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LIFE CYCLE ASSESSMENT OF BIODIESEL: ENERGY BALANCE, GREENHOUSE GAS EMISSIONS, AND OTHER ENVIRONMENTAL IMPACTS

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Abstract
Biodiesel's generation to consumption cycle must be evaluated from a sustainability perspective, just like all other energy sources, including renewable ones. A potential method for helping decision-makers identify the adverse environmental impacts of current or proposed biodiesel production strategies is life cycle assessment, or LCA. For example, an LCA of biodiesel production cycles may yield recommendations spanning from agricultural practices to production and combustion phases, depending on the feedstocks, production technology, downstream processes used, etc. There are still a lot of difficult problems with doing life cycle assessments (LCAs) on the production and consumption of biodiesel, even though there is an ISO standard for doing so. These difficulties include the selection of system boundaries, the functional unit, the effect categories that need to be evaluated, how land use change is handled.

1. Introduction

As we know there is the rapid surge in the fossil fuel consumption that starts with developments, industrialization and urbanization Over the past few decade (BP. Statistical Review of World Energy, 2020). Too much uses of fossil fuel led to the environmental problem like global warming as well as depletion of these resources that need millions of years for their formation (Dale, 2008; Srivastava & Prasad, 2000) As in developing countries energy production is solely based on petroleum products which are obtained from fossil fuels these led to the production of greenhouse gases. If we look at the consumption of the fossil fuels (that gives energy by burning them) led to the production of CO2, CO oxides of nitrogen oxide of sulfur and other hazardous gases(Agreement., 2015). About six developing countries are listed in the list of top 10 countries that emit greenhouse gases at highest level (Crippa et al., 2019; Khan et al., 2021). In these countries fossil fuel products are used for transportation 58% (Escobar et al., 2009), electricity production, household or commercial purposes, due to this rapid use, fossil fuel may lead to its depletion causing worldwide energy crisis due to its solely dependence for obtaining energy(Khan et al., 2021). Transport sector only reduces 16 % of total gags around globe it has estimated that after about approximately 50 years oil and gas will completely run out (Resource], 2017). Only US consume about 7.39 billion barrels of oil per year in 2025 ,this is a huge number of petroleum US(For U.S. petroleum demand statistics, (last updated oct 9 , 2025),) . Therefore there is a critical need for the conversion of the energy production from fossil fuels to renewable energy resources that must be cheaper , environment friendly and easily available(Ingle et al., 2018; Serrano et al., 2009) . For this purpose, US have started the production of biofuels in the early years of 21st century they have started the production of renewable energy through solar and wind but they can't largely replace the use of oil (Perona, 2017). Therefore, researches must be done in order to stop the emission of greenhouse gases. Also to prevent the consumption of petroleum based (fossil fuels) products, and lowering of temperature researches must focus on finding the new sources or methods of renewable energy that are cheaper and sustainable for every nation irrespective of that they are developing or developed countries so that they can easily adopt them (Khan et al., 2021). These efforts must include the reduction in the emissions of greenhouse gases also most of the sector must be converted or electrified like using electric vehicles and hybrid engine in the transportation sector(Cui, 2020;). Like many countries are adopting the policy of promoting electrical vehicles and publicity introduced programs for their electrification goals. As us have set their goal to make half of all new vehicles in the US having zero greenhouse gases emission features(Transportation et al., 2025). If we look at traditional renewable energy sources like hydro wind solar and nuclear .they all give us electrical form of energy but it cannot compete the need of oil(Arutyunov & Lisichkin, 2017). The fossil fuels like call oil gas etc. give us electrical and mechanical energy in different sectors i.e. domestic agriculture industrial (Demirbas, 2009). As there are many problems associated with electrical energy like their transmission line losses etc. For this purpose biofuel emerges as potentially more favorable source of renewable energy in all sectors especially transportation sector . These are basically obtained from the biomass which include the feed stocks animal and plant waste household waste (Bandyopadhyay, 2015).These biofuels are non hazardous cheap environmental friendly , biodegradable and are carbon neutral (Cramer et al., 2006; NREL, 2009.). There are different type of biofuels these include bioethanol biodiesel other fuel additives biomethane and biohydrogen. If we compare bioethanol with the biodiesel bad is it will be the more energetic rather than bioethanol it's because bioethanol is derived from the fermented sugars while biodiesel is drived from the vegetable or the animal oils and then a process name tranesterification is done in order to produce it(DIESEL & FUELS 1-2, (visited,2025).). the biodiesel have very much chemical resemblance with the diesel fraction refined form crude oil so with some minor alteration it can be used to produce petroleum or plastic products. (Fuel Property Comparison, (Oct. 29, 2014))Further if we look deeper into the biodiesel there are further two types one is named as "FAME " (fatty acid methyl easter) that is produced to a process of trans easterification while the second one is the " renewable diesel " which is obtained from the purified plant hydrocarbons two process named as hydrogenation.(Perona, 2017) If we look at the greenhouse gases emission (particulate matter, carbon monoxide,carbon dioxide, oxides of nitrogen and sulphur) from the biofuel ,these are very much lower than from the fossil fuel , biofeul becomes very important form of energy (Correa et al., 2019; Čuček et al., 2012). In order to compare the implications of biodiesel or other biofuels with the fossil fuels counterparts life cycle analysis is used (Gheewala, (2021).).It is done to understand how much amount of greenhouse gases and other harmful substances are released from the production and usage of biofuel (Hosseinzadeh-Bandbafha et al., 2021).The results of LCA can be used by policy makers consumers to make decisions regarding the future policies that have critical impact on both nationally and globally(Gheewala, 2023). However LCA can also be used to determine or evaluate the environmental impacts that are occurring as the results of nations policies and decision toward shifting on biofuel.(Panichelli & Gnansounou, 2017). Despite the fact that biodiesel production and performance have been the subject of several research, there are still few thorough evaluations that integrate life cycle analysis (LCA), energy balance, and environmental trade-offs across various feedstocks. Researches' that has already done frequently concentrates on certain areas or types of feedstocks, which leads to conflicting results and differences in methodology. By methodically assessing biodiesel production pathways from different feedstocks and contrasting their energy efficiency, greenhouse gas emissions, and wider environmental impacts through the lens of life cycle assessment (LCA), this review seeks to close these gaps. The goal is to present a cohesive picture of biodiesel's potential for sustainability and pinpoint important areas for methodological advancement and further study.

2. Overview of Life Cycle Assessment (LCA)

Historical overview:

LCA has received more and more attention in the first ten years of the twenty-first century. The Life Cycle Strategy is an International Life Cycle Collaboration that was started in 2002 by the Society for Environmental Toxicology and Chemistry (SETAC) and the United Nations Environment Program (UNEP).(UNEP, 10 OCTOBER 2025) The primary goals of the Life Cycle Project were to implement life cycle thinking and enhance the supporting resources with improved data and indicators. As evidenced by the European Commission of the European Communities Communication (CEC) on Integrated Product Policy (IPP) (Com, 2003), life cycle thinking continued to gain popularity in European policy. Additionally, the concept of life cycles was included in themed initiatives such as the Avoidance and Reuse of Waste (PELLETIER et al., 2013) and the Beneficial Use of Resources (Guinée et al., 2011). The European Commission emphasized the value of life cycle assessment and the necessity of encouraging the use of life cycle thinking among IPP stakeholders in its 2003 Communication on Integrated Product Policy (IPP) (40). The European Platform on Life Cycle Assessment (commmision, 2025) was founded in 2005 in response, with the goal of encouraging the availability, sharing, and application of quality-assured life cycle data, methodologies, and studies for trustworthy decision support in industry and (EU) public policy. In the United States, LCA began to be promoted by the Environmental Protection Agency in the United States (Curran, 1992). Numerous national LCA networks have additionally formed, such as the American Center for LCA (ACLA), which began operations in 2001, and the larger Australian LCA Network which was a nonprofit organizations (ALCAS), as well as the smaller Thai network (TLNW), which was organized in 2000.

