	MJ	8.53	3.22	7.5E-03
Renewable, wind, solar, geothermal	MJ	0.23	0.13	1.3E-03
Renewable, water	MJ	0.41	0.29	7.0E-03
NER		1.53	3.95	4.19
NEV		14.97	32.27	32.89
Rn		2.50	6.87	4.20
NRnEV		25.94	36.91	32.91

The energy balance assessment, as tabulated in Table 4.11, indicates that all feedstocks exhibit positive net energy performance, as reflected by NER values greater than unity and substantial NEV values. Higher NER and NRnEV values for corn stover and cassava straw suggest better energy efficiency and greater net renewable energy gains compared to rice straw. Additionally, the Rn values indicate a stronger contribution from renewable energy in these systems, suggesting improved sustainability in energy utilization.

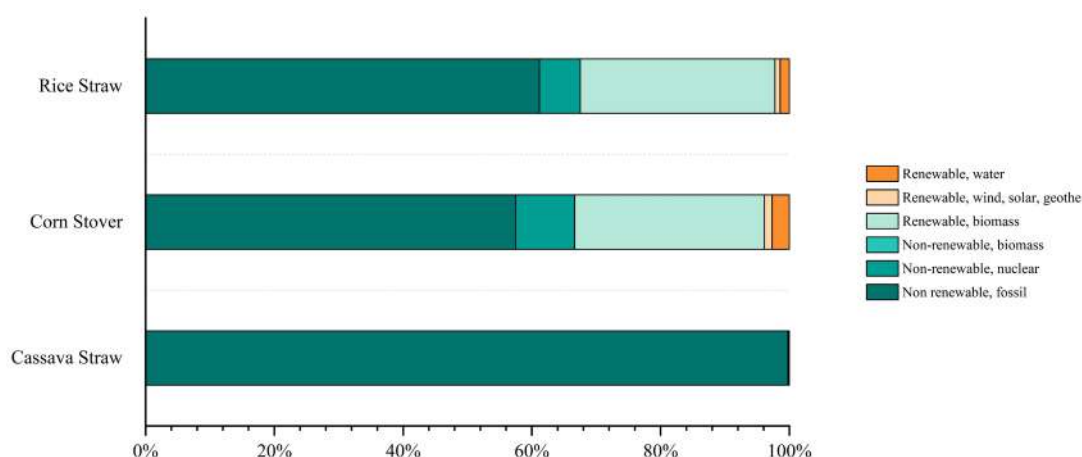


Figure 4.13 Cumulative energy demand results obtained for the LCA of bioethanol from agricultural residue.

4.2.3.3 Sensitivity and uncertainty analysis

The MCS results associated with bioethanol production from the considered agro-residues are shown in Table 4.12. The table presents details regarding the uncertainty in impact categories, including the mean, standard deviation, coefficient of variation (CoV), standard error of the mean (SEM), and skewness. The results indicate that variation across most environmental impact categories remains within $\pm 10\%$, suggesting the acceptability of the findings. However, the CoV of rice-based bioethanol is high, indicating high uncertainty in its production. Figure 4.14 shows the probability distributions of selected impact categories derived from Monte Carlo simulations, illustrating the variability and uncertainty ranges across different environmental indicators. The alignment of histograms with the fitted density curves indicates that the results are well approximated by lognormal distributions, consistent with the nature of environmental inventory data. The cumulative distribution functions and the delineated 5th and 95th percentile bounds provide a clear representation of the confidence intervals, demonstrating constrained uncertainty for most impact categories. Relatively narrower distributions observed for global warming suggest lower variance and higher model stability, whereas broader distributions in aquatic and terrestrial ecotoxicity indicate greater sensitivity to key input parameters.

Table 4.12 Uncertainty analysis of the LCA of agricultural residue-based bioethanol

Environmental Impact Category	Rice Straw					Corn Stover					Cassava Straw				
	Mean	SD	CoV (%)	SEM	Skewness	Mean	SD	CoV (%)	SEM	Skewness	Mean	SD	CoV (%)	SEM	Skewness
Aquatic acidification	0.009	0.001	10.1	8.60E-06	0.039	4.10E-03	2.60E-04	6.4	2.60E-06	0.09	1.40E-03	1.00E-04	7.3	1.00E-06	0.13
Aquatic ecotoxicity	260.778	15.517	6	1.60E-01	0.118	89.491	5.431	6.1	5.40E-02	0.08	4.033	0.277	6.9	2.80E-03	0.12
Aquatic eutrophication	0.001	1.5E-05	14.6	8.10E-07	0.005	3.00E-04	2.20E-05	7.5	2.20E-07	0.08	8.10E-04	6.40E-05	7.8	6.40E-07	0.13
Carcinogens	0.014	0.001	6.2	8.80E-06	0.138	6.60E-03	3.20E-04	4.9	3.20E-06	0.08	5.00E-04	3.80E-05	7.6	3.80E-07	0.13
Global warming	0.793	0.101	12.7	1.00E-03	-0.02	0.439	0.023	5.3	2.30E-04	0.04	1.108	0.066	5.9	6.60E-04	0.13
Ionizing radiation	14.141	1.511	10.7	1.50E-02	0.022	6.036	0.456	7.6	4.60E-03	0.07	0.176	0.01	5.7	1.00E-04	0.06
Non-carcinogens	0.116	0.008	6.8	7.90E-05	0.149	0.042	0.003	6.8	2.90E-05	0.09	1.30E-03	9.80E-05	7.8	9.80E-07	0.13
Ozone layer depletion	2.70E-06	2.10E-07	7.5	2.10E-09	0.103	4.30E-08	2.50E-09	5.8	2.50E-11	0.08	4.00E-09	2.60E-10	6.4	2.60E-12	0.11
Respiratory inorganics	-4.60E-04	3.70E-04	-81.6	3.70E-06	-0.06	5.20E-04	3.40E-05	6.6	3.40E-07	0.08	1.30E-04	8.30E-06	6.6	8.30E-08	0.14
Respiratory organics	3.30E-04	2.10E-05	6.3	2.10E-07	0.138	1.20E-04	7.40E-06	6.1	7.40E-08	0.08	1.80E-04	1.40E-05	7.7	1.40E-07	0.13
Terrestrial acid/nutri	0.05	0.004	8.6	4.30E-05	0.122	0.021	0.002	7.2	1.50E-05	0.09	1.70E-03	1.10E-04	6.4	1.10E-06	0.13
Terrestrial ecotoxicity	208.486	15.557	7.5	1.60E-01	0.147	76.161	5.714	7.5	5.70E-02	0.08	1.193	0.085	7.2	8.50E-04	0.14

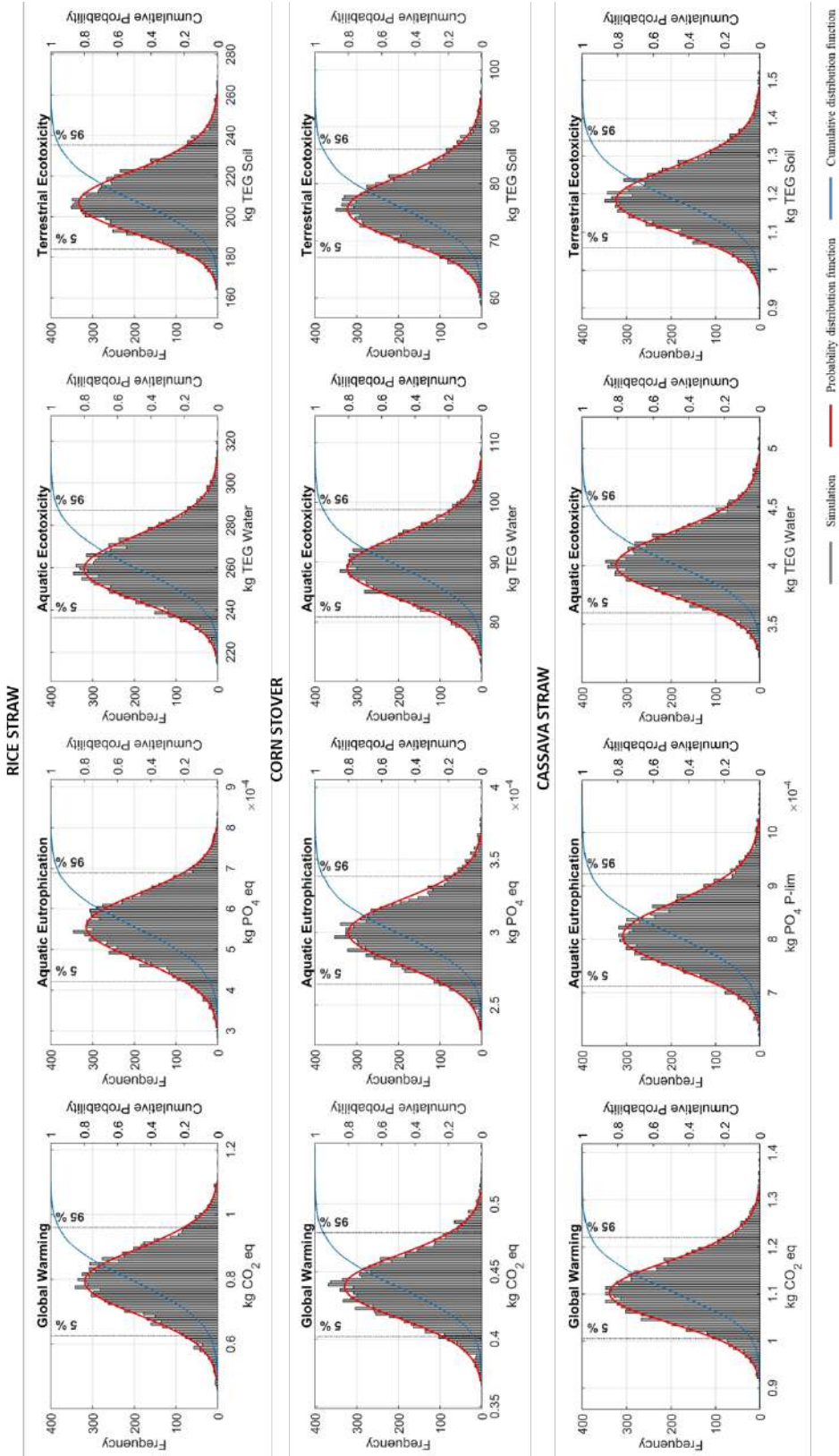


Figure 4.14 Monte Carlo Uncertainty calculations for agro-residue based bioethanol production.

4.2.4 Municipal solid waste-based bioethanol

First-generation biofuels are primarily derived from food crops through fermentation (UN Report, 2007). However, this approach faced significant criticism, particularly regarding using food crops for fuel production when food shortages were prevalent, leading to societal discontent (Ahlgren and Di Lucia, 2014). In response to these challenges, second-generation biofuels were developed, aiming to overcome the limitations of the first generation. These biofuels were produced from non-food organic sources such as crop residues, wood, municipal solid waste, and other biomass materials, thus mitigating the primary drawback (Liska et al., 2009). As urbanization continues to rise, so does the amount of waste generated per person. Since the 1970s, researchers have been exploring ways to convert MSW into ethanol, with particular interest in enzymatic conversion and sulfuric acid hydrolysis processes (Cardona and Sánchez, 2007; Curtiss and Kreider, 2010). However, beyond the technical challenges of biomass-to-ethanol conversion, there needs to be more discussion regarding the environmental and economic impacts of bioethanol from MSW. Bioethanol from MSW provides a sustainable solution to waste management challenges and contributes to reducing GHG emissions, aligning with the principles of a circular and low-carbon economy. The gravity pressure vessel (GPV) developed by GeneSyst was employed to model the conversion of MSW into ethanol (Kalogo et al. 2007; GeneSyst International 2012). Designed explicitly for MSW, the GPV utilizes a lengthy subterranean pipe to circulate a mixture of MSW and water, taking advantage of high-pressure and high-temperature conditions at the pipe's base to facilitate the dissolution of nearly any organic chemicals present in the MSW (Kalogo et al. 2007).

4.2.4.1 Environmental assessment

This study effectively integrates MSW into biofuel production, demonstrating their potential for solving energy and waste management challenges. This work contributes to the literature by offering new insights into the comparative benefits and challenges of utilizing MSW for biofuel production.

Goal and scope. This work analyzes and compares the production of bioethanol from MSW using a cradle-to-gate system boundary, as shown in Figure 4.15. The system boundary of the study assumes the availability of MSW as a feedstock and does not consider energy use and environmental implications of the processes and products that generate the MSW. MSW-fluff (organic residual remaining after conventional extraction of commodities that can be recycled, e.g., aluminum, glass, steel, and plastics, from raw MSW), as initially referenced by (Broder and Henson, 1993), is considered the primary input (Shakelly et al., 2023). Table 4.13 displays the weight-based composition of MSW. The transformation of MSW-fluff into ethanol utilizes a GPV. The key stages in the conversion process include shredding and separating MSW-fluff, subjecting it to continuous dilute acid hydrolysis under high-temperature and high-pressure conditions within a GPV to convert the cellulose fraction into sugars, fermenting the sugars into ethanol, and distilling to obtain ethanol of fuel quality (Kalogo et al. 2007; GeneSyst International 2012). To enable accurate comparisons across products or services, a functional unit (FU) is used as a quantitative measure, typically expressed in terms of weight, volume, or energy content. The FU used in this study is per liter of bioethanol produced, but for comparison purposes, results are converted into per kg bioethanol produced.

Table 4.13 The composition of municipal solid waste

Component	Percent weight composition	Reference
Cellulose	58.51	(Mahmoodi et al., 2018)
Hemicellulose	11.92	(Mahmoodi et al., 2018; Verhe et al., 2022)
Lignin	15.3	(Verhe et al., 2022)
Others	14.28	(Verhe et al., 2022)

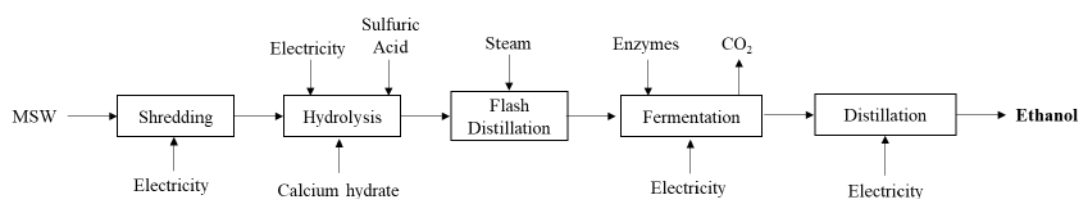


Figure 4.15 System boundary of bioethanol production from MSW

Inventory analysis. The background inventory analysis is based on the Ecoinvent v3 database (Wernet et al. 2016), and the foreground data are obtained from several studies in the literature on biofuels, as discussed in Table 3.1 in Chapter 3. Inventory data for ethanol production using MSW is presented in Table 4.14.

Table 4.14 Inventory data for MSW and Rice-straw based bioethanol production per functional unit

Material	Unit	MSW
Inputs		
Electricity	MJ	6.26
Diesel	g	78
Calcium hydrate	g	600
Sulfuric acid	g	400
Enzymes	g	620
Natural Gas	m ³	0.33
Steam	kg	1.72
Outputs		
Ethanol	L	1
CO ₂	g	344.4

Impact assessment. The IMPACT World+ impact assessment method is used for analysis in the study, and it comprises Eco-Indicator, IPCC, Impact 2002+, and CML (Patel and Singh, 2022; PRé Sustainability, 2022). The cumulative energy demand method is used to assess the total energy required for biofuel production.

Interpretation. The damage categories associated with biofuel production per functional unit using the IMPACT World+ impact assessment method are as follows.

Human Health. Toxicity, Climate change (short-term), ozone layer depletion, photochemical oxidant formation, particulate matter, ionizing radiation (impacting human health), and water availability midpoint categories contribute to the human health damage category and are measured in DALY (“Disability-adjusted life years”) per kg emission. Climate change, short-term, refers to the shorter-term impacts of climate change occurring within the first 100 years after the emission of greenhouse gases. This category focuses on the immediate effects of greenhouse gas emissions on the rate of temperature change and other climate-related impacts over a relatively short

time horizon. The short-term climate change for MSW is 5.02 kg CO₂ eq., as shown in Table 4.15.

The bioethanol production causes 2.3E-07 CTUh (Comparative toxicity unit for human health) of carcinogen toxicity, 6.7E-07 CTUh of non-carcinogen toxicity, 4.4E-07 kg CFC-11 eq. of ozone layer depletion, 2.5E-03 kg PM_{2.5} eq. of particulate matter formation, 39.01 Bq C-14 eq. of ionizing radiation, and 8.7E-04 DALY of water availability (human health), as shown in Table 4.16. The conditions to decide which substance is taken as a midpoint reference substance are based on (i) a substance with proven effects, (ii) a generally accepted substance, and (iii) a substance with low uncertainties in exposure and effect modeling. The high human health damage category for MSW is mainly due to electricity use (77.2%), followed by enzymes (21.2%).

Ecosystem Quality. The ecosystem quality endpoint category comprises acidification, eutrophication, ecotoxicity, climate change (both short- and long-term), ionizing radiation (affecting ecosystem quality), water scarcity (affecting water availability in terrestrial and freshwater ecosystems), and land biodiversity (considering transformation and occupation). It is measured in PDF*m²*yr (“potentially disappeared fraction of species in a certain area over a certain period”). The freshwater ecotoxicity potential of MSW bioethanol is highest (51%), primarily due to the hydrolysis (46%) converting cellulose to glucose and electricity use (40%), followed by impacts from land transformation, biodiversity loss (30.5%), and long-term climate change (7%). Figure 4.16 shows the midpoint impact categories of MSW-based bioethanol production.

The water scarcity impact for MSW is 2.59 m³ World eq., as shown in Table 4.16, with enzyme production contributing 69% of the impact. In terms of the damage level indicator for water availability impacts, as shown in Table 4.3, the terrestrial ecosystem contributes 95% for MSW bioethanol, followed by the freshwater ecosystem, which accounts for 3.4%. Freshwater and marine eutrophication of MSW bioethanol is high due to hydrolysis, which accounts for 88% and 79% of the impacts, respectively, followed by electricity consumption, which accounts for 2% and 11%, respectively. The results of the study are compared with the incineration method of

waste management, shown in Table 4.17, as it is the most commonly adopted method for waste management. This result is in line with the study by (Bozorgirad et al., 2013; Elginos et al., 2020; Patel and Singh, 2022). This comparison shows that the environmental impacts of bioethanol production are much lower than those of incineration, with a significant gap between the two. However, the energy recovery system is not considered for incineration.

Table 4.15 Endpoint damage categories of bioethanol production from MSW

Impact category	Unit	MSW
A) Damage on Area of Protection		
Human Health	DALY	9.0E-4
Ecosystem Quality	PDF.m ² .yr	43.22
B) Damage Level Indicators		
Climate change, human health, short term	DALY	5.2E-06
Climate change, human health, long term	DALY	1.4E-05
Photochemical oxidant formation	DALY	5.1E-10
Ionizing radiation, human health	DALY	8.2E-09
Ozone layer depletion	DALY	6.7E-10
Human toxicity cancer, short term	DALY	4.3E-07
Human toxicity cancer, long term	DALY	1.8E-08
Human toxicity non-cancer, short term	DALY	6.6E-07
Human toxicity non-cancer, long term	DALY	5.7E-07
Particulate matter formation	DALY	3.0E-06
Water availability, human health	DALY	8.7E-04
Climate change, ecosystem quality, short	PDF.m ² .yr	1.13
Climate change, ecosystem quality, long	PDF.m ² .yr	3.18
Marine acidification, short term	PDF.m ² .yr	0.08
Marine acidification, long term	PDF.m ² .yr	0.75
Freshwater ecotoxicity, short term	PDF.m ² .yr	0.10
Freshwater ecotoxicity, long term	PDF.m ² .yr	22.17
Freshwater acidification	PDF.m ² .yr	0.05
Terrestrial acidification	PDF.m ² .yr	0.37
Freshwater eutrophication	PDF.m ² .yr	4.3E-03
Marine eutrophication	PDF.m ² .yr	0.01
Ionizing radiation, ecosystem quality	PDF.m ² .yr	8.0E-10
Land transformation, biodiversity	PDF.m ² .yr	13.21
Land occupation, biodiversity	PDF.m ² .yr	2.12
Water availability, freshwater ecosys.	PDF.m ² .yr	2.3E-05
Water availability, terrestrial ecosys.	PDF.m ² .yr	6.3E-04
Thermally polluted water	PDF.m ² .yr	8.4E-06

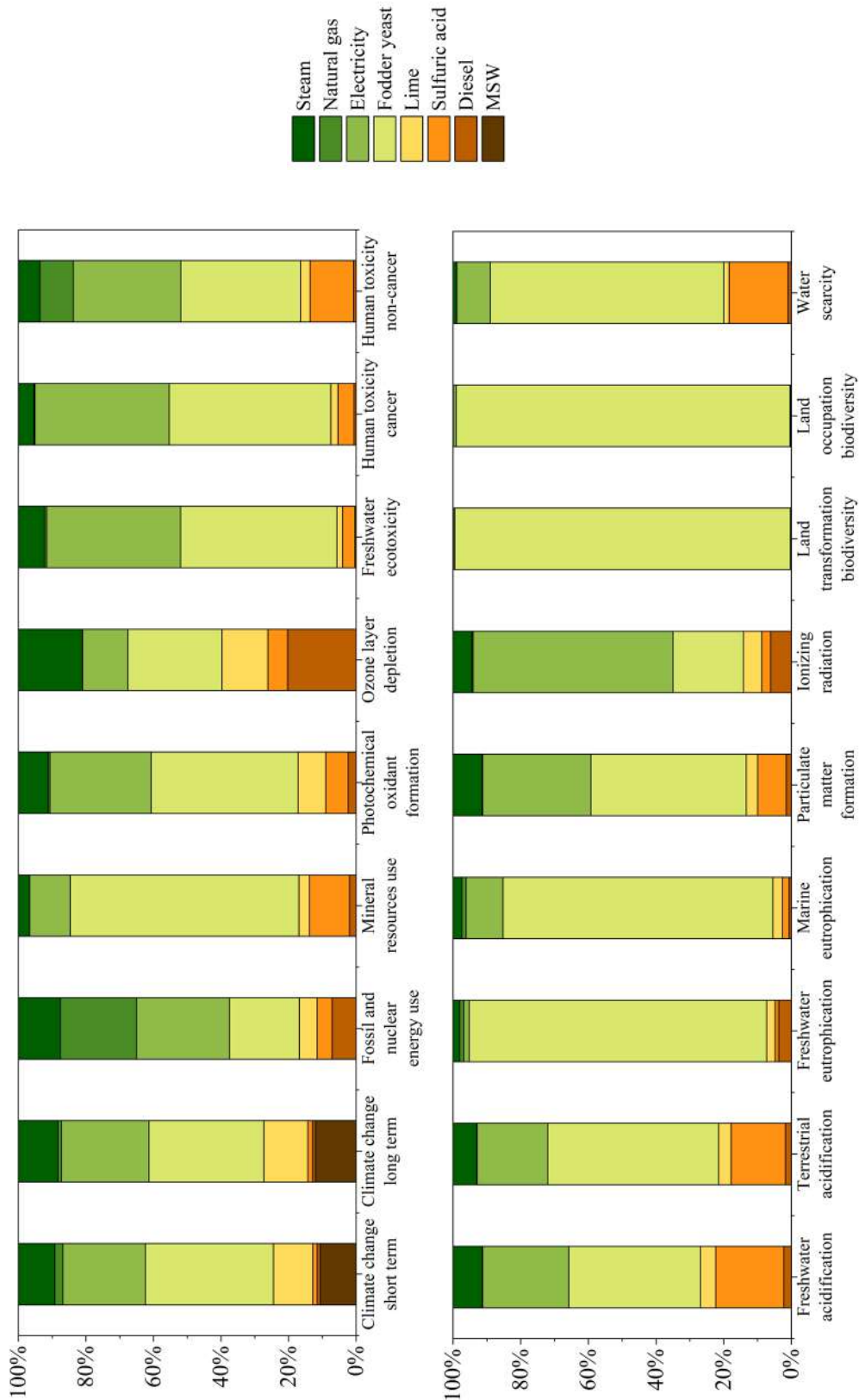


Figure 4.16 Midpoint impact categories of MSW based bioethanol

Table 4.16 Midpoint impacts of bioethanol production

Impact category	Unit	MSW
Climate change, short term	kg CO ₂ eq	6.36
Climate change, long term	kg CO ₂ eq	5.62
Fossil and nuclear energy use	MJ deprived	78.94
Mineral resources use	kg deprived	0.05
Photochemical oxidant formation	kg NMVOC eq	0.01
Ozone layer depletion	kg CFC-11 eq	4.4E-07
Freshwater ecotoxicity	CTUe	38672.76
Human toxicity cancer	CTUh	2.3E-07
Human toxicity non-cancer	CTUh	6.7E-07
Freshwater acidification	kg SO ₂ eq	5.8E-08
Terrestrial acidification	kg SO ₂ eq	5.7E-05
Freshwater eutrophication	kg PO ₄ eq	3.8E-04
Marine eutrophication	kg N eq	7.6E-04
Particulate matter formation	kg PM _{2.5} eq	2.5E-03
Ionizing radiation	Bq C-14 eq	39.01
Land transformation, biodiversity	m ² yr arable	5.2E-02
Land occupation, biodiversity	m ² yr arable	3.02
Water scarcity	m ³ world eq	2.59

Table 4.17 Comparison of bioethanol production system with incineration

Impact category	Unit	Bioethanol Production	Incineration
Abiotic depletion	kg Sb eq.	5.3E-04	4.7E-04
Global warming	kg CO ₂ eq.	84.494	519.129
Ozone layer depletion	kg CFC-11 eq.	2.8E-06	3.1E-06
Human toxicity	kg 1,4-DB eq	11.452	6532.022
Acidification	kg SO ₂ eq.	0.195	0.242
Eutrophication	kg PO ₄ ³⁻ eq.	0.026	0.309

Resources. Mineral resources, fossil fuels, and nuclear energy contribute to the Resource endpoint category. The mineral resource impact category assesses resource depletion based on the mass of mineral resources deprived per mass dissipated, whereas the fossil and nuclear energy use evaluates the energy deprived per mass of resource dissipated. Biofuel production from MSW has the highest fossil and nuclear

energy use, with 78.94 MJ of energy being deprived. Electricity consumption contributes to 28% of the resource damage category for MSW. Damages from mineral resource use are 0.04 kg deprived/FU for MSW bioethanol. The serious damage from mineral resource use in MSW is mainly due to enzyme production (68%), followed by electricity (12%).

4.2.4.2 Energy analysis

Fossil fuels remain a significant energy source for biofuel production. Table 4.18 shows the single-score results from CED analysis. MSW shows the highest fossil fuel consumption (~74%), followed by renewable biomass (17%), nuclear (5.4%), and wind, solar, and geothermal energy (0.7%), as shown in Figure 4.17.

Table 4.18 Single score result of CED of bioethanol production from MSW

Impact category	Unit	MSW
Non-renewable, fossil	MJ	66.83
Non-renewable, nuclear	MJ	4.93
Non-renewable, biomass	MJ	0.55
Renewable, biomass	MJ	15.33
Renewable, wind, solar, geothermal	MJ	0.67
Renewable, water	MJ	2.28
NER		0.48
NEV		-47.39
Rn		0.65
NRnEV		-23.63

The energy balance results for MSW indicate an unfavorable energy performance, with an NER value below unity (0.48), suggesting that the energy output is lower than the total energy input. The negative NEV and NRnEV values further confirm that the system results in a net energy loss, despite a moderate renewability index ($R_n = 0.65$). This implies that although a portion of the energy input is renewable, the overall process is not energetically sustainable.

4.2.4.3 Sensitivity and uncertainty analysis

Uncertainty analysis, as discussed in Chapter 3, uses methods such as Monte Carlo simulation to quantify and assess the variability and reliability of environmental impact results, ensuring robust, informed decision-making. Table 4.19 shows the uncertainty values for each impact category. The results of the Monte Carlo analysis for midpoint impact categories for MSW are shown in Figure 4.18. This study uses a lognormal distribution to reduce the possibility of negative emission for uncertainty analysis. The analysis also evaluates parameters such as mean, standard deviation, coefficient of variation (CoV), standard error of the mean (SEM), and skewness. A higher CoV value represents high uncertainty in results. The SEM represents the precision of the estimate of the mean, and the smaller SEM value shows more precision. The SEM values for MSW indicate the precision of the mean estimates, which impacts the reliability and accuracy of the analysis. This highlights the importance of SEM in research and practical applications to ensure informed and accurate decision-making. The Monte Carlo simulation results indicate low parametric uncertainty, with coefficients of variation largely within 4–8%, low SEM values, and near-zero skewness, confirming statistically stable and well-constrained model outputs. Impact dominance is primarily driven by freshwater ecotoxicity and water scarcity, followed by fossil and nuclear energy use and ionizing radiation, reflecting the significance of emissions and resource-intensive processes in the MSW pathway. In contrast, acidification and toxicity-related categories exhibit negligible magnitudes,

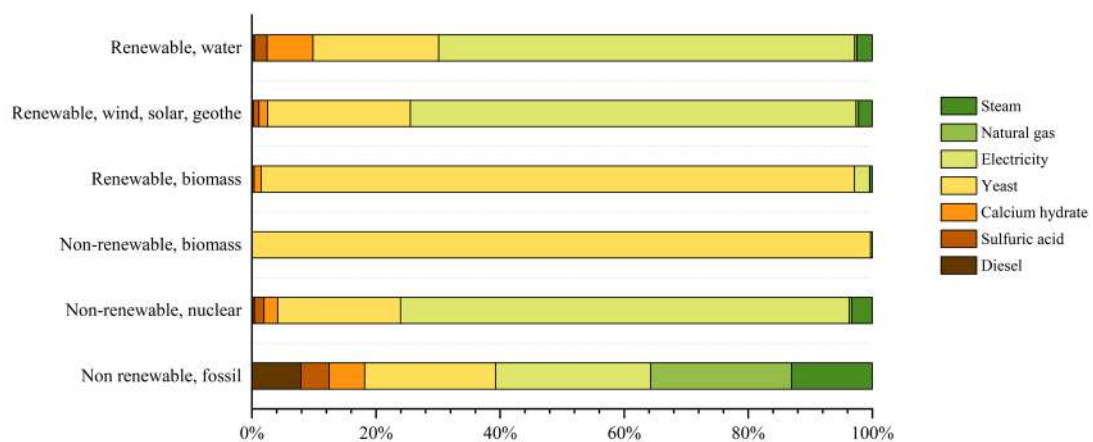


Figure 4.17 System boundary of bioethanol production from MSW

contributing minimally to the overall impact profile. Figure 4.18 depicts the frequency distributions and cumulative probabilities of midpoint environmental impacts of the LCA of bioethanol from MSW. The consistency in the data, as indicated by the narrow ranges between the 5th and 95th percentiles, suggests that the process has predictable environmental impacts, which is valuable for planning and optimization. These graphs are crucial for understanding the environmental impacts of bioethanol production. By analyzing the frequency distribution and cumulative probability of each impact category, stakeholders can identify the most significant environmental concerns and target areas for improvement. It shows how probabilities accumulate as values increase, showcasing trends of medians and variability across different values. This aids in statistical reasoning and decision-making by presenting a holistic view of probabilities and their cumulative nature.

