



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

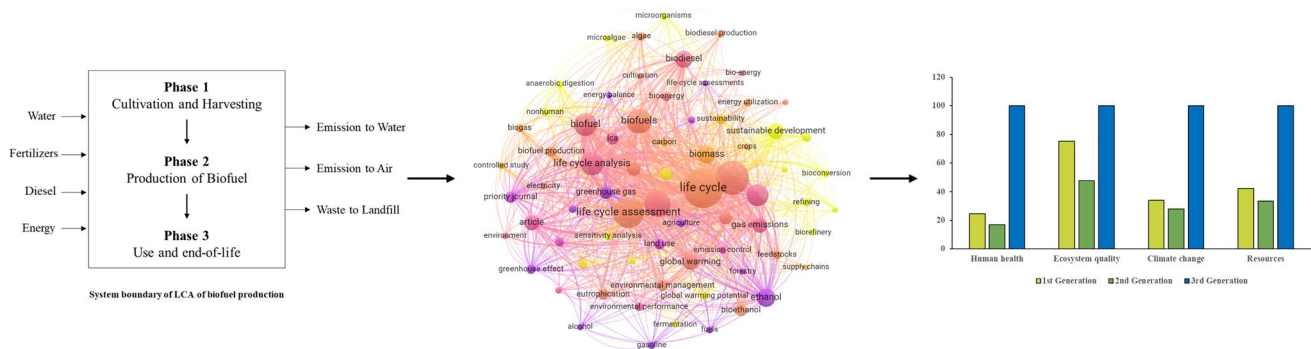
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Abstract

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 The literature review focused mainly on research published from 2012 to 2022 to avoid outdated information.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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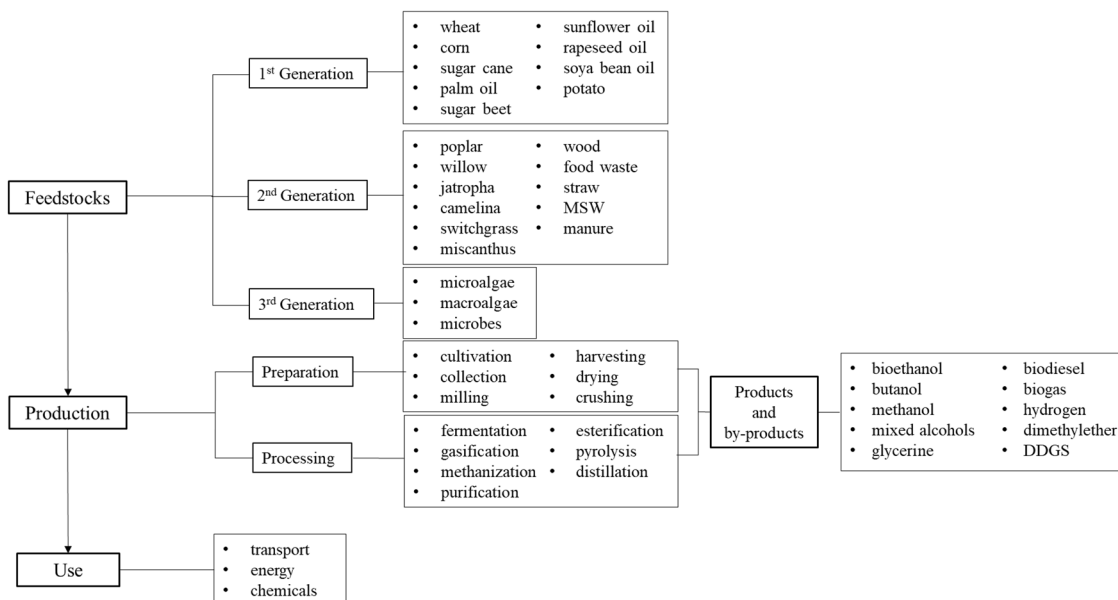


Fig. 1 Feedstock and production processes for different biofuels

a critical problem (Fawzy et al. 2020; Osman et al. 2021a). 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 2019, the total energy supply worldwide increased 2.6 times, from 230 to 606 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 2021). 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 (Sims and Schaeffer 2014; Uusitalo et al. 2014; Jeswani et al. 2020). 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.

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-based crops (first generation), lignocellulose-based (second generation) (Chen et al. 2019), and algae-based (third generation) (Kumar Sharma et al. 2021; Ocreto et al. 2021). Figure 1 provides an outline of several biofuel types, feedstocks, and conversion pathways.