An examination of European legal acts & communications from 1990 to 2020 shows that LCA is being used more and more in policy (Sala et al., 2021). The Circular Economy Action Plan and the EU-Taxonomy1 are two recent examples. The Circular Economy Action Plan proposes legislative as well as other initiatives that will enhance circularity in the European Union, while the Taxonomy requires financial institution a to assess and communicate how they impact the environment (Commission.). The growing overall count of company environmental reports that reference life cycle assessments (LCAs) is a sign of the increasing acceptance of LCAs in businesses around the world, even though the proportion of LCA mentions in such reports stays relatively constant (Stewart et al., 2018).

Definition and structure:

Life cycle analysis is globally used method that is used to evaluate ecosystem burdens of various product processes and human impact throughout their whole life cycle from the extraction of raw material to their use and even their disposal like from cradle to grave (Conradi-Galnares et al., 2025). It is used to help in consumer in making decisions that will help ultimately in maintaining the ecosystem and environment(Mercader-Moyano & Porras-Pereira, 2025). Life cycle analysis is a tool that is basically a computational tool used to assess the sustainability of future biofuel industry by comparing their energy consumption and releases of the greenhouse gases into the environment with the traditional fuels i.e. petroleum products. We can also use life cycle analysis to avoid resolving one environmental problem while preventing creation of other, therefore it is considered as a powerful decision taking tool that is very important to make consumption and production more sustainable to the environment. It has four major components including goal and scope, life cycle inventory, life cycle impact assessment and interpretation, as illustrated in **Figure 1**.

Goal & Scope: It is basically used to understand the reason why we are doing the study what is our productive function how to identify it what is our targeted audience the limitation understanding the data requirements on which specific categories we want to focus mainly(Bribián et al., 2011; Liebsch, 2019).

Inventory: It is the next phase which is called as life cycle inventory, in it we gather information make descriptions validate the data before entering it look out for the processes that are being used or data needed to be used gases emissions and other factors that are relating to our study and to the life cycle. It also include gathering the data into organized form(Buyle et al., 2013; Quist, 2019).

Impact Assessment: In this stage we categorize all the information place it into the relevant portions and use different evaluating factors and other procedures methods to evaluate or raw data into the usable form, which can be used to further analyzed to see their impact on human health and environment in which they are living (Buyle et al., 2013; Pamu et al., 2022; Quist, 2019).

Interpretation: This is step which is the fourth and the final step in it we basically interpret the results making the most suitable conclusions and recommendations regarding the study.(Bribián et al., 2011) It is a very important step as you need the result must be forcing to a third party critical analyzing the results externally for comparison the result must indicate important implications and recommendation like various methods for countering the problems.(Buyle et al., 2013)**.**There are two type of the approaches for calculating environmental implications data (Conradi-Galnares et al., 2025).

First one is **Attributional LCA** it tells us about the environments significant flow in a specific time frame however **Constitutional LCA** interpret it and tells us how these flaws developed over the time and what potential measures that have been taken against them. Most of the research recommend consequential LCA over attributional as it helps in decision making process (Guine et al., 2002; Ortiz-Rodríguez et al., 2010).

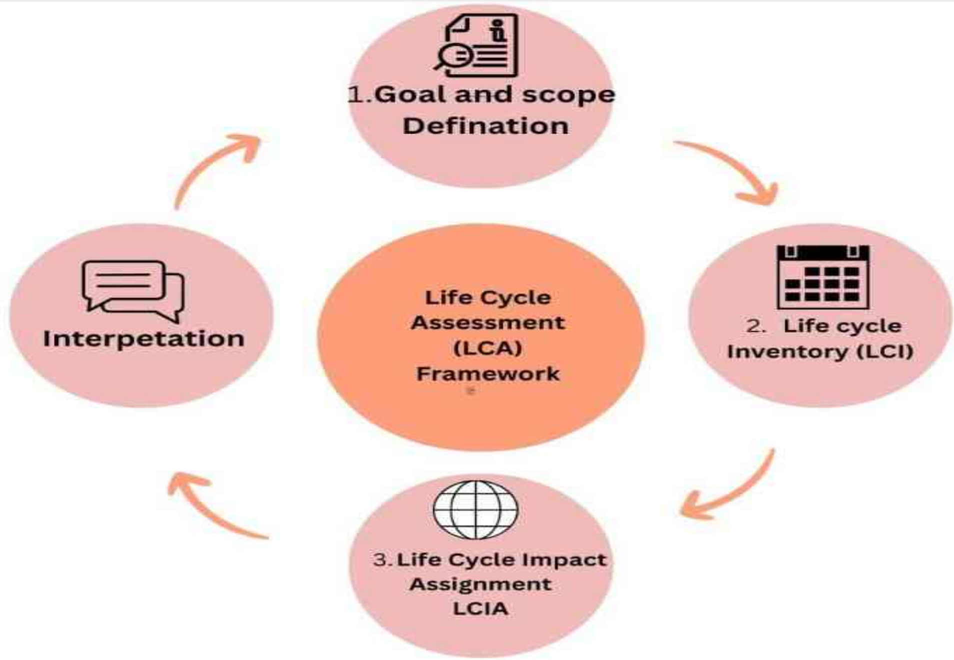

Figure 1 The Four Phases of an LCA. This figure illustrates the standardized framework for conducting a Life Cycle Assessment(LCA), which is structured into four distinct phases: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. The sequence shows the iterative process of an LCA study.

Efficient resources and emissions handling is now more important than ever due to the acceleration of climate change, growing environmental effects, and global crises like the current energy supply problems brought on by the conflict in Ukraine(Subal et al., 2024). By guiding environmentally friendly choices, life cycle assessment, or LCA, can be a helpful tool for customers, firms, and authorities to lower utilization of resources and environmental impacts. Originally, the packaging of products was compared ecologically using life cycle assessment (LCA). LCAs are widely used in a variety of contexts, including research and development (R&D), planning for strategic growth, comparing product and service systems, "green" marketing, and hot-spot analysis (Moro Piekarski et al., 2013). Over the past several years, global harmony and standardization have been established, and the range of potential uses has expanded (Bjørn et al., 2017).

Relevance of LCA to Biofuels:

Emissions of greenhouse gases and reductions in comparison to fossil fuels are the main focus of the majority of LCA biofuel research. Other environmental effect categories including eutrophication, acidification, photochemical smog, human toxicity, and ecotoxicity are also taken into account in biofuel life cycle assessment (LCA) research(Patel & Singh, 2023). Even for the same feedstock, LCA studies yield varying results for Global Warming Potential (GWP), that vary from positive to negative.(Yan & Crookes, 2009). LCA findings are taken into account for all decisions and communication efforts pertaining to production and use, as well as for determining whether biofuels are tax-exempt under the mineral oil tax law. One example of such a communication endeavor is the administration of an online platform that lists and assesses sustainability labels. 8. Public procurement also uses these designations as a factor (Interviewee PA1)(Subal et al., 2024).Like Switzerland, national agencies in the US and Australia make data available to the public and business sectors to help with LCA usage

(Sonnemann et al., 2018). Additionally, the Netherlands, Germany, the UK, and California all evaluate tax exemptions for biofuels, much like Switzerland does(Sonnemann et al., 2017).