Table 4.19 Uncertainty analysis for the production of MSW based bioethanol

Environmental Impact Categories	MSW				
	Mean	SD	CoV (%)	SEM	Skewness
IMPACT World+					
Climate change, long term	4.006	0.169	4.2	5.4E-03	0.183
Climate change, short term	4.529	0.191	4.2	6.0E-03	0.093
Fossil and nuclear energy use	20.208	1.664	8.2	5.3E-02	0.156
Freshwater acidification	1.8E-13	8.1E-15	4.5	2.6E-16	0.114
Freshwater ecotoxicity	16772.878	974.555	5.8	3.1E+01	0.160
Freshwater eutrophication	2.9E-05	1.6E-06	5.6	5.0E-08	0.123
Human toxicity cancer	1.1E-07	6.7E-09	6.2	2.1E-10	0.115
Human toxicity non cancer	2.7E-07	1.2E-08	4.4	3.7E-10	0.222
Ionizing radiations	21.116	0.888	4.2	2.8E-02	0.230
Land occupation, biodiversity	0.016	0.001	6.8	3.5E-05	0.158
Land transformation, biodiversity	6.8E-04	3.0E-05	4.4	9.4E-07	0.211
Marine eutrophication	5.0E-04	2.9E-05	5.7	9.1E-07	0.201
Mineral resources use	1.7E-02	1.1E-03	6.7	3.6E-05	0.069
Ozone Layer Depletion	6.1E-07	2.8E-08	4.6	8.8E-10	0.257
Particulate matter formation	2.2E-03	1.0E-04	4.7	3.3E-06	0.103
Photochemical oxidant formation	1.2E-02	5.9E-04	4.9	1.9E-05	0.171
Terrestrial acidification	1.3E-07	5.9E-09	4.6	1.9E-10	0.106
Water scarcity	214.056	10.986	5.1	3.5E-01	0.147

SD: Standard Deviation; CoV: coefficient of variation; SEM: standard error of the mean

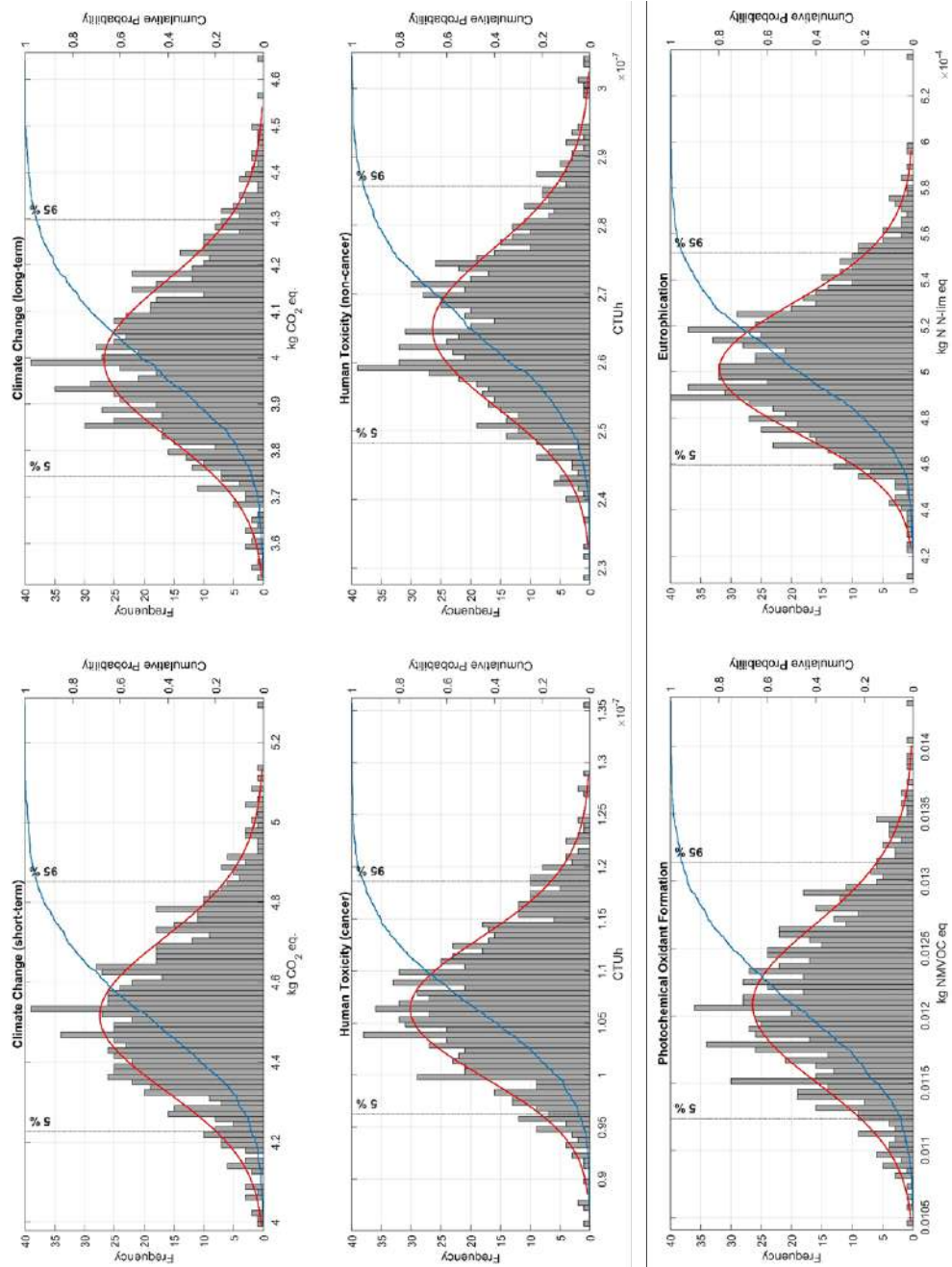


Figure 4.18 Uncertainty associated with the global warming, eutrophication, ecotoxicity, carcinogens and non-carcinogens of bioethanol production from MSW.

4.3 Environmental impacts of biodiesel feedstocks

Biodiesel has gained significant attention as a renewable alternative to fossil diesel, but its environmental performance is strongly influenced by the type of feedstock and the associated production processes. First-generation biodiesel, produced from edible oils such as soybean, palm, sunflower, and canola, as well as animal fats, involves transesterification of triglycerides with alcohol in the presence of a catalyst to yield fatty acid methyl esters and glycerol (JORD, 2024). While it offers advantages such as biodegradability, reduced greenhouse gas emissions, and compatibility with existing engines, its sustainability is constrained by dependence on food crops, leading to concerns over food security, land-use competition, and environmental impacts such as deforestation and biodiversity loss (DoE, 2025; Drishti IAS, 2019; JORD, 2024). In contrast, second-generation biodiesel utilizes non-edible and lignocellulosic feedstocks including agricultural residues, forest biomass, and municipal solid waste, thereby avoiding the food-versus-fuel conflict and reducing pressure on arable land (Kowalski et al., 2022; Verma et al., 2021). The conversion of such biomass involves advanced biochemical and thermochemical processes such as consolidated bioprocessing, although challenges related to feedstock recalcitrance, process efficiency, and logistics persist (Le et al., 2024; Sulis et al., 2025). Life cycle assessments indicate that second-generation biodiesel can achieve significant greenhouse gas reductions when biomass is sustainably sourced, highlighting its potential as a more sustainable alternative to first-generation systems (Kowalski et al., 2022).

4.3.1 Rapeseed and Jatropha-based biodiesel

Rapeseed- and jatropha-based biodiesel represent important pathways for renewable fuel production, contributing to reduced dependence on fossil fuels and improved environmental performance. Rapeseed, as an edible oil crop, supports established biodiesel production systems but raises concerns related to land use and competition with food resources. In contrast, jatropha, a non-edible oilseed, offers advantages by utilizing marginal lands and avoiding the food-versus-fuel conflict, thereby enhancing sustainability. Both feedstocks contribute to lowering greenhouse

gas emissions compared to conventional diesel, although their overall environmental benefits depend on cultivation practices, resource inputs, and processing efficiency.

4.3.1.1 Environmental assessment

As discussed in Chapter 3, the LCA framework is based on ISO 14040/44 which includes: (i) goal and scope, which entails a precise and consistent characterization of the research (ii) conduct a life cycle inventory (iii) conduct a life cycle impact assessment using the data gathered at the LCI phase (iv) interpretation of the results simultaneously with the other phases. LCA may examine and assess how different systems or activities affect the environment globally. This analysis compares the impacts of two promising and unconventional biomass types, Jatropha and Rapeseed Oil, for biodiesel production.

Goal and scope. The LCA takes a cradle-to-gate approach i.e. the system boundary of ends at the biodiesel factory gate. The functional unit used for the analysis is per kg of biodiesel produced. Figure 4.19 and Figure 4.20 show the system boundary of the study. The stages considered in this study for biodiesel production are the plantation of jatropha and rapeseed, the second stage is oil extraction, and the biodiesel production stage.

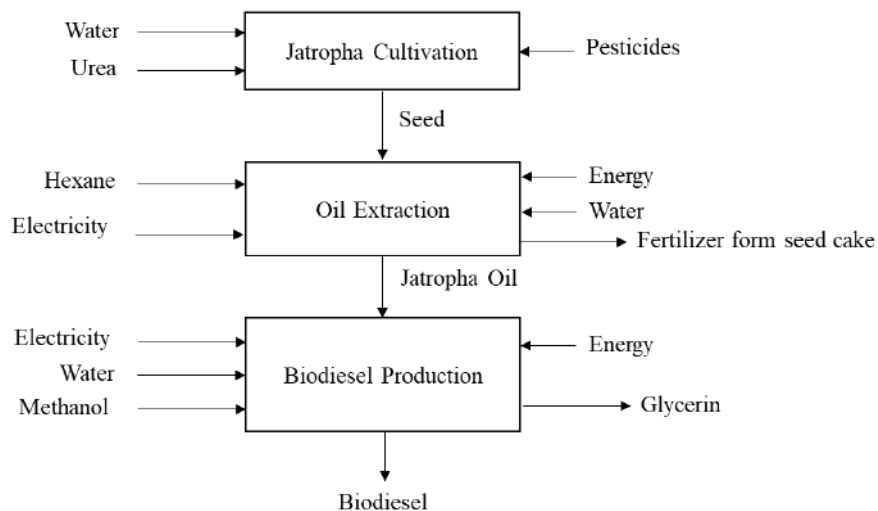


Figure 4.19 Process Flow Diagram for the production of biodiesel from jatropha oil.

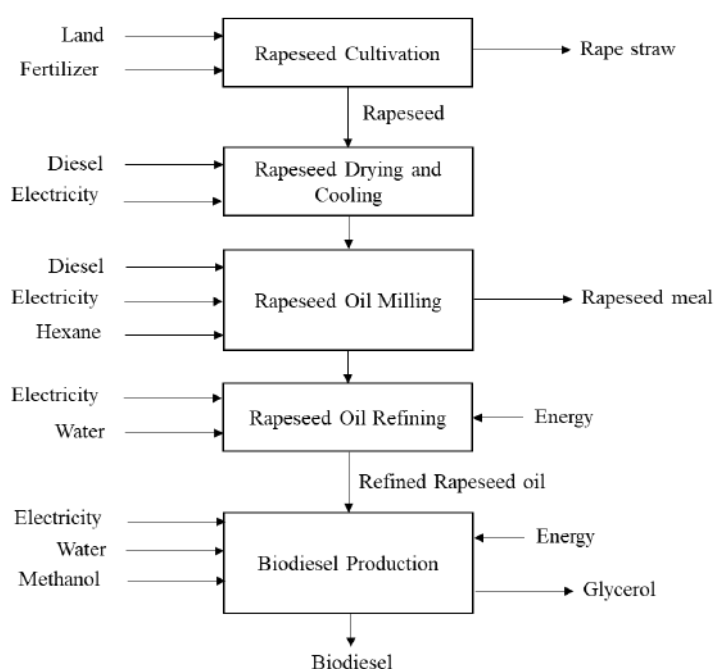


Figure 4.20 Process Flow Diagram for the production of biodiesel from rapeseed oil.

Inventory analysis. For each system boundary phase, input/output data such as raw materials, products, and pollutants are gathered and recorded. The LCI is significant because it directly impacts the LCIA phase and essential for interpreting data and conclusions. The Ecoinvent v3.6 database and previously published studies on the potential biodiesel production techniques were compiled in this analysis as discussed in Table 3.1 in Chapter 3. The inventory data of the biodiesel production from jatropha and rapeseed is shown in Table 4.20.

Impact assessment. LCIA is a phase that analyze and assess the environmental impacts of a system or a process. It composed of several steps; selection of impact categories, classification, characterization, normalization, grouping, and weighting (Nieuwlaar, 2013). In this study, IMPACT 2002+ method is used for the analysis. This method is the compilation of four method: Impact 2002, Eco-indicator – 99, CML and IPCC (Patel and Singh, 2022), and consist of 15 midpoint impact categories and 4 endpoint impact categories.

Table 4.20 Inventory Data of Jatropha and Rapeseed Biodiesel

Stage	Materials	Unit	Jatropha	Rapeseed
Cultivation	Input			
	Water	kg	24.7	-
	Urea	g	155.5	-
	Phosphorus Pentoxide	g	155.5	69
	Nitrogen	g	-	129
	Potassium Oxide	g	-	60
	Sulfur	g	-	60
	Diesel	g	16.5	87.46
	Output			
	Seed	g	3296.7	2580
Oil Extraction	Input			
	Seed	g	3296.7	2580
	Hexane	g	13.1	2.54
	Heat	MJ	2.97	2.82
	Electricity	kWh	0.18	0.2
	Water	kg	39.6	2.5
	Phosphoric Acid	g	-	1.06
	Output			
Jatropha Oil	g	1050	1031	
Biodiesel Production	Input			
	Jatropha Oil	g	1050	1031
	Methanol	g	124.9	219.8
	Sodium hydroxide	g	10.5	1.55
	Potassium hydroxide	g	-	15.5
	Sulphuric acid	g	15.8	10.4
	Electricity	kWh	0.041	0.124
	Heat	MJ	5.6	1.62
	Water	kg	0.14	0.2
	Output			
Biodiesel	g	1000	1000	

Interpretation. A comparative analysis of LCA of different biodiesel production methods was done in this study. The impact scores obtained from the analysis are as follows.

Human Health. Human Toxicity, respiratory effects, ionizing radiation, and ozone layer depletion all contributes to human health damage category expressed in DALY/kg emission (Disability adjusted life years per kg of emission) (Jolliet et al., 2003). The use of fertilizers for cultivation rapeseed causes highest impact on human health

(61.7%) followed by the use of electricity for processing (17.1%), methanol (7.9%), heat (4.3%), and other inputs (9%), as shown in Figure 4.21. For jatropha biodiesel human health impact is mainly caused by use of fertilizers (41.2%), followed by urea (19%), electricity (17%), heat (12%), methanol (6.5%), and others (4.3%).

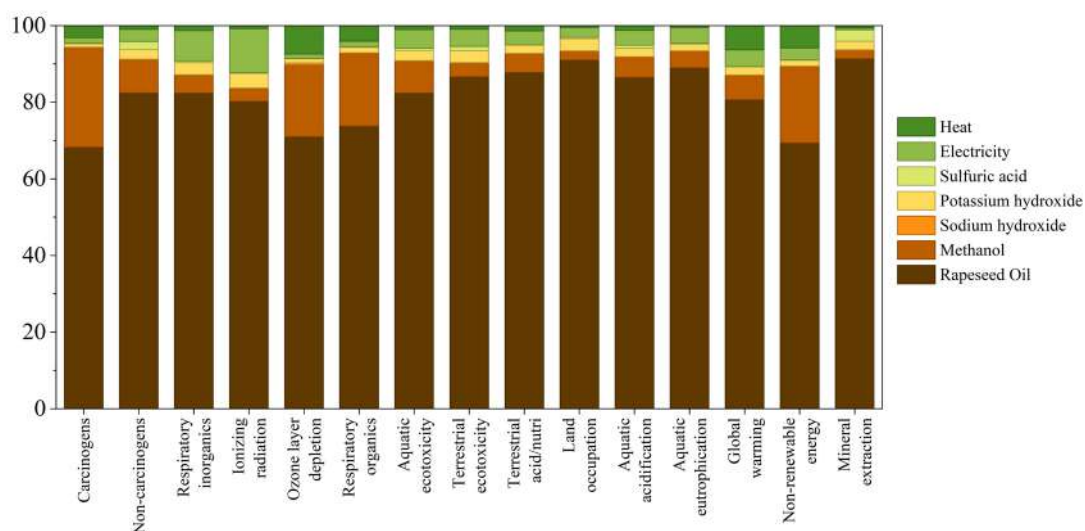


Figure 4.21 Midpoint impact category score of rapeseed biodiesel

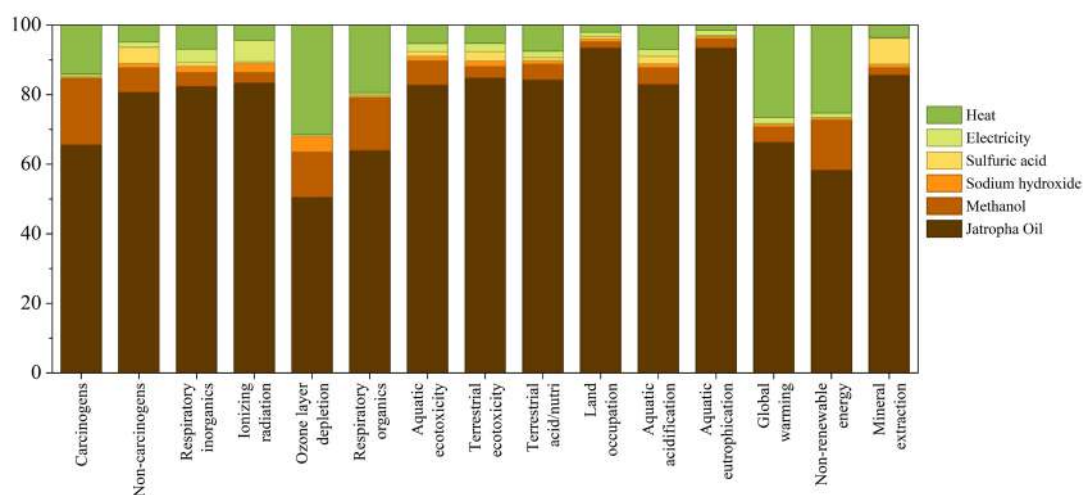


Figure 4.22 Midpoint impact category score of jatropha biodiesel

Ecosystem Quality. It is expressed in potential disappeared fraction of species over a certain area in a certain period ($\text{PDF} \cdot \text{m}^2 \cdot \text{yr} / \text{kg}_{\text{emitted}}$). Rapeseed biodiesel causes the highest impact on ecosystem quality primarily due to the use of fertilizers (73.3%) during cultivation of rapeseed, followed by use of electricity during production (11.1%), and other inputs (15.6%). Damage to ecosystem quality by jatropha biodiesel is $0.34 \text{ PDF} \cdot \text{m}^2 \cdot \text{yr} / \text{per functional unit}$, as shown in Table 4.21. This is mainly due to fertilizers (49.2%), followed by urea (21.3%), electricity (12.1%), heat (7.8%), methanol (3.3%), and others (6.3%).

Table 4.21 Endpoint Impact Category Score

Damage category	Unit	Jatropha Biodiesel	Rapeseed Biodiesel
Human health	DALY	1.16E-06	1.68E-06
Ecosystem quality	$\text{PDF} \cdot \text{m}^2 \cdot \text{yr}$	0.34	0.54
Climate change	kg CO ₂ eq	1.53	1.86
Resources	MJ primary	30.5	38.5

Climate Change. The rapeseed biodiesel production (RBP) has the highest global warming potential then jatropha biodiesel production (JBP). The GWP of RBP is 1.86 kg CO₂ eq. and that of JBP is 1.53 kg CO₂ eq. The damage category impact value is shown in Table 4.21. Major cause of GWP for RBP is again the cultivation stage causing 61.8% of total GWP. The midpoint score is shown in Figure 4.21. For jatropha biodiesel it is mainly due to heat (40.6%) used in oil extraction phase, fertilizers (27.4%) and urea (16.2%) used during cultivation, electricity (9.4%) used in entire production process, methanol (4.4%) used in transesterification process, and other inputs contributed 2% of total GWP. Figure 4.22 shows the midpoint score of jatropha biodiesel.

Resources. The mineral extraction and non-renewable energy contribute to resources endpoint category. The use of fertilizers during cultivation and electricity in biodiesel production causes highest resource depletion (54.4% and 12.2%, respectively) in rapeseed biodiesel. For jatropha biodiesel, resource depletion is mainly from heat (38.6%), fertilizers (17.9%), urea (16.7%), methanol (14.3%), electricity (7.1%), and other inputs contribute 5.4%.

4.3.1.2 Energy analysis

Table 4.22 shows the cumulative energy demand and energy balance of jatropha and rapeseed biodiesel production.

Table 4.22 Cumulative energy demand and energy balance of biodiesel production.

Impact category	Unit	Jatropha Biodiesel	Rapeseed Biodiesel	Conventional Diesel
Non-renewable, fossil	MJ	27.07	34.17	50.76
Non-renewable, nuclear	MJ	0.79	1.17	0.13
Non-renewable, biomass	MJ	2.07E-03	2.63E-03	1.35E-04
Renewable, biomass	MJ	0.27	0.39	0.03
Renewable, wind, solar, geother	MJ	0.13	0.18	0.02
Renewable, water	MJ	0.47	0.70	0.08
NER		1.39	1.09	0.84
NEV		11.27	3.39	-8.21
Rn		1.48	1.17	0.84
NRnEV		12.93	5.83	-7.96

The CED for jatropha biodiesel is 28.73 MJ, while for rapeseed biodiesel it is 36.61 MJ per functional unit. The results indicate that biodiesel production from both feedstocks still depends largely on fossil energy, accounting for 94.2% in jatropha and 93.3% in rapeseed systems. However, the NER values are positive, at 1.39 for jatropha and 1.09 for rapeseed, compared to 0.84 for conventional diesel, suggesting that producing biodiesel from these feedstocks provides an energetic advantage over fossil diesel.

4.3.1.3 Sensitivity and uncertainty analysis

In this study, Monte Carlo Simulation with 1000 iterations is used to assess the impact of uncertainty and variability in the environmental impacts of biodiesel production. The results are shown in Figure 4.23 and Figure 4.24, which shows the distribution of global warming potential, eutrophication, terrestrial and aquatic ecotoxicity potential for jatropha and rapeseed biodiesel, respectively. The graph

provides insights into the range of potential outcomes and enhances the robustness of the assessment.

Table 4.23 Uncertainty analysis of the LCA of jatropha and rapeseed-based biodiesel.

Environmental Impact Category	Unit	Jatropha			Rapeseed		
		Mean	SD	CoV (%)	Mean	SD	CoV (%)
Respiratory inorganics	kg PM2.5 eq	9.1E-04	4.9E-05	5.4	1.50E-03	6.7E-05	4.5
Terrestrial ecotoxicity	kg TEG soil	21.74	1.1E+00	4.9	37.58	1.6E+00	4.2
Carcinogens	kg C2H3Cl eq	4.7E-02	2.3E-03	4.8	5.1E-02	2.2E-03	4.3
Aquatic eutrophication	kg PO4 P-lim	8.4E-05	3.6E-06	4.4	1.1E-03	6.4E-05	5.9
Ozone layer depletion	kg CFC-11 eq	1.5E-07	5.9E-09	4.0	2.1E-07	7.2E-09	3.4
Aquatic ecotoxicity	kg TEG water	101.04	4.7E+00	4.6	235.92	1.1E+01	4.8
Non-carcinogens	kg C2H3Cl eq	1.9E-02	1.0E-03	5.3	3.4E-02	1.7E-03	5.0
Mineral extraction	MJ surplus	2.3E-02	1.5E-03	6.7	3.5E-02	2.3E-03	6.5
Respiratory organics	kg C2H4 eq	3.1E-04	1.3E-05	4.3	3.8E-04	1.4E-05	3.7
Aquatic acidification	kg SO2 eq	4.7E-03	2.4E-04	5.1	9.4E-03	4.2E-04	4.5
Non-renewable energy	MJ primary	19.92	8.7E-01	4.4	26.10	9.7E-01	3.7
Ionizing radiation	Bq C-14 eq	4.40	2.0E-01	4.6	9.90	3.8E-01	3.8
Land occupation	m2org.arable	5.6E-03	3.0E-04	5.4	0.09	6.4E-03	7.1
Global warming	kg CO2 eq	0.95	4.7E-02	4.9	1.18	4.4E-02	3.7
Terrestrial acid/nutri	kg SO2 eq	1.9E-02	1.1E-03	5.7	0.03	1.0E-03	4.0

The Coefficient of Variation (CoV) values in the Table 4.23 indicate the relative variability in environmental impact measurements for key categories between Jatropha and Rapeseed. For important categories like respiratory inorganics, terrestrial ecotoxicity, aquatic ecotoxicity, global warming, and non-renewable energy use, CoV values generally range from about 3.7 to 5.4, reflecting moderate consistency in these impacts for both crops. Notably, land occupation shows a higher CoV for Rapeseed (7.1) compared to Jatropha (5.4), suggesting greater variability in the amount of land Rapeseed occupies. Aquatic eutrophication also has a higher variability for Rapeseed (5.9) than Jatropha (4.4), implying more fluctuation in nutrient-related water impacts. Overall, most key environmental impact categories exhibit moderate variability, indicating that while the data are reasonably consistent, some impacts can fluctuate notably depending on specific conditions or measurements.

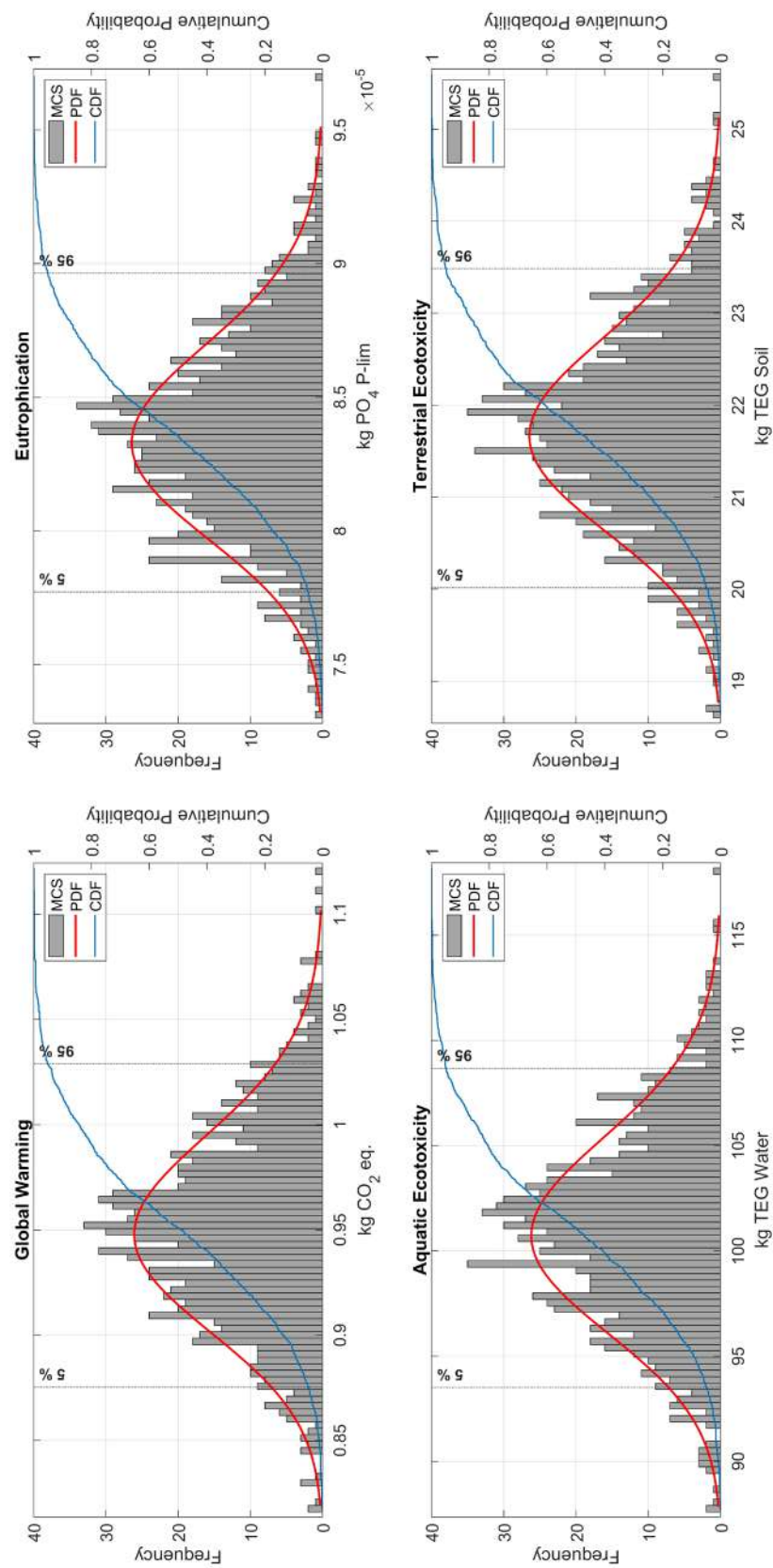


Figure 4.23 Uncertainty analysis of midpoint impact categories of jatropha biodiesel

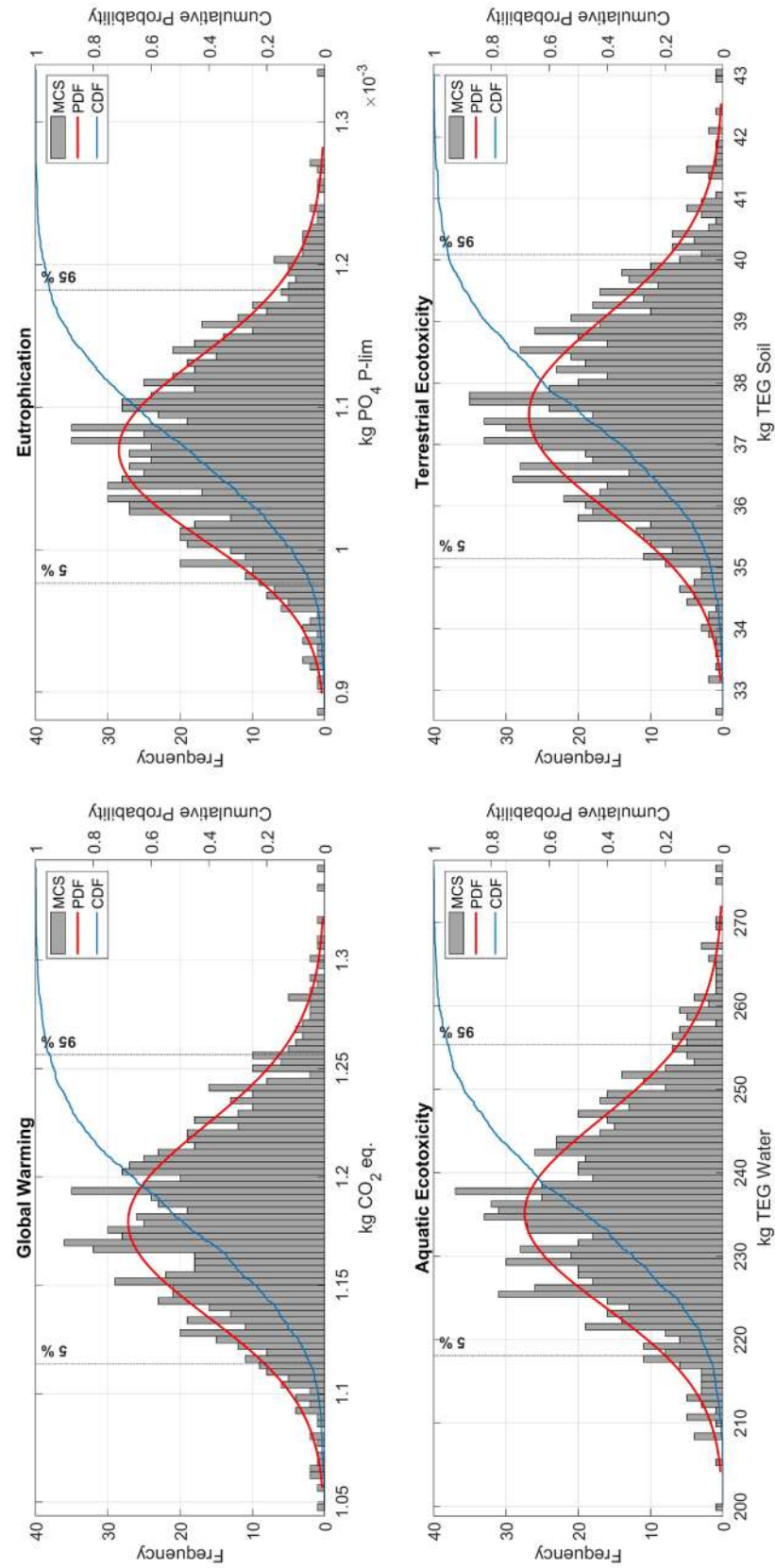


Figure 4.24 Uncertainty analysis of midpoint impact categories of rapeseed biodiesel

4.3.2 Palm-based biodiesel

Palm oil and Palm stearin, both products of the oil palm industry, are feedstock that shows potential for palm-based biodiesel production (Lim and Lee, 2011; Yung et al., 2020; Zulqarnain et al., 2021). To truly assess its sustainability as a biodiesel source, it's essential to evaluate the entire lifecycle of palm oil and palm stearin, considering its benefits and environmental footprint. Some biofuels require significant energy and resources to produce, which can lead to GHG emissions that may counteract the environmental benefits of using biofuels (Patel and Singh, 2026c; Plevin et al., 2014; Sreekumar et al., 2020; Vashist et al., 2024). This makes it crucial to thoroughly assess the environmental impact of various biofuels and their production processes to understand the true effect of climate change. By implementing policies that support sustainable biofuel production and encourage low-carbon transportation options, we can enhance the benefits of biofuels while reducing their impact on the environment.

4.3.2.1 Environmental assessment

This study uses LCA to evaluate the energy and environmental impacts of biodiesel production. This study helps identify key areas for improvement in the production process, compare the environmental and energy impacts of different biodiesel options, and guide more effective and sustainable practices for biodiesel production. This study examines both palm oil and palm stearin in the context of biodiesel as an alternative to conventional diesel. Palm oil and stearin is widely used in biodiesel production in India due to its high oil yield, but its production is associated with significant environmental issues (Arguelles-Arguelles et al., 2021; Mohd YUSOF et al., 2019; Pleanjai and Gheewala, 2009).

Goal and scope. By conducting an LCA on palm oil and stearin biodiesel, this study aims to analyze energy efficiency and environmental impacts, offering insights into the sustainability of biodiesel as an alternative to traditional fossil fuels. A cradle-to-gate approach is used for system boundary, as shown in Figure 4.25. Functional unit used is per kg of biodiesel produced.

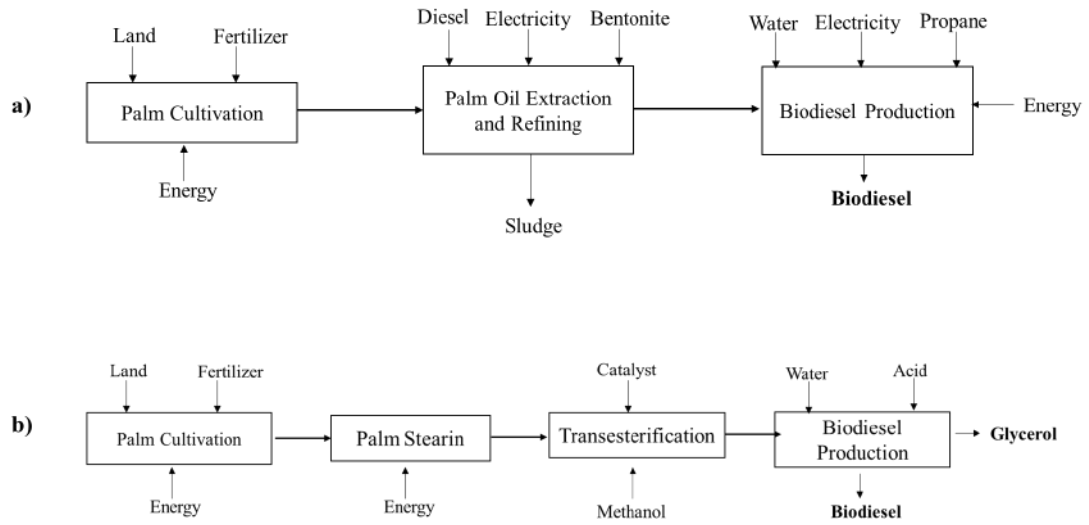


Figure 4.25 System boundary of the production of biodiesel from a) palm oil
b) palm stearin

Inventory analysis. In this research, the foreground data was collected from published literatures, biodiesel production facilities, and the background data inventory was based on the Ecoinvent database (Wernet et al., 2016), which provided detailed information about inputs like emissions, resource use, and energy consumption. In addition, previously published literature, as presented in Table 3.1 in Chapter 3, on biodiesel production from palm oil and palm stearin was also used to fill in any gaps and ensure a complete data set. This dual approach helped capture essential details, such as how much water, energy, and raw materials were used, along with the emissions released to air, land, and water. Table 4.24 and Table 4.25 shows inventory data of biodiesel production from palm oil and palm stearin.