Systems for producing, converting, and supplying sustainable renewable energy must be effective and sustainable in terms of the environment, the economy, and society for both the present and future. Identifying biofuel sources can potentially lessen the environmental effect 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 lower energy use and improve energy security by using fewer 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 the conversion of starch or biomass with high sugar content (like sugar cane or grains) into sugar, which is then fermented and distilled. Another method for producing bioethanol or bio-oil is through 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 (Sinha et al. 2013; Foteinis et al. 2020). 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. Some of the research that suggests that biofuel production using a biorefinery platform might lower carbon emissions is shown in Table 1. Brazil is the global leader with a fleet of vehicles that uses gasoline-ethanol blends with a 27% content (USDA 2021a). In all of its fleet vehicles, the United States now uses roughly 7.1% biofuels, while the European Union (EU) has a bold ambition to utilize 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).

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, a life cycle assessment (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 carbon footprints of various liquid biofuels (Khanna et al. 2011). The study evaluates the techniques and environmental sustainability of biofuels by examining the prior LCA studies, highlighting significant methodological approaches, and presenting critical conclusions.

Bibliometric analysis

To locate pertinent publications and pinpoint areas where research on the environmental effects of biofuel production is lacking, a search strategy using Boolean operators was employed in the WoS core collection database. The bibliometric mapping data shown in Figure S1a (Online Resource) were obtained from the WoS and visualized using VOSviewer software to show the co-occurrence of keywords in the literature from 2012 to 2022. Bibliometric research methodology: TOPIC: "life cycle assessment" AND TOPIC: 'Biofuels' OR TOPIC: 'Bioethanol' OR TOPIC: 'Biodiesel'

Table 1 Carbon emission reduction from various feedstocks during the biofuel production

Feedstock	Products & Co-products	Reduction in CO ₂ emissions	References
Sugarcane	Bioethanol, Biogas, Electricity, steam, and power	40–70%	(Gnansounou et al. 2015; Silalertruksa et al. 2017)
Palm oil	Biodiesel	20–25%	(Lim and Lee 2011; Lee and Ofori-Boateng 2013)
Corn stover & wheat straw	Bioenergy	47–50%	(Cherubini and Ulgiati 2010; Gallejones et al. 2015)
Forest residue	Biodiesel, Biogas, Electricity	51–80%	(Karlsson et al. 2014; Spatari et al. 2020)
Jatropha, Sorghum	Biodiesel	75–80%	(Kumar et al. 2012; Vrech et al. 2019; Martinez-Hernandez et al. 2019)
Rapeseed	Biodiesel, Energy	30–50%	(Fernández-Tirado et al. 2016; Gupta et al. 2022)
Used cooking oil	Biodiesel	30–55%	(Vrech et al. 2019; Bhonsle et al. 2022)

OR TOPIC: ‘Lignocellulosic.’ The bibliographic search was limited to articles and reviews, and only documents published between 2012 and 2022 were taken into account. Over ten years (2012–2022), 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 S1b (Online Resource) 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, greater research is needed on social life cycle assessment, water footprint, waste management, bio-economy, land use change, and techno-economic analysis.

The bibliometric analysis shows a diverse geographical distribution of research. The United States takes the lead, accounting for 24% of the studies, followed by China at 12%. Europe also emerges as a significant contributor, with noteworthy contributions from countries like the UK (8%), Italy (6%), Spain (6%), Germany (5%), and France (3%). Moreover, emerging economies such as Brazil (8%) and India (7%) demonstrate a growing interest in this field, showcasing significant research efforts, as shown in Figure S2 and Figure S3 (Online Resource). These findings highlight the global reach and interest in LCA studies of biofuels across different regions. The network map of keyword co-occurrence among 53 research is shown in Figure S4 (Online Resource) and was created using the VOSViewer (Perianes-Rodriguez et al. 2016) full counting approach.

Methodology and framework

Literature search and selection criteria

We performed a literature search in different databases, including Web of Science (WoS), Scopus, Science Direct, and PubMed, to identify peer-reviewed studies on the sustainability of biofuels. 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 literature search mainly concentrated on studies published between 2012 and 2022 to minimize obsolete material. A total of 53 articles were selected for analysis in the present study, including the life cycle analysis of biofuels, the geographic location, functional unit, feedstock used, impact assessment methodology, system boundaries, and findings. The articles consist of different kinds of biofuels from various feedstocks, classified into first, second, and third generations, with over 25 types of feedstocks being used. Table 2 shows an overview of the evaluated studies on

feedstock, life cycle tools, impact methods, and functional units. Among the selected articles, 26% evaluated first-generation biofuels, 57% evaluated second-generation biofuels, and 17% evaluated third-generation biofuels.