1. Biodiesel Production Pathways

Feedstock

A range of biomass sources, such as agriculture crops, organic waste and microbiological biomass, can be used to produce biodiesel feedstocks, which support the manufacture of sustainable biofuels, as illustrated in **Figure 2**

First generation feedstock:

Freshly extracted raw materials from a variety of sources make up this kind of feedstock. These feedstocks include common edible vegetable oils (palm, coconut, sunflower, soybean, rapeseed, and a few other oils like avocado and olive oils) and animal fats (Linganiso et al., 2022). The aforementioned raw materials are good feedstocks for premium biodiesel. However, when the manufacturing of biodiesel depends on these resources, the food cycle is upset. This is because there is more competition for these resources to be used for food or as raw materials to make biodiesel, which is required to meet the demand for fuel worldwide(Murphy et al., 2022). The cultivation of these feedstocks requires the availability of arable land. One consequence of employing first-generation feedstocks as a raw material for biodiesel is deforestation (Tulashie et al., 2025).

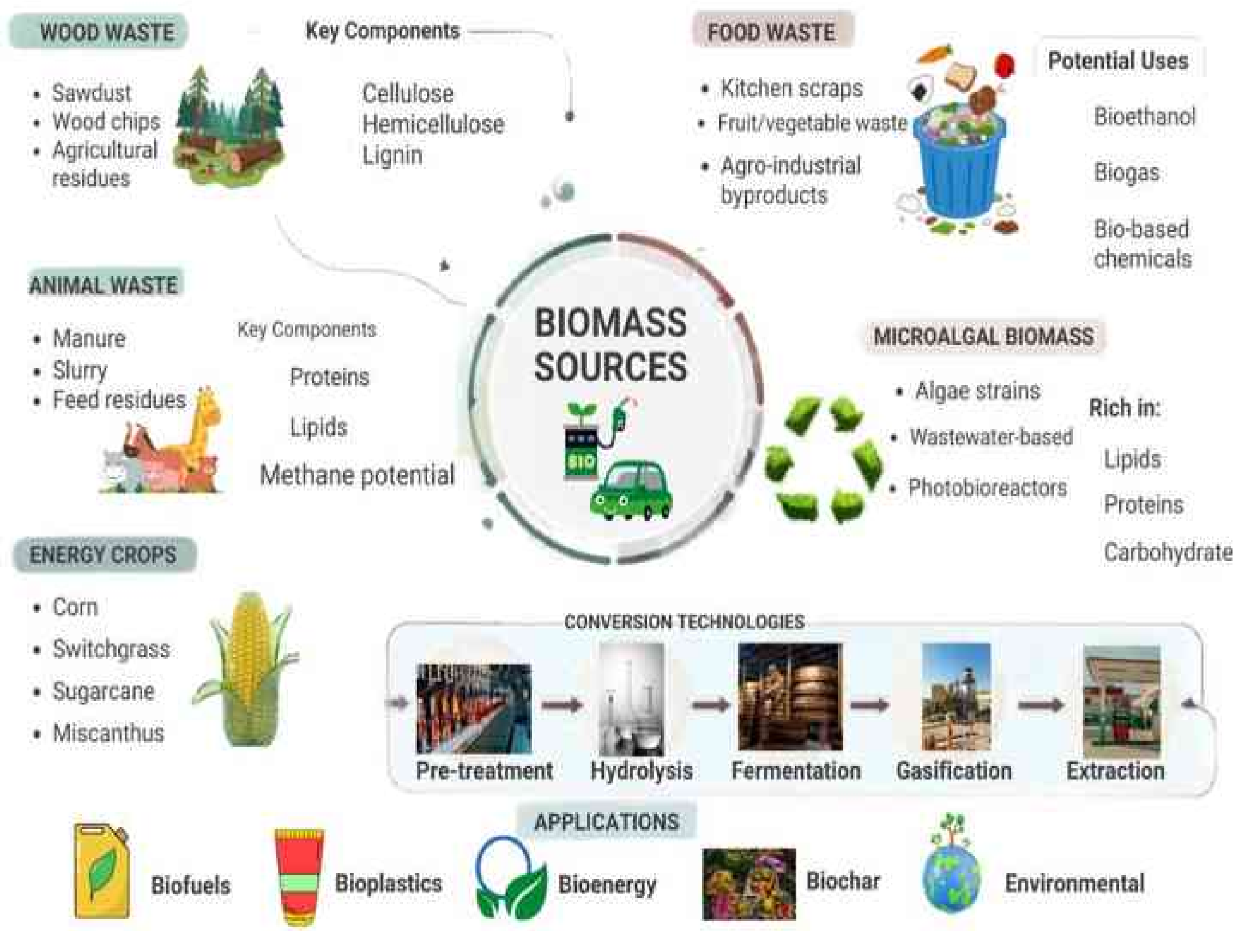

Figure 2 Illustrating the diverse origins of sustainable feedstocks ,this figure categorizes key biomass sources, highlighting the importance of waste valorization (from wood, food, and animals) alongside the cultivation of dedicated biological resources like microalgae and energy crops.

Second generation feedstock:
This category of feedstocks includes non-edible food crops and oils that are unhealthy for human consumption due to the presence of toxic compounds. Examples of these include oils derived from tobacco seed, jojoba, cottonseed, mahua, sea mango, salmon oil, WCO, restaurant grease, and animal fats like beef tallow, pork lard, and mahua (Atabani et al., 2013). These feedstocks are preferable choices for turning into biodiesel because they don't immediately interfere with the human food supply chain. A variety of food crops can be cultivated in a specific area since these feedstocks can be grown on wasteland, negating the need for large amounts of farmland (Yang et al., 2014). The second-generation biofuels are those that are made from plant biomass, which is primarily made up of lignocellulosic materials. This is because it accumulates the majority of the abundant and affordable nonfood chemicals that are available from plants. However, it is currently not cost-effective to generate these fuels since many mechanical barriers must be overcome before their potential is taken into account (Naik et al., 2010). For the manufacturing of biodiesel, these feedstocks are therefore more effective and environmentally benign. Second generation, Ethanol and methanol produced from woody biomass are examples of second-generation biofuels that are more energy-efficient and versatile in terms of their source (Mahmood et al., 2023). Reduced expenses are suggested by the possibility of using cellulosic and heterogeneous biomass (Havlík et al., 2011)

Third generation feedstock:
This specific feedstock consists of microorganisms and algae. The best source of lipids for producing biodiesel on a wide scale is microalgae (Chhandama et al., 2023). Previous studies have described the primary capabilities of green algae-derived biomass for the creation of a superior form**:** third-age biofuels**,** in an effort to find viable and workable alternatives to non-renewable energy sources(Behera et al., 2015; Mahmood et al., 2023). Their rapid reproduction makes cultivation relatively simple. Because microalgae grow so quickly, biomass is produced quickly as well, making it a great substitute source of feedstock for biodiesel. Because of their high lipid content, microalgae can be used as feedstocks for biodiesel .Research volumes on biodiesel made from used cooking oil (WCO generate an oil yield that is 25 times higher (Lee & Lavoie, 2013). Their growth does not necessarily require the arable area needed for conventional agriculture (Udayan et al., 2023). High production costs, low lipid productivity, and challenging large-scale cultivation, harvesting, and extraction are just a few of the obstacles that still need to be addressed despite the extensive literature of the past 20 years (Gaurav et al., 2024; Neeti et al., 2023)Another option for third-generation biodiesel sources is waste fats and oils (Lopresto, 2025).