Impact assessment. The study utilizes the IMPACT World+ method for impact assessment, which includes tools such as “Eco-Indicator, IPCC, Impact 2002+, and CML” (Ritesh Kumar et al., 2024; PRé Sustainability, 2022) and the “Cumulative Energy Demand” approach for evaluating the energy balance.

Table 4.24 Inventory data for palm oil biodiesel production

Material	Unit	Amount
Inputs		
Water	m3	28.8
Fertilizers	g	533
Pesticides	g	19
Phosphoric acid	g	1.36
Bentonite	g	67.3
Hydrogen	g	25.7
Electricity	MJ	12.4
Outputs		
Carbon Dioxide	g	64.7
Carbon monoxide	g	21
Fatty acid	g	47.2
Propane	g	62.3
Biodiesel	g	1000
Sludge	g	4.28E3

Table 4.25 Inventory data for palm stearin biodiesel production

Item	Unit	Amount
Inputs		
Palm stearin	kg	1
Cooling water	l	0.21
Process water	l	0.01
Nitrogen	Nm3	0.001
Citric acid	g	1
Methanol	g	103
Sodium methoxide	g	18.5
Hydrochloric acid	g	10
Neutralizing agent	g	1
Steam	g	350
Electricity	kWh	0.04
Outputs		
Biodiesel	kg	1
Glycerol	g	120

Interpretation. This study conducted a comparative analysis of LCA of biodiesel production from palm oil and palm stearin. The result shows that palm cultivation, stearin production, electricity, and methanol use during biodiesel production contribute to most of the environmental impacts. The impact scores from this analysis are presented as follows.

Human health. This damage category includes “toxicity, short-term climate change, ozone layer depletion, photochemical oxidant formation, particulate matter, ionizing radiation (affecting human health), and water availability”. These impacts are measured in DALYs (“disability-adjusted life years”) per kilogram of emissions. The analysis shows that the short-term climate change impact of biodiesel production from palm oil and palm stearin is 5.95 and 4.28 kg of CO₂ eq., respectively. For palm oil it is primarily due to fertilizer (57.8%), followed by electricity consumption (40.8%), pesticide (3.35%), and other materials (1.55%), however, the fatty acid and propane as an avoided product reduces health impact by -3.5% and -0.9%, respectively. For palm stearin, the impacts are primarily due to the process involved in the separation of palm stearin from crude palm oil (90%), followed by steam use (4.7%), methanol use (1.7%), sodium methoxide (0.7%), and others (2.9%). Table 4.26 shows the analysis values for endpoint impact categories.

The human health damage category for palm stearin is 6.62E-5 DALY/f.u., primarily contributed by crude palm oil in stearin formation (43.9%), electricity consumption (18.9%), sodium methoxide (13.5%), methanol (5.64%), hydrochloric acid (5.26%), and others (12.8%). The production also causes per f.u. 4.41E-8 CTUh of carcinogenic toxicity, 3.93E-7 CTUh of non-carcinogenic toxicity, 1.68E-7 kg CFC-11 eq of ozone layer depletion, 2.2E-3 kg PM_{2.5} eq of particulate matter formation, 7.72 Bq C-14 eq of ionizing radiation, 1.1E-2 kg NMVOC eq of photochemical oxidant formation, and 4.75E-5 DALY related to water availability for human health, shown in Figure 4.26. Similarly, for palm oil biodiesel production, the climate change impact is 5.95 kg CO₂ eq (short-term), mainly from nitrogen fertiliser (57.8%) and electricity (40.8%). The human toxicity burdens are 3.90E-07 CTUh for carcinogenic effects and 9.59E-07 CTUh for non-carcinogenic effects, with nitrogen fertiliser (~62–63%) and electricity (~35%) as the dominant contributors.

Other midpoint impacts per f.u. are $7.14\text{E-}07$ kg CFC-11 eq of ozone layer depletion (largely from pesticide and fertiliser production), 0.00282 kg $\text{PM}_{2.5}$ eq of particulate matter formation (mainly from fertiliser and electricity), 50.78 Bq C-14 eq of ionizing radiation (dominated by electricity $\sim 71\%$), 0.0166 kg NMVOC eq of photochemical oxidant formation (driven by fertiliser and electricity), and 1241.4 m³ world eq. of water scarcity, almost entirely caused by palm oil production ($\approx 99.7\%$).

Ecosystem quality. The ecosystem quality endpoint category includes factors such as “acidification, eutrophication, ecotoxicity, climate change (both short-term and long-term), ionizing radiation (affecting ecosystem quality), water scarcity (impacting water availability in terrestrial and freshwater ecosystems), and land biodiversity (considering land use and occupation)”. This category is measured in $\text{PDF}\cdot\text{m}^2\cdot\text{yr}$ (“potentially disappeared fraction of species in a specific area over a certain time period”).

For palm oil-based biodiesel, freshwater ecotoxicity shows the highest impact (70.5%), followed by long-term climate change (58.1%), short-term climate change (57.9%), water scarcity (dominated by palm oil cultivation at $>99\%$), and marine eutrophication (78.7%), with particulate matter formation also contributing (53%). These effects are primarily driven by nitrogen fertiliser (43–70%) and electricity (25–40%), while palm oil itself is the major hotspot for water use. Fatty acid and propane provide small negative offsets, slightly reducing the overall impact burdens in some categories. For palm stearin biodiesel, the dominant impact is also freshwater ecotoxicity (39%), followed by long-term climate change (32%), short-term climate change (9.8%), marine acidification (7.7%), and others (11.5%). These impacts are largely contributed by crude palm oil to stearin formation (42.5%), electricity (18.9%), sodium methoxide (13.5%), methanol (5.6%), hydrochloric acid (5.3%), and others (14.2%), as shown in Table 4.27.

Table 4.26 Endpoint impact categories of biodiesel production

Impact Category	Palm Oil	Palm Stearin
(A) Damage on area of protection		
Human health (DALY)	4.6E-03	6.6E-05
Ecosystem quality (PDF.m ² .yr)	56.1	7.705
(B) Damage level indicators		
Human Health (DALY)		
Climate change, human health, short term	4.87E-06	3.5E-06
Climate change, human health, long term	1.46E-05	1.1E-05
Photochemical oxidant formation	6.44E-10	4.2E-10
Ionizing radiation, human health	1.07E-08	1.6E-09
Ozone layer depletion	1.72E-09	3.0E-10
Human toxicity cancer, short term	8.64E-07	1.1E-07
Human toxicity cancer, long term	2.96E-08	1.9E-08
Human toxicity non-cancer, short term	8.93E-07	3.8E-07
Human toxicity non-cancer, long term	7.79E-07	5.7E-07
Particulate matter formation	3.38E-06	2.7E-06
Water availability, human health	0.00459	4.8E-05
Ecosystem Quality (PDF.m².yr)		
Climate change, ecosystem quality, short	1.053	0.757
Climate change, ecosystem quality, long	3.213	2.512
Marine acidification, short term	0.081	0.065
Marine acidification, long term	0.751	0.596
Freshwater ecotoxicity, short term	0.143	0.017
Freshwater ecotoxicity, long term	50.470	3.009
Freshwater acidification	0.050	0.020
Terrestrial acidification	0.347	0.175
Freshwater eutrophication	0.001	1.3E-03
Marine eutrophication	0.015	4.7E-03
Ionizing radiation, ecosystem quality	9.0E-10	1.7E-10
Land transformation, biodiversity	-0.016	0.637
Land occupation, biodiversity	-0.002	-0.089
Water availability, freshwater ecosys.	0.009	1.7E-05
Water availability, terrestrial ecosys.	1.7E-04	2.5E-04
Thermally polluted water	1.7E-05	1.2E-06

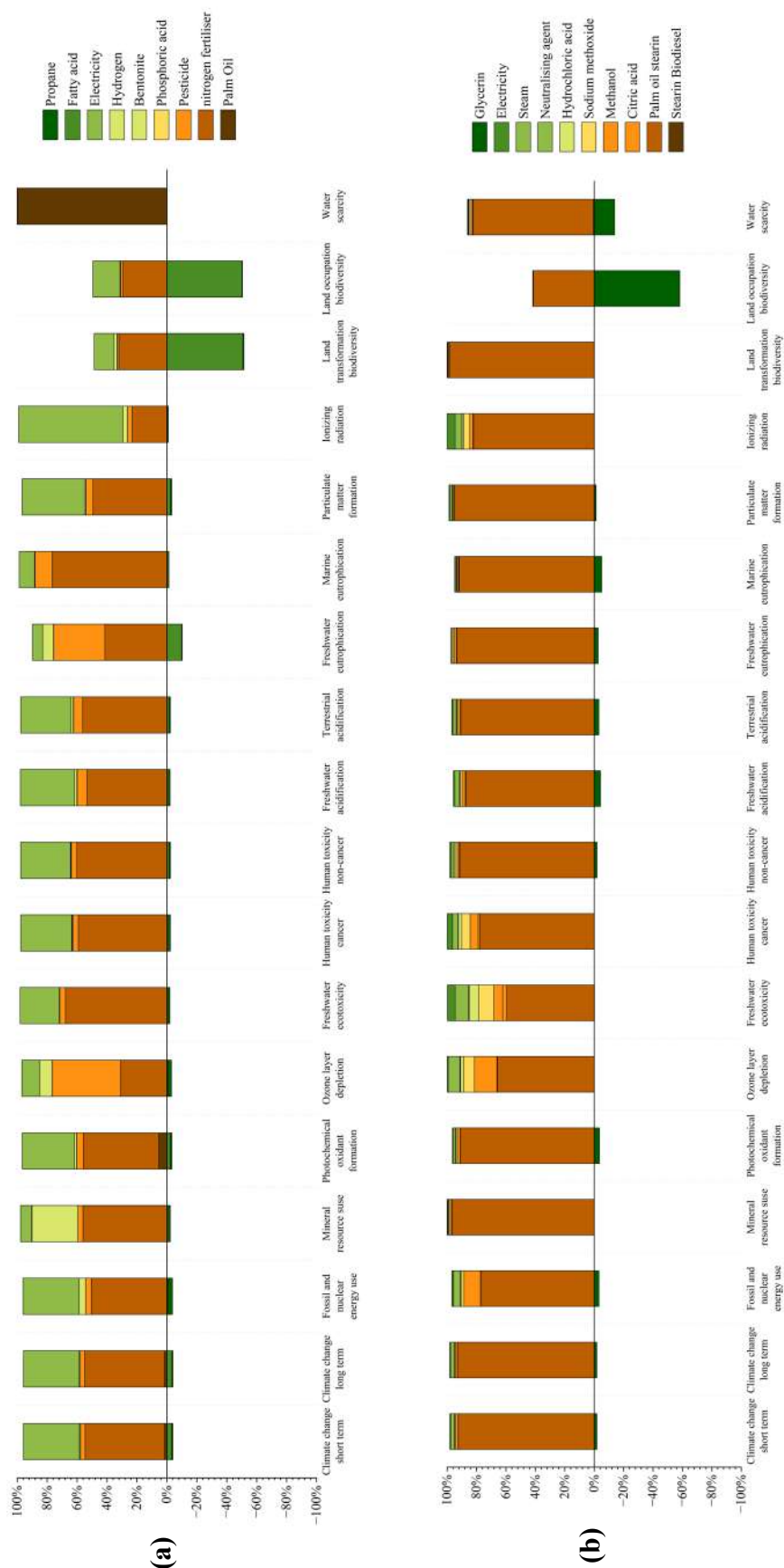


Figure 4.26 Midpoint impact category scores of a) palm oil and b) palm stearin biodiesel

Table 4.27 Midpoint impact categories of biodiesel production

Impact Category	Unit	Palm oil	Palm Stearin
Climate change, short term	kg CO ₂ eq	5.950	4.279
Climate change, long term	kg CO ₂ eq	5.621	4.218
Fossil and nuclear energy use	MJ deprived	83.470	31.571
Mineral resources use	kg deprived	0.128	0.063
Photochemical oxidant formation	kg NMVOC eq	0.017	0.011
Ozone layer depletion	kg CFC-11 eq	7.1E-07	1.7E-07
Freshwater ecotoxicity	CTUe	87931.243	5.2E+03
Human toxicity cancer	CTUh	3.9E-07	4.4E-08
Human toxicity non-cancer	CTUh	9.6E-07	3.9E-07
Freshwater acidification	kg SO ₂ eq	6.1E-08	2.4E-08
Terrestrial acidification	kg SO ₂ eq	5.3E-05	2.7E-05
Freshwater eutrophication	kg PO ₄ eq	1.1E-04	1.1E-04
Marine eutrophication	kg N eq	1.2E-03	3.8E-04
Particulate matter formation	kg PM _{2.5} eq	0.003	2.2E-03
Ionizing radiation	Bq C-14 eq	50.776	7.717
Land transformation, biodiversity	m ² yr arable	-6.2E-05	2.5E-03
Land occupation, biodiversity	m ² yr arable	-0.002	-0.127
Water scarcity	m ³ world eq	1241.407	1.276

4.3.2.2 Energy analysis

The cumulative energy demand method thoroughly assesses energy requirements, highlighting the most energy-intensive stages in a product's life cycle. By understanding how much energy is needed, we can better compare different products or processes, helping us see which ones are more energy-efficient and environmentally friendly. For palm stearin, the single score for cumulative energy demand is 87.7 MJ, with a dominant contribution from renewable biomass (65%), mainly caused by the cultivation of palm, followed by fossil energy (33.4%), nuclear (1%), and hydro energy (0.5%), shown in Figure 4.27. Major contributors in its life cycle include the palm fruit bunch during cultivation (56.8 MJ), methanol (3.26 MJ), steam (2.64 MJ), and other process inputs (25 MJ). In contrast, the cumulative energy demand for palm oil is slightly lower at 79.2 MJ, with the major share derived from non-renewable fossil sources (69.6 MJ, ~88%), followed by nuclear energy (7.1 MJ, ~8.9%), and smaller contributions from renewable water (3.39 MJ, ~4.3%), renewable

wind/solar/geothermal (0.99 MJ, ~1.3%), while renewable biomass (-1.67 MJ) and non-renewable biomass (-0.18 MJ) are marginal and even negative, indicating avoided burdens. Within palm oil production, the main energy hotspots are nitrogen fertilizer (42.97 MJ, ~54%) and electricity consumption (35.5 MJ, ~45%), supplemented by smaller inputs such as pesticides (3.37 MJ) and hydrogen (3.6 MJ). Negative contributions from fatty acid (-3.7 MJ) and propane (-2.6 MJ) suggest credits due to energy recovery or substitution effects. Overall, while palm stearin is more dependent on renewable biomass energy from cultivation, palm oil is dominated by fossil and electricity-related inputs, highlighting distinct energy demand patterns that reflect differences in processing stages and input dependencies.

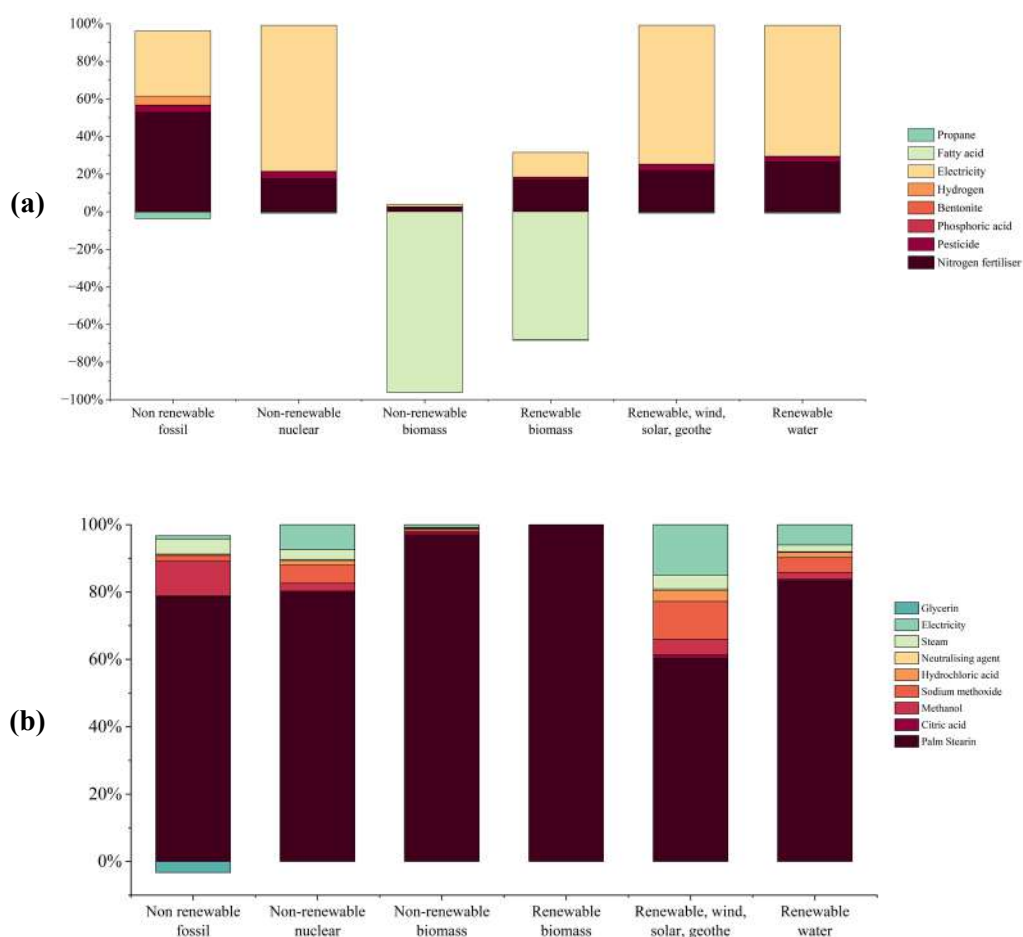


Figure 4.27 Contribution to energy demand for production of a) palm oil and b) palm stearin biodiesel

The Table 4.28 compares the energy performance of palm oil, palm stearin, and conventional diesel as fuels. Palm oil shows the most favorable results, with a NER above one (1.58), a large positive NEV of 45.8, and a good renewability score, meaning it generates significantly more energy than is required for its production while relying largely on renewable inputs. Palm stearin, in contrast, performs poorly from an energy efficiency standpoint, with a NER of 0.64 and a strongly negative NEV of -31.6, indicating that it requires more energy to produce than it delivers; however, the high Rn score suggests that much of this energy comes from renewable rather than fossil sources, which explains the large positive NRnEV. Conventional diesel also fares poorly, with a NER of 0.84 and a negative NEV of -8.21, while being largely dependent on non-renewable resources, as shown by its low Rn and negative NRnEV. Overall, palm oil emerges as the most sustainable option in this comparison, whereas both palm stearin and diesel show significant energy inefficiencies, although for different reasons.

Table 4.28 Energy balance of biodiesel production.

Impact category	Unit	Palm Stearin	Palm Oil
Non-renewable, fossil	MJ	29.39	69.6
Non-renewable, nuclear	MJ	0.87	7.1
Non-renewable, biomass	MJ	3.5E-3	-0.18
Renewable, biomass	MJ	57.02	-1.67
Renewable, wind, solar, geothermal	MJ	0.05	0.99
Renewable, water	MJ	0.46	3.39
NER		0.50	0.55
NEV		-44.29	-35.73
Rn		1.48	0.63
NRnEV		14.11	-26.10

4.3.2.3 Sensitivity and uncertainty analysis

Uncertainty analysis in Life Cycle Assessment studies of palm-based biodiesel is crucial for ensuring the reliability of environmental impact results. During an LCA study, uncertainties can arise from several sources, including data variability, methodological choices, and assumptions made throughout the life cycle stages of

palm biodiesel production. For instance, the selection of system boundaries, impact assessment models, and allocation methods all introduce variability to the results. Quantitative uncertainty analysis methods, such as sensitivity analysis and Monte Carlo simulations, are often employed to assess the effects of these uncertainties on overall environmental performance metrics. By explicitly evaluating the range and sources of uncertainty, researchers can better inform policymakers and industry stakeholders about the robustness and limitations of their conclusions regarding palm-based biodiesel sustainability. Table 4.29 shows the coefficient of variation of various environmental impact categories. For climate change impacts, both long- and short-term, palm oil shows relatively low CoVs of about 5.3%, while palm stearin is much higher, at around 8.6–8.7%. This means palm oil's greenhouse gas-related impacts are more consistent across simulations, whereas palm stearin's outcomes are less stable. A similar trend is seen in freshwater ecotoxicity, where palm oil has 7.1% variation compared to 7.9% for stearin, indicating slightly greater uncertainty in stearin. When looking at land occupation and biodiversity, palm oil stands out with the highest CoV overall at 10%, suggesting that the results in this category are highly variable and uncertain. Palm stearin is somewhat lower at 8%, but still reflects significant variability. Another important case is human toxicity (non-cancer), where palm stearin shows a CoV of 9.9%, much higher than palm oil's 6.1%, signaling a greater spread of uncertainty for stearin in this category. For water scarcity, while palm oil's absolute impacts are much larger, its CoV (6.9%) is again lower than that of palm stearin (7.9%), showing that even in critical categories, palm oil's outcomes are more consistent. Figure 4.28 and Figure 4.29 show the probability distributions of selected impact categories, highlighting the uncertainty ranges between the 5% and 95% confidence intervals. The results indicate relatively stable and well-defined distributions across all categories.

Overall, palm oil tends to have lower CoV values in most categories, making its impacts more predictable, whereas palm stearin consistently shows greater variability, especially in climate change, toxicity, and land-use related categories. This suggests that results for stearin are more sensitive to uncertainties in input parameters.

Table 4.29 Uncertainty analysis of the LCA of palm-based biodiesel.

Environmental impact categories	Unit	Palm Oil			Palm Stearin		
		Mean	SD	CoV (%)	Mean	SD	CoV (%)
Freshwater ecotoxicity	CTUe	56983.39	4043.23	7.1	111559.18	8774.38	7.9
Mineral resources use	kg deprived	8.6E-02	4.6E-03	5.4	2.8E-02	2.2E-03	8.0
Photochemical oxidant formation	kg NMVOC eq	2.0E-02	1.1E-03	5.5	1.1E-02	9.0E-04	8.4
Ozone Layer Depletion	kg CFC-11 eq	1.2E-06	6.0E-08	4.9	4.3E-07	3.0E-08	7.0
Freshwater acidification	kg SO ₂ eq	2.7E-13	1.4E-14	5.4	7.5E-14	5.9E-15	7.8
Particulate matter formation	kg PM _{2.5} eq	3.3E-03	1.7E-04	5.3	2.3E-03	1.9E-04	8.2
Land occupation, biodiversity	m ² arable land eq .yr	2.4E-02	2.4E-03	10.0	0.17	0.01	8.0
Fossil and nuclear energy use	MJ deprived	43.84	3.22	7.3	26.55	1.72	6.5
Climate change, long term	kg CO ₂ eq (long)	6.41	0.34	5.3	3.63	0.32	8.7
Land transformation, biodiversity	m ² arable land eq	8.8E-04	5.2E-05	5.9	-1.9E-02	1.7E-03	-9.1
Water scarcity	m ³ world-eq	1483.39	102.39	6.9	9.36	0.74	7.9
Climate change, short term	kg CO ₂ eq (short)	6.63	0.35	5.3	4.02	0.34	8.6
Marine eutrophication	kg N N-lim eq	6.5E-04	3.2E-05	4.8	1.1E-03	8.8E-05	7.9
Human toxicity cancer	CTUh	2.5E-07	1.7E-08	7.1	1.6E-07	1.3E-08	8.5
Terrestrial acidification	kg SO ₂ eq	1.7E-07	9.3E-09	5.3	5.9E-08	4.7E-09	7.9
Freshwater eutrophication	kg PO ₄ P-lim eq	4.6E-05	2.8E-06	6.0	7.1E-03	5.6E-04	7.9
Human toxicity non cancer	CTUh	4.4E-07	2.7E-08	6.1	3.9E-07	3.9E-08	9.9
Ionizing radiations	Bq C-14 eq	30.65	1.61	5.3	25.18	1.93	7.7

SD: standard deviation; CoV: coefficient of variation

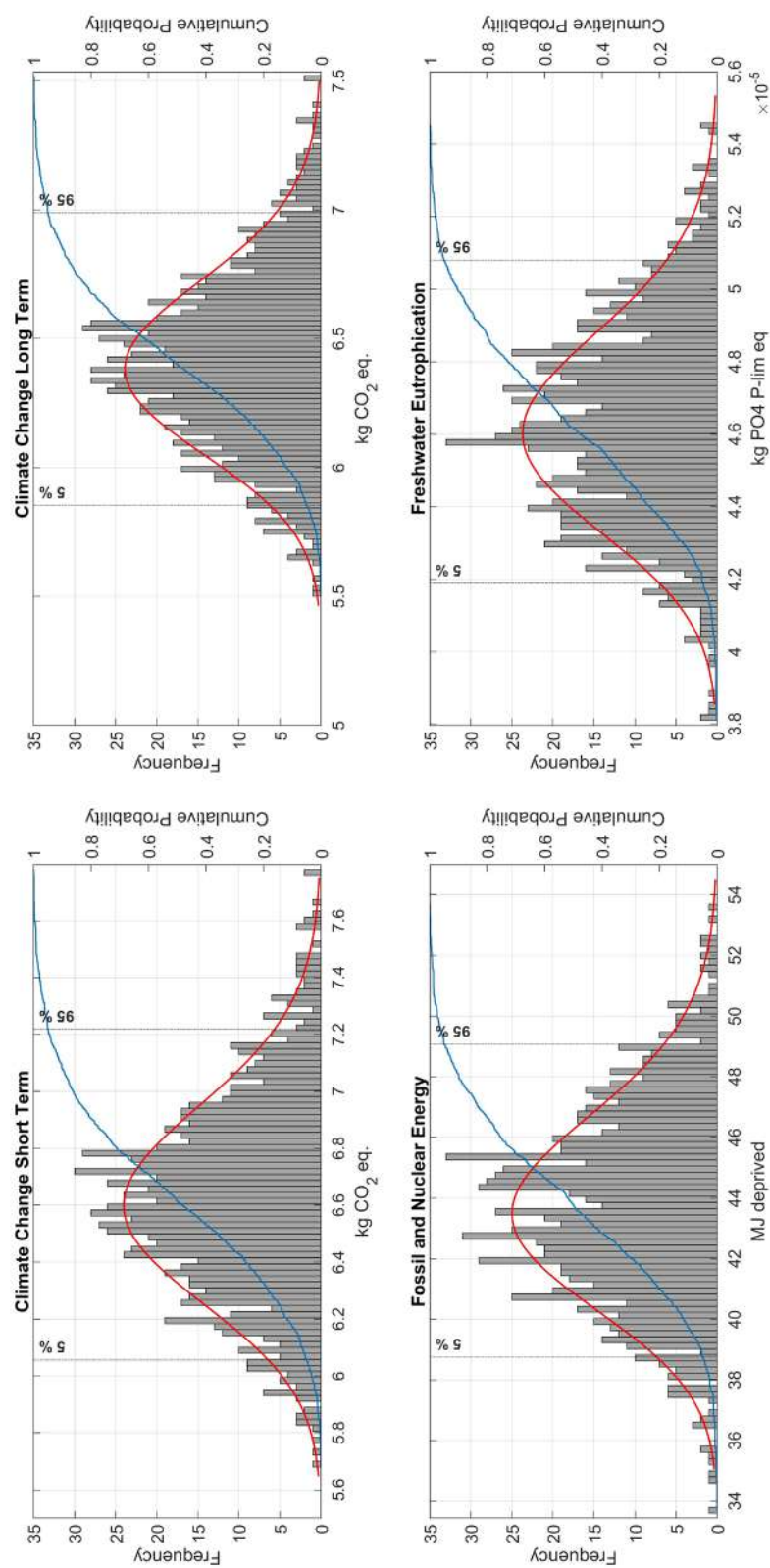


Figure 4.28 Uncertainty analysis of midpoint impact categories of palm oil biodiesel.

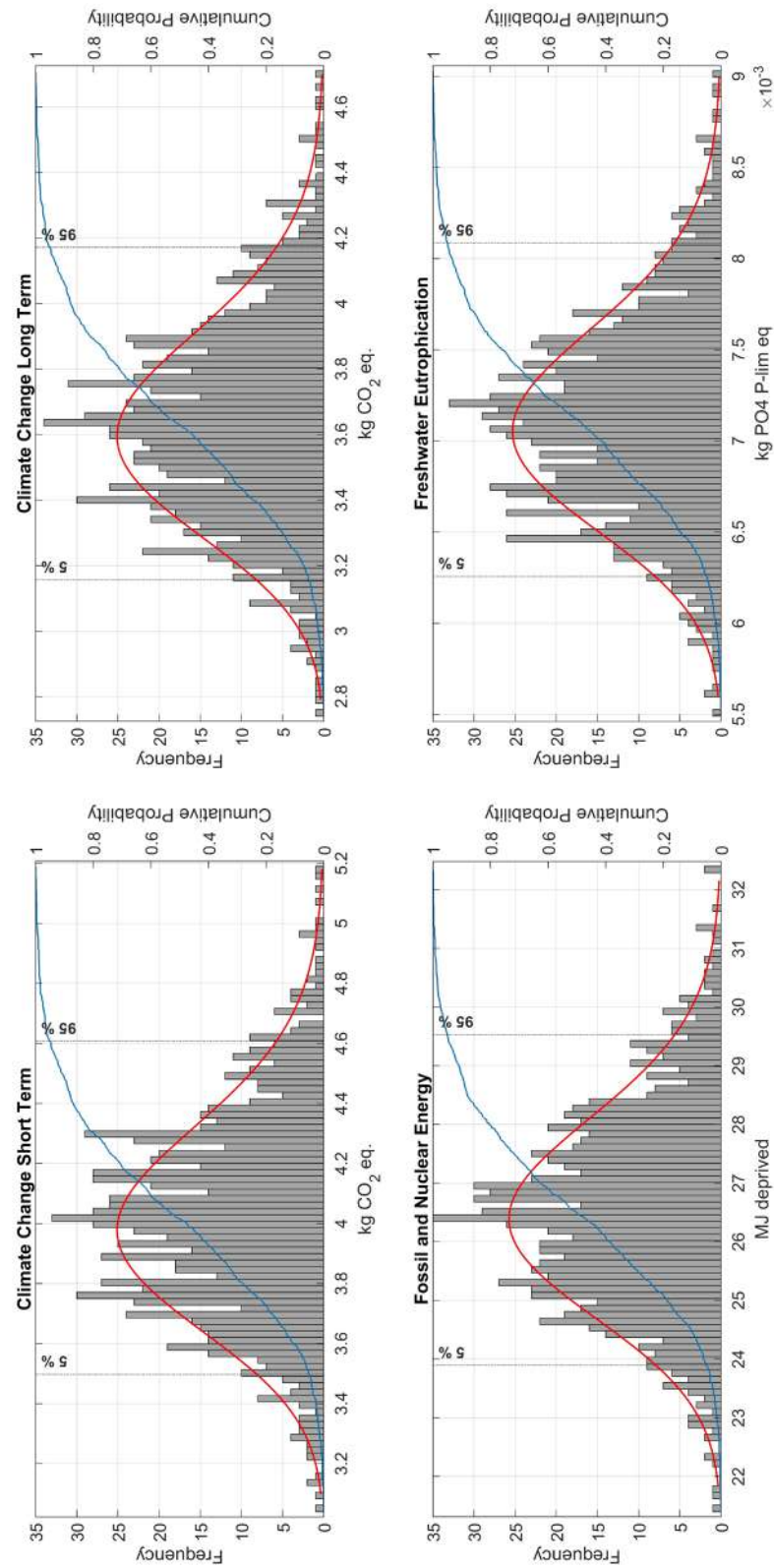


Figure 4.29 Uncertainty analysis of midpoint impact categories of palm stearin biodiesel

4.3.3 Used cooking oil-based biodiesel

UCO is a waste product generated in the food industry, primarily from cooking processes in households, restaurants, and commercial kitchens. Recycling UCO for biodiesel production contributes to sustainability and waste reduction. Using UCO in biodiesel production aligns with principles of circular economy and resource efficiency (Bhonsle et al., 2022; Sanglard et al., 2023; Srikumar et al., 2024). By converting waste cooking oil into a valuable biofuel, there is a reduction in the reliance on virgin vegetable oils, which might otherwise be used for biodiesel and are associated with land use changes and potential environmental impacts. According to the FSSAI, India can convert 3–4 million metric tons of UCO into biodiesel (FSSAI, 2018). Consequently, incorporating used cooking oil into the production of biodiesel not only redirects this waste from the food supply chain but also establishes a consistent and sustainable source of feedstock for biodiesel production.