Life cycle assessment

LCA is a method or procedure used to evaluate the potential environmental effects of a product, process, or activity by considering every step of the products and the raw materials supply chains, from production to final disposal. It was carried out in accordance with the ISO 14040:2006 and 14044:2006 standard framework to ensure that exact conclusions were achieved (Wang et al. 2013a; Chau et al. 2015; Patel and Singh 2022a). An LCA study might be from “cradle to grave” or “cradle to gate,” depending on the goal and scope (Khoo et al. 2019). Figure 2a shows the generalized system boundaries for the production of biofuels. Phase 1 includes cultivation, use of water, diesel, fertilizers, and air and water emissions due to the cultivation and harvesting process. Phase 2 includes the conversion of biomass to biofuels through various processes, the use of energy, and the associated emissions to air and water. Phase 3 incorporates biofuel and co-product transportation and emissions due use of biofuel. According to ISO 14,040, LCA consists of four phases: (i) goal and scope; (ii) life cycle inventory (LCI); (iii) life cycle impact assessment (LCIA); and (iv) interpretation.

Goal and scope definition

This initial step in every LCA study critical for understanding general outcomes and LCA findings, including defining the functional units and system boundaries (ISO 2006a; Harris et al. 2016). Figure 2b shows the percentage of reviewed studies considering different phases of the system boundary. All the studies have considered Phase 2 of the LCA system boundary, and only 14 studies have considered all three phases in the reviewed studies. This suggests that only a small number of studies have considered the use phase of biofuel and compared them with conventional fuels, indicating a significant gap in the LCA application for decision-making. The functional unit (FU) acts as a reference point for linking inputs and outputs. This reference point is essential to ensure that LCA outcomes are comparable; this is especially critical when comparing different systems and ensuring that comparisons are made consistently (ISO 2006b; Martínez-Blanco et al. 2011; Patel and Singh 2022b). Figure 3 shows the percentage of reviewed studies considering different FUs with land use change (LUC) and without LUC analysis. It was observed that 22 studies had used biomass production as FU (kg or ton of biofuel produced), 18 studies had considered the unit of bioenergy (MJ, GJ, or

Fig. 2 a General system boundaries of LCA of biofuel production, **b** Phases of LCA for production of biofuels considered in the reviewed studies

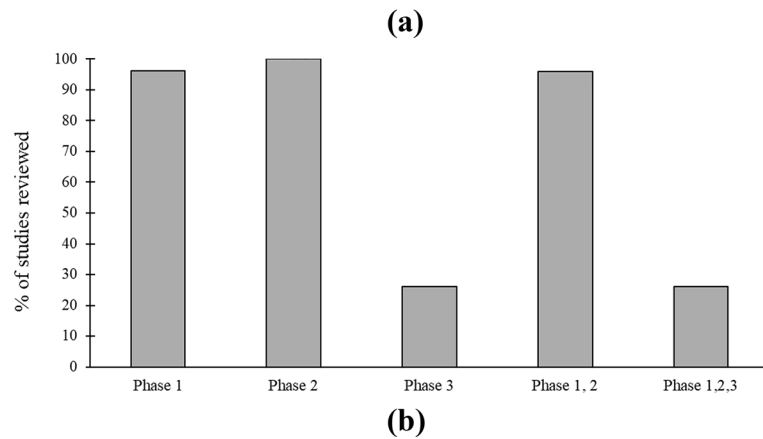
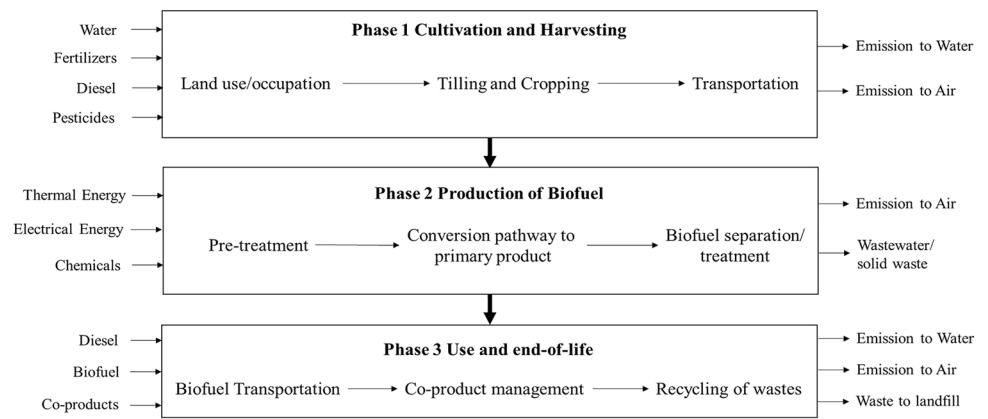
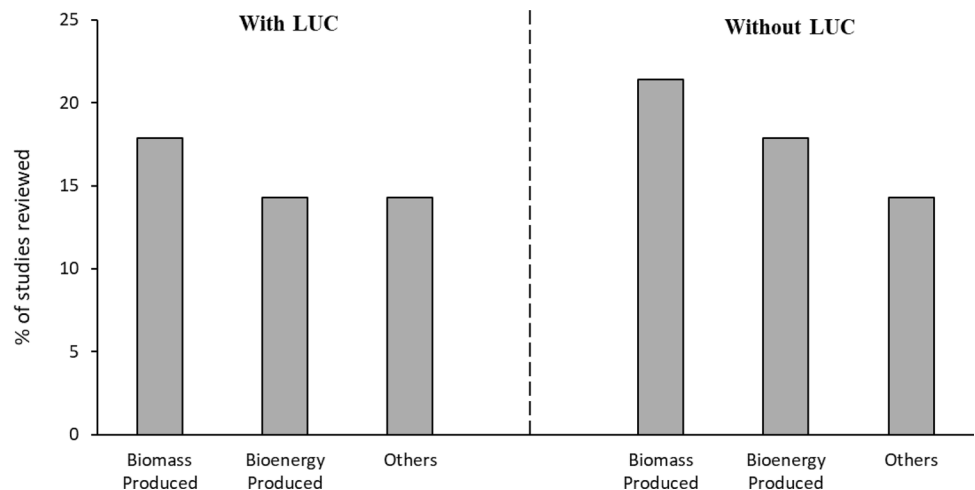