Fourth generation feedstock:
This feedstock contains biomass that has been genetically altered to trap more carbon dioxide and solar energy. Electro fuels and photobiological solar fuels are among them. Because they have no adverse environmental effects, feedstocks in this group are less contentious (Banga & Pathak, 2023). However, because of their high initial cost, sluggish yield, and lengthy processing time, fourth-generation feedstock has received very little research over the years (Singh et al., 2020). This type of feedstock has a high energy level, is inexpensive, easily accessible, and infinite (Tulashie et al., 2025). The two main technologies that enable photosynthetic water to split using sun energy are artificial and direct solar photosynthesis. Through the use of inorganic catalysts or photovoltaic systems, microorganisms—possibly designed from a metabolic perspective—can facilitate this conversion. Despite their potential, these technologies are still in their infancy and come with a hefty upfront cost (Lopresto, 2025; Singh et al., 2020).

2. Biodiesel technologies:
An environmentally responsible and renewable alternative to traditional fossil fuels is biodiesel (Suzihaque et al., 2022). It is made from natural materials, usually leftover restaurant grease, vegetable oils, or animal fats. The most widely used

feedstocks for the manufacturing of biodiesel are palm, sunflower, canola, and soybean oils.(Atabani et al., 2012).

Process of biodiesel through pyrolysis:
Pyrolysis, sometimes referred to as thermal cracking, is a process that breaks down organic materials by subjecting them to extremely high temperatures (141–200 °C) in an oxygen-free atmosphere (Bow et al., 2021; Maheshwari et al., 2022).This process yields

Figure 3 Depicts the major waste cooking oil producing countries.

fuel properties that are remarkably close to petroleum diesel, including calorific value, cetane number, density, flash point, and kinematic viscosity. (Mohamed et al., 2020) reported that the biodiesel made by pyrolysis using WCO had a calorific value and flash point that were roughly 2% higher than petroleum diesel, with a kinematic viscosity and density differential that were 44% and 2.3% higher, respectively. However, the environmental benefit of biodiesel is eliminated by the costly and gas-releasing equipment necessary for thermal cracking (Abbaszaadeh et al., 2012). The distribution of waste cooking oil production across various countries is illustrated in **Figure 3**, highlight the regions of potential for biodiesel feedstock collection.

Esterification:
Lipid feedstocks with high concentrations of free fatty acids (FFA), like WCO, are frequently prepared using this method. As seen in Table 1, the esterification reaction uses a catalyst in conjunction with alcohol and FFAs to create FAMEs (Ala'a et al., 2021). For this reaction, acid catalysis is typically preferred, and sulfuric acid (H_2SO_4) is frequently employed as the catalyst (Ala'a et al., 2021). 500,000 tons of used WCO are wasted into the environment each year, causing environmental issues. This used cooking oil can act as a potential feedstock to produce biodiesel, which will be more affordable, accessible, renewable, and easier to assemble at homes and restaurants (Mhetras and Gokhale 2025). Additionally, the requirement for land will be reduced, which is used for crops that produce biodiesel. Despite being important for the production of biodiesel, used cooking oils have been thrown unsafely, causing pollution in the environment (Elgharbawy, Sadik et al. 2021).
With just three fundamental raw materials needed—oil, alcohol, and a catalyst—this is the most popular industrial biodiesel manufacturing

technique (Rezania et al., 2019). Using an alcohol and a catalyst, the procedure shown in Figure 3 transforms the triglycerides found in oils into fatty acid mono alkyl esters known as fatty acid methyl esters (FAMEs) (Ala'a et al., 2021). The success of this process in creating biodiesel of outstanding quality is dependent on the type of lipid feedstock utilized. Triglycerides must be used to carry out the transesterification procedure, which calls for the usage of a very pure lipid raw material. The primary cause of this is the sensitivity of the majority of catalysts to FFA concentrations above 2% (Rezania et al., 2019). A three-step transesterification procedure must be followed in order to manufacture high-quality biodiesel from a lipid source that contains a high percentage of free fatty acid (>2% by weight) (Cerón Ferrusca et al., 2023). Triglycerides are changed into diglycerides, monoglycerides, and biodiesel throughout this process. It is advised to use a pretreatment procedure, like esterification, to guarantee that the finished product satisfies the required quality criteria. The finest quality final product will be guaranteed by this pretreatment procedure (Ala'a et al., 2022).

Direct Transesterification:
When the lipids are removed and trans esterified from the biomass in a single step, the in-situ transesterification reaction occurs, and this uses a co-solvent to increase the effectiveness of the reaction (De Jesus et al., 2020; Faried et al., 2017; Katre et al., 2018; Nguyen et al., 2018). Alcohol's capacity to dissolve in lipids is improved by the presence of a co-solvent (Cerón Ferrusca et al., 2023). In direct transesterification, methanol was previously used as a reagent and a solvent. This resulted in an excess of methanol, which reduced the catalyst's activity in the reaction and its capacity to break down the cell wall (Cerón Ferrusca et al., 2023). As a result, the amount of biodiesel produced was decreased (Hidalgo et al., 2014). To lower the quantities of methanol and prevent the aforementioned issues, a variety of organic solvents, including petroleum ether, diethyl ether, acetone, n-hexane, n-pentane, chloroform, and isopropanol, have traditionally been used in the direct transesterification process (Hidalgo et al., 2014; Nguyen et al., 2018).Considering that these chemicals are hazardous, their use may have negative environmental implications (Henderson et al., 2011). Several studies have emphasized the use of greener co-solvents as substitutes for conventional solvents that are thought to be more environmentally friendly, such as cyclopentylmethyl ether (CPME), 1,8-Diazabicyclo(5.4.0)undec-7-ene (DBU), and 2-Methyltetrahydrofuran (2-MeTHF) (de Jesus et al., 2018; de Jesus et al., 2019; Sicaire et al., 2015).

Electrolysis:
Using feedstocks with a sizable percentage of both FFA and water is made possible by this technique (Fereidooni & Mehrpooya, 2017; Guan & Kusakabe, 2009; Moradi et al., 2021). This approach has the benefit of not requiring pretreatment to lower lipid moisture and free fatty acid levels (Fereidooni et al., 2018). In the electrolysis cell, methoxide ions are formed quickly and reliably (Guan & Kusakabe, 2009). At the cathode, water molecules undergo electrolysis to form hydroxide ions these ions mix with methanol molecules to produce methoxide ions. Due to specific steps taken (Putra et al., 2015), it is possible to accomplish both esterification and transesterification processes within a single electrolytic cell because He ions are generated at the anode and OH— ions are formed at the cathode (Aulia, 2023; Moradi et al., 2021). When NaCl is added to the mixture (Moradi et al., 2021), the conductivity rises, increasing the reaction rate (Rachman et al., 2018). In transesterification, methyl esters are created when methoxide ions attack the carbonyl carbon (Cerón Ferrusca et al., 2023).Depending on its purity, biodiesel made using these techniques can be used in engines either straight or in blends (Cerón Ferrusca et al., 2023). Blending is accomplished by combining diesel with biodiesel. In order to increase the efficiency of compression engines, the goal is to consume fewer fossil fuels and lower the mixture's viscosity (Maheshwari et al., 2022; Tulashie et al., 2025)

Overview of Biodiesel production pathway

The production of agricultural inputs (such as seeds, fertilizers, pesticides, and fuels), the production of capital goods (such as buildings and machinery), and fieldwork activities (such as land preparation, planting, fertilizing, tillage, and harvesting) are some of the substages that make up the agricultural cultivation stage. Annual and perennial crops go through different stages since the latter need extra steps like pre-nursery and nursery cultivation. During the crop's whole life (for example, 25–30 years for oil trees), these processes and associated emissions from input production must be taken into account and averaged appropriately (Schmidt 2007; Choo et al. 2011; Van Zutphen and Wijbrans 2012; Rajaeifar et al. 2016). US and Brazil are producing 3% of their transport fuel from biofuels methods due to recent advances in this field in the last 10 years (Eisentraut et al., 2011; Timilsina, 2014).