4.3.3.1 Environmental assessment

Even though biodiesel from UCO is considered a sustainable source, conducting a thorough LCA remains crucial for a comprehensive understanding of its environmental implications and resource efficiency. The research gap addressed by this paper lies in the need for a comprehensive and comparative analysis of biodiesel production from UCO, specifically in the context of sustainability, energy efficiency, and uncertainty. Current literature often focuses on the environmental benefits of biofuels but may only partially account for part of the life cycle impacts, particularly in the case of biodiesel derived from waste materials. Furthermore, the energy efficiency of converting UCO into biodiesel, including the energy inputs required for collection, processing, and refining, still needs to be explored compared to traditional biodiesel sources. In addition, existing studies frequently need to pay more attention to the uncertainties associated with the availability, quality, and processing of UCO, leading to an incomplete understanding of the risks and variability in biodiesel production outcomes. Figure 4.30 shows the overview of the study.

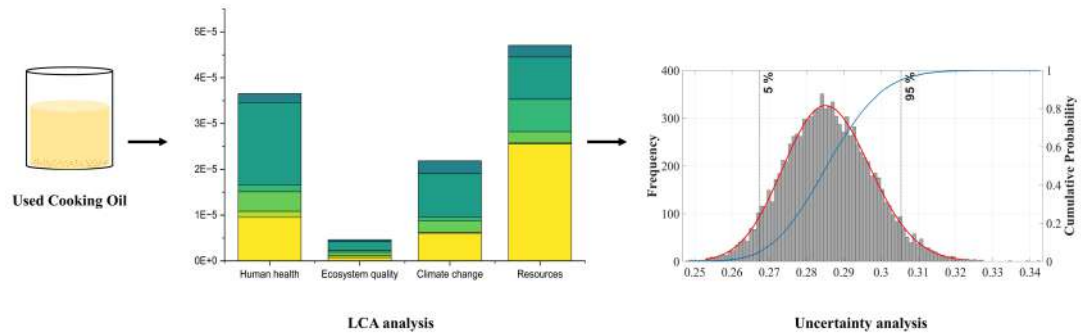


Figure 4.30 Overview of LCA analysis of biodiesel production

Goal and scope. LCA for biodiesel production from UCO adopts a cradle-to-gate methodology. The system boundary for UCO encompasses the collection of UCO, followed by transport to a pre-treatment facility (Figure 4.31). UCO undergoes mechanical pre-treatment at this facility to reduce solid waste content and water (Foteinis et al., 2020; Wahyono et al., 2022). Subsequently, the treated UCO is transported to a production facility where biodiesel is obtained through transesterification. Using Used Cooking Oil as a feedstock for biodiesel production presents a promising waste management strategy due to its abundant generation from culinary activities. Improper disposal of UCO can lead to environmental issues, making repurposing for biodiesel production an environmentally responsible alternative (Pratika et al., 2024; Siregar et al., 2020). This approach addresses waste concerns and reduces reliance on virgin vegetable oils like palm oil, associated with deforestation and biodiversity loss. Choosing UCO as a feedstock aligns with circular economy principles, extending the resource lifecycle and promoting sustainability. The distribution and biodiesel consumption are not included in the goal of the study. In this study, the per kg of biodiesel produced was considered as functional unit (FU). This FU was selected because (i) it establishes context within the current literature, (ii) it facilitates a direct comparison of the outcomes of this study with the existing knowledge on biodiesel, and (iii) it allows for a more accessible understanding and effective communication of results to non-specialized audiences, including policymakers.

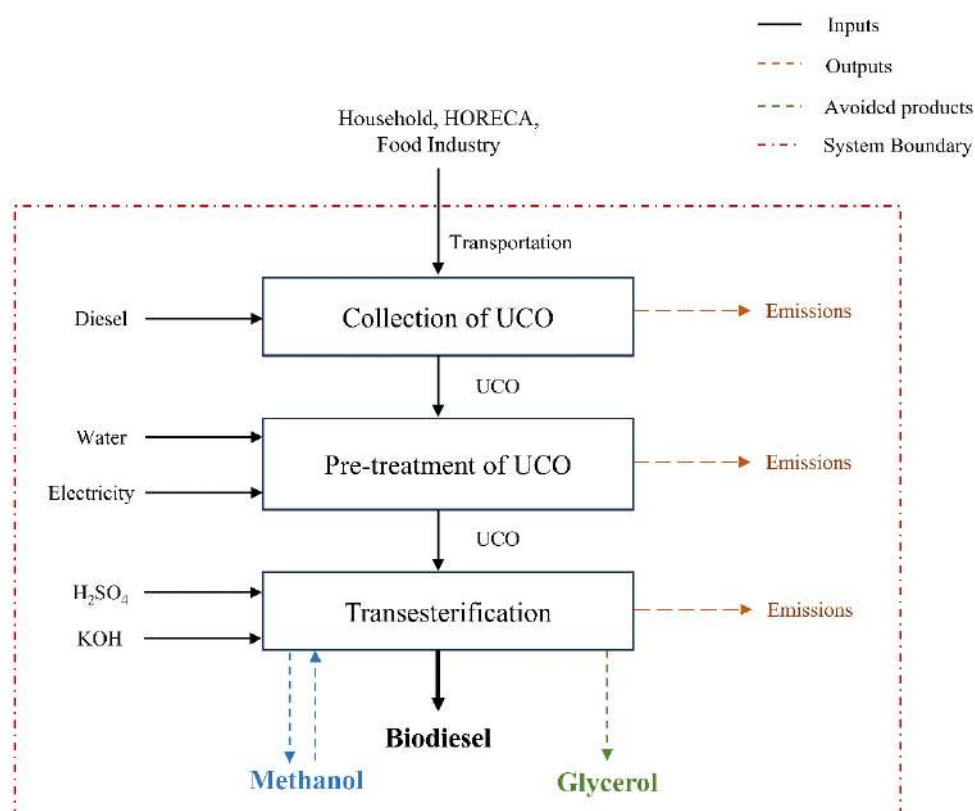


Figure 4.31 System boundary of production of biodiesel from UCO

Inventory analysis. In this study, the LCI was taken from several sources to obtain a complete and comprehensive picture, presented in Chapter 3. Table 4.30 presents an overview of the materials and energy resources used and generated in producing 1 kg of biodiesel. Moreover, this study adopted the attributional approach instead of the consequential approach.

Impact assessment. The ReCiPe 2016 impact method was utilized for this assessment, encompassing various impact categories such as climate change, ozone depletion, acidification, eutrophication, human toxicity, and more, as outlined in (Jolliet et al., 2003). This broad coverage enables a more holistic evaluation of the environmental performance of a product, process, or system (Patel and Singh, 2023b). Additionally, this study utilizes the cumulative energy demand method, specifically focusing on quantifying cumulative energy consumption associated with the life cycle (Frischknecht et al., 2015).

Table 4.30 Inventory data for the production of biodiesel from UCO

Materials	Unit	UCO
Inputs		
Used cooking oil	kg	1.18
Water	kg	0.092
Methanol	kg	0.12
Sulfuric acid	kg	0.01
Potassium hydroxide	kg	0.01
Diesel	kg	0.02
Electricity	MJ	0.52
Steam	MJ	0.24
Outputs		
Biodiesel	kg	1.0
Glycerol	kg	0.1
Emission to air	kg	0.06
Wastewater	kg	0.16
Waste	kg	0.08

Interpretation. The Table 4.31 shows the environmental impact associated with the production of 1 kg of UCO biodiesel. The system considers UCO to be a waste product. As a result, its generation does not require additional material and energy inputs or has no environmental impact. Therefore, UCO is excluded from the environmental assessment. The analysis shows that for UCO biodiesel, electricity use has significant contribution in impact categories of ecotoxicity (40%), acidification (41%), global warming (43%), and eutrophication (47%), whereas methanol use in transesterification has significant contribution in carcinogens (78%) and non-carcinogens (35%), ozone layer depletion (52%), and respiratory organics (62%) impact categories.

Human health potential (HHP). HHP associated with UCO biodiesel stands at 5.7E-7 DALY per FU. The primary contributors to HHP are electricity consumption (49%), methanol usage (26%), and potassium hydroxide (11.6%). The midpoint categories responsible for HHP include carcinogens (14.8%), non-carcinogens (7.1%), respiratory inorganics (77.8%), and other factors (0.3%). For both carcinogens and non-carcinogens, environmental impacts were mainly due to methanol (78.7% and

35.1%, respectively), followed by electricity (9.3% and 28.9%), and heat (6.3% and 16.5%). In the case of respiratory inorganics, impacts were due to electricity (58.5%), methanol (15.1%), and the use of potassium hydroxide (13.3%). Figure 4.32 shows the midpoint impact categories of UCO biodiesel.

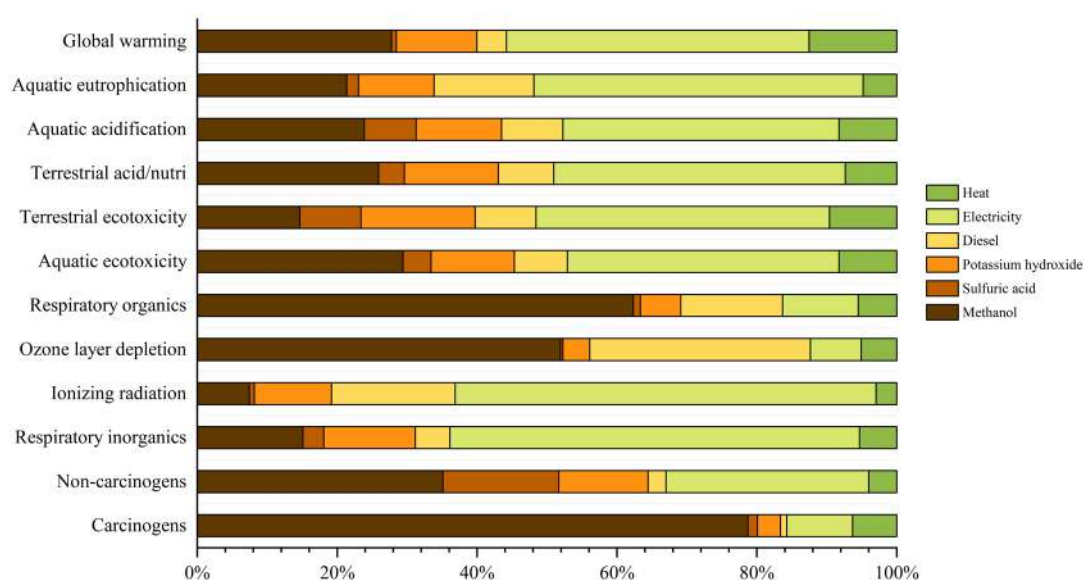


Figure 4.32 System boundary of production of biodiesel from UCO

Table 4.31 Environmental impacts of biodiesel production from UCO

Impact Category	Unit	UCO
Human Health	DALY	5.7E-7
Ecosystem	species.yr	1.1E-9
Resources	USD	0.05
Global warming potential (GWP)	kg CO ₂ eq	0.25
Ionizing radiation potential (IRP)	kBq Co-60 eq	0.02
Ozone formation, Human health (OF-HH)	kg NO _x eq	5.4E-04
Fine particulate matter formation (FPMF)	kg PM _{2.5} eq	4.2E-04
Ozone formation, Terrestrial ecosystems (OF-TE)	kg NO _x eq	5.5E-04
Terrestrial acidification (TA)	kg SO ₂ eq	8.7E-04
Eutrophication potential (EUP)	kg P eq	9.1E-05
Terrestrial ecotoxicity potential (TExP)	kg 1,4-DCB	0.71
Freshwater ecotoxicity potential (FExP)	kg 1,4-DCB	7.5E-03
Marine ecotoxicity potential (MExP)	kg 1,4-DCB	1.0E-02
Human carcinogenic toxicity (HCT)	kg 1,4-DCB	9.1E-03
Human non-carcinogenic toxicity (HNCT)	kg 1,4-DCB	0.19
Fossil resource scarcity (FRS)	kg oil eq	0.15
Water consumption (WC)	m ³	1.6E-03

Ecosystem quality potential (EQP). EQP for UCO biodiesel accounts for $1.1\text{E-}9$ species.yr per FU. The primary contributors to EQP are electricity use (42%), with potassium hydroxide as a transesterification catalyst contributing 16.6%, methanol at 15.8%, and heat at 9.2%. Regarding midpoint contributors to ecosystem quality, terrestrial ecotoxicity has a significant impact (87%), with aquatic ecotoxicity contributing 3% and other factors making up 10%. The notable terrestrial ecotoxicity is primarily attributed to electricity consumption throughout biodiesel production stages (42%), followed by potassium hydroxide (16.3%) and methanol use (14.6%).

Climate change potential (CCP). Biodiesel production from UCO results in an emission of $0.25 \text{ kg CO}_2 \text{ eq. / FU}$. The primary factors influencing this emission are electricity (43.3%), methanol (27.8%), steam-derived heat (12.5%), KOH (11.5%), and other factors (4.9%). The major emissions are CO_2 (93.6%), followed by CH_4 , fossil (5.39%), dinitrogen monoxide (0.4%), and others (0.71%).

Resources depletion potential (RDP). The RDP for UCO biodiesel (0.05 USD) is majorly by methanol (54.3%), electricity (19.6%), diesel (15%), and other factors (11.1%). The primary midpoint contributor is non-renewable energy, constituting 99.9%. In comparison, palm oil biodiesel has an RDP of 19.3 MJ, with methanol (22.3%), electricity (18.1%), diesel (17.2%), fertilizers (26%), and other factors (16.4%) being the major contributors, shown in Figure 4.32. For UCO biodiesel, the major contributors from non-renewable energy are natural gas (62.1%) used in methanol production, crude oil (18.9%), hard coal (12.6%) and brown coal (1.95%) used in electricity production, and others (4.45%); impact of mineral extraction from copper (72.5%) used for fertilizers, nickel (12.3%), zinc (4.88%), aluminium (2.54%), lead (1.92%), tin (1.88%), and others (3.98%).

4.3.3.2 Energy analysis

As shown in Figure 4.33, the energy sources required to produce biodiesel from UCO still predominantly rely on fossil fuels. The total CED for producing biodiesel from UCO was quantified as 6.78 MJ per FU, with the majority arising from fossil fuel sources (92.4%), followed by nuclear energy (4.4%), hydro energy (1.97%), renewable sources such as wind, solar, and geothermal (0.6%), and others (0.63%).

The Table 4.32 reveals that UCO biodiesel production relies heavily on non-renewable fossil fuels, making up the largest share of energy use per functional unit. Contributions from nuclear, hydro, and other renewable sources remain comparatively small, with fossil energy still dominating the cumulative energy demand profile.

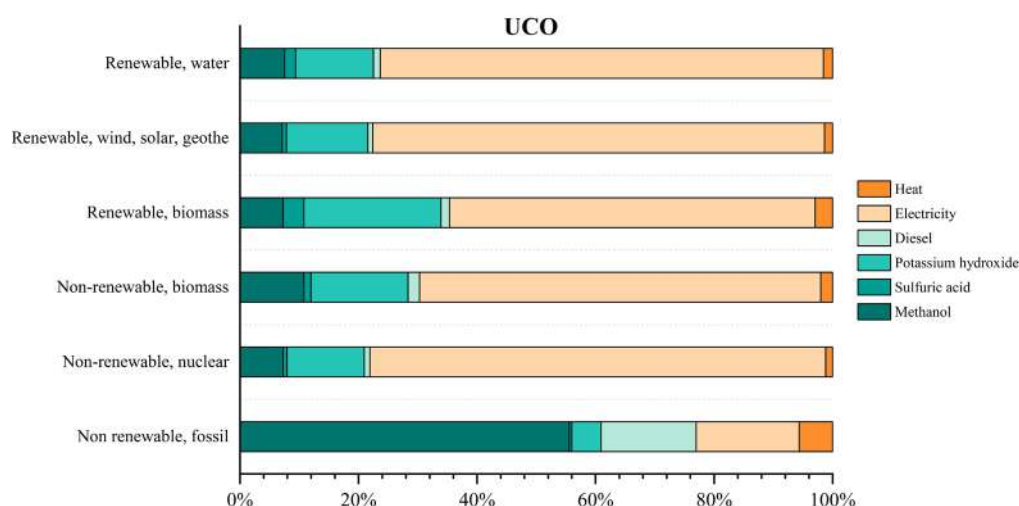


Figure 4.33 Cumulative energy demand results obtained for biodiesel from UCO

The study shows that UCO biodiesel exhibits positive NEV and NRnEV, indicating efficient utilization of energy resources and a greater net energy gain per kg of biodiesel. Additionally, the NER and Rn values for UCO biodiesel are high, demonstrating a more efficient conversion process that generates more energy than is needed for production. The high NER of UCO, recorded at 6.41, is largely attributed to the reduced fossil energy required during biodiesel production, highlighting its effective energy balance and sustainability profile. These results align with findings from (Consiglio, 2017) and (Farid et al., 2020). Table 4.32 shows the energy balance of biodiesel production and compared with conventional diesel.

Table 4.32 Cumulative energy demand in the biodiesel production from UCO

Impact category	Unit	UCO
Non-renewable, fossil	MJ	6.268
Non-renewable, nuclear	MJ	0.302
Non-renewable, biomass	MJ	0.00015
Renewable, biomass	MJ	0.040
Renewable, wind, solar, geothermal	MJ	0.041
Renewable, water	MJ	0.133
NER		6.41
NEV		36.72
Rn		6.94
NRnEV		37.23

Scenario analysis. Conducting scenario analysis through the adjustment of the system boundary, especially by incorporating the avoided products, offers valuable insights into the life cycle impacts of biodiesel production. Biodiesel production results in the generation of by-products, specifically glycerol (Talens Peiró et al., 2010). During the scenario analysis, the research considered the resources and energy inputs required for the recovery of these by-products. Table 4.33 shows the environmental impacts associated with the production of biodiesel per kg from UCO with the extended system boundary.

The analysis shows that the UCO biodiesel results in a 28.57% reduction in carcinogens, whereas palm oil achieves a slightly lower reduction of 24.32%. In the case of non-carcinogens, the impact reductions are significantly higher, with UCO at 228.57% and palm oil at 140.74%, indicating a substantial decrease in harmful chemical emissions. UCO shows similar trends with several environmental impact categories. However, a significant difference is observed in global warming potential and terrestrial ecotoxicity, where UCO biodiesel achieves a reduction of 138.89% and 471.83%, respectively compared to 7.43% and 272.06%, respectively for palm oil biodiesel. This shows UCO's effectiveness in reducing GHG emissions and environmental benefits over multiple impact categories. Glycerol contributes -0.3 kg CO₂ eq. to GWP for UCO biodiesel, meaning it substantially reduces CO₂ emission, making it a major factor in net negative CO₂ eq.

Table 4.33 Percentage reduction due to avoided product in production of biodiesel

Impact category	Unit	UCO	
		Impact Value	% Reduction
Carcinogens	kg C ₂ H ₃ Cl eq	0.010	28.57
Non-carcinogens	kg C ₂ H ₃ Cl eq	-0.009	228.57
Respiratory inorganics	kg PM _{2.5} eq	-7.6E-05	126.39
Ionizing radiation	Bq C-14 eq	1.056	58.56
Ozone layer depletion	kg CFC-11 eq	5.6E-09	86.24
Respiratory organics	kg C ₂ H ₄ eq	-5.1E-05	153.07
Aquatic ecotoxicity	kg TEG water	3.105	91.29
Terrestrial ecotoxicity	kg TEG soil	-25.935	471.83
Terrestrial acid/nutri	kg SO ₂ eq	-0.006	250.00
Aquatic acidification	kg SO ₂ eq	-5.8E-04	158.00
Aquatic eutrophication	kg PO ₄ P-lim	-6.3E-05	274.03
Global warming	kg CO ₂ eq	-0.084	138.89

4.3.3.3 Sensitivity and uncertainty analysis

The MCS shows that the CoV, which measures the relative stability, is 7.6% and 5.1% for non-carcinogens and carcinogens, respectively, suggesting that data for non-carcinogens is slightly more consistent. The SD, representing the data spread around the mean, is 0.012 and 2.0E-4 kg C₂H₃Cl eq. for non-carcinogens and carcinogens, respectively. Higher SD indicates greater variability in the data set. Additionally, the SEM, which reflects how accurately the sample mean approximates the population mean (De Marco et al., 2018), is 1.0E-05 and 2.0E-06 for non-carcinogens and carcinogens, respectively. Altogether, this statistical measure shows that while the data for both is reliable, non-carcinogens show slightly better consistency and accuracy. Table 4.34 shows the uncertainty parameters for each impact category. The CoV ranges from 3.3% to 7.6%, indicating moderate variability in impact data. UCO exhibits its highest CoV in categories like carcinogens (7.6%) and aquatic eutrophication (6.5%). Meanwhile, the SEM values suggest that UCO typically has smaller SEM values, which suggests that its mean impact measurements are slightly more precise.

Table 4.34 Uncertainty analysis of the LCA of UCO-based biodiesel

Environmental Impact Categories	UCO				
	Unit	Mean	SD	CoV (%)	SEM
IMPACT 2002+					
Aquatic acidification	kg SO ₂ eq	1.3E-03	6.1E-05	4.9	6.1E-07
Aquatic ecotoxicity	kg TEG water	20.035	0.929	4.6	9.3E-03
Aquatic eutrophication	kg PO ₄ P-lim	9.6E-05	6.3E-06	6.5	6.3E-08
Carcinogens	kg C ₂ H ₃ Cl eq	0.012	0.001	7.6	1.0E-05
Global warming	kg CO ₂ eq	0.286	0.012	4.1	1.2E-04
Ionizing radiation	kg CO ₂ eq	2.513	0.114	4.5	1.1E-03
Non-carcinogens	kg C ₂ H ₃ Cl eq	3.9E-03	2.0E-04	5.1	2.0E-06
Ozone layer depletion	kg CFC-11 eq	4.1E-08	2.0E-09	4.9	2.0E-11
Respiratory inorganics	kg PM _{2.5} eq	6.2E-04	4.3E-05	6.9	4.3E-07
Respiratory organics	kg C ₂ H ₄ eq	8.7E-05	5.0E-06	5.8	5.0E-08
Terrestrial acid/nutri	kg SO ₂ eq	3.4E-03	1.5E-04	4.5	1.5E-06
Terrestrial ecotoxicity	kg TEG soil	3.382	0.126	3.7	1.3E-03

The frequency distribution and cumulative probabilities for midpoint impact categories for UCO biodiesel are shown in Figure. 4.34. The narrow ranges between the 5th and 95th percentiles reflect a high level of consistency in the data, suggesting that the environmental impacts of the process are quite predictable. This predictability is crucial for effective planning and optimization. The graphs serve as essential tools for illustrating the environmental consequences of biofuel production. By analyzing the frequency distribution and cumulative probability for each impact category, stakeholders can identify the most critical environmental challenges and focus their efforts on areas that need improvement. These visualizations also show how probabilities accumulate as values increase, highlighting trends in medians and variability across different ranges. This comprehensive perspective enhances statistical reasoning and supports informed decision-making by showcasing the interrelatedness of probabilities and their cumulative effects.

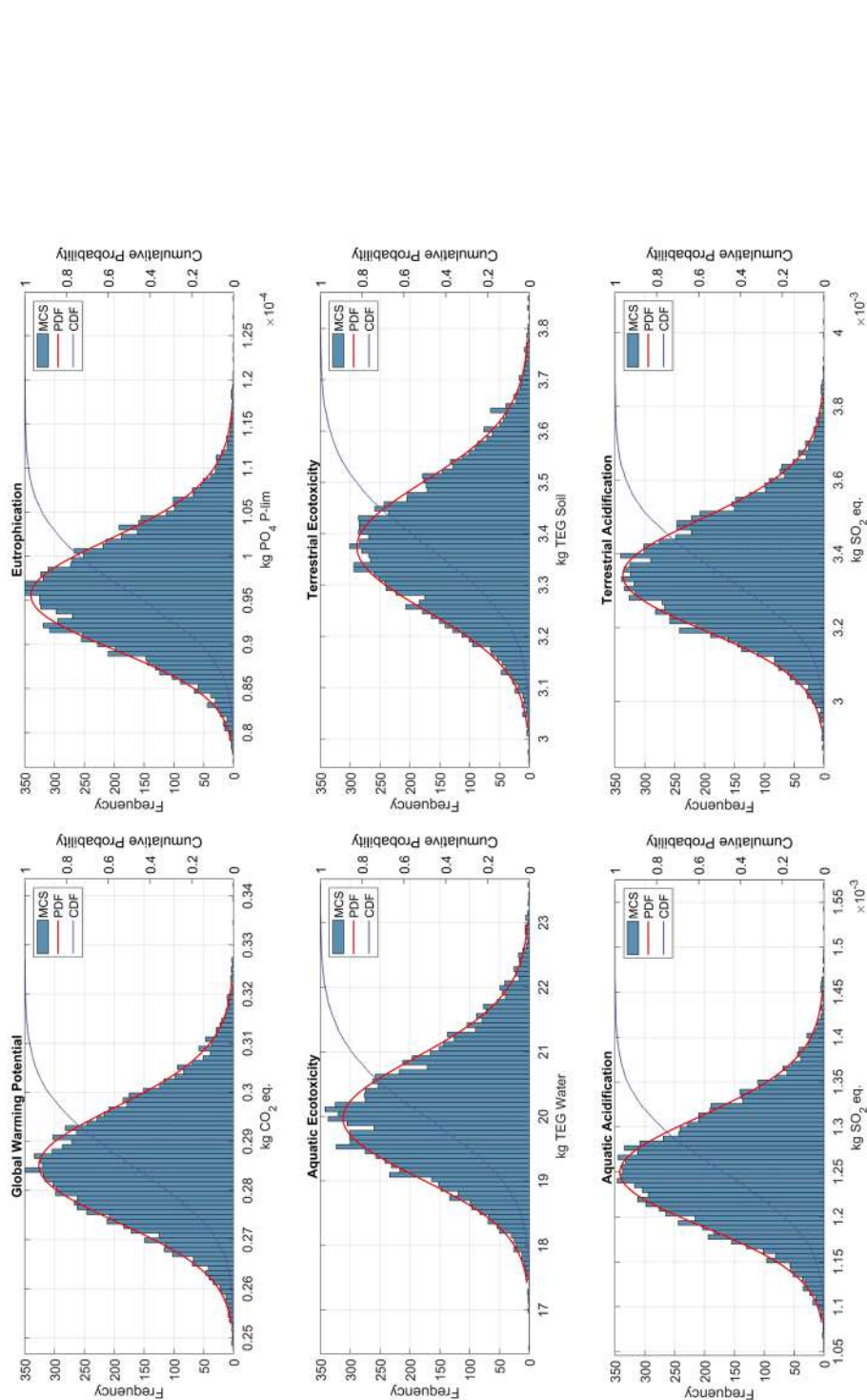


Figure 4.34 Probability Density and Cumulative Probability Function of midpoint impact category for the biodiesel production from UCO

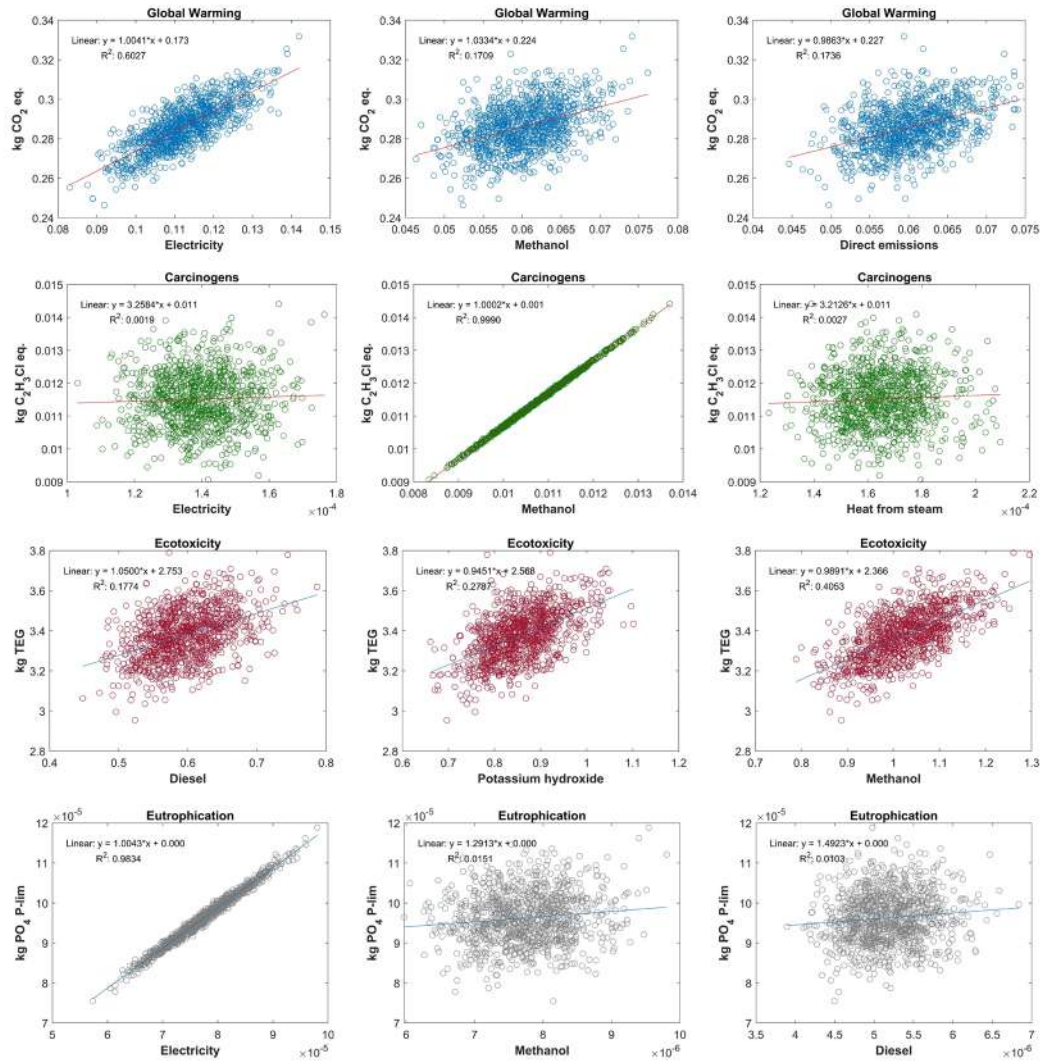


Figure 4.35 Cumulative energy demand results obtained for biodiesel from UCO

Figure 4.35 presents scatter plots illustrating the correlation between LCI inputs and environmental impact categories obtained through Monte Carlo simulation. The regression lines and R^2 values indicate the strength of these relationships, helping identify key contributors. Electricity consumption shows the highest influence on global warming potential ($R^2 = 0.6027$) and eutrophication ($R^2 = 0.9834$), while methanol usage strongly correlates with carcinogens ($R^2 = 0.9990$) and moderately with ecotoxicity ($R^2 = 0.4053$), followed by potassium hydroxide ($R^2 = 0.2787$). These results highlight critical inputs affecting environmental impacts and support targeted strategies for improving sustainability.

4.3.4 Microalgae-based biodiesel

Examining biodiesel from microalgae, its production process, advantages, and role in pollution reduction highlights its significance in advancing a greener and more sustainable future (Patel and Singh, 2026d). Algal oil is particularly appealing due to its high yield potential without requiring extensive arable land and the added value it offers through co-products (Patel and Singh, 2025; Rizwan et al., 2015). Microalgae with high lipid content have the potential to produce over 12 kg of biodiesel/m² annually, whereas rapeseed oil and palm oil—among the highest-yielding vegetable sources—produce less than 0.1 kg and 0.5 kg of biodiesel/m²/year, respectively (Mata et al., 2010). Although biodiesel from microalgae is regarded as a sustainable source, a detailed life cycle assessment is essential to fully evaluate its environmental impact and resource efficiency (Wei et al., 2024).

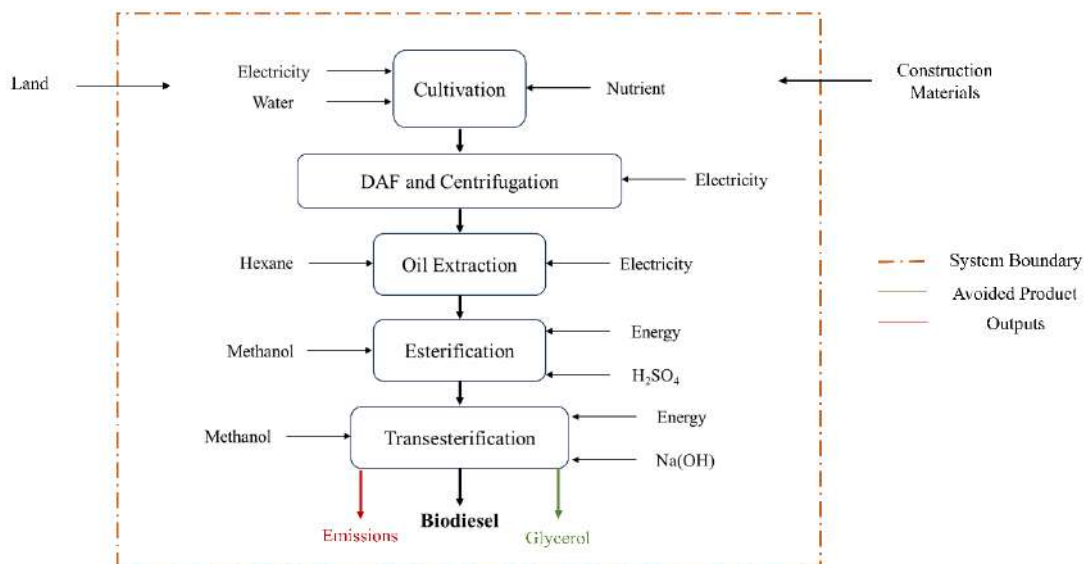
4.3.4.1 Environmental assessment

LCA helps in identifying the hotspots of environmental impacts in biodiesel production, enabling stakeholders to make well-informed decisions that promote sustainability. The objective of the study is to analyze the environmental impact of biodiesel production from microalgae. The study not only focuses on the GHG emissions and energy efficiency but also includes water footprint, energy balance, renewability, and scenario analysis. The uncertainties in the LCA analysis are taken into account to provide a clearer and more reliable assessment of biodiesel's sustainability. Through these findings, policymakers, researchers, and industry professionals can develop and adopt microalgae-based biodiesel with reduced impacts and high net energy, contributing to a sustainable energy future.