Fig. 3 Types of functional units used in reviewed LCA studies



kWh of energy produced) production as FU and 16 studies had used other FUs (Litre of biofuel, per km of car driven, and per hectare-area) (Borrion et al. 2012; Sreekumar et al. 2020; Isler-Kaya and Karaosmanoglu 2022).

Life cycle inventory and life cycle impact assessment

The LCI methodology includes gathering and evaluating information regarding the resources used, such as materials,

energy, and water, and the emissions generated at every phase of the production of biofuels. LCI provides a detailed inventory of inputs and outputs of the biofuel production process (Chung et al. 2019; Chopra et al. 2020), while LCIA evaluates the potential environmental impacts associated with these inputs and outputs, including emissions from the cultivation of feedstocks, transportation, and processing of biofuel and helps in understanding the results of LCI (Rocha et al. 2014).

Fig. 4 Frequencies of LCIA methods in reviewed studies

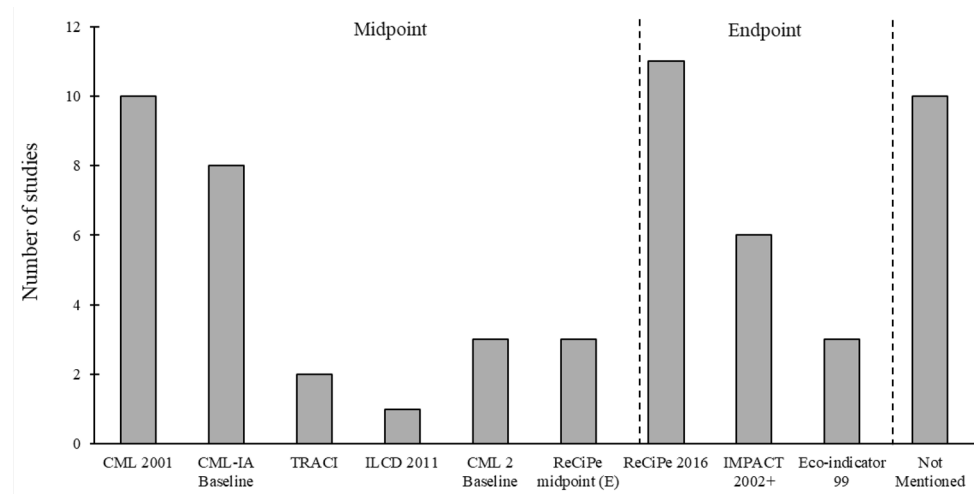