The **agricultural cultivation** stage is typically left out of second-generation biodiesels, which are mostly made from waste or low-value oils. Nonetheless, the agricultural stage of non-edible oil feedstocks is included when they are grown especially for biodiesel. Since animal fats are by-products with minimal market significance, upstream activities associated with livestock production are usually ignored in this scenario (Dufour and Iribarren 2012; Jørgensen et al. 2012; Escobar et al. 2014; Rajaeifar et al. 2017b). Pre-cultivation in photobioreactors is also taken into consideration while cultivating algae for third-generation biodiesels (Sander and Murthy 2010). On the other hand, dewatering is handled as a distinct step. The **transportation stage** covers all transport activities, including movement of agricultural outputs, oils, and biodiesel to various processing or use points. It accounts for vehicle fuel use, material consumption, and infrastructure,

though the latter two add uncertainty since vehicles and roads serve multiple purposes (Escobar et al. 2014; Rajaeifar et al. 2014). Agricultural products are converted into oil and meal in the oil mill stage using a variety of **extraction methods**, including solvent extraction and cold pressing, with continuous improvements to lower wastewater and boost treatment effectiveness (Moreno et al. 2003; Shah et al. 2005; Rajaeifar et al. 2013; Hodaifa et al. 2013; Lim et al. 2014; Liew et al. 2015; Yu et al. 2017). Production of capital goods, mill activities, and input materials are all included in this stage. The oil mill stage is typically skipped for second-generation feedstocks unless rendering of animal fats is necessary. The method used to convert the extracted oil into biodiesel has a major impact on life cycle emissions, however not as much as feedstock production (Wiloso and Heijungs 2013; Altamirano et al. 2016). Lastly, the **combustion step**, which measures the tailpipe emissions from engines running on biodiesel, is the "well-to-wheel" phase. Tests in the lab or in the real world are used to gather emission data. Upstream emissions for diesel or additives must also be considered when biodiesel is blended with them (Xue et al. 2012; Rajaeifar et al. 2017b). For this stage, there are no differences between feedstock generations.

Global Prospective

It doesn't change the natural carbon cycle by adding more carbon dioxide to the atmosphere; on the other hand, it just needs small adjustments rather than new engines and technology, which encourages its use and economic sustainability. By transferring electricity from Petro-based conventional refineries to agro-industry, biodiesel use has become more flexible and appealing to the current energy picture, which guarantees energy security, environmental sustainability, and rural development (Hassan & Kalam, 2013).

According to the EU Commission's report "EU Agricultural Outlook 2021–2031" (European Commission 2021), the consumption of gasoline and diesel, two fossil fuels, will drop by 32% in 2031 compared to 2022, reaching 139 billion liters for diesel and 62 billion liters for gasoline(Lopresto, 2025). Biodiesel use is predicted to peak at 18.9 billion liters in 2023 and then drop by 24% to 14.3 billion liters in 2031. According to a different analysis, Europe's biodiesel output is expected to reach 16 billion liters in 2023 and 18.7 billion liters by 2028. Germany is expected to dominate the market, producing 3 billion liters and Transportation accounts for 31% of Italy's yearly energy consumption, or 35 million tons of oil equivalent(Size, 2023) Although this fraction fell by 26% between 2005 and 2021, fossil fuels still account for almost 90% of this percentage.

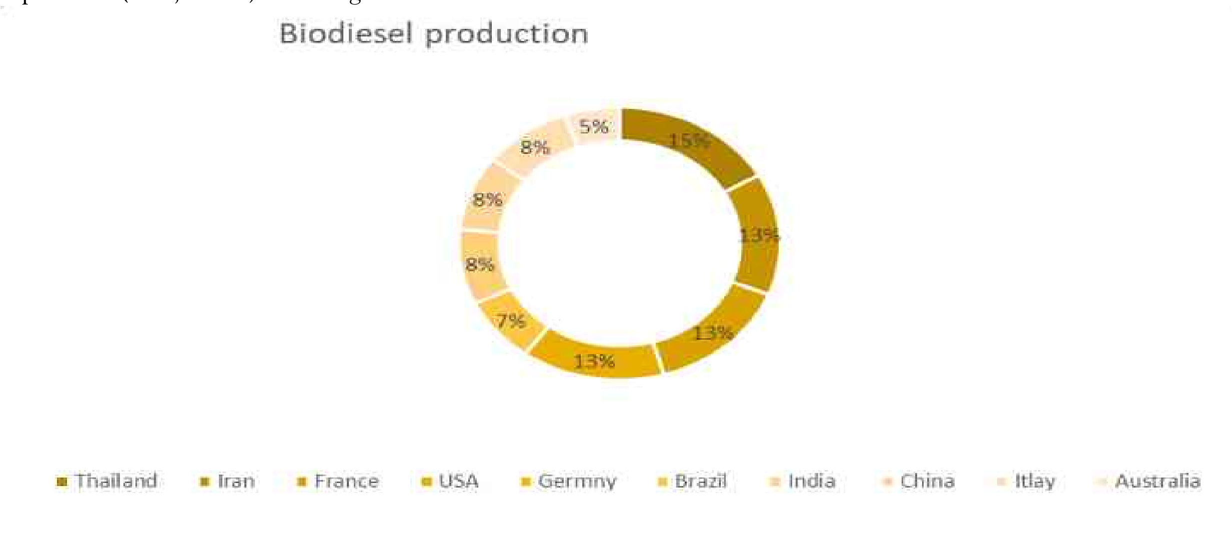

Figure 4. Top Biodiesel Producing Countries.This chart lists a selection of the world's leading biodiesel producers., highlight the global scale and geographic diversity of the biodiesel industry. This figure provides context for the international market and supply chain relevant to the life cycle assessment.

Europe should set aside 20% of its arable land for energy crops if it hopes to replace just 5% of its fossil fuels with first-generation biofuels. a situation that encourages the use of productions outside the EU .The European Commission has planned to stop using palm oil for biodiesel production by 2030, despite the fact that the use of palm oil for food is decreasing in favor of other oils. This is because the use of biodiesel made from palm oil has a climate impact that is three times worse than that of fossil diesel, primarily because of indirect emissions caused by deforestation in the countries of origin, which are primarily Malaysia and Indonesia (https://www.rinnovabili.it/mobilita/olio-di-palma-ue-biodiesel).Large tracts of land are needed for the production of fuels through plant agriculture. Over the past ten years,large swaths of Latin America, Africa, China, India, and Southeast Asia have been impacted by the competition for land for energy crops.(Lopresto, 2025). Growth in U.S. biodiesel manufacturing, exports, as well as consumption from 2001 and 2023 are depicted in this figure. 2008 saw a peak in biodiesel exports, mostly due to an unforeseen consequence of a biofuels tax incentive in the EU. As the effect was removed, exports then fell. The Fuel Standard was a major factor in the rise in production and use starting in 2011. Both manufacturing and consumption have decreased in recent years, which may have been caused by the rise in renewable diesel on the market (EIA, 2025,OCT) .