Goal and scope. In this study, we conducted a comparative analysis of three pathways for biodiesel production associated with algae systems: i) biodiesel production utilizing hexane extraction (BD1), ii) biodiesel production employing dynamic cross-flow (DCF) microfiltration (BD2) (Gnansounou and Kenthorai Raman, 2016) and iii) biodiesel production involving flocculation/sedimentation with DCF (BD3) (Ríos et al., 2013). Seven alternative scenarios were developed to enhance different processes involved in the production of biodiesel from microalgae (Table 4.35).

Table 4.35 Scenario description for biodiesel production.

Approach	Scenario	Description
Business-As-Usual (BAU)	BD1	This scenario uses the average weighted value of materials and energy input for algal biodiesel production.
Process Alternatives	BD2	This scenario represents using dynamic cross flow and centrifuge as the harvesting pathway followed by direct esterification.
	BD3	This scenario represents flocculation/sedimentation and dynamic cross-flow as the harvesting pathway followed by direct esterification.
Avoided Product	S1	Glycerine produced was considered as an avoided product in the Business-As-Usual scenario.
	S2	The environmental impacts of biodiesel production are calculated by using the IMPACT World+ method for the BD1 scenario.
Differentiated Impact Assessment Approach	S3	The environmental impacts of biodiesel production are calculated by using the IMPACT World+ method for the BD2 scenario.
	S4	The environmental impacts of biodiesel production are calculated by using the IMPACT World+ method for the BD3 scenario.

**Figure 4.36** Scope of the study and system boundary of BAU scenario of biodiesel production from microalgae.

A cradle-to-gate methodology was applied to analyze the potential environmental impacts of biodiesel from microalgae. Biodiesel production from microalgae biomass, across all process alternatives (BD1, BD2, and BD3), is structured into four main stages: cultivation, harvesting, extraction, and transesterification. Additionally, the study did not address aspects related to land use or construction materials. The functional unit (FU) used in the study was per kg of biodiesel produced. This methodological choice ensures that observed environmental differences across scenarios are attributable to harvesting and lipid recovery processes. *Chlorella vulgaris* was used as the primary feedstock for biodiesel production in this study owing to its high lipid accumulation capacity, rapid growth rate, and adaptability to diverse cultivation conditions. Its ability to efficiently convert carbon dioxide into biomass rich in triglycerides makes it particularly suitable for sustainable biofuel production. The system boundary for BD1 is shown in Figure 4.36. BD2 employed a cost-effective harvesting process combining flocculation and sedimentation, followed by microfiltration, as shown in Figure 4.37. However, in BD3, microalgae biomass was concentrated using a high-energy process involving dynamic cross-flow microfiltration followed by centrifugation.

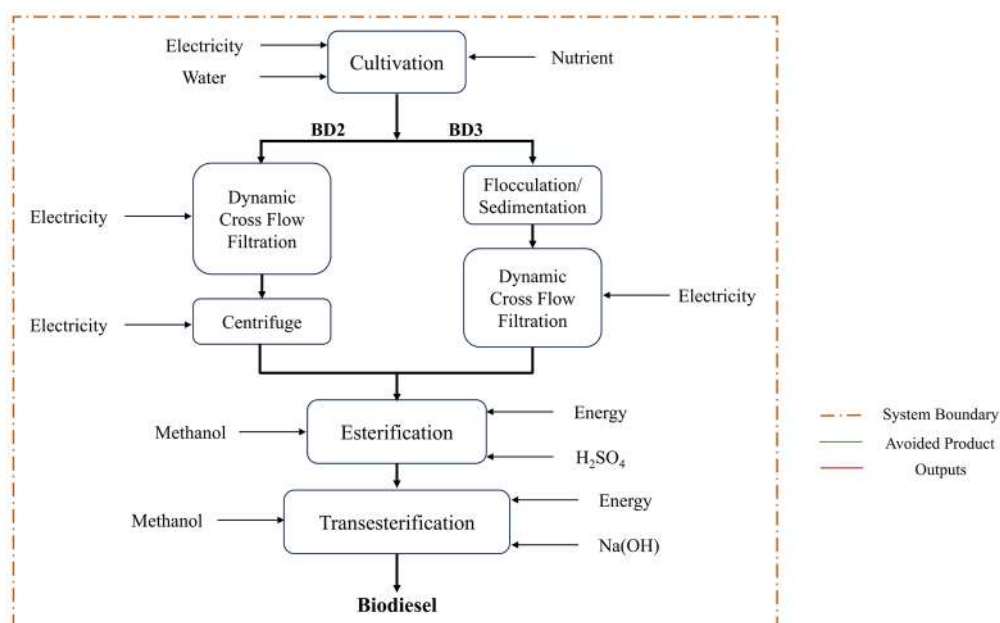


Figure 4.37 System boundary of process alternatives BD2 and BD3 analyzed for the microalgae derived biodiesel.

Inventory analysis. Table 4.36 explicitly presents the material and energy inputs and outputs per functional unit across all scenarios. These data correspond to the representative values and allow traceability of each input assumption. Supply chain emissions represented the indirect emissions from producing raw materials and energy used in the production system, such as fertilizers, fuels, and electricity. Foreground data for onsite emissions were obtained from peer-reviewed literature, as discussed in Chapter 3.

Table 4.36 Inventory data of biodiesel production from microalgae from different process alternatives.

Materials	Unit	BD1	BD2	BD3	Reference
Inputs					
Water	m ³	0.22	0.22	0.22	(Gnansounou and Kenthorai Raman, 2016; Wernet et al., 2016)
Urea	g	88	-	-	(Bradley et al., 2023; Gnansounou and Kenthorai Raman, 2016)
Fertilizer (N)	g	-	742.8	223	(Shurtz et al., 2017; Wernet et al., 2016)
Fertilizer (P)	g	-	234.1	70.2	(Shurtz et al., 2017; Wernet et al., 2016)
Diammonium phosphate	g	80	-	-	(Wernet et al., 2016)
Hexane	g	2.95			(Wernet et al., 2016)
Methanol	g	125	2.9E-03	5.5E-03	(Nazloo et al., 2022)
Sodium hydroxide	g	10.5	-	178	(Nazloo et al., 2022)
Potassium hydroxide	g	-	7.9E-06	7.8E-06	(Bradley et al., 2023; Gnansounou and Kenthorai Raman, 2016)
Sulfuric acid	g	15.8	1.2E-04	3.3E-04	(Bradley et al., 2023; Gnansounou and Kenthorai Raman, 2016)
Trichloromethane	g	-	0.13	0.52	(Gnansounou and Kenthorai Raman, 2016)
Carbon dioxide	g	-	7221	7220	(Gnansounou and Kenthorai Raman, 2016)
Phosphoric acid	g	-	6.9E-06	290	(Gnansounou and Kenthorai Raman, 2016)
Electricity	kWh	6.98	5.61	0.348	CEA India Mix (adjusted Ecoinvent (Wernet et al., 2016))
Steam	MJ	7.9	3.344	9.013	(Wernet et al., 2016)
Outputs					
Biodiesel	kg	1	1	1	Functional Unit
Glycerine	g	113.3	1.2E-05	1.2E-05	(Nazloo et al., 2022)
Residues	kg	-	5.73	16.67	(Nazloo et al., 2022)

Impact assessment. In this study, the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) (Barreiros et al., 2022) and ReCiPe 2016 (Huijbregts et al., 2016) were used to analyze the environmental impacts of biodiesel production. The IPCC 2021 method provided different types of characterization factors, which quantified global warming potential (GWP) and global temperature change potential (GTP) for different time horizons: 20 years, 100 years, and 500 years (PRé Sustainability, 2023). The ReCiPe 2016 method provided a harmonized implementation of cause-effect pathways for calculating both midpoint and endpoint characterization factors (Huijbregts et al., 2016). In addition, the energy analysis was evaluated using the Cumulative Energy Demand methodology outlined by (Frischknecht et al., 2015) and discussed in Chapter 3.

Interpretation. The results, obtained using LCIA methods such as IPCC 2021, ReCiPe 2016, energy analysis, and uncertainty analysis, provide insights into the environmental impacts, resource consumption, and variability associated with each pathway. The study highlights key differences in GHG emissions, energy efficiency, and water use, offering a comprehensive assessment of the sustainability of microalgae-based biodiesel production.

IPCC 2021. The IPCC published the sixth assessment report, which revealed an updated table of GHG metrics applicable to compute various impact assessment categories (Barreiros et al., 2022). The GWP100 of the BAU scenario is 6.79 kg CO₂ eq., which is primarily due to the emission of carbon dioxide, fossil (96.6%), methane, fossil (2.18%), and other emissions (1.22%), which mainly comes from the consumption of electricity, heat, and urea in biodiesel production. The analysis shows that BD2 exhibits a high GWP (9.60 kg CO₂ eq. for GWP100) compared to alternative production routes. Primarily, this is attributed to utilizing fertilizers during the cultivation phase, which represents 55% of the impact, followed by 40% from electricity consumption, 4% from heat generated from steam, and 1% attributed to other factors, as shown in Table 4.37. When evaluating climate change impacts, it is observed that impacts tend to rise when considering shorter timescales, leading to higher impacts for GWP20 compared to GWP100. This discrepancy arises from the differing global warming impact of methane emitted over a 100-year period. In the life

cycle of microalgae biodiesel, a majority of methane emissions originate from energy generation. This underscores the debate regarding whether short-term or long-term timescales should be prioritized in climate change-informed decision-making and the challenge of balancing these perspectives to achieve an equilibrium (Bradley et al., 2023). The Absolute Global Warming Potential (AGWP) is also high for BD2 (0.29, 0.88, and 2.76 pW m⁻² yr for 20, 100, and 500-year periods, respectively), highlighting the significant contribution of BD2 production alternative to global warming, particularly in the short-to-medium term. AGWP is calculated by integrating the radiative forcing due to emission pulses over a chosen time horizon, clarifying the energy-trapping potential of each gas throughout the product's lifecycle. Figure 4.38 shows the variation of GWP and AGWP over different periods for all production scenarios.

Global Temperature change Potential (GTP) is also considered in this study. In contrast to GWP, this metric considers the impact on the planet's temperature, normalized against CO₂ rather than changes in radiative forcing levels (Cherubini et al., 2016). The GTP50 and GTP100 values for BD2 are 9.24 kg CO₂ eq. and 8.95 kg CO₂ eq., respectively (shown in Table 4.37). Fertilizer usage accounts for 56% of the total emissions, with electricity consumption contributing 40%, and heat accounting for 4%. BD3 has the lowest GTP50 and GTP100 (3.43 and 3.34 kg CO₂ eq., respectively), primarily due to fertilizer use (45%), heat (31%), phosphoric acid (11%), electricity (7%), and sodium hydroxide (6%). AGTP (Absolute Global Temperature change Potential) and CGTP (Cumulative Global Temperature change Potential) are also calculated in this study. AGTP measures temperature change caused by one-time emission of a substance over a specified period, whereas CGTP measures the temperature impact of sustained emissions over time, emphasizing long-term effects. Both parameters are highest for the BD2 scenario, caused by electricity consumption and fertilizer use, respectively.

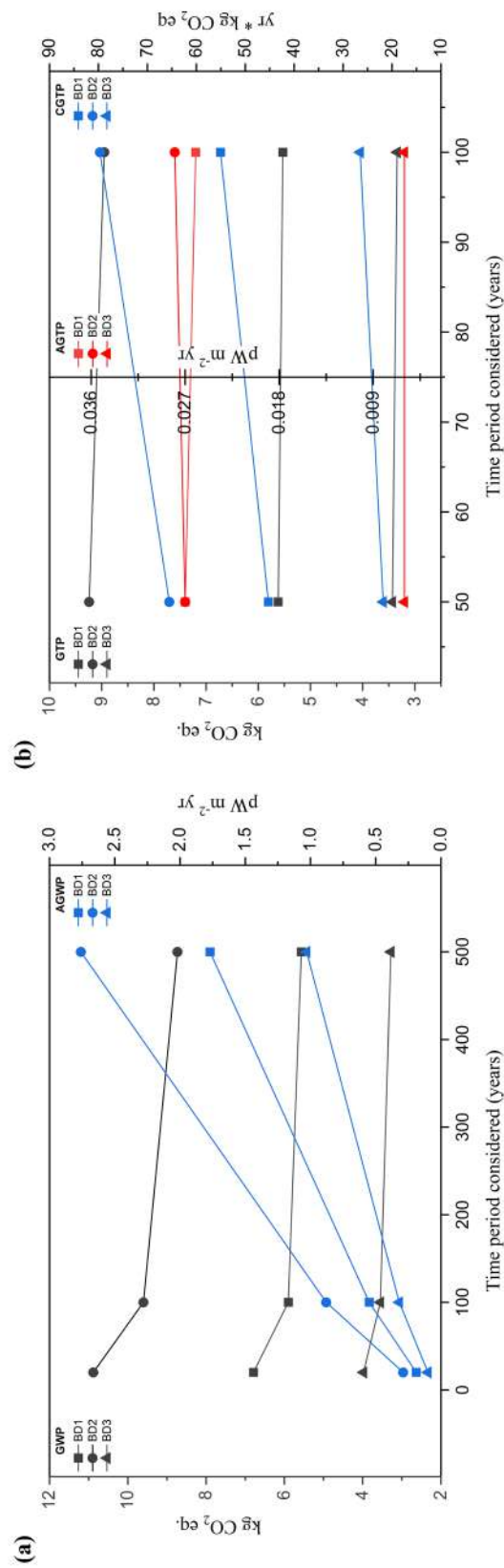


Figure 4.38 Temporal trends of (a) global warming potential and (b) global temperature potential for BDI, BD2, and BD3 over different time horizons.

Table 4.37 Environmental impacts of the three microalgae-derived biofuel production pathways.

Impact Category	Unit	BD1	BD2	BD3
IPCC 2021				
GWP20	kg CO ₂ eq.	6.79	10.88	3.98
GWP100	kg CO ₂ eq.	5.90	9.60	3.55
GWP500	kg CO ₂ eq.	5.57	8.73	3.28
GTP50	kg CO ₂ eq.	5.62	9.24	3.43
GTP100	kg CO ₂ eq.	5.53	8.95	3.34
AGWP20	pW m ⁻² yr	0.19	0.29	0.10
AGWP100	pW m ⁻² yr	0.55	0.88	0.32
AGWP500	pW m ⁻² yr	1.77	2.76	1.03
AGTP50	pW m ⁻² yr	0.027	0.027	0.006
AGTP100	pW m ⁻² yr	0.026	0.028	0.006
CGTP50	yr * kg CO ₂ eq	45.28	65.52	21.81
CGTP100	yr * kg CO ₂ eq	55.07	79.68	26.53
ReCiPe Endpoint				
Ecosystems	species.yr	3.06E-08	4.83E-08	1.91E-08
Human health	DALY	1.49E-05	2.45E-05	1.07E-05
Resources	USD2013	0.37	0.67	0.30
ReCiPe Midpoint				
Global warming potential (GWP)	kg CO ₂ eq.	6.48	10.22	3.78
Stratospheric ozone depletion (SOD)	kg CFC11 eq	1.9E-06	3.00E-05	9.57E-06
Ionizing radiation potential (IRP)	kBq Co-60 eq	0.62	0.60	0.12
Ozone formation, Human health (OF-HH)	kg NO _x eq	1.4E-02	2.17E-02	7.74E-03
Fine particulate matter formation (FPMF)	kg PM _{2.5} eq	1.2E-02	1.66E-02	6.79E-03
Ozone formation, Terrestrial ecosystems (OF-TE)	kg NO _x eq	1.4E-02	2.25E-02	8.09E-03
Terrestrial acidification potential (TAP)	kg SO ₂ eq	2.1E-02	3.63E-02	1.83E-02
Freshwater eutrophication potential (FEP)	kg P eq	2.5E-03	3.41E-03	1.38E-03
Marine eutrophication potential (MEP)	kg N eq	1.8E-04	4.07E-04	1.31E-04
Terrestrial ecotoxicity potential (TExP)	kg 1,4-DCB	11.96	42.46	27.74
Freshwater ecotoxicity potential (FExP)	kg 1,4-DCB	0.15	0.43	0.24
Marine ecotoxicity potential (MExP)	kg 1,4-DCB	0.20	0.57	0.33
Human carcinogenic toxicity potential (HT-C)	kg 1,4-DCB	0.25	0.48	0.47
Human non-carcinogenic toxicity potential (HT-NC)	kg 1,4-DCB	4.37	9.94	5.29
Mineral resource scarcity (MRS)	kg Cu eq	9.8E-03	9.46E-02	4.86E-02
Fossil resource scarcity (FRS)	kg oil eq	1.71	2.60	0.98
Water consumption (WC)	m ³	0.27	0.36	0.08

The superior performance of BD3, particularly its low global warming potential and energy use, can be attributed to specific mechanistic advantages in its harvesting and concentration stages. BD3 uses a flocculation/sedimentation step prior to microfiltration, unlike BD2 which relies solely on dynamic cross-flow filtration and centrifugation—both energy-intensive processes. This significantly reduces electricity demand during biomass concentration by avoiding high-pressure operations, leading to a net reduction in emissions from energy generation. Furthermore, this approach limits the need for steam and other heat sources during downstream processing, contributing to a lower overall carbon footprint.

Table 4.38 Environmental impact areas and corresponding categories considered in ReCiPe 2016.

Impact area	Impact categories
Climate and Atmospheric Impacts	Global warming potential, stratospheric ozone depletion, ionizing radiation potential, and ozone formation affecting human health and terrestrial ecosystems.
Air and Water Quality Impacts	Fine particulate matter formation, terrestrial acidification potential, freshwater eutrophication potential, and marine eutrophication potential.
Toxicity Impacts	Terrestrial ecotoxicity potential, freshwater ecotoxicity potential, and marine ecotoxicity potential.
Resource Depletion and Water Scarcity	Mineral resource scarcity, fossil resource scarcity, and water consumption.

ReCiPe 2016. The ReCiPe method is used in this study due to its ability to translate environmental impacts into midpoint and endpoint indicators, offering a comprehensive assessment of potential ecological and human health impacts. Table 4.38 outlines the environmental impact area and associated categories used in this method. The result shows that the production pathway utilizing DCF microfiltration (BD2 process alternative) has the highest environmental impacts, contributing to global warming, ozone depletion, acidification, ecotoxicity, particulate matter formation, and resource scarcity. However, the BAU scenario primarily shows a significant ionizing radiation impact, while the BD3 process alternative is

characterized by high carcinogenic toxicity. The midpoint and endpoint impact of all the considered production alternatives are shown in Table 4.37.

Climate and atmospheric impacts. The climate and atmospheric impacts encompass environmental concerns associated with emissions and their effects on global and regional atmospheric systems. These include global warming potential, stratospheric ozone depletion, ionizing radiation effects, and ozone formation, impacting human health and terrestrial ecosystems. The BAU scenario causes 6.48 kg CO₂ eq. emissions (shown in Table 4.37), primarily due to electricity consumption, which accounts for 78.3%, followed by heat at 15.4%, urea at 2.4%, diammonium phosphate at 2.16%, and other sources contributing 1.74%. Electricity emerges as the significant contributor across all categories, with particularly high contributions to SOD (85.9%), IRP (97.1%), OF-HH (83.1%), and OF-TE (82.8%). Heat also plays a major role, particularly in ozone formation categories, contributing 9.86% to human health and 9.99% to ecosystem impacts. The contributions of diammonium phosphate, urea, and other inputs are relatively smaller, with minor impacts in all categories. This assessment highlights electricity as the most significant factor driving the environmental footprint of biofuel production, suggesting it should be a primary focus for improving sustainability.

Among the alternative processes, BD2 has high environmental impacts across all impact categories, primarily due to the use of fertilizers during cultivation and high electricity consumption throughout its production. For GWP, electricity accounts for 40%, organic fertilizers account for 55.8%, heat contributes 4.1%, and other sources make up 0.1%, as shown in Figure 4.39. These impacts result primarily from the emission of CO₂ (82.6%), methane (8.56%), dinitrogen monoxide (8.21%), and other gases (0.63%). For SOD, nitrogen and phosphorus fertilizers contribute more than 94% of the total impact, followed by 5% from electricity consumption during production and 1% from other inputs. For IRP, electricity accounts for 80.1%, fertilizers comprise 19.3%, and other materials represent 0.6%. Regarding the impacts of OF-HH and OF-TE, fertilizers contribute 55.5% and 55.8%, respectively, while electricity accounts for 41.9% and 41.5%, respectively, of the impacts due to the emissions of nitrogen oxides (95.9%), non-methane volatile organic compounds, NMVOC (3.58%), and other

emissions (0.52%). In contrast, the BD3 pathway has the least impact because it requires less electricity and fertilizer during biodiesel production, primarily contributing to environmental effects, followed by heat requirements, and sodium hydroxide and phosphoric acid. The IRP for BD3 is 0.12 kBq Co-60 eq., which is 80.64% lower than the BAU scenario, primarily originating from electricity (25.4%), organic nitrogen fertilizer (24.8%), sodium hydroxide (21.5%), phosphoric acid (15.3%), heat (8.1%), and other sources (4.9%). The OF-HH impact ($7.74\text{E-}03$ kg NO_x eq.) mainly results from NO_x (96.8%) and NMVOC (2.72%), while for OF-TE ($8.09\text{E-}03$ kg NO_x eq.), these two emissions are 94.9% and 4.3%, respectively. Other impact categories are also lower for BD3, except for SOD, which is lowest for the BAU scenario. This occurs because SOD primarily results from the release of dinitrogen monoxide, which comes from the application of fertilizers during the cultivation stage.

The normalized score of biodiesel production, shown in Figure 4.39, however, depicts that the impact categories contributing to climate and atmospheric impacts only account for 7.5%, 5.5%, and 2.4% for BD1, BD2, and BD3, respectively, of the total environmental impact. The majority of the impacts are due to the impact of ozone formation on both human health and the ecosystem.

Air and water quality impacts. The impact categories under air and water quality impacts include fine particulate matter formation, terrestrial acidification, freshwater eutrophication, and marine eutrophication. The BD1 shows FPMF of $1.2\text{E-}02$ kg PM_{2.5} eq., primarily attributed to electricity consumption (86.4%), followed by heat (7.57%), diammonium phosphate (3.18%), and other sources (2.85%), as shown in Figure 4.39. This results in the emission of particulates <2.5μm (50.6%), sulfur dioxide (37.6%), nitrogen oxides (11.3%), and small fraction of other emissions (0.5%). BD2 has the highest FPMF, accounting at $1.66\text{E-}02$ kg PM_{2.5} eq., primarily because of the emission of sulfur dioxide (41.7%) and particulates <2.5μm (40.9%), which results from electricity consumption (50.9%), and the use of organic fertilizers (46.8%). For TAP, BD1 and BD3 exhibit similar impacts, with sulfur dioxide emissions accounting for 76.2% and 75.7%, respectively, and nitrogen oxides contributing 21.6% for BD1 and 14% for BD3. These emissions are primarily due to electricity and heat consumption in BD1, while in BD3, they arise from using phosphoric acid and fertilizers.

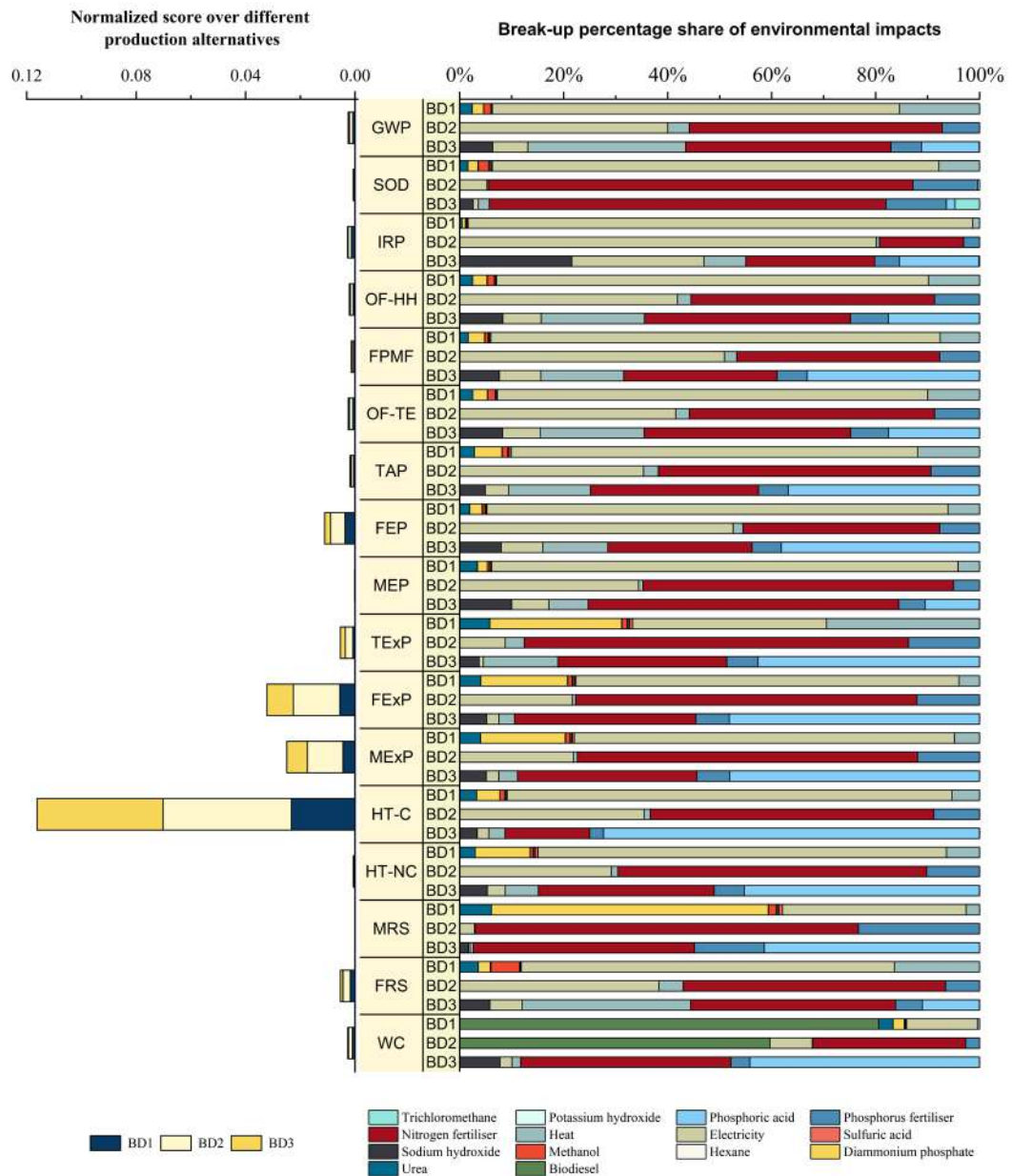


Figure 4.39 Comparative environmental impact assessment of different biodiesel production pathways. On the left side, the results are separated into production pathways, and the right side shows the contribution of the individual impact

BD2 has the highest impact on FEP and MEP, mainly due to electricity consumption, contributing 52.6% to FEP and 34.4% to MEP, along with fertilizers, which account for 45.6% and 64.7%, respectively. FEP resulted from the phosphate emission 86.5%, chemical oxygen demand 7.9%, biochemical oxygen demand 3.6%, phosphorus emission to water 1.9%, and other emissions of 0.1%. Similarly, MEP resulted from the emission of nitrate (56.3%), ammonium ions (42.5%), nitrogen (1.1%), and other emissions (0.1%) to water. BD3 has the lowest air and water quality impact, but still causes FEP of $1.38\text{E-}03$ kg P eq., due to phosphoric acid (38.1%), nitrogen fertilizer (27.8%), heat (12.5%), and electricity (7.98%), and other sources (13.62%), and MEP of $1.31\text{E-}04$ kg N eq., primarily due to nitrogen fertilizer (59.8%), phosphoric acid (10.5%), sodium hydroxide (10%), heat (7.58%), and electricity (7.12%), and other sources (5%).

The normalized score of biodiesel production shows that the air and water quality impacts account for 11.3%, 7.82%, and 4.4% for BD1, BD2, and BD3, respectively, of the total environmental impact. The majority of the impacts are because of FEP, which accounts for 9.1%, 6.1%, and 3.4% for BD1, BD2, and BD3, respectively.

Toxicity impacts. Toxicity impacts encompass various detrimental effects on ecosystems and human health. These impacts include terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity, all measured in kilograms of 1,4-dichlorobenzene (kg 1,4-DCB). Additionally, toxicity impacts cover human health concerns, such as human carcinogenic and non-carcinogenic toxicity, also expressed in kg 1,4-DCB. Understanding these impacts is essential for assessing the potential harm caused by chemicals and pollutants in different environments and their long-term implications for ecological and human well-being. The analysis shows that BAU production pathway has the lowest impact among the considered alternatives, results in 11.96, 0.15, and 0.20 kg 1,4-DCB of TExP, FExP, and MExP, respectively, with electricity contributes 37.3%, 73.6%, and 73.1%, respectively, followed by heat at 29.5%, 4%, and 4.84%, diammonium phosphate at 25.4%, 16.7%, and 16.3%, urea at 5.77%, 4%, and 4%, and other sources contributing 2.03%, 1.7%, and 1.76%, respectively, shown in Figure 4.39. These sources lead to emissions primarily composed of copper, zinc,

nickel, and other air emissions. The HT-C and HT-NC impact of BAU is due to electricity contributing 85.5% and 78.6%, respectively. Diammonium phosphate accounts for 4.42% and 10.5%, while heat contributes 5.22% and 6.38%, respectively. Other sources collectively contribute 4.75% and 4.52%, respectively.

For the alternative pathways, BD2 has the highest toxicity impact, mainly due to TExP and HT-NC resulting from fertilizers, electricity, and heat. TExP is caused by emissions of copper (73.7%), nickel (7.91%), zinc (5.8%), and other airborne emissions (12.59%), while HT-NC is caused by waterborne zinc emissions (57.1%) and arsenic (25.4%), as well as airborne emissions of arsenic (5.39%), lead (3.51%), and other substances (8.6%). The HT-C is mainly because of the emission of Cr(VI) (90.9%), arsenic (2.2%), nickel (1.85%), and other emissions (5.05%). The HT-NC is primarily due to waterborne emissions of zinc (57.1%) and arsenic (25.4%), as well as airborne emissions of arsenic (5.39%), lead (3.51%), and other emissions (8.6%). The use of fertilizers, electricity, heat, and trichloromethane predominantly causes these emissions. BD3 alternative production pathway has a higher impact than BAU but has a lower impact than the BD2 alternative, except HT-C, which is equivalent to BD2 because of the high impact due to phosphoric acid use, followed by fertilizers and sodium hydroxide. These sources cause waterborne emissions of Cr(VI), arsenic, and nickel, as well as airborne emissions of nickel, Cr(VI), formaldehyde, and other emissions.

The normalized score shows that the toxicity impact is highest in biodiesel production, accounting for 75.1%, 82.3%, and 91.3% for BD1, BD2, and BD3, respectively, with HT-C causing the highest impact, accounting for 49.5%, 47.5%, and 64.3%, respectively.

Resource depletion and water scarcity. Resource depletion and water scarcity encompass critical environmental impacts related to the extraction and consumption of natural resources. These impacts include mineral resource scarcity, which refers to the depletion of essential minerals; fossil resource scarcity, which highlights the consumption of non-renewable fossil fuels; and water consumption, which accounts for the total volume of water used, reflecting its availability and potential stress on freshwater ecosystems. These factors collectively show the strain on natural resources

due to human activities, necessitating sustainable management strategies. As shown in Table 4.37, the BAU scenario exhibits a moderate environmental impact concerning resource depletion and water consumption. It has the lowest impact on MRS at $9.8\text{E-}03$ kg Cu eq., while its impact on FRS (1.71 kg oil eq.) and WC (0.27 m^3) falls within the mid-range. The FRS impact mainly arises from the use of coal (42.3%), natural gas (40.2%), crude oil (10.6%), and other energy sources (6.9%), which contribute to electricity generation, heat production, and methanol production.

The BD2 process shows the highest levels of resource depletion and water scarcity, mainly due to fertilizers, which contribute 97.1% to MRS and 57.1% to FRS. Electricity also plays a significant role, accounting for 2.82% of MRS and 38.3% of FRS, while other sources contribute 0.08% and 4.6%, respectively. For BD3 production pathways, the primary contributors to MRS impact are nitrogen fertilizer (42.6%), phosphoric acid (41.4%), phosphorus fertilizer (13.4%), and other sources (2.6%). Regarding FRS, the main factors include nitrogen fertilizer (39.4%), heat (32.4%), phosphoric acid (11%), electricity (6.2%), and other sources (11%). The impact of fertilizers results from the use of natural gas (56.4%), coal (27%), crude oil (15.3%), and other sources (1.3%).

The normalized score in Figure 4.39 indicates that resource depletion and water scarcity contribute 6%, 4.3%, and 1.9% of the total impact for BD1, BD2, and BD3, respectively. The largest portion of these impacts comes from FRS, which accounts for 3.8%, 2.8%, and 1.5% for BD1, BD2, and BD3, respectively.

The endpoint analysis shows that BD2 has the highest environmental impact, particularly affecting ecosystems ($4.83\text{E-}08$ species.yr), human health ($2.45\text{E-}05$ DALY), and resource depletion (0.67 USD2013). BD3 emerges as the most sustainable option, with the lowest impact across all categories, as shown in Table 4.37.

Scenario analysis. Adjusting the system boundary to include the avoided product when conducting the scenario analysis (scenario S1) provides valuable insights into the life cycle impacts of biodiesel production. Producing biodiesel also leads to the generation of glycerine as a co-product (Patel and Singh, 2024c). In scenario S1, glycerine production is treated using the substitution method, also known as system expansion or the avoided burden approach. This method addresses multifunctionality

by crediting the biodiesel system for the production of glycerine, which displaces the need for an equivalent amount of conventionally produced glycerine on the market. As a result, the environmental impacts associated with the production of conventional glycerine are subtracted from the total impacts of the system. This approach aligns with ISO 14044 recommendations and reflects a consequential LCA perspective, focusing on system-level effects and real-world consequences of co-product generation. Table 4.39 shows the environmental impacts associated with scenario S1.

Table 4.39 Percentage decrease resulting from avoided products in biodiesel production.

Impact Categories	Unit	Impact values with avoided product	% Reduction
Global warming	kg CO ₂ eq.	6.09	6.04
Stratospheric ozone depletion	kg CFC11 eq	-2.8E-07	114.4
Ionizing radiation	kBq Co-60 eq	0.61	1.43
Ozone formation, Human health	kg NO _x eq	1.3E-02	5.06
Fine particulate matter formation	kg PM _{2.5} eq	1.1E-02	4.96
Ozone formation, Terrestrial ecosystems	kg NO _x eq	1.4E-02	4.89
Terrestrial acidification	kg SO ₂ eq	1.9E-02	8.41
Freshwater eutrophication	kg P eq	2.4E-03	3.82
Marine eutrophication	kg N eq	-3.6E-04	300.4
Terrestrial ecotoxicity	kg 1,4-DCB	11.26	5.84
Freshwater ecotoxicity	kg 1,4-DCB	0.14	4.15
Marine ecotoxicity	kg 1,4-DCB	0.19	3.36
Human carcinogenic toxicity	kg 1,4-DCB	0.24	2.63
Human non-carcinogenic toxicity	kg 1,4-DCB	3.98	8.99
Mineral resource scarcity	kg Cu eq	9.0E-03	7.96
Fossil resource scarcity	kg oil eq	1.65	3.62
Water consumption	m ³	0.26	3.57

The analysis shows that incorporating the avoided products within the system boundary reduces impacts across various environmental categories in biodiesel production. Significant reduction is observed in marine eutrophication (300.4%) and stratospheric ozone depletion (114.4%). These reductions are because of the avoidance of dinitrogen monoxide emissions (206% reduction) and CFC-10 emissions (19% reduction) for SOD, as well as a 103% reduction in waterborne nitrate emissions for MEP.

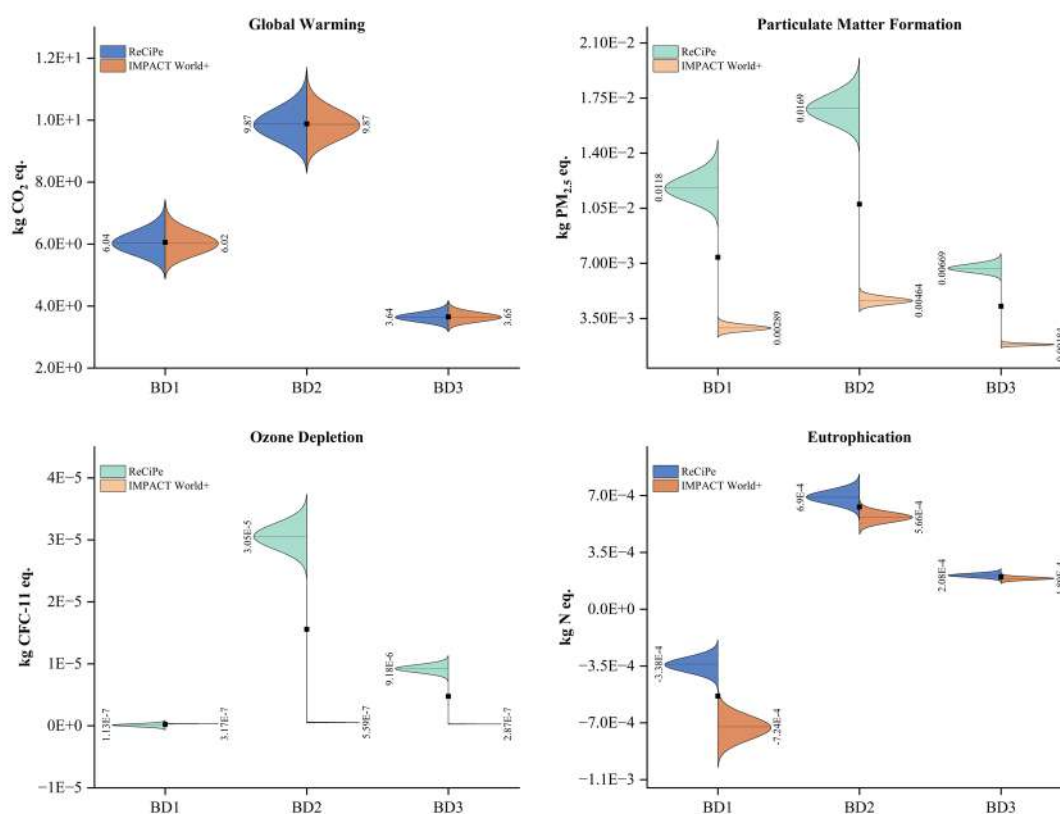


Figure 4.40 Comparison of environmental impact categories for biodiesel production using two LCIA methods.

The study also compares the environmental impact results obtained from two different LCIA methods (scenarios S2 to S4) to evaluate their consistency, sensitivity, and applicability in assessing the sustainability of biodiesel production. The ReCiPe method is being compared with the IMPACT World+ method. Both methods offer robust impact assessment models, science-based approaches, and global applicability, but they have distinct characteristics that make them complementary for comparative analysis. Figure 4.40 shows the comparative environmental impacts of microalgae-based biodiesel production pathways across four impact categories, highlighting methodological differences. Both methods show similar impact values for GWP across all production pathways, suggesting that both methods use comparable characterization factors for GHG emissions. However, for PMF, ReCiPe generally estimates higher values than the IMPACT World+ method, especially for BD1 and BD3, indicating different modeling assumptions for air pollution impacts. Similarly,

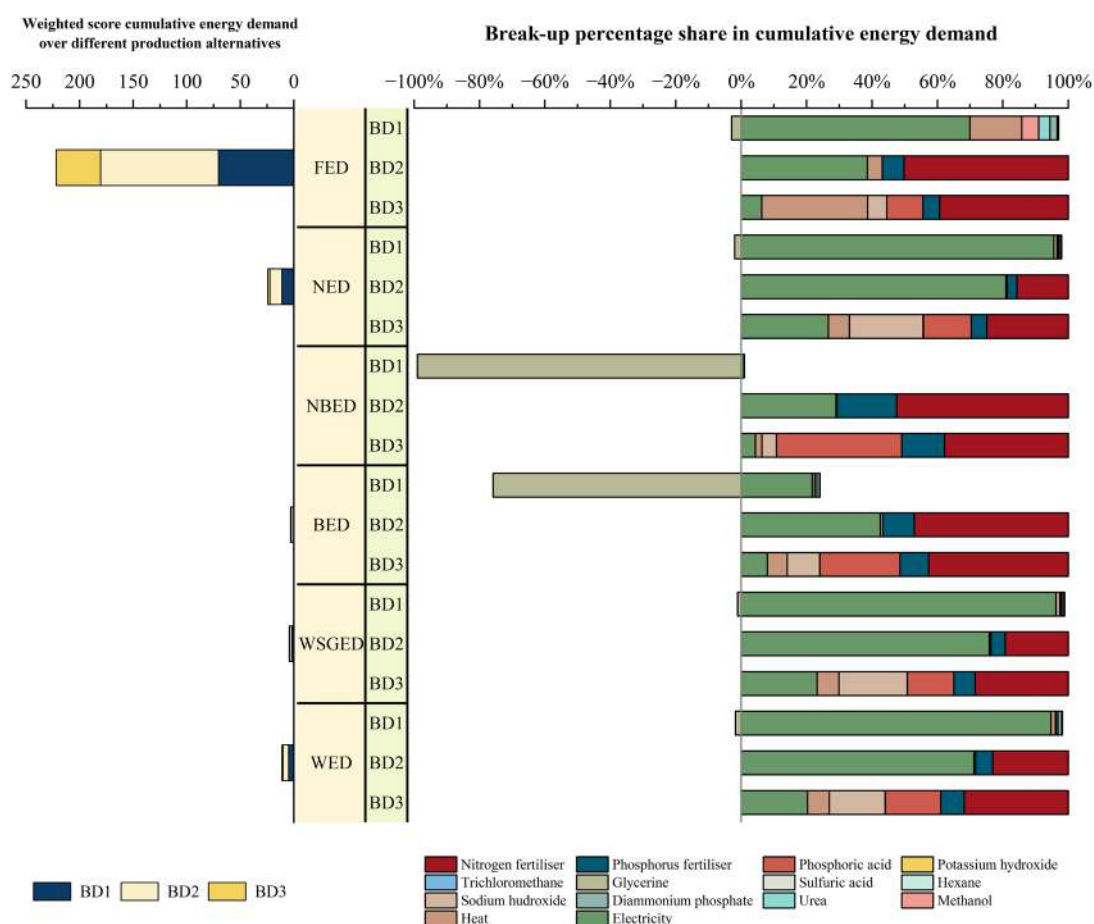
ODP shows a significant difference between the two methods, particularly BD2, where ReCiPe estimates a much higher impact than IMPACT World+. Marine eutrophication shows notable variations, with ReCiPe showing both positive and negative values for BD1, suggesting different impact pathways considered by the two methods. This difference is due to variations in characterization models, regionalization approaches, and impact assessment methodologies used by ReCiPe and IMPACT World+, which influence how emissions and resource use are translated into environmental impacts.

4.3.4.2 Energy analysis

As shown in Table 4.40, the CED of BD2 is highest (130.5 MJ / FU), primarily due to fertilizers (52%), electricity (44%), heat (3.9%), and other sources (0.1%). The impacts from these sources are caused by the use of natural gas (36.7%), coal (32%), crude oil (11.2%), uranium (8.5%), and other sources (11.6%). The weighted score of CED for biodiesel production, shown in Figure 4.41, indicates that FED is the highest across all scenarios. This suggests that biodiesel production from microalgae remains heavily dependent on fossil fuels as its primary energy source. The key contributors to NED are the production of phosphate, urea, and fertilizers, as uranium is used as a fuel in the process (Wahyono et al., 2023). The analysis shows that the BAU and BD2 scenarios have comparable NED values. However, in the BAU scenario, the energy demand comes from electricity (11.2 MJ), heat (0.1 MJ), and other sources (0.1 MJ), whereas in the BD2 scenario, the energy demand comes from electricity (9 MJ), nitrogen fertilizer (1.7 MJ), phosphorus fertilizer (0.3 MJ), and other sources (0.2 MJ). In the BAU scenario, glycerine reduces overall energy demand since it is treated as an avoided product in the analysis, leading to a total energy demand reduction of 0.2 MJ / FU. The weighted score of NBED and BED is negative for BAU because glycerine is an avoided product, and is also lower for other scenarios. Biomass is a potential renewable energy source that should be encouraged due to its abundance and ability to substitute fossil fuels (Wahyono et al., 2023).

Table 4.40 Environmental impacts derived from cumulative energy demand in biodiesel production.

Impact category	Unit	Microalgae
Non-renewable, fossil	MJ	70.3
Non-renewable, nuclear	MJ	11.2
Non-renewable, biomass	MJ	-0.56
Renewable, biomass	MJ	-2.95
Renewable, wind, solar, geothermal	MJ	1.95
Renewable, water	MJ	4.85
NER		0.51
NEV		-41.29
Rn		0.62
NRnEV		-26.80

**Figure 4.41** CED for biodiesel production across different alternatives, showing weighted scores and percentage contributions of various energy sources.

The WSGED is primarily due to electricity at 98.1%, 76.3%, and 23.2% in BD1, BD2 and BD3, respectively. This is followed by heat, which contributes 1.3% in BD1, and fertilizers, which comprise 23% and 34% in BD2 and BD3, respectively. WSGED contributes 2.3%, 1.5%, and 0.9% of total impacts for BD1, BD2, and BD3, respectively. Similarly, WED is also due to electricity at 98.5%, 74.3%, and 21.5% for BD1, BD2, and BD3, respectively. However, for the BD2 and BD3 scenarios, the fertilizers also significantly impact WED at 25% and 35.2%, respectively. Due to the impact of climate change, the production of fertilizers requires relatively low water and energy. Climate-related risks influence hydropower efficiency by shifting precipitation patterns and timing. Extreme weather events, including floods and droughts, create challenges in planning hydropower projects. During the summer, reduced river flow reduces hydroelectric capacity. Therefore, hydropower contributes less to biodiesel production, accounting for 5.7%, 4.0%, and 2.4% in BD1, BD2, and BD3, respectively.

The analysis shows that BD1 and BD2 exhibit negative NEV and NRnEV (Table 4.40), indicating that these pathways consume more energy than they produce and that their production pathways rely heavily on non-renewable energy sources, making them unsustainable. In contrast, NEV and NRnEV for BD3 are positive, indicating a net energy gain and making it a more viable option. The positive energy balance observed in BD3 primarily results from simplifying the harvesting process. BD3 achieves a positive energy balance by shifting the primary concentration task from continuous, high-power equipment to gravity-driven separation. In our inventory, BD3 consumes 0.348 kWh / kg biodiesel for electricity in harvesting/concentration compared with 5.61 kWh / kg for BD2 and 6.98 kWh / kg for BD1, representing a ~94–95% reduction in electrical energy for concentration when flocculation/sedimentation is used. The flocculation step agglomerates cells into millimeter-scale flocs that settle rapidly under gravity, whereas centrifuges and dynamic cross-flow filters require sustained high rotational speeds and pump power to achieve equivalent solid–liquid separation. Because electrical energy is the dominant contributor to upstream fossil energy in our system, reducing pump and rotor loads via gravity thickening directly lowers cumulative energy demand and flips the net energy balance to positive (NER = 1.33 for BD3). These causal links are reflected in the

energy and CED results and explain why BD3 outperforms the other pathways. These findings confirm that integrating flocculation/sedimentation enables BD3 to overcome the negative energy balance that limits other process alternatives, making it both more efficient and sustainable. Conventional diesel is used as a benchmark, with an NER of 0.83, suggesting that the BD3 alternative is more energy-efficient. BD3 has the highest renewability (1.47), indicating minimal dependence on fossil fuels, while BD1 (0.87) and BD2 (0.55) show greater reliance on fossil energy sources. Diesel, in comparison, has an Rn value of 0.84, further reinforcing BD3 as the most environmentally favorable pathway among those assessed.

4.3.4.3 Sensitivity and uncertainty analysis

The analysis provides key statistical parameters, including the mean, standard deviation (SD), coefficient of variation (CoV%), and standard error of the mean (SEM), shown in Table 4.41. The MCS results show that the CoV, a measure of relative variability, ranges from 3.6% to 220.7%. The highest CoV is observed in stratospheric ozone depletion for BD1 (220.7%), indicating significant uncertainty in this category. In contrast, the lowest CoV is observed in marine ecotoxicity for BD3 (3.6%), suggesting relatively stable data. The SD values, which reflect the dispersion of data around the mean, are highest for water consumption in BD1 (3.062) and BD2 (2.546), indicating a broader spread, whereas BD3 shows a lower SD (0.299), suggesting greater consistency in this category.

The SEM, which represents the accuracy of the sample mean in estimating the population means, is lowest for fine particulate matter formation in BD3 (2.6E-06), implying high precision in its mean estimate. In contrast, water consumption in BD1 has the highest SEM (3.1E-02), showing greater variability in mean estimation. Overall, BD3 consistently demonstrates lower CoV% and SD in most impact categories, making it the most stable and predictable biodiesel production pathway in terms of environmental impact. Meanwhile, BD2 tends to exhibit higher SD and impact magnitude values, especially in categories such as global warming (9.902 kg CO₂ eq) and terrestrial ecotoxicity (39.045), indicating a greater environmental burden.

The probability distribution and cumulative probabilities for midpoint impact categories for the BAU scenario are shown in Figure 4.42. For the BD2 and BD3 scenarios, the MCS analysis is shown in Figures 4.43 and 4.44, which show the 5th and 95th percentiles with small ranges, indicating a high degree of consistency in the data, suggesting that the environmental impacts of the process are predictable. The use of graphs to illustrate the frequency distribution and cumulative probabilities for the LCA of microalgae-based biodiesel production is essential. These visual tools help identify critical environmental factors, enabling focused efforts on the areas with the highest impact. By closely analyzing the MCS, stakeholders can understand how probability values change as different impacts accumulate, revealing trends in the median and variability across production scenarios. The analysis revealed that fertilizer inputs (both nitrogen and phosphorus) and electricity consumption during cultivation and harvesting stages were the dominant contributors to variability in global warming potential, eutrophication, and fossil resource scarcity. For BD2, fertilizer use alone accounted for more than half of the observed variation in GWP, while electricity was the primary driver of variability in ionizing radiation potential and particulate matter formation. In BD3, reduced fertilizer and electricity demand resulted in lower CoV% values across most categories, confirming the robustness of its environmental performance.

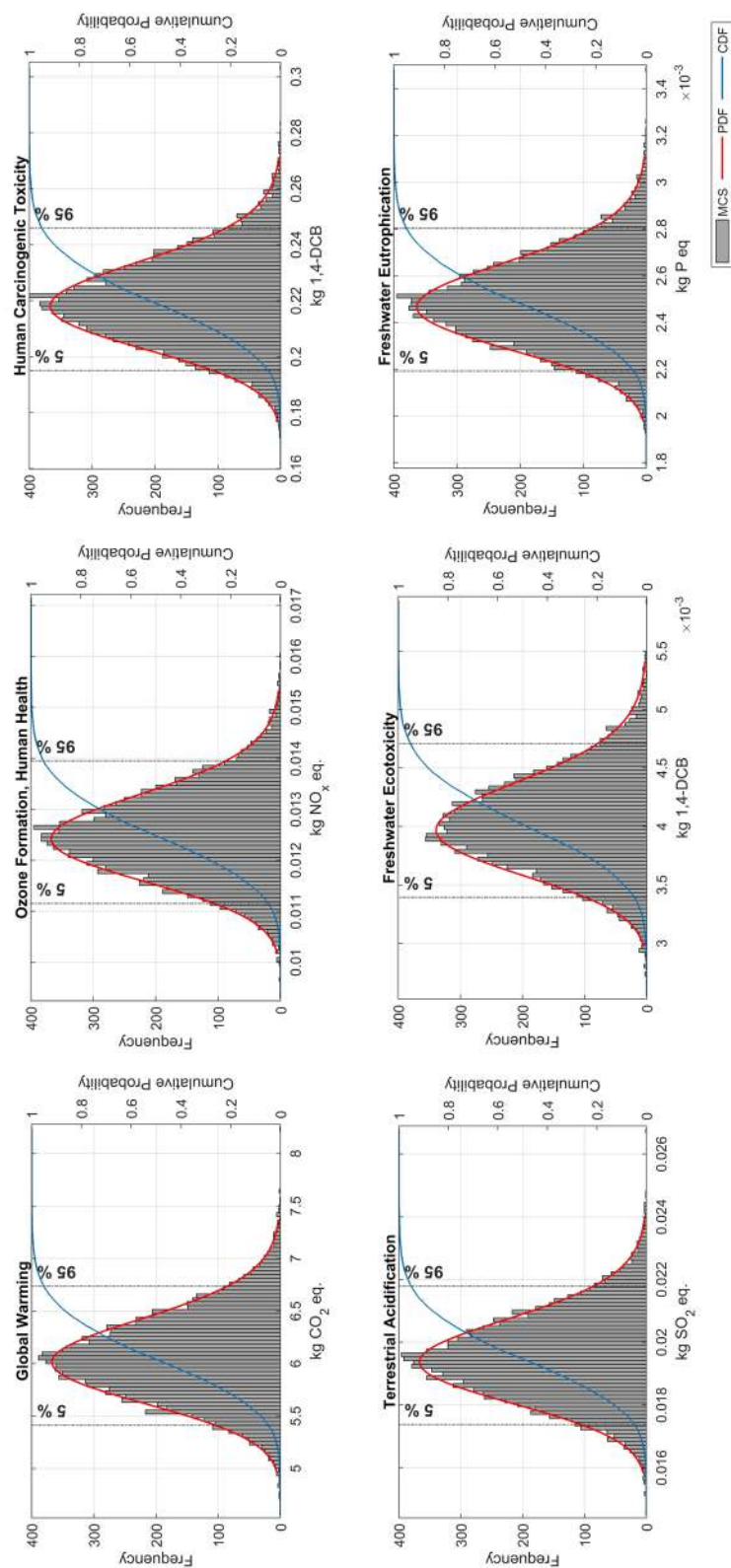


Figure 4.42 Monte Carlo simulation for biodiesel production using the BAU scenario, where the Probability Density Function (PDF) represents the distribution of impact values, and the Cumulative Distribution Function (CDF) represents their cumulative probability.

Table 4.41 Assessment of uncertainties in the life cycle analysis of microalgae-derived biodiesel production.

Impact Category	BD1					BD2					BD3				
	Mean	SD	CoV (%)	SEM		Mean	SD	CoV (%)	SEM		Mean	SD	CoV (%)	SEM	
Fine particulate matter formation	0.012	0.001	7.3	8.60E-06		0.017	0.001	5	8.80E-06		6.70E-03	2.60E-04	4	2.60E-06	
Freshwater ecotoxicity	4.00E-03	4.00E-04	9.9	4.00E-06		0.012	0.001	5	6.60E-06		8.60E-03	4.20E-04	5	4.20E-06	
Freshwater eutrophication	2.50E-03	1.90E-04	7.6	1.90E-06		3.30E-03	1.80E-04	5	1.80E-06		1.30E-03	5.40E-05	4	5.40E-07	
Global warming	6.054	0.403	6.7	4.00E-03		9.902	0.503	5	5.00E-03		3.647	0.152	4	1.50E-03	
Human carcinogenic	0.22	0.016	7.1	1.60E-04		0.443	0.023	5	2.30E-04		0.454	0.027	6	2.70E-04	
Human non-carcinogenic toxicity	0.322	0.032	10	3.20E-04		1.745	0.099	6	9.90E-04		1.133	0.054	5	5.40E-04	
Ionizing radiation	0.618	0.049	8	4.90E-04		0.615	0.041	7	4.10E-04		0.12	0.004	4	4.40E-05	
Marine ecotoxicity	0.013	0.001	5.9	7.60E-06		0.038	0.002	6	2.10E-05		0.027	0.001	5	1.20E-05	

Impact Category	BD1					BD2					BD3				
	Mean	SD	CoV (%)	SEM		Mean	SD	CoV (%)	SEM		Mean	SD	CoV (%)	SEM	
Marine eutrophication	-3.40E-04	4.70E-05	-13.7	4.70E-07		6.90E-04	4.20E-05	6	4.20E-07		2.10E-04	1.20E-05	6	1.20E-07	
Mineral resource scarcity	9.60E-04	5.20E-05	5.4	5.20E-07		5.10E-03	3.20E-04	6	3.20E-06		3.50E-03	1.80E-04	5	1.80E-06	
Ozone formation, Human health	0.013	0.001	6.9	8.60E-06		0.02	0.001	5	1.00E-05		7.10E-03	2.80E-04	4	2.80E-06	
Ozone formation, Terrestrial	0.013	0.001	6.9	8.60E-06		0.02	0.001	5	1.00E-05		7.10E-03	2.80E-04	4	2.80E-06	
Stratospheric ozone depletion	1.10E-07	2.40E-07	221	2.40E-09		3.10E-05	2.00E-06	7	2.00E-08		9.20E-06	6.10E-07	7	6.10E-09	
Terrestrial acidification	0.02	0.001	6.9	1.30E-05		0.037	0.002	5	1.90E-05		0.018	0.001	4	7.60E-06	
Terrestrial ecotoxicity	10.723	0.495	4.6	4.90E-03		39.045	2.349	6	2.30E-02		26.63	1.187	5	1.20E-02	
Water consumption	39.143	3.062	7.8	3.10E-02		40.385	2.546	6	2.50E-02		8.249	0.299	4	3.00E-03	

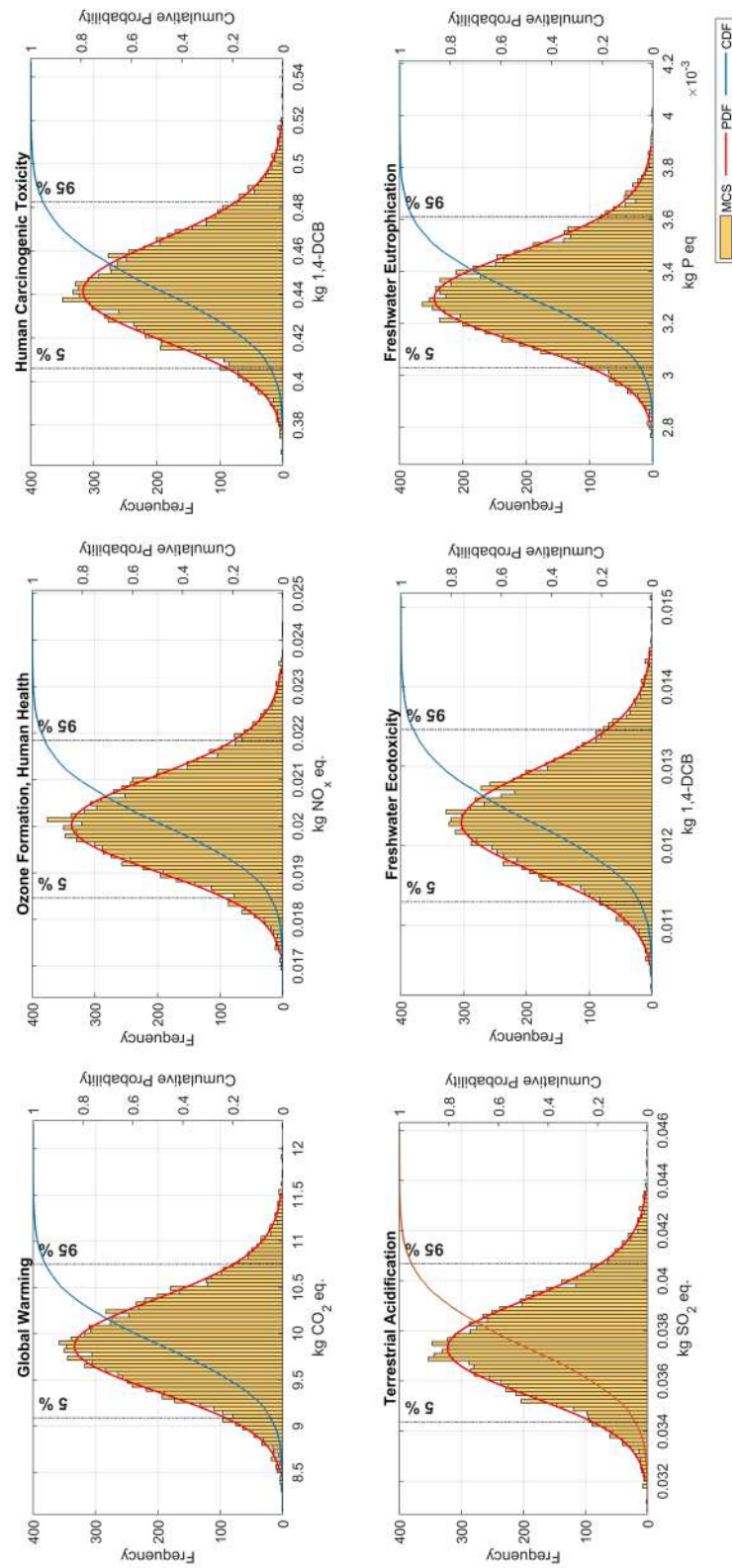


Figure 4.43 Monte Carlo simulation for biodiesel production using the BD2 scenario, analyzing environmental impact distributions.

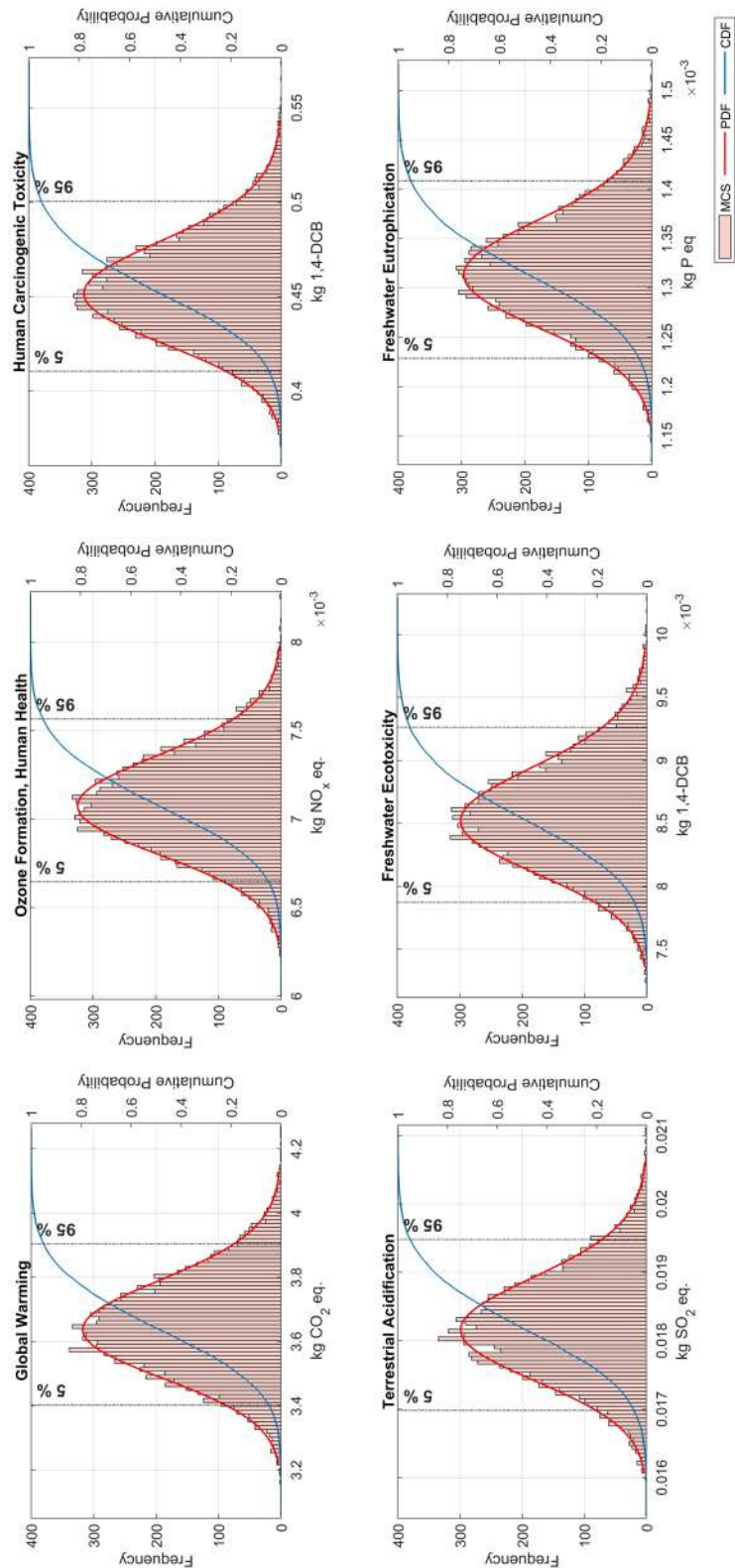


Figure 4.44 Monte Carlo simulation for biodiesel production using the BD3 scenario, analyzing environmental impact distributions.

4.4 Comparative environmental impacts of biofuel production

The comparative environmental assessment of bioethanol production across different feedstocks reveals significant variability in impact profiles, strongly influenced by feedstock type and associated processing requirements. As shown in Table 4.42, among all pathways, MSW-based bioethanol exhibits the highest global warming potential (6.35 kg CO₂ eq) and fossil resource scarcity (1.6 kg oil eq), indicating substantial energy and emission burdens, whereas corn stover shows the lowest GWP (0.54 kg CO₂ eq) and fossil resource use (0.15 kg oil eq), highlighting its environmental advantage. First-generation feedstocks such as molasses and broken rice demonstrate moderate impacts, with relatively higher terrestrial ecotoxicity and fossil energy demand.