In order to fulfill the growing need for biodiesel and to provide economic advantages, biodiesel production has increased by around 4 to 14 percent in the past decade (Cerón Ferrusca et al., 2023). The pattern of biodiesel usage by region between 2010 and 2024 is depicted in Figure 1. 2000 out of 2500 articles that were obtained from Scopus were used to construct Figure 1. These chosen articles focused specifically on nations that utilize or consume biodiesel worldwide. The data from the analysis of these articles, which were converted into Microsoft Excel, is displayed in the figure together with the nations' % usage of biodiesel. As seen in this statistic, Thailand is the country that generates the most biodiesel globally (15%).From 2023 to 2027, the output of biodiesel is anticipated to increase between 50 to 52.5

Table 1 lists the overall energy amounts provided by providers for the various fossil fuels and biofuels sold in the 27 Member States of European Union. (EU, 2022 Published).

FUEL	Total quantity (PJ)		
Fossil fuels	**9 862**	**Biofuels**	**723**
Diesel	5 934	Biodiesel	449
Petrol	2 354	HVO	146
Gas oil	1 337	Bioethanol	97
Liquid petroleum gas (LPG)	189	Bio-ETBE	11
Compressed natural gas (CNG)	32	Biogas	10
Liquefied natural gas (LNG)	15	Other	10
Other	1		

billion of liter (Cerón Ferrusca et al., 2023; Tulashie et al., 2025).

3. Energy Balance of Biodiesel

Comparison with fossil fuels and other biofuels: The "ETC CM Report 2022/2023"'s "GHG emissions savings from the use of biofuels" (Table 3) offers a thorough assessment of the GHG emission offsets attained by using biofuels instead of fossil fuels. An in-depth analysis of the table according to the data is provided below. In the table, three fossil fuels—diesel, gasoline, and compressed natural gas [CNG]—are contrasted with the biofuels that they replace: biogas, bioethanol + ETBE, and biodiesel + HVO. Two distinct sets of anticipated GHG emission figures are included. Including preliminary mean quantities of the projected ILUC emissions and excluding preliminary mean amounts of the assumed estimates of indirect land use change emissions.(EU, 2022 Published).As shown in **Table 2**.

Table 2 GHG emissions savings from the use of biofuels (EU, 2022 Published).

Fossil fuel	Substituting biofuel	Excluding/including provisional mean values of the estimated ILUC emissions	GHG emissions from fossil fuels (kt CO2e)	Emissions savings (kt CO2e)	GHG emission reduction from substitution (%)
Diesel	Biodiesel + HVO	Excluding	56,555	43,034	76.1
		Including	56,555	22,721	40.2
Petrol	Bioethanol + ETBE	Excluding	10,115	7,799	77.1
s		Including	10,115	6,601	65.3
CNG	Biogas	Excluding	708	565	79.7
		Including	708	555	78.4

4. **Greenhouse Gas (GHG) Emissions:**

Carbon footprint of biodiesel vs. petroleum diesel:

Taking average values into consideration, the GWP of the majority of **first-generation biofuels**, with the exception of Rapeseed biodiesel, is lower than that of conventional gasoline (72.8 to 96 g CO2 eq. / MJ; (González-García et al., 2010; 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). Rapeseed biodiesel emits between 2.8 and 350 g CO2 equivalent per MJ of energy, according to certain LCA studies that have been examined (González-García et al., 2013; Gupta et al., 2022; Uusitalo et al., 2014). The stages of drying and chilling seeds, extracting oil, and refining contributed very little in comparison to fertilizer application in the agricultural stage, which uses 70% more energy and 80% more GWP (Gallejones et al., 2015).The stagewise contribution of GHG emissions for different biodiesel feedstocks is summerized in **Table 3**. The research by (Arguelles-Arguelles et al., 2021)found that the manufacture of biodiesel from palm oil had negative GHG emissions since the quantity of carbon dioxide absorbed during the cultivation phase was more than the GHG emission of biofuel. Compared to traditional gasoline, the majority of research on palm oil, soybeans, and sugarcane (Arpornpong et al., 2015; Fernández-Tirado et al., 2016; Lee & Ofori-Boateng, 2013; Munagala et al., 2022; Rocha et al., 2014)showed reduced GHG emissions.

A few of the studies that were analyzed indicate that the generation of biofuels results in negative greenhouse gas emissions (Jeswani et al., 2015).For the **Second generation** the study by (Pradhan et al., 2022) examined the esterification an d transesterification procedures utilized to produce biodiesel utilizing used rice bran oil. Compared to regular diesel (102 g CO2/MJ), the GHG emissions were found to be significantly higher (831.5 to 1138.4 g CO2 equivalent). eq. / MJ (Ou et al., 2009), which yields findings comparable to those of the (Sun et al., 2022) investigation. Nonetheless, the investigation demonstrates that the solid catalyst impregnated with vanadium reduces GWP by 26.96%. compared to a commercial catalyst backed by hydroxyapatite.(Patel & Singh, 2023) It was discovered that the GHG emissions for **third-generation biofuels** have been computed by seven LCA studies. When it comes to regulating feedstocks, nutrients, and co-products as well as establishing system limits and process designs, these researches, however, employed various strategies, techniques, and presumptions. This has resulted in a wide range of GHG emissions, from 10.2 to 1910 g CO2 eq. /MJ. These results imply that, in comparison to diesel, microalgae diesel can either greatly lower or raise GHG emissions, according to the basic presumptions (Soratana et al., 2014).

Table 3 provides Comparison of damage categories using Eco-Indicator 99 and ReCiPe 2016 LCIA method. compares the endpoint or damage categories of Eco-indicator 99 and ReCiPe 2016 impact method for biofuel production. By comparing the two methods, it helps to assess the consistency and reliability of the results obtained. (Patel & Singh, 2023).

Feedstocks	Unit	Human health (Eco-Indicator 99)	Human health (ReCiPe 2016)	Ecosystem quality (Eco-Indicator 99)	Ecosystem quality (ReCiPe 2016)	Resources (Eco-Indicator 99)	Resources (ReCiPe 2016)
Rapeseed	%	47.6	94.5	5.7	3.2	46.6	2.4
Palm Oil	%	54.8	91.9	21.3	7.9	23.9	0.2
Used Cooking Oil	%	31.8	92.4	2.6	3.1	65.6	4.6
Jatropha	%	44.2	93.9	5.1	3.6	50.8	2.5

Microalgae	%	56.9	94.9	2.2	3.5	40.9	1.7

5. Other Environmental Impacts

Eco-Indicator 99 & ReCiPe 2016 are two well-known life cycle impact assessment (LCIA) techniques that are used to evaluate the wider environmental effects of biofuel production. Both approaches assess the possible harm from biofuel production in three primary domains: resource depletion, ecosystem quality, and human health (Touset et al., 2014).As summerized in **Table 4**.

Table 4 Stage wise GHG Contribution of Biodiesel. The respective tables provide the detailed information about the step-wise greenhouse gas contribution of the biodiesel into the environment.(Chopra et al., 2020; Deshmukh et al., 2019; Kalaivani et al., 2014; Kumar et al., 2012; Uppalapati et al., 2022; Vrech et al., 2019)

Biomass source	Cultivation (%)	Transportation (%)	Oil Processing (%)	Biofuel Production (%)
Jatropha	55–62	8–10	28–32	5–8
Soybean	34–40	16–23	18–24	18–26
Calophyllum	40	19	21	20
Rapeseed	68–72	8–11	5–7	11
Sugarcane	53–63	6–10	12–15	20–21
Palm Oil	40	6–12	7–9	41–46
Microalgae	30–33	–	20–23	43–47
Oleaginous yeast	40–43	–	2–6	49

Created the damage-oriented Eco-Indicator 99 technique, which aggregates different environmental loads into a single score according to their effects on resource consumption, ecosystem quality, and human health. It makes it evident which phases of the life cycle in biofuel producing systems are the most harmful (Huijbregts et al., 2017). characterize ReCiPe 2016 as a more sophisticated and standardized approach that incorporates both endpoint (damage-oriented) and midway (cause-oriented) indications. By connecting emissions including resource use to their ultimate impacts on ecosystems, health, and resource availability, this approach provides a more thorough assessment. In order to provide uniform and comparable results across studies, both methodologies are applied in accordance with the general life cycle assessment requirements provided by the ISO 14044 standard.

The environmental effects of various biofuel feedstocks were compared using these evaluation instruments. According to the investigation, used cooking oil has the least detrimental effects on human health in this category, while microalgae along with palm oil possess the worst.

Once more, palm oil has the biggest detrimental impact on ecosystem quality, whereas microalgae and used cooking oil have comparatively little effect. Palm oil is the least resource-efficient, rapeseed and jatropha have intermediate effects, and used cooking oil performs best in terms of resource depletion. Similar results were published by (Musharavati et al., 2023) and (Foteinis, (2020).), who showed that biofuels made from waste oils have less of an overall impact on the environment than those made from crops. Similar to this, (Kazemi et al., 2023)pointed out that although microalgae cultivation can provide larger yields, it frequently uses greater nutrition and energy, which has a greater impact on resources and health under both the Eco-Indicator 99 and ReCiPe frameworks. In conclusion, palm oil has the largest overall environmental impact, whereas used cooking oil is the most ecologically friendly feedstock overall. Microalgae have a high health effect but balanced performance in other categories, whereas jatropha and rapeseed are possibilities with an acceptable impact. Comparison of damage categories using Eco-Indicator 99 and ReCiPe 2016 LCIA method (Patel & Singh, 2023).

Air pollution:

When biodiesel, either pure or mixed with diesel, is burned, there are hardly any emissions of sulfur oxides or aromatic compounds and less CO, particulates, hydrocarbons, and sulfur compounds. When there is carbon monoxide in the exhaust gases, it means that there is inadequate mixing or an air fault, which results in inefficient combustion. CO emissions are reduced by 15% for biodiesel, 20% (BD20), and up to 40% for pure biodiesel (BD100) due to the higher amount of oxygen in plant-based fuels compared to fossil fuels, which are about 10% and 2%, respectively. In addition to losing their calorific value, unburned hydrocarbons can be harmful to human health and, in certain situations, can cause cancer, particularly when they are aromatic hydrocarbons. For BD100, utilizing biodiesel reduces unburned hydrocarbon emissions by around 15% to 20%. Additionally, since there are nearly no aromatic hydrocarbons present, there is little risk of an emission. Biodiesel's flue emissions don't include sulfur dioxide since it doesn't contain sulfur. The oxides of nitrogen are harmful air pollutants given that, in addition to irritating people, they also cause acid rain when there is moisture present and the so-called "photochemical smog" when there is intense solar radiation (volatile organic compounds, or VOCs, react with nitrogen oxides, or NOx, in the presence of sunlight and OH radicals, forming photo-oxidants)(Chien et al., 2009).The main environmental harm caused by using biodiesel is this kind of pollutant as its emissions rise by around 13% as a result of the higher concentration of oxygen. However, several studies also found NOx reductions of 4–26% when compared to diesel (Pinto et al., 2005). The typical size of the fragments that make up particulate matter and the chemicals that are adsorbed on their surface are closely related to the risk of particulate matter, which might lead to respiratory illnesses and even cancer. In engines powered by biodiesel, fine particulates—which are especially hazardous because they are easily inhaled—form in amounts of less than 20–60% as well as are less cancerous since there are fewer aromatic hydrocarbons present (Lopresto, 2025).

Stage wise distribution of GHGs

Water impacts:

The production of bio-feedstocks, especially first-generation biofuels, depends heavily on water usage (Dominguez-Faus et al., 2009). The growth of biofuel crops might result in a significant increase in world water use, and excessive irrigation can conflict with the demands of food production. This increased demand may exacerbate environmental effects in areas with limited water supplies. First generation biofuels use 36.2–540 m^3/GJ, whereas second-generation biofuels use 1.28–188.8 m^3/GJ. Because biofuels are produced in water-stressed locations, their water footprints (WF) can be 50–240 times greater than those of fossil fuels when regional water scarcity is taken into account (Berger et al., 2015). Since feedstocks are usually agricultural leftovers that have previously been taken into consideration in earlier LCAs, agriculture is not included in the second-generation biofuel analysis (Soam et al., 2016).

In Phase 1 of LCA, sugarcane used the most water, whereas sorghum stalk biofuel was determined to be more water-efficient (Mandade et al., 2015). While (Xie et al., 2017) observed that the ethanol WF of cassava and sorghum ranged from 1760 to 5290 L/L, primarily as a result of agriculture, (Mathioudakis et al., 2017) recorded the WF of rice straw at 129 L/kg. Similar to the findings of (Gerbens-Leenes & Hoekstra, 2011), (Arguelles-Arguelles et al., 2021)found that more than 90% of the water utilized in the manufacture of palm oil biodiesel (218–540 m^3/GJ) came from palm agriculture.WFs are much greater for third-generation biofuels, ranging from 373.4 to 1481 m^3/GJ (Siqueira et al., 2018; Wu et al., 2019). This is particularly true for microalgae-based fuels, which rely on regional water supplies and manufacturing techniques (Banerjee et al., 2019). Both blue WF (surface/groundwater for irrigation) and green WF (rainwater and soil moisture) constituents are included in the WF to account for process water, inputs, and credits from co-products (Mekonnen & Hoekstra, 2011; Patel & Singh, 2023).

Land-use and biodiversity impacts: Biomass for bioenergy depends on land, land-use change (LUC), both directly and indirectly, is a significant source to GHG emissions. LUC was responsible for 13 Gt CO_2-eq worldwide in 2019 (Lee et al., 2023). According to land-use databases, only 46% of the assessed studies incorporated LUC (Harris et al., 2015). Studies like (Fargione et al., 2008) and (Lapola et al., 2010), GHG emissions from LUC can occasionally be higher than those obtained by switching to biofuels from fossil fuels. Because land conversion adds substantial emissions and ecological stress, studies that include LUC generally show larger overall environmental impacts compared with those that do not. In line with (Spinelli et al., 2013), (Isler-Kaya & Karaosmanoglu, 2022) observed land-use impacts for safflower biodiesel production of 9.21 and 9.94 PDF·m²·yr for methyl (SOME) and ethyl esters (SOEE). According to (Humpenöder et al., 2013), removing LUC reduced GHG emissions by 50% as compared to fossil fuels(Bhonsle et al., 2022). found that the land-use consequences of UCO biodiesel were 6.59 m²a crop eq. for the room temperature scenario and 86.6 m²a crop eq. for traditional biodiesel (oil boiler use). According to(Chung et al., 2019), LUC effects were also seen throughout UCO processing: 1.26 PDF·m²·yr for transesterification, 0.472 PDF·m²·yr for catalyst preparation, and 0.433 PDF·m²·yr for pretreatment(Fernández-Tirado et al., 2016).(Carneiro et al., 2017; Gnansounou & Raman, 2016) and (Vrech et al., 2019) others all provided similar findings. In general, even while biodiesel lessen reliance on petroleum and other petroleum products, the additional emissions from land transformation generally offset their net environmental advantages when LUC impacts are considered.