Table 4.42 Midpoint Impact Categories of bioethanol production from various feedstocks

Impact Category	Unit	Molasses	Broken Rice	Rice Straw	Corn Stover	Cassava Straw	MSW	Gasoline
Global warming potential	kg CO ₂ eq	2.40	4.17	1.37	0.54	1.40	6.35	1.592
Ionizing radiation potential	kBq Co-60 eq	3.9E-02	1.1E-01	9.7E-02	5.4E-02	6.6E-04	2.7E-01	1.1E-02
Ozone formation, Human health	kg NO _x eq	4.1E-03	5.0E-03	4.1E-03	1.7E-03	1.3E-04	9.8E-03	8.9E-03
Fine particulate matter formation	kg PM _{2.5} eq	4.0E-03	4.1E-03	3.0E-03	1.4E-03	5.2E-04	8.9E-03	5.1E-03
Ozone formation, Terrestrial ecosystems	kg NO _x eq	4.2E-03	5.1E-03	4.2E-03	1.7E-03	1.8E-04	1.0E-02	9.5E-03
Terrestrial acidification	kg SO ₂ eq	6.1E-03	9.0E-03	1.3E-02	5.0E-03	1.8E-03	2.6E-02	0.017
Eutrophication potential	kg P eq	1.6E-03	8.1E-04	9.0E-04	4.0E-04	4.3E-05	2.3E-03	1.8E-04
Terrestrial ecotoxicity potential	kg 1,4-DCB	3.81	9.53	9.56	3.41	0.34	14.06	0.739
Freshwater ecotoxicity potential	kg 1,4-DCB	5.0E-02	3.5E-02	1.0E-01	3.8E-02	3.0E-03	1.3E-01	0.050
Marine ecotoxicity potential	kg 1,4-DCB	7.0E-02	5.1E-02	1.1E-01	4.1E-02	4.0E-03	1.7E-01	0.067
Human carcinogenic toxicity	kg 1,4-DCB	2.2E-01	6.4E-02	6.5E-02	3.0E-02	1.3E-03	1.7E-01	0.012
Human non-carcinogenic toxicity	kg 1,4-DCB	2.14	1.38	3.17	1.14	0.06	3.64	2.632
Fossil resource scarcity	kg oil eq	5.9E-01	9.4E-01	4.1E-01	1.5E-01	2.4E-01	1.6E+00	2.868
Water consumption	m ³	1.9E-02	1.6E-02	1.4E-01	5.4E-02	2.9E-03	7.3E-02	7.4E-04

In contrast, second-generation feedstocks, particularly cassava straw, exhibit consistently lower impacts across most categories, including eutrophication and toxicity indicators, reflecting efficient resource utilization and reduced upstream burdens. However, rice straw shows elevated ecotoxicity impacts and significantly higher water consumption, indicating sensitivity to agricultural residue management. Compared to gasoline, which shows a GWP of 1.592 kg CO₂ eq and significantly

higher fossil resource scarcity, most bioethanol pathways demonstrate reduced dependence on fossil resources but may exhibit higher impacts in ecotoxicity and water consumption depending on the feedstock. Overall, the results emphasize that lignocellulosic residues, especially corn stover and cassava straw, offer superior environmental performance, whereas waste-based and conventional systems require targeted improvements in energy efficiency and emission control to enhance sustainability.

Table 4.43 Midpoint Impact Categories of biodiesel production from various feedstocks

Impact Category	Unit	Rapeseed	Palm Oil	Plam Stearin	Jatropha	UCO	Microalgae	Diesel
Global warming potential	kg CO ₂ eq	2.11	5.92	4.38	1.70	0.25	5.89	1.650
Ionizing radiation potential	kBq Co-60 eq	0.07	0.38	0.05	0.04	0.02	0.62	0.048
Ozone formation, Human health	kg NO _x eq	4.1E-03	1.3E-02	7.0E-03	2.8E-03	5.4E-04	1.2E-02	4.1E-03
Fine particulate matter formation	kg PM _{2.5} eq	3.0E-03	1.0E-02	6.1E-03	1.9E-03	4.2E-04	1.2E-02	3.3E-03
Ozone formation, Terrestrial ecosystems	kg NO _x eq	4.2E-03	1.3E-02	7.5E-03	2.9E-03	5.5E-04	1.2E-02	4.2E-03
Terrestrial acidification	kg SO ₂ eq	7.9E-03	2.3E-02	1.3E-02	4.9E-03	8.7E-04	1.9E-02	7.2E-03
Eutrophication potential	kg P eq	6.1E-04	2.3E-03	3.4E-04	4.3E-04	9.1E-05	2.7E-03	8.8E-04
Terrestrial ecotoxicity potential	kg 1,4-DCB	9.02	23.43	3.70	5.70	0.71	10.67	3.427
Freshwater ecotoxicity potential	kg 1,4-DCB	9.0E-02	2.6E-01	2.5E-02	5.9E-02	7.5E-03	1.5E-01	0.020
Marine ecotoxicity potential	kg 1,4-DCB	1.2E-01	3.5E-01	3.2E-02	7.8E-02	1.0E-02	2.0E-01	0.030
Human carcinogenic toxicity	kg 1,4-DCB	9.2E-02	2.9E-01	3.4E-02	6.0E-02	9.1E-03	2.3E-01	0.050
Human non-carcinogenic toxicity	kg 1,4-DCB	1.93	6.29	2.35	1.23	0.19	4.28	0.820
Fossil resource scarcity	kg oil eq	0.81	1.64	0.33	0.65	0.15	1.68	1.530
Water consumption	m ³	3.1E-02	2.9E+01	5.7E-02	8.7E-02	1.6E-03	2.7E-01	0.011

Similarly, the environmental comparison of biodiesel production pathways (Table 4.43) reveals significant variation in impact intensities across different feedstocks, primarily governed by cultivation inputs and process energy requirements. Palm oil biodiesel exhibits the highest environmental burden, with a global warming potential of 5.92 kg CO₂ eq, along with substantial ecotoxicity and extremely high water consumption, indicating intensive resource use. Microalgae-based biodiesel also shows elevated impacts due to energy- and nutrient-intensive processing. In contrast, used cooking oil biodiesel demonstrates the lowest impacts across most categories, including GWP (0.25 kg CO₂ eq) and fossil resource scarcity (0.15 kg oil eq),

highlighting the advantages of waste-derived feedstocks. Jatropha-based biodiesel presents moderate impacts (1.70 kg CO₂ eq), while rapeseed shows comparatively higher burdens due to agricultural inputs, particularly in ecotoxicity (9.02 kg 1,4-DCB eq). Compared with conventional diesel, biodiesel impacts vary widely depending on the feedstock. UCO shows consistently lower impacts, jatropha is comparable, while rapeseed, palm oil, and microalgae exhibit higher impacts, particularly in ecotoxicity and resource use. Overall, the results emphasize the superior environmental performance of waste-based and non-edible feedstocks compared to conventional and resource-intensive pathways.

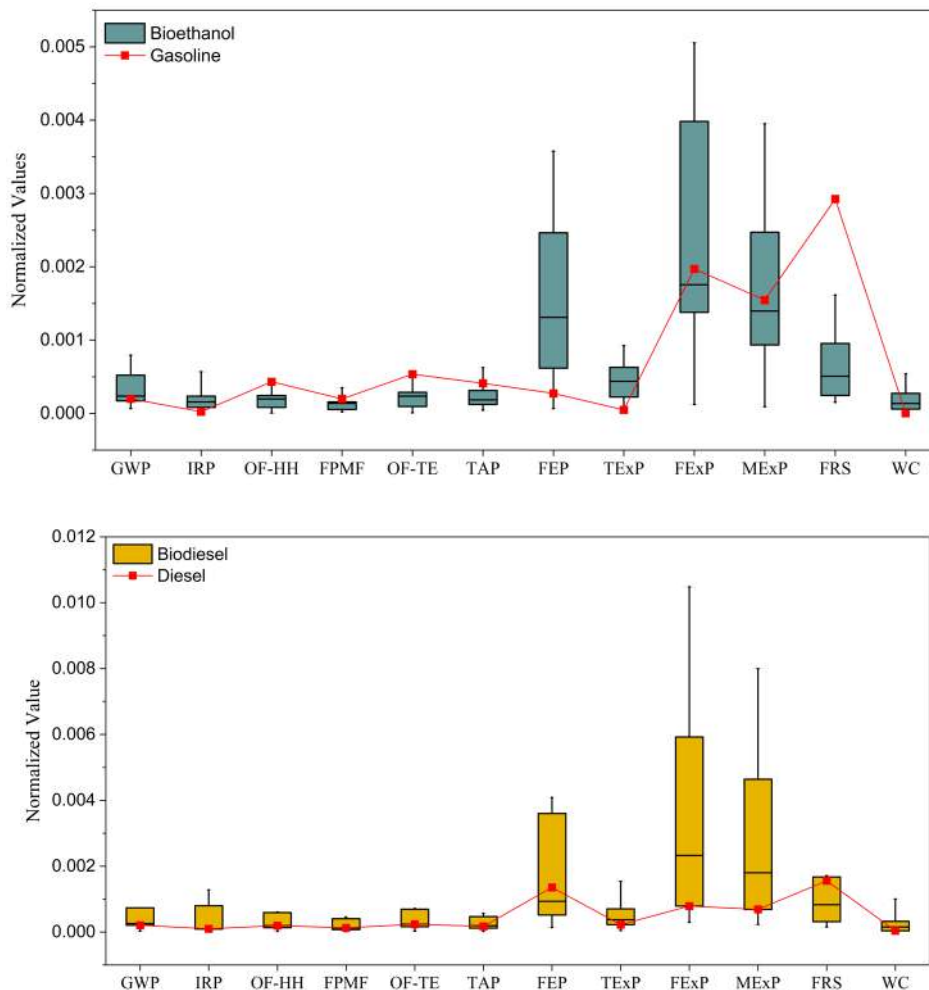


Figure 4.45 Normalized LCA impact scores for bioethanol and biodiesel production from different feedstocks

4.5 Normalization

The comparative LCA shows that the environmental performance of biofuels relative to conventional gasoline and diesel is highly pathway-dependent. In terms of climate change, second-generation biofuels achieve meaningful greenhouse gas reductions and generally outperform fossil fuels, while first-generation biofuels show only moderate improvements due to fertilizer use and agricultural emissions. Third-generation biofuels currently have significant environmental impacts, largely driven by energy-intensive cultivation and processing. For air-quality-related categories such as particulate matter formation, ozone formation, and acidification, fossil fuels remain major contributors, but electricity generation, steam use, and fertilizers dominate impacts in biofuel pathways, with second-generation routes again showing the lowest overall burdens. However, a favourable GHG profile alone is not considered sufficient to establish overall environmental preference, as a pathway may perform poorly in other impact categories. Therefore, environmental performance in this study is evaluated using a multi-criteria perspective, considering the combined results across the relevant impact categories. This interpretation is further supported by the normalized LCA results shown in Figure 4.45 for bioethanol and biodiesel, where normalization enables comparison of the relative significance of different impact categories. Thus, pathways showing lower normalized impacts across multiple categories provide a more balanced environmental profile than pathways whose advantage is limited primarily to climate change. However, biofuels perform less favorably than fossil fuels in water consumption and eutrophication, particularly for first-generation pathways that rely on irrigated crops and nutrient-intensive agriculture. Accordingly, the results highlight environmental trade-offs, and no pathway is considered environmentally preferable solely on the basis of its GHG performance.

4.6 Summary

The chapter presents a comprehensive life cycle assessment of bioethanol and biodiesel production pathways in India, integrating environmental impact assessment, energy analysis, and uncertainty quantification across multiple first-, second-, and

third-generation feedstocks. For bioethanol, feedstocks include molasses, grain (broken rice), agricultural residues (rice straw, corn stover, cassava straw), and municipal solid waste, while biodiesel pathways encompass edible oils (rapeseed, palm), non-edible oils (jatropha), waste-derived feedstocks (used cooking oil), and microalgae. The analysis adopts a cradle-to-gate system boundary and a standardized functional unit, employing ReCiPe 2016 and IMPACT World+ methodologies for environmental impacts, along with cumulative energy demand (CED) and life-cycle energy indicators (NER, NEV, Rn, NRnEV), and is supported by a Monte Carlo simulation to ensure robustness.

The results demonstrate that environmental performance is highly feedstock-dependent across both bioethanol and biodiesel systems. In bioethanol production, energy-intensive stages such as pre-treatment, enzymatic hydrolysis, and distillation dominate environmental impacts, with global warming potential ranging between 3.3–3.8 kg CO₂ eq and higher contributions from ecotoxicity categories (up to 7.21 kg 1,4-DCB eq). First-generation bioethanol pathways exhibit moderate impacts but are strongly influenced by electricity and steam consumption, whereas second-generation systems improve waste valorization but increase process complexity. In biodiesel systems, similar trends are observed, where first-generation feedstocks such as rapeseed show higher emissions (~2.14 kg CO₂ eq) due to intensive agricultural inputs, while non-edible and waste-derived feedstocks such as jatropha (~1.53 kg CO₂ eq) and used cooking oil (0.22–0.73 kg CO₂ eq) demonstrate significantly lower environmental burdens. Microalgal biodiesel, although promising, exhibits comparatively higher impacts (up to 3.55 kg CO₂ eq) due to energy-intensive cultivation and processing stages, with electricity, heat, and nutrient inputs identified as major contributors.

Energy analysis reveals that most agricultural residue-based bioethanol systems are energy-positive, with NER values up to 4.19 and NEV values around 32–33 MJ, indicating strong net energy gains, whereas MSW-based bioethanol shows poor performance (NER = 0.48, NEV = −47.39 MJ, NRnEV = −23.63 MJ) despite moderate renewability (Rn = 0.65). In contrast, biodiesel systems derived from waste feedstocks, such as used cooking oil, exhibit superior energy efficiency (NER = 5.49) and lower cumulative energy demand (6.78 MJ/kg) than conventional palm oil biodiesel (18.5 MJ/kg). Across both fuel types, fossil energy use, agricultural inputs (particularly

fertilizers), and electricity consumption emerge as key hotspots influencing overall environmental and energy performance.

Uncertainty analysis using Monte Carlo simulation indicates low to moderate variability across most impact categories, with coefficients of variation generally within 4–10%, confirming high statistical reliability of the model outputs. For instance, particulate matter formation in bioethanol systems shows a mean of 0.00311 kg PM_{2.5} eq with a tightly bounded 95% confidence interval (0.00246–0.00408), while similar robustness is observed in biodiesel systems with uncertainty typically within ~10%. However, higher variability is observed in toxicity and ecotoxicity-related categories, indicating sensitivity to input parameters. The probabilistic distributions follow near-lognormal behavior with well-defined confidence intervals, demonstrating consistent model performance across both systems.

Overall, the results highlight that the sustainability of biofuel production is strongly governed by feedstock selection, process efficiency, and energy integration. Second-generation and waste-derived pathways consistently outperform first-generation systems in terms of environmental and energy metrics, while third-generation systems require further optimization. The integrated LCA–energy–uncertainty framework provides a robust basis for identifying environmental hotspots and supports the development of sustainable, resource-efficient biofuel production strategies aligned with circular economy principles and greenhouse gas mitigation goals.

CHAPTER 5

CONCLUSION, FUTURE SCOPE AND SOCIAL IMPACT

5.1 Conclusion

The study demonstrates that life cycle assessment serves as a rigorous and comprehensive framework for evaluating the environmental sustainability of biofuels in India, systematically capturing impacts across the entire production chain. The findings reveal that the environmental performance of biofuels is highly dependent on feedstock type, conversion technology, and process energy requirements. Although several waste-based and second-generation biofuels show favourable environmental performance compared to some first-generation alternatives, this advantage is not consistent across all impact categories or pathways. Energy-intensive processes, such as electricity and steam generation, emerge as key environmental hotspots that influence overall impacts. While biofuels contribute significantly to greenhouse gas reduction and energy security, certain trade-offs, particularly in water use, eutrophication, and energy performance, remain critical. The following conclusions are drawn from the study:

- The LCA-based evaluation indicates that several second-generation and waste-derived biofuels exhibit lower environmental impacts in selected impact categories compared to first-generation alternatives, largely due to reduced dependence on intensive agricultural inputs. Key environmental hotspots identified include electricity use, steam generation, and pre-treatment processes, which significantly contribute to emissions and resource depletion. The results highlight the critical role of feedstock selection in determining sustainability outcomes. Utilization of waste materials can reduce certain environmental burdens and support resource recovery and waste management; however, these benefits do not necessarily translate into

superior performance across all indicators. For example, the MSW-based bioethanol pathway demonstrates relatively poor energy performance despite its potential circular-economy benefits. Therefore, targeted optimization of these stages is essential to enhance overall environmental performance.

- The comparative assessment shows that biofuels generally offer reduced greenhouse gas emissions relative to fossil fuels, supporting their role in climate change mitigation. However, notable trade-offs are observed, particularly for first-generation biofuels, which exhibit greater impacts on water use, eutrophication, and land use. Similarly, waste-derived pathways may provide advantages in resource recovery while requiring substantial energy inputs. Therefore, second-generation and waste-derived biofuels should not be considered universally environmentally preferable; their performance is pathway- and impact-category-specific. The findings underline the importance of adopting a multi-criteria evaluation framework. This ensures that reductions in carbon emissions or benefits from waste utilization do not result in adverse environmental consequences elsewhere.
- The life cycle energy analysis indicates that several biofuel pathways, especially those based on agricultural residues and waste feedstocks, are energy-positive. This reflects their ability to generate more energy than is consumed during production, enhancing their sustainability potential. Energy performance varies with feedstock type and conversion technology. Improved process efficiency and optimized operational conditions further strengthen the energy balance. Consequently, enhancing energy efficiency remains a key factor in maximizing the viability of biofuel systems.
- The sensitivity analysis reveals that environmental outcomes are highly influenced by critical input parameters such as electricity source, feedstock characteristics, and process efficiency. Variations in these parameters can lead to significant changes in LCA results, indicating inherent system uncertainties. The findings emphasize the importance of accurate, region-specific data for reliable assessments. Additionally, the analysis demonstrates that shifts toward renewable energy inputs and improved process efficiencies can substantially reduce environmental impacts. Thus,

sensitivity analysis plays a crucial role in identifying key leverage points for system optimization and informed policy decisions.

- The combined assessment of environmental impacts, energy performance, and sensitivity parameters highlights the need for an integrated approach to biofuel sustainability. This ensures balanced decision-making across multiple environmental indicators.
- The outcomes collectively emphasize that both feedstock selection and process technology significantly influence overall system performance. Feedstock selection largely determines the baseline environmental profile through differences in resource use, agricultural inputs, and emissions, while process optimization can further reduce impacts through improved conversion efficiency, energy integration, and resource utilization. Therefore, the results indicate that feedstock selection and process optimization are complementary rather than competing priorities, and their relative importance is pathway- and impact-category-dependent. Optimizing both factors is critical for achieving environmentally and energetically efficient biofuel systems.
- The findings provide a scientific basis for policy formulation by identifying key drivers of sustainability and system variability. This supports the development of targeted strategies for large-scale and sustainable biofuel deployment in India.

The results emphasize that sustainable biofuel development in India requires careful feedstock selection, process optimization, and integration of cleaner energy sources. Overall, the study establishes that biofuels can be a viable component of India's sustainable energy transition when aligned with efficient technologies and environmentally responsible practices.

5.2 Recommendations

Based on the findings of the present study, the following recommendations are made to enhance the environmental sustainability and energy performance of biofuel production systems in India. These recommendations may support researchers, policymakers, and industry stakeholders in developing sustainable, efficient biofuel strategies aligned with national energy and environmental goals.

- Greater emphasis should be placed on second-generation and waste-derived biofuels, as these pathways can demonstrate lower environmental impacts in several impact categories, although their performance is pathway-specific. Agricultural residues and non-edible feedstocks should therefore be considered where sustainable feedstock availability, collection infrastructure, technological feasibility, and competing uses permit. Large-scale deployment should be region-specific and based on reliable assessment of feedstock availability and supply-chain requirements rather than assuming that a single pathway is suitable nationwide.
- Biofuel production systems should integrate cleaner and renewable energy sources such as solar and wind energy into electricity and steam generation processes. Since energy-intensive stages have been identified as major environmental hotspots, replacing fossil-based utilities with renewable alternatives can significantly reduce greenhouse gas emissions and improve overall life-cycle sustainability. The results also indicate that the assumed electricity mix can influence the environmental performance and relative ranking of biofuel pathways, particularly for electricity-intensive processes. Therefore, future deployment assessments should consider regional and future electricity-mix scenarios when evaluating pathway performance.
- Future biofuel assessments in India should adopt a comprehensive cradle-to-grave LCA framework instead of limiting the analysis to cradle-to-gate boundaries. Including transportation, distribution, combustion emissions, land-use change, biodiversity impacts, and end-of-life stages would provide a more realistic and policy-relevant evaluation of environmental sustainability.
- Region-specific databases and primary industrial data collection mechanisms should be strengthened to improve the reliability and accuracy of LCA and life cycle energy analysis results. The study's sensitivity analysis showed that environmental outcomes are highly dependent on parameters such as the electricity mix, feedstock properties, and process efficiency, highlighting the need for accurate local data.
- Biofuel pathways should be promoted according to their demonstrated feasibility and scalability, considering feedstock availability, conversion efficiency, infrastructure requirements, environmental performance, and local energy

conditions. Pilot- and demonstration-scale projects can help address supply-chain and technological constraints before large-scale implementation.

- Policymakers and researchers should promote integrated biorefinery and circular economy approaches for biofuel production. Combining waste valorization, resource recovery, and energy-efficient technologies can simultaneously reduce environmental burdens, improve energy efficiency, generate rural employment, and support India's Sustainable Development Goals (SDGs) related to clean energy, climate action, and responsible production. Such approaches should be implemented selectively where adequate feedstock, infrastructure, and technological capacity are available to ensure long-term feasibility and scalability.

5.3 Future scope

The present study provides a strong foundation for further research, but several areas require deeper investigation to enhance the robustness and applicability of findings. Expanding the system boundary from cradle-to-gate to cradle-to-grave would allow for a more comprehensive assessment by including distribution, end-use, and combustion emissions. Future studies should incorporate land-use change, biodiversity impacts, and region-specific environmental conditions, which are particularly relevant in the Indian context. There is also a need for improved access to primary industrial data to reduce uncertainty and increase the accuracy of LCA outcomes. Advancements in third-generation biofuels, especially microalgae, should focus on reducing energy intensity and improving technological feasibility. Integrating renewable energy sources, such as solar and wind, into production systems can significantly reduce the environmental impacts of electricity and heat generation. Additionally, future research should explore integrated biorefinery models, circular economy approaches, and combined techno-economic and environmental assessments. Furthermore, the LCA results can be integrated with energy, economic, and social indicators using multi-criteria decision analysis to identify region-specific biofuel pathways. Such assessments should consider spatial variability, biomass supply-chain constraints, competing uses of biomass, and social and economic life-cycle impacts. This integrated approach would enable a more holistic sustainability evaluation and support region-specific decision-making for feasible and scalable

biofuel development. Policy-driven scenario analysis aligned with national biofuel programs will further support sustainable decision-making and large-scale implementation.

5.4 Social impact

The findings of this study indicate that biofuels can generate substantial social benefits in India, particularly when derived from waste and non-edible feedstocks. The use of agricultural residues and municipal waste contributes to improved waste management, reduced open burning, and mitigation of environmental pollution, thereby supporting cleaner, healthier communities. Biofuels also enhance national energy security by reducing dependence on imported fossil fuels and diversifying the energy mix. From a socio-economic perspective, the biofuel sector has the potential to create employment opportunities across rural and semi-urban regions, supporting farmers and promoting inclusive economic growth. However, the study also highlights challenges, such as the food-versus-fuel debate and pressures on land and water resources, particularly for first-generation biofuels. These concerns reinforce the need to prioritize sustainable feedstocks and adopt responsible production practices.

The study aligns strongly with several United Nations SDGs, including SDG 7 (Affordable and Clean Energy) through the promotion of renewable energy sources, SDG 12 (Responsible Consumption and Production) by encouraging waste-to-energy pathways and circular economy practices, and SDG 13 (Climate Action) through the reduction of greenhouse gas emissions, as shown in Figure 5.1. Additionally, it contributes to SDG 8 (Decent Work and Economic Growth) by generating employment opportunities and to SDG 2 (Zero Hunger) by emphasizing the importance of avoiding conflicts over food-based feedstocks. Overall, the research highlights that sustainable biofuel development can play a crucial role in achieving environmental sustainability while supporting broader socio-economic development goals in India.

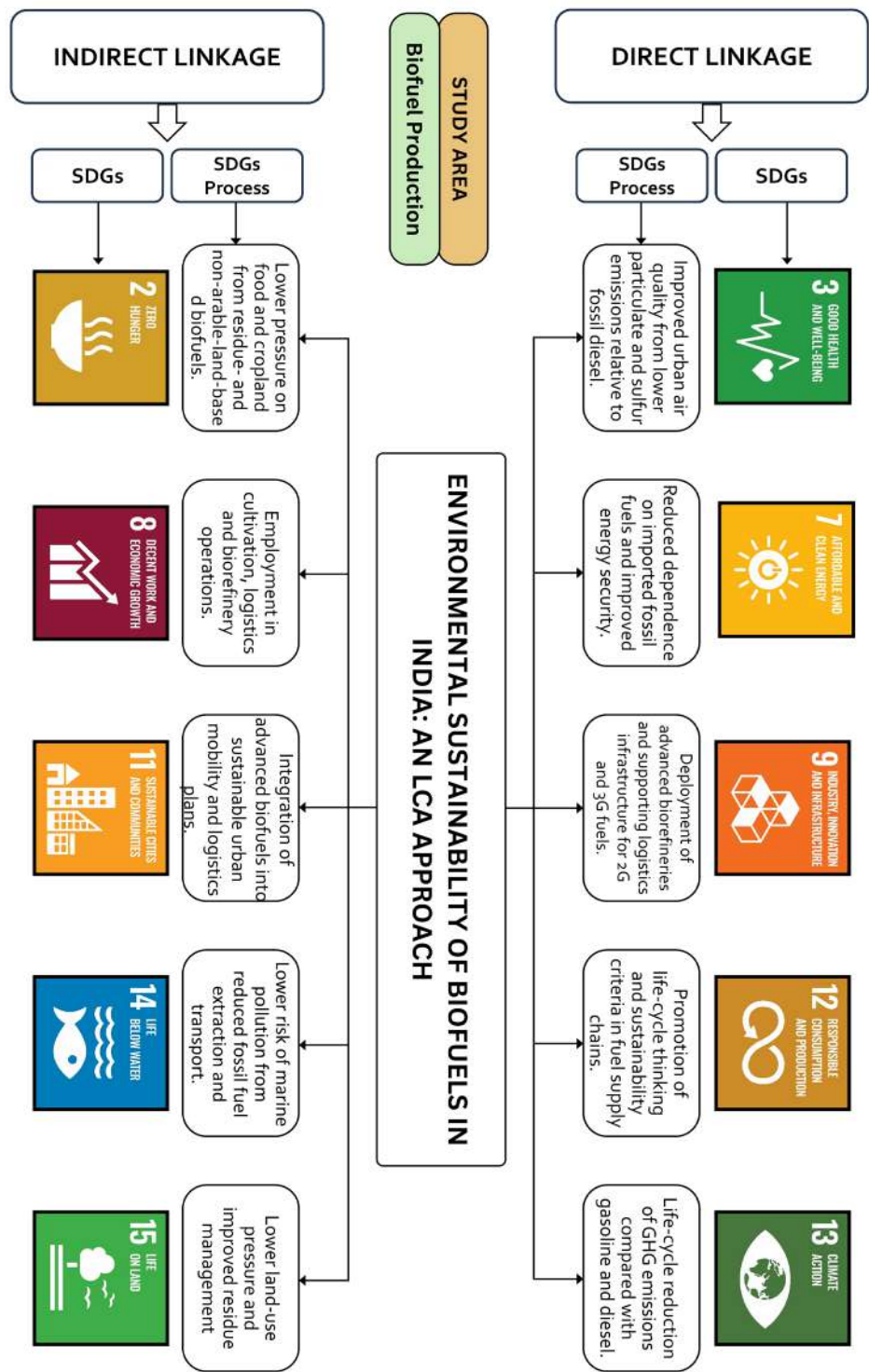


Figure 5.1 UN SDGs Alignment

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PUBLISHED PAPERS



Advancing Uncertainty Decomposition in Environmental Assessment: The LMDI Method in Life Cycle Analysis of Bioethanol

Kulvendra Patel¹ and S. K. Singh²

Abstract: Understanding the environmental impact of products such as bioethanol requires comprehensive tools, and life cycle assessment (LCA) plays a central role in this. However, LCAs often rely on numerous assumptions and data sources, which introduce uncertainties that complicate decision making. This study presents a practical way to break down and better understand these uncertainties using a combination of Monte Carlo simulation (MCS) and the logarithmic mean Divisia index (LMDI) method. Focusing on bioethanol production from broken rice in India, the research applied a cradle-to-gate LCA using the ReCiPe 2016 method across seven key environmental impact categories. By running 1,000 MCS iterations, the study simulated the range of possible outcomes based on data variability. The LMDI method was then used to trace how much each input—such as electricity, steam, or additives—contributed to the overall uncertainty in the results. The findings show that electricity and polydimethylsiloxane are the biggest sources of uncertainty, although the latter contributes little to the actual environmental impact. This highlights a critical insight: while insignificant, some minor ingredients can introduce large uncertainty levels due to poor data quality or lack of reliable emission factors. Overall, this approach makes it easier to see where improvements in data or methods can significantly boost the confidence in LCA results. The method supports smarter environmental choices, more reliable assessments, and better-informed sustainability planning by making the uncertainty more transparent and easier to interpret. **DOI: 10.1061/JOEEDU.EEENG-8423.** © 2026 American Society of Civil Engineers.

Author keywords: Bioethanol production; Life cycle assessment (LCA); Logarithmic mean Divisia index (LMDI); Uncertainty analysis; Variability decomposition.

Introduction

Environmental impacts from products and processes are often complex and occur across multiple life cycle stages, making it difficult to assess their true sustainability. As concerns about climate change, resource depletion, and pollution increase, there is a need for comprehensive tools that can evaluate these impacts holistically. Life cycle assessment (LCA) is an environmental assessment tool for evaluation of the impacts that a product or process has on the environment over the entire period of its life—from raw material extraction and production to distribution and use, reuse, and maintenance of the product, and on to its eventual recycling or disposal as waste at the end of its useful life (ISO 2006a). Due to the comprehensive nature of LCA evaluation, it inherently relies on a wide range of data and assumptions across different life cycle stages. LCA involves different data sources, several assumptions, and impact calculations, each of which can introduce variability and potential error into the results. These uncertainties come from factors such as input data variability, emission factors and resource use, gaps or approximations in life cycle inventory (LCI) data, methodological decisions such as system boundaries, allocation rules, and

temporal or geographic differences in processes. LCA results may present a misleading sense of precision or confidence without acknowledging and quantifying these uncertainties. Understanding uncertainty in LCA results is crucial for informing and guiding the decisions that use them (Heijungs 2024a; Qin and Suh 2021). Uncertainty has been quantified through various approaches, including sensitivity analysis, probabilistic modeling, and scenario analysis, each aiming to capture the variability and limitations inherent in data, methodological choices, and system boundaries (Clavreul et al. 2012; Igos et al. 2019).

The Monte Carlo simulation (MCS) is one of the most widely used probabilistic methods to determine the variability in LCA (von Brömssen and Røös 2020; Mendoza Beltran et al. 2018; Morales et al. 2021; Patel and Singh 2024a). MCS evaluates uncertainty by running repeated simulations using input values from defined probability distributions. However, detailed statistical data needed to define these distributions are unavailable or incomplete in many real-world cases, especially in environmental assessments. To deal with this, the pedigree matrix offers a practical workaround. Originally introduced by Weidema and Wesnæs (1996) as a data quality indicator scheme and further elaborated by Weidema (1998), the method has since been adopted and expanded in different forms, most notably inecoinvent documentation (Ciroth et al. 2016; Frischknecht et al. 2005; Weidema et al. 2013). A recent comprehensive overview of differing pedigree systems in LCA, including their evolution and applications, is provided by Heijungs (2024a). In LCA practice, the pedigree scores are typically translated into uncertainty values and used to parameterize probability distributions for Monte Carlo simulation. It allows researchers to assign qualitative ratings to each input based on reliability, completeness, and how well the data matches in time, space, and technology.

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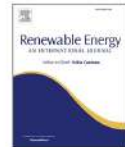
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Clean energy from algae: Tracing the sustainable biodiesel pathway through environmental impact, energy demand, and uncertainty assessment

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ABSTRACT

Rising environmental concerns and reliance on fossil fuels make sustainable energy essential. Microalgae-based biodiesel is a promising option, but its environmental performance requires thorough evaluation. This study presents a comparative life cycle assessment of three harvesting and lipid recovery techniques: BD1 (hexane extraction), BD2 (dynamic cross-flow (DCF) microfiltration), and BD3 (flocculation/sedimentation with DCF), while maintaining a uniform downstream transesterification process across all cases. Using IPCC 2021, ReCiPe 2016, cumulative energy demand (CED), and water footprint, the study identifies clear differences in global warming potential (GWP), energy use, and resource efficiency driven solely by variations in harvesting and lipid recovery. Results show that BD2 has the highest GWP at 9.60 kg CO₂ eq. and CED (130.5 MJ), due to fertilizer use and high electricity consumption throughout the production, and indicating significant fossil energy dependence. In contrast, BD3 had the lowest GWP (3.55 kg CO₂ eq.), highest energy efficiency, and minimal toxicity and water use. BD3 also exhibited lower variability in environmental impacts, confirming its sustainable performance. The study shows that efficient harvesting and lipid recovery reduce environmental impacts and improve energy efficiency, stressing the need for optimal pathways to make biodiesel more sustainable.

Abbreviations

AGTP	Absolute Global Temperature Change Potential
AGWP	Absolute Global Warming Potential
BAU	Business As Usual
CGTP	Cumulative Global Temperature Change Potential
DAF	Dissolved Air Flotation
DCF	Dynamic Cross-Flow
FED	Fossil Energy Demand
FEP	Freshwater Eutrophication Potential
FExp	Freshwater Ecotoxicity Potential
FPMF	Fine Particulate Matter Formation
FRS	Fossil Resource Scarcity
GHG	Greenhouse Gas
GTP	Global Temperature Change Potential
GTP100	Global Temperature Change Potential over 100 years
GTP50	Global Temperature Change Potential over 50 years
GWP	Global Warming Potential
GWP100	Global Warming Potential over 100 years
GWP20	Global Warming Potential over 20 years
GWP500	Global Warming Potential over 500 years
HT-C	Human Carcinogenic Toxicity Potential

(continued on next column)

(continued)

HT-NC	Human Non-Carcinogenic Toxicity Potential
IPCC	Intergovernmental Panel on Climate Change
IRP	Ionizing Radiation Potential
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MCS	Monte Carlo Simulation
MEP	Marine Eutrophication Potential
MExP	Marine Ecotoxicity Potential
MRS	Mineral Resource Scarcity
NMVOC	Non Methane Volatile Organic Compounds
NRnEV	Net Renewable Energy Value
OF-HH	Ozone Formation, Human Health
OF-TE	Ozone Formation, Terrestrial Ecosystems
SOD	Stratospheric Ozone Depletion
TAGs	Triacylglycerols
TAP	Terrestrial Acidification Potential
TExP	Terrestrial Ecotoxicity Potential
WC	Water Consumption
WSI	Water Scarcity Index

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Comprehensive Life Cycle Analysis of Bioethanol from Molasses: Addressing Energy Use and Uncertainty

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Abstract

The growing global demand for cleaner and renewable energy sources has intensified interest in bioethanol production from agro-industrial byproducts such as molasses. This study presents a comprehensive life cycle assessment of bioethanol production from sugarcane molasses to evaluate its environmental sustainability, energy efficiency, and associated uncertainties. The analysis employs the ReCiPe 2016 and cumulative energy demand methods to quantify midpoint and endpoint environmental impacts along with total energy use across the production chain. A gate-to-gate system boundary was adopted, encompassing molasses preparation, fermentation, distillation, and dehydration processes. Results indicate that electricity and steam generation are the dominant contributors to environmental burdens, particularly influencing global warming, fine particulate matter formation, and human toxicity categories. The total energy requirement was found to be 26.98 MJ per kg of ethanol produced, with fossil energy accounting for 93% of this demand. Despite this, the process demonstrated a slightly positive energy balance, reflected by a net energy ratio of 1.04, confirming marginally favorable energy performance. Uncertainty analysis using Monte Carlo simulation revealed stable results with low variability, indicating model robustness. Human non-carcinogenic toxicity and global warming potential were identified as the impact categories contributing most significantly to the overall uncertainty in the results. Overall, the findings suggest that molasses-based bioethanol is a viable renewable fuel option with potential to reduce fossil energy dependence, provided that efficiency improvements in electricity and steam usage are implemented. The study underscores the importance of integrating energy and uncertainty analyses for more reliable environmental sustainability assessments of biofuel systems.

Keywords Biofuel · Environmental Sustainability · Life Cycle Assessment · Renewable Energy · Sustainability Analysis

Introduction

The rapid global increase in energy demand poses a pressing challenge, as more than 80% of primary energy needs are currently met by non-renewable fossil resources, notably coal, oil, and natural gas [1–3]. Nations such as India face acute energy security concerns, grappling with rising crude oil imports and associated environmental impacts, particularly from the transportation sector, which accounts for a significant fraction of total energy consumption [1]. This

scenario exacerbates greenhouse gas (GHG) emissions and underlines the imperative to identify alternatives that reduce reliance on conventional fossil fuels. Addressing this multifaceted problem, the promotion of renewable energy—most notably, biofuels—has been widely recognized as a pragmatic pathway to achieve both energy independence and lower carbon emissions. Biofuels, unlike fossil fuels, are derived from biomass and can play a pivotal role in decarbonizing transportation sectors [4]. Ethanol, in particular, stands out for its compatibility with existing fuel infrastructures and for its potential to reduce net CO₂ emissions when used as a gasoline blendstock [5, 6]. Among available feedstocks, molasses—a byproduct of sugarcane processing—is especially attractive in regions with strong sugar industries, as it leverages existing supply chains without directly competing with food crops.

Bioethanol production from molasses provides an effective pathway for valorizing a sugar-industry by-product

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Environmental sustainability, energy efficiency and uncertainty analysis of agricultural residue-based bioethanol production: A comprehensive life cycle assessment study

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ABSTRACT

Bioethanol produced from agro-residue provides a sustainable alternative to fossil fuels, mitigating pollution, reducing waste, and promoting a circular economy. However, challenges arise in sustainable sourcing, resource conflicts, water quality concerns, and managing environmental footprints to maximize agro-residue-based bioethanol benefits. The environmental impacts, net energy ratio (NER), net energy value, water footprint, and uncertainties associated with bioethanol production from agro-residues are analyzed in this study. The analysis followed a cradle-to-gate approach using 1 L of bioethanol produced as a functional unit (FU), allowing for a direct comparison of the environmental performance of the different feedstocks. The result shows that rice straw-based bioethanol exhibited higher environmental impacts, particularly in terms of ecotoxicity, ionizing radiation, human toxicity, and ozone layer depletion, except for greenhouse gas emission, which is lowest for corn stover (0.37 kg CO₂ eq. per FU) and highest for cassava straw (1.1 kg CO₂ eq. per FU). Furthermore, the Cumulative Energy Demand analysis highlighted a significant reliance on fossil fuels from agricultural biomass throughout the bioethanol production process. The energy balance analysis shows that the agricultural residues are feasible for bioethanol production with NER of 1.20, 3.10, and 3.28 for rice straw, corn stover, and cassava straw, respectively. To enhance the accuracy and reliability of the LCA results, Monte Carlo simulation was employed to account for uncertainty and variability in the data. This methodology provides a better understanding of the impacts of bioethanol production, with a focus on sustainability and advancements in reducing our reliance on fossil fuels.

1. Introduction

In a context where the most pressing concerns for many nations center on issues like climate change and energy security, there has been a significant upsurge in renewable energy production. The primary objective behind this surge is to diminish our reliance on fossil fuels. Bioenergy, which possesses certain advantages such as requiring minimal additional point-of-use infrastructure and not being immediately contingent on weather conditions, emerges as a distinctive renewable energy source [1]. Biofuels derived from lignocellulosic biomass hold the potential to furnish a substantial and sustainable reservoir of clean, low-carbon, and dependable energy [2,3].

Cellulosic biomass, such as cassava straw, corn straw, and various agricultural and forestry residues, does not necessitate additional land and does not impede grain production. It stands as a substantial,

promising, and abundant resource for bioethanol production [4,5]. The utilization of agricultural waste (agro-waste) to produce biofuels is extensively advocated due to its potential for effective waste management and energy advantages. Significant quantities of agro-waste are generated through agricultural activities, especially in developing nations [6,7]. Worldwide, 140 billion metric tons of agricultural waste are generated. India, being a predominantly rural nation, produces approximately 620 million tons of agricultural waste annually, with just 25–30 % being utilized for animal feed and energy production [8]. The prevalent method of managing agricultural residue in India involves burning it in the fields to prepare it for the subsequent crop [9,10]. Utilizing agricultural residues for ethanol production in India could thus yield significant benefits, enhancing energy security, fulfilling rising demands for fossil energy, mitigating environmental pollution, and improving rural economies [11]. The primary components of

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Sustainable biodiesel from used cooking oil: a comparative life cycle, energy, and uncertainty analysis

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Abstract

This study focuses on analyzing the environmental impacts of biodiesel production from Used Cooking Oil (UCO) as a waste management strategy. Using a cradle-to-gate life cycle assessment approach, it compares UCO-derived biodiesel with the first-generation biofuel derived from palm oil. The research addresses the pressing need for sustainable energy alternatives that reduce environmental impacts while promoting waste utilization. The study analyzes multiple environmental impact categories, cumulative energy demand (CED), and includes uncertainty analysis to address variability in data and assumptions across the life cycle. Regression and scatter plot analyses are used to identify correlations between inventory inputs and environmental effects. The study shows that the total carbon and environmental footprint per kg of biodiesel produced from UCO was 0.22 kg CO₂ eq. and 0.11 mPt, compared to 9.87 kg CO₂ eq. and 1.34 mPt for palm oil biodiesel. Electricity, methanol, and steam-derived heat are the primary factors influencing this emission. The total CED for UCO biodiesel was 6.78 MJ, compared to that of palm oil at 18.5 MJ. The net energy ratio of UCO biodiesel is 5.49, outperforming palm oil biodiesel (2.01) and conventional diesel (0.83). The study also shows significant reduction in impacts when including avoided products into the system boundary. The uncertainty of the study is within 10%, which confirms the reliability and robustness of the impact results for UCO biodiesel. This study provides valuable insights for decision-makers in the biofuel industry, promoting waste-to-energy solutions to reduce environmental footprints and support the transition to greener energy systems.

Keywords Cumulative energy demand · Environmental impact assessment · Life cycle assessment · Net energy ratio · Sustainability analysis

1 Introduction

In light of escalating energy requirements, the depletion of fossil fuels and the adverse environmental consequences linked to their utilization in transportation underscores the imperative for the widespread introduction of alternative, environmentally sustainable

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Sustainable waste management: a comprehensive life cycle assessment of bioethanol production from agricultural and municipal waste

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Abstract

Biofuels have emerged as a promising and eco-friendly alternative to conventional fossil fuels. Biofuel sourced from rice straw (RS) and municipal solid waste (MSW), which are abundant residues from agricultural and municipal activities, present a sustainable solution to address waste management challenges. Utilizing life cycle assessment, this study quantifies the environmental advantages by assessing the reduction in greenhouse gas emissions, energy consumption, and other environmental impacts linked with employing these waste materials for biofuel production. Employing a cradle-to-gate approach as the system boundary for bioethanol production, with the functional unit set as per liter of bioethanol produced, the analysis reveals that the global warming potential (GWP) for ethanol from MSW is 4.4 kg CO₂ eq., whereas for RS, it is 2.1 kg CO₂ eq. per functional unit. The total environmental impacts were primarily due to enzymatic hydrolysis and electricity consumption for ethanol production from MSW and RS. Despite advancements, fossil fuel consumption remains a potential energy source for biofuel production. The cumulative energy demand stands at 18.6 MJ for RS and 71.5 MJ for MSW per functional unit, underscoring the potential to significantly reduce overall impacts by transitioning to a more environmentally sustainable energy source. The uncertainty analysis acknowledges the inherent uncertainties associated with data, assumptions, and methodologies, highlighting the crucial need for ongoing research and updates to enhance the accuracy of future assessments. This analysis forms the foundation for well-informed decision-making, providing valuable insights for policymakers, industry stakeholders, and consumers.

Keywords Biofuel · Cumulative energy demand · Environmental impact assessment · Greenhouse gas reduction · Municipal solid waste · Sustainable energy · Uncertainty analysis

Introduction

Over the recent decades, a noticeable shift towards biofuel production has occurred. This shift has been primarily motivated by the urgent need to curb carbon emissions, address climate change, and mitigate the depletion of fossil fuel reserves. The development of biofuels as a feasible substitute for traditional fossil fuels led to substantial debates over how well they can achieve environmental sustainability goals (Fargione et al. 2008; Searchinger et al. 2008). The evolution of biofuels can be categorized into three distinct generations.

First-generation biofuels are primarily derived from food crops through fermentation (UN Report 2007). However, this approach faced significant criticism, particularly regarding using food crops for fuel production when food shortages were prevalent, leading to societal discontent (Ahlgren and Di-Lucia 2014). In response to these challenges, second-generation biofuels were developed, aiming to overcome the limitations of the first generation. These biofuels were produced from non-food organic sources such as crop residues, wood, municipal solid waste (MSW), and other biomass materials, thus mitigating the primary drawback (Liska et al. 2009). The third generation of biofuels explores novel biomass sources for biofuel synthesis, including unique energy crops or species like algae (Chisti 2007). Among renewable energy sources, bioenergy, mainly derived from lignocellulosic biomass such as wheat straw, corn stover, rice straw, and MSW, has garnered significant attention for its potential to reduce global greenhouse gas (GHG) emissions (Jiang

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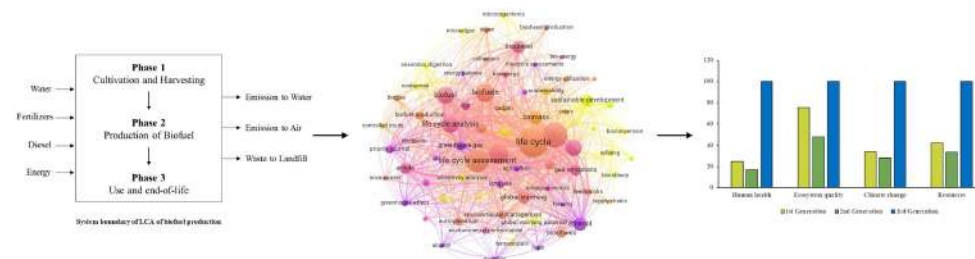
Environmental sustainability analysis of biofuels: a critical review of LCA studies

Kulvendra Patel¹ · S. K. Singh¹Received: 26 April 2023 / Accepted: 10 August 2023
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Abstract

The use of fossil fuels in the transportation sector has significantly increased the greenhouse gas (GHG) emissions, leading to concerns about their environmental impact. As a result, biofuels have been promoted as a promising alternative to fossil fuels to mitigate GHG emissions. However, while biofuels are considered a low-carbon solution, there are concerns that its widespread use could have unforeseen environmental effects. This study analyzes the intricacies involved in biofuel's life cycle assessment (LCA). Fifty-three peer-reviewed studies were examined, covering a broad range of biofuels produced from over 25 different feedstocks. The literature review focused mainly on research published from 2012 to 2022 to avoid outdated information. The study found that second-generation biofuels have a greater potential for reducing GHG emissions than first-generation biofuels. However, the GHG emissions from third-generation biofuels are higher than those from conventional fuel, ranging from 10.2 to 1910 g CO₂ eq. / MJ. The net energy ratio for biofuels ranges from 1.23 to 12.49 for first-generation, 0.003 to 15.04 for second-generation, and 3 to 18.5 for third-generation biofuels. The analysis also shows that the water footprint of biofuels is 50–240 times greater than fossil fuels. The study also examines the critical methodological aspects and sources of uncertainty in the LCA of biofuels and suggests solutions to address these problems. Overall, the study highlights the importance of taking a comprehensive approach when assessing the environmental impact of biofuels and the need for continued research to develop sustainable and effective biofuels.

Graphical abstract

**Keywords** Biofuels · Environmental impact assessment · Global warming potential · Life cycle assessment · Sustainability

Introduction

Energy production and use have been related to urbanization, modernization, and industrialization in various economic, scientific, and social fields. The depletion of non-renewable fuels and the subsequent rise in GHG emissions has become

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ORIGINAL RESEARCH

Sustainability

ENVIRONMENTAL PROGRESS
& SUSTAINABLE ENERGY

Environmental impacts of NMC811 and LFP lithium-ion batteries in India's electric vehicle sector

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Abstract

Electric vehicles are increasingly adopted in India to reduce transport-related greenhouse gas emissions. The study evaluates the environmental impacts of two widely used lithium-ion battery chemistries—Nickel Manganese Cobalt 8:1:1 (NMC811) and Lithium Ferro Phosphate (LFP)—using life cycle assessment under present Indian conditions and a projected 2040 scenario. Inventory data were obtained from established scientific literature and assessed across 10 environmental impact categories using the ReCiPe 2016 method. The comparative LCA showed that the Li-ion battery with an LFP cathode has the lowest environmental impact compared to NMC811. The global warming potential of NMC811 is 9.31 kg CO₂-eq, nearly twice that of LFP (4.44 kg CO₂-eq per kg). NMC811 also exhibits higher impacts in fossil fuel potential, water consumption, marine eutrophication, ozone depletion, human toxicity, and ionizing radiation. LFP performs worse only in terrestrial acidification potential, mainly due to mining and material production. The 2040 scenario indicates increased impacts for both chemistries across all categories, with impacts rising by about 60–75% for LFP and nearly doubling for NMC811, driven by higher electricity demand and fossil fuel dependence. The impact can be decreased by increasing the share of renewables in the Indian energy grid.

KEYWORDS

Electric Vehicles, Life Cycle Assessment, Lithium Ferro Phosphate, Lithium-Ion Batteries, Sustainability

1 | INTRODUCTION

India is the second most populous country in the world, with a population of over 1.3 billion people.¹ The transport sector is a significant contributor to the country's economic growth and development, providing a crucial link between production and consumption. According to the Ministry of Road Transport and Highways, the total number of registered vehicles in India has grown rapidly in recent years, from 56.5 million in 2006 to 300 million in 2020. Out of these, around 82% are two-wheelers, 14% are cars, and the remaining 4% are buses, trucks, and other commercial vehicles.² With such an expansive

transport sector, ranking 5th in terms of the total number of registered passenger cars³ in the world, it is also one of the largest contributors to overall environmental degradation, including deforestation, land use change, and climate change. The construction of roads and highways has led to deforestation and habitat destruction, while the use of fossil fuels in vehicles contributes to GHG emissions, which are a major cause of climate change. According to a report by the Ministry of Environment, Forest, and Climate Change, the transport sector is responsible for around 18% of India's total GHG emissions.⁴

In recent years, EVs have emerged as potential solutions to mitigate the negative impact of traditional fossil-fuel-based vehicles. The



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ORIGINAL RESEARCH

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From waste to resource: A life cycle assessment of biochar from agricultural residue

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Abstract

In recent years, biochar has emerged as a versatile product. Producing biochar from agricultural residue is an environmentally friendly alternative to in-situ burning, reducing the requirement for chemical fertilizers. This study presents a comprehensive assessment of the environmental impact of biochar production. Four feedstocks are compared – rice straw, palm shell, corn stover, and mixed crop residue. The cradle-to-gate system boundary comprises all stages of biochar production – feedstock acquisition, transport and pre-treatment, and biochar production. Results show that the main hotspots are emissions and electricity consumption during production. The palm shell had the highest impact on human health (4.889 kg PM_{2.5} eq) and ecosystem quality due to high terrestrial and aquatic acidification potential (159.600 kg SO₂ eq). Mixed crop residue had the greatest global warming potential (281.884 kg CO₂ eq) and resource consumption. Corn stover and rice straw had moderate impacts, with corn stover contributing significantly to ecotoxicity (2.2E+04 kg TEG water) and rice straw impacting respiratory inorganics (3.545 kg PM_{2.5} eq), and causes severe depletion of resources, consuming 4339.672 MJ of non-renewable energy. These findings emphasize the importance of selecting low-impact feedstocks for biochar production. While corn stover has high impacts in midpoint categories like carcinogens, non-carcinogens, ionizing radiation, aquatic and terrestrial toxicity, and eutrophication, it has the lowest GWP. Rice straw has the lowest impact on human health and resources. Finally, uncertainty analysis using Monte Carlo Simulation shows that the coefficient of variation for impact categories is within ±10%, indicating that the results are reliable.

KEYWORDS

agricultural residue, biochar, life cycle assessment, sustainability, uncertainty analysis

1 | INTRODUCTION

The global population has grown from 3.7 billion in 1970 to 8.1 billion in 2021.¹ It is projected to rise to 9 billion by 2050 and 11 billion by 2100.^{2,3} This fast-growing population is resulting in an ever-increasing demand for food products worldwide. Thus, the world over, there is a rise in crop production, livestock farming, and other agricultural activities to deal with the severe challenge of present and future food

security.^{4,5} Also, these activities result in millions of tons of waste generation in the form of agricultural residues every year (approximately 1 billion ton yearly).^{3,6–8} Conventionally, crop residues were utilized for animal feed, soil mulching, fuel, thatching roofs, and manufacturing matchsticks and paper, but massive waste generation in the present scenario has resulted in their inadequate management.^{6,9,10} Studies have shown crop residues are often abandoned in fields,¹¹ emitting harmful gases, smog, and pollutants like particulate



Biological wastewater treatment: a comprehensive sustainability analysis using life cycle assessment

Ritesh Kumar · Kulvendra Patel · S. K. Singh

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Abstract The research conducts a life cycle assessment (LCA) on wastewater treatment (WWT) methods—membrane bioreactor (MBR), soil biotechnology (SBT), and bio-electrochemical constructed wetlands (BCW)—in comparison with the conventional activated sludge process (ASP). Employing SimaPro v9.5 with a cradle-to-gate system boundary, the analysis utilizes the IMPACT 2002+ method, employing per cubic meter of treated wastewater as the functional unit. The analysis shows that SBT exhibits the lowest environmental impacts among the considered WWT methods. The global warming potential was 0.0996 kg CO₂ eq. for SBT, 1.33 kg CO₂ eq. for MBR, 0.131 kg CO₂ eq. for BCW, and 0.544 kg CO₂ eq. for ASP. BCW demonstrates a 75.91% decrease, while MBR exhibits a 144.48% increase compared to ASP. Notably, electricity consumption emerges as the primary contributor to environmental impact in MBR and ASP. The resource impact category varies with a 138.15% increase in MBR and an 83.41% decrease in SBT compared to ASP. Additionally, the research indicates that the high human health impact observed in MBR results mainly from increased carcinogens (0.00176 kg C₂H₃Cl eq.), non-carcinogens (0.01 kg C₂H₃Cl eq.), and ionizing radiation (3.34 Bq C-14 eq.). The findings

underscore the importance of considering treatment efficiency and broader environmental implications in selecting WWT methods. As the world emphasizes sustainability, such LCA studies provide valuable insights for making informed decisions in wastewater management.

Keywords Environmental impact assessment · Global warming potential · Life cycle assessment · Sustainability · Wastewater treatment

Introduction

Water is an essential substance among other renewable resources that cannot be replenished. Water plays an important role in food production, economic development, and sustaining life itself. Purification of water is a difficult task, and it is costly to transport (Mehta, 2012). Rapid urbanization, growth in population, and requirements for increasing economic activities are the primary reasons for increased water demand (McDonald et al., 2014). Concern over releasing partially/untreated municipal and/or industrial wastewater into the environment is growing in developed and developing nations. Several strategies were considered to address this issue, and creating wastewater treatment systems (WWTS) has proven to be one of the most successful (Lutterbeck et al., 2017). Singh et al. (2017) estimated the

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BOOK CHAPTERS

Energy and Environmental Life Cycle Analysis of Biodiesel Production from Palm Stearin



Kulvendra Patel and S. K. Singh

Abstract With the increasing global demand for sustainable energy, biodiesel is becoming a crucial alternative to fossil fuels. However, not all biodiesel feedstocks have the same environmental and energy impacts, making it essential to identify the most sustainable options. This study uses life cycle assessment (LCA) using the IMPACT World + (midpoint and endpoint) method within a cradle-to-gate system boundary to compare the environmental and energy impacts of producing biodiesel from palm stearin and compared with the advanced biodiesel produced from microalgae. The findings reveal that palm stearin generally has a lower environmental footprint, especially in terms of human health and ecosystem quality, with reduced impacts in areas like freshwater ecotoxicity and particulate matter formation. On the other hand, while microalgae draws from a broader range of renewable energy sources, they consume more energy overall, particularly from nonrenewable sources. This study highlights the value of LCA in providing a detailed understanding of the environmental impacts of biodiesel production, helping stakeholders make informed decisions, and advancing more sustainable energy solutions.

Keywords Biodiesel production · Energy analysis · Life cycle assessment · Microalgae · Sustainability

1 Introduction

The environmental issues caused by the “greenhouse effect” and “global warming” have prompted a quest for alternative energy sources to decrease dependence on petroleum-based fuels [1]. Biofuels have gained attention as a viable solution for reducing reliance on fossil fuels and addressing climate change. Biofuels are produced from renewable organic materials like crops and waste, which can be replenished [2]. This makes them a more sustainable option, with the added benefit

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Chapter 25

Comparative Life Cycle Assessment of Palm Oil-, UCO-, and Microalgae-Based Biodiesel Production



Kulvendra Patel and S. K. Singh

Abstract To move toward a new energy pool with low-carbon emissions, it is necessary to gradually substitute fossil fuels with cleaner sources of energy and biofuels. In this analysis, the environmental life cycle assessment of palm oil (PO) (first generation)-, used cooking oil (UCO) (second generation)-, and microalgae (third generation)-based biodiesel production is compared. The functional unit is per kg of biodiesel produced. The system boundary is from cradle to gate. SimaPro v9.4 is used for the analysis using Ecoinvent v3.6 database. IMPACT 2002+ method is utilized for impact assessment. The research shows that the first-generation biofuel (palm oil) has more greenhouse gas (GHG) emissions than second-generation (UCO) biofuel, 5.35 kg CO₂ eq., and 0.73 kg CO₂ eq., respectively. The third-generation biofuel has the highest GHG emission, 5.47 kg CO₂ eq. However, there was an increase in acidification for the PO biodiesel (20%) compared to microalgae biodiesel. This indicates that the decisions when defining the system boundary and functional units are sensitive to a set of variables.

Keywords Biodiesel · Life cycle assessment · Microalgae · Palm oil · SimaPro · Used cooking oil

25.1 Introduction

The greenhouse effect and global warming have resulted in significant environmental challenges, leading to a quest for alternative energy sources that can reduce our reliance on petroleum-based fuels. To reduce dependence on fossil fuels and mitigate climate change, biofuels are viewed as promising alternative fuels [1]. Compared to fossil fuels, biofuels are considered to be a more sustainable alternative because they are produced from renewable organic sources that can be regrown, such as

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Chapter 7

Environmental Sustainability Assessment of Wastewater Treatment Methods: An LCA Approach



Kulvendra Patel, Mallika Vashist, Rachna Garg, and S. K. Singh

Abstract Sustainability holds profound implications for the field of engineering, particularly in the design and operation of wastewater treatment plants. The life cycle assessment (LCA) approach is suited for evaluating the sustainability of a wastewater treatment plant design. The current study compared several wastewater treatment systems using an LCA methodology. The assessment focuses on two WWT methods: moving bed biofilm reactor (MBBR) and sequential batch reactor (SBR), which was compared with the conventional activated sludge process (ASP). Environmental impacts were analyzed using the CML-IA baseline impact assessment method and SimaPro software using the Ecoinvent database. The analysis shows that the MBBR has the highest environmental impacts compared to SBR and ASP. Electricity consumption emerged as the primary driver of these environmental impacts. The global warming potential for MBBR is recorded at 1.82 kg CO₂ equivalent, marking the highest among the considered treatment methods. In cases where the ASP method might be impractical, the SBR method presents itself as a more sustainable alternative, boasting lower scores across all critical effect areas considered. This study not only sheds light on the environmental hotspots within the WWT process but also aids in assessing potential environmental effects associated with WWTPs. Furthermore, it is important to note that an uncertainty analysis was conducted in this study, enhancing the robustness and reliability of the findings.

Keywords Environmental impacts · Life cycle assessment · SimaPro · Sustainability · Wastewater treatment

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Chapter 6

Mitigating Water Pollution: The Synergy of Phytoremediation and Constructed Wetland Technology



Mallika Vashist, Rachna Garg, Kulvendra Patel, and S. K. Singh

Abstract The confluence of water pollution and the diminishing water supply significantly strain the environment. This water quality issue is exacerbated by rapid urbanization, intensified agricultural practices, and the unregulated discharge of geothermal water, which contribute to the escalating release of wastewater into the environment. The increasing levels of wastewater significantly threaten the environment and human health. Considering the increasing demand for water in urban regions and the growing environmental and health concerns associated with wastewater generation, developing effective wastewater treatment strategies has become imperative. Numerous techniques are available for wastewater treatment, including adsorption, bioremediation, filtration, coagulation, and phytoremediation. Among these approaches, phytoremediation is a nature-based, feasible, easy-to-use, and efficient approach. It leverages the capabilities of macrophytes to remove pollutants from the water by absorbing, sequestering, and degrading pollutants, thus substantially mitigating the environmental impact of wastewater. Moreover, no sludge production in phytoremediation enhances its sustainability with respect to other approaches. The macrophytes can be employed in water remediation through different systems, such as constructed wetlands, wild macrophyte planting systems, and floating treatment wetlands. Constructed wetlands have extensive application in the remediation of diverse contaminants found in wastewater, including heavy metals, explosives, petroleum hydrocarbons, dye effluents, domestic and industrial wastewater, radionuclides, and pesticides present in the wastewater. Acquiring comprehensive insight into the mechanisms behind phytoremediation and constructed wetland technology offers a viable and easily implementable solution for addressing the escalating wastewater problem.

Keywords Constructed wetlands · Aquatic plants · Environmental sustainability · Phytoremediation · Wastewater treatment

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Chapter 5

Microalgal Treatment of Wastewater and Production of Value-Added Products



Rachna Garg, Kulvendra Patel, Mallika Vashist, and S. K. Singh

Abstract Wastewater treatment in the twenty-first century needs to drastically change from its current practices due to the global energy crisis and the need for sustainable human activities. These must work toward creating a new wave of resource recovery and energy-efficient operations while adhering to the increasingly stringent environmental standards. Microalgae can treat wastewater as a growth medium while supplying a renewable biomass feedstock for biofuel generation, making them a desirable treatment alternative. The toxic contaminants in highly polluted organic wastewater like organic phosphorus, nitrogen, and salt, have been known to be resistant to microalgae, and they are also very good at absorbing heavy metals and new emerging contaminants. Algae are the variety of photosynthetic organisms known to have significant bioremediation potential as well as industrial uses that can lower the cost of purchasing energy and fuels. Algae are highly sought-after as possible feedstocks for a wide range of uses, such as the production of biofuels, environmental sustainability, and the creation of high-value bioproducts. Widespread attentiveness about the use of microalgae for wastewater treatment has been sparked by the requisite for efficient nutrient recovery, wastewater treatment, biomass reuse, and greenhouse gas reduction. Additionally, bioenergy and high-value bioproducts can be produced from algal biomass. Researchers from all over the world have considered the use of microalgae as biofertilizers, biofuel, medicine (generation of bioactive and therapeutic chemicals) and food additives. Algae commercial use is limited by financial and technological constraints, as well as efficient downstream processes are required to lower production costs. Therefore, using microalgae together for wastewater treatment and biofuel generation could be a lucrative answer to these problems.

Keywords Microalgae · Wastewater treatment · Value-added products · Bioenergy · Nutrient removal

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Assessing the Sustainability of Jatropha and Rapeseed Biodiesel: An LCA Approach



Kulvendra Patel and S. K. Singh

Abstract Biodiesel offers the ability to reduce carbon emissions from fossil fuels while also addressing energy insecurity. Few studies have explored the effects of biodiesel production on the environment, although such information would help direct practical system design. Life cycle assessment (LCA) is a systematic framework for estimating and analyzing the environmental impacts of a product's life cycle. This study uses the LCA approach to investigate the environmental effects of biodiesel manufacturing from Jatropha and Rapeseed oil. In this analysis, IMPACT 2002+ method and the Ecoinvent v3.6 database were used to calculate damage category scores using SimaPro software. The analysis shows Rapeseed oil biodiesel production has more environmental effects than Jatropha biodiesel production. The global warming potential (GWP) of Rapeseed oil biodiesel production is 2.14 kg CO₂ eq., whereas the GWP of Jatropha biodiesel production is 1.53 kg CO₂ eq. More than 53% of the carbon emissions came from rapeseed cultivation. This study helps in assessing the potential environmental impacts and identifying the hotspot of biodiesel production.

Keywords Biodiesel · Energy · Life cycle assessment · SimaPro · Sustainability

1 Introduction

The development of biofuels has been prompted by the depletion of fossil fuels and efforts to mitigate global warming. One of the difficult problems for scientific communities and governments worldwide is climate change brought on by the increasing usage of fossil fuels. The world's population is predicted to reach 8.5 billion by 2030 due to the strong population growth in several nations (UNDP 2015). Economic development is accelerating, particularly in developing nations like India and China. These nations have now reached the stage of economic development when energy use is at its highest due to industrialization. Over the next ten years,

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SUMMARY

Environmental Engineer with advanced expertise in Life Cycle Assessment (LCA), environmental sustainability, and circular economy. Experienced in conducting comprehensive life cycle and uncertainty analyses of biofuels, wastewater treatment, and solid waste management. Skilled in using LCA software tools (SimaPro, OpenLCA) to evaluate environmental impacts and guide sustainable decision-making. Proven record of impactful research published in peer-reviewed journals and presented at international conferences.

EDUCATION

- | | |
|-------------|--|
| 2022 - 2026 | Ph.D., Environmental Engineering
Delhi Technological University <ul style="list-style-type: none">Working in the field of LCA of Biofuels, Sustainability, and Circular economyPublished SCI Paper/Conferences on LCA |
| 2019 - 2021 | M.Tech, Environmental Engineering
Delhi Technological University <ul style="list-style-type: none">Pursued a passion for Life Cycle Assessment and SustainabilityPublished SCI papers on LCACGPA: 8.78 |
| 2014 – 2018 | B.Tech, Civil Engineering
Deenbandhu Chhotu Ram University of Science and Technology <ul style="list-style-type: none">Worked on comprehensive structural finite element analysis (STAAD Pro)Published paper on Wind and Seismic analysis of Elevated Water TankCGPA: 7.81 |

RESEARCH PAPERS

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- Life cycle assessment of first- and second-generation biofuel: A comparative study, 5th International Conference Advances In Power Generation, Renewable Energy and Sustainable Development (APGRES 2023), 03 – 04 February, 2023, Rajasthan Technical University, Kota, Rajasthan, India

REVIEWER FOR ACADEMIC JOURNALS

- Scientific Reports, Nature
- Journal of Cleaner Production, Elsevier
- Energy, Elsevier
- Energy for Sustainable Development, Elsevier

- Sustainable Production and Consumption, Elsevier
- Proceedings of the Institution of Civil Engineers - Water Management
- Clean Technologies and Environmental Policy, Springer
- Environmental Monitoring and Assessment, Springer
- Discover Sustainability, Springer
- Discover Water, Springer
- Sustainable Energy Research, Springer
- Biotechnology for Biofuels and Bioproducts, Springer
- Environmental Science and Pollution Research, Springer

PROFESSIONAL MEMBERSHIPS

- Associate Member, The Institution of Engineers (India)
- Student Member, American Society of Civil Engineers

AREA OF INTEREST

- Life Cycle Assessment
- Environmental Impact Analysis
- Biofuels
- Solid Waste Management
- Water and Wastewater Engineering
- Environmental Auditing
- Sustainability
- Circular Economy

SKILLS

- SimaPro
- OpenLCA
- MATLAB
- OriginPRO
- STAAD Pro
- MS Word, Powerpoint, Excel

DECLARATION

I hereby declare that all the information furnished by me is true to the best of my knowledge and belief.

Kulvendra

Kulvendra Patel