1. Challenges and Limitations of LCA for Biodiesel

Biodiesel LCAs are much more complex due to high data variability in agriculture, production, and combustion stages, methodological challenges such as defining system boundaries, choosing functional units, selecting impact categories, and dealing with land-use change and biogenic carbon. Uncertainties arising from agricultural expansion and global supply-demand shifts. Market and land-use effects, which make environmental impact calculations less certain. These factors lead to inconsistent and varied LCA results even for similar biodiesel systems. The section aims to review these challenges systematically (Jeswani et al., 2020).

Regionalized Impact Assessment in LCA There are a number of obstacles and restrictions that limit the accuracy and practical use of regionalization in life cycle assessment (LCA). Detailed location-specific data is necessary for inventory and impact evaluations in regionalized life cycle assessments. However, especially for agricultural systems like the production of biodiesel, such region-specific statistics are frequently lacking, inconsistent, or unavailable. The accuracy of the results is limited by this lack of trustworthy data.

Local factors including soil type, temperature, and ecosystem sensitivity have a significant influence on environmental repercussions. It is methodologically challenging to account for these intricate, changing aspects across many places, which raises uncertainty in effect estimates. Current LCA approaches are limited in their capacity to depict genuine environmental differences in biodiesel production and consumption systems, despite the fact that agricultural phases are extremely site-dependent.Global categories like ozone depletion or global warming are simpler to evaluate consistently, while local and regional categories like eutrophication, acidification, land use, and water usage need region-specific modeling that is seldom used in practice because of its complexity. Real-world studies seldom conduct regionalized life cycle assessments (LCAs), which leads to uneven methodology and restricted cross-region comparability. Global standardization is challenging since even recent efforts to enhance regional effect categories are still region-specific, namely for the USA or Europe.

Accurate spatial modeling is necessary to translate environmental impacts onto local or regional scales, but spatial variability is frequently oversimplified, and mapping and characterization errors further reduce the dependability of regionalized LCIA conclusions. Overall, there are significant methodological, data-related, and practical obstacles to regionalized impact assessment in LCA. The quality and consistency of LCAs linked to biodiesel are severely constrained by the lack of thorough regional data, the complexity of local environmental circumstances, and the limited worldwide application of current models (Rajaeifar et al., 2018).

Lack of standardized methodologies

The absence of defined procedures presents significant obstacles for biofuels' life cycle assessment (LCA). Due to variations in assumptions, data quality, system boundaries, and impact models, studies on greenhouse gas emissions and other environmental consequences can provide wildly disparate conclusions. Both Attributional (ALCA) and Consequential (CLCA) approaches lack common techniques, even if they adhere to generic ISO standards (14040 and 14044). This is particularly true in areas such as indirect land-use change (ILUC), soil carbon modeling, N2O emissions, and counterfactual scenarios.This discrepancy creates doubt and makes it challenging to compare findings from different research or geographical areas. Furthermore, modeling is made more difficult by dynamic elements including shifting supply chains, plant regrowth, and variations in soil carbon. The policy relevance of many LCAs is further limited by their failure to incorporate socioeconomic and ecosystem-level consequences. Standardized models for ILUC and biogenic carbon accounting, accessible databases, and methodological harmonization are all critically needed to overcome these problems. Without these, biofuel LCAs continue to be dispersed, rendering their findings untrustworthy for sustainable policy and decision-making (Jeswani et al., 2020).

Future perspective:

Enhancing the use of life cycle assessment (LCA) in biodiesel production systems offers numerous important prospects. First and foremost, harmonizing methodological frameworks is imperative. Future LCAs should openly disclose uncertainty and sensitivity analyses and conform more closely to standards like ISO 14040/44. The second step is to improve the data's temporal and regional specificity. Instead of locally measured data, a large number of current LCAs rely on generic inventory databases. The review on biodiesel made from waste cooking oil (WCO), for instance, highlights the significance of logistics, transportation distances, and energy mixes that are specific to a given context. Environmental estimates will be more accurate if geospatially explicit inventories and dynamic modeling of feedstock cultivation, conversion, and grid electricity are included. Third, to account for wider environmental and societal trade-offs, impact assessments should go beyond energy balance and GHG emissions. Reviewing environmental performance by itself is not enough to direct investment and policy choices. Integrating social, economic, and environmental metrics will allow for a comprehensive assessment of sustainability for biodiesel pathways. Fourth, the environmental effects of new feedstocks and production technologies, like advanced catalysts or algal systems, must be evaluated early on in the development process using life cycle assessment (LCA). Despite its great potential, the study on microalgae-derived biodiesel shows that there are still a lot of unknowns in real-world data and energy regimes. Sixth, increasing the robustness of LCA requires stakeholder engagement, open inventory sharing, and data transparency. Creating verified, shared life cycle inventory (LCI) databases tailored to regions and biodiesel feedstock would help with meta-analysis and uncertainty reduction. Lastly, policy-relevant scenarios and the integration of the circular economy must be supported by future LCAs to direct the deployment of sustainable biodiesel. In conclusion, standardized methodology, location/temporal specificity, a wider impact scope (environmental + social + economic), integration with TEA/LCC, evaluation of new pathways, improved data transparency, and alignment with policy and circular economy frameworks should be characteristics of the next generation of biodiesel life cycle assessments. By doing this, LCA can realize its full potential.

Conclusion

In conclusion, this research thoroughly examined the life cycle assessment (LCA) of producing biodiesel from a variety of feedstocks, focusing on the energy balances, greenhouse gas (GHG) emissions, and wider environmental effects of each. The results show that there is a considerable variation in the environmental performance of biodiesel made from various feedstocks, including vegetable oils, leftover cooking oil, animal fats, and algae. While some approaches provide good energy returns and lower greenhouse gas emissions when compared to petroleum diesel, others have significant trade-offs, especially when it comes to water use, fertilizer use, and land use. Additionally, the study emphasizes that feedstock origin, local production circumstances, and technical efficiency all have a significant role in the overall sustainability of biodiesel. Alternatives that are more sustainable include waste-based and algae-based biodiesel, which typically exhibits reduced life-cycle emissions and improved energy efficiency. Direct comparisons are made more difficult by methodological flaws in LCA research, data ambiguity, and geographical heterogeneity, which continue to be constraints. To strengthen sustainability evaluations, future studies should focus on standardizing LCA techniques, incorporating indirect land-use change consequences, and adding socioeconomic factors. In conclusion, biodiesel is still a potential renewable fuel, but its benefits for the environment and the economy depend on the use of sophisticated, resource-efficient production techniques and the choice of suitable feedstocks.

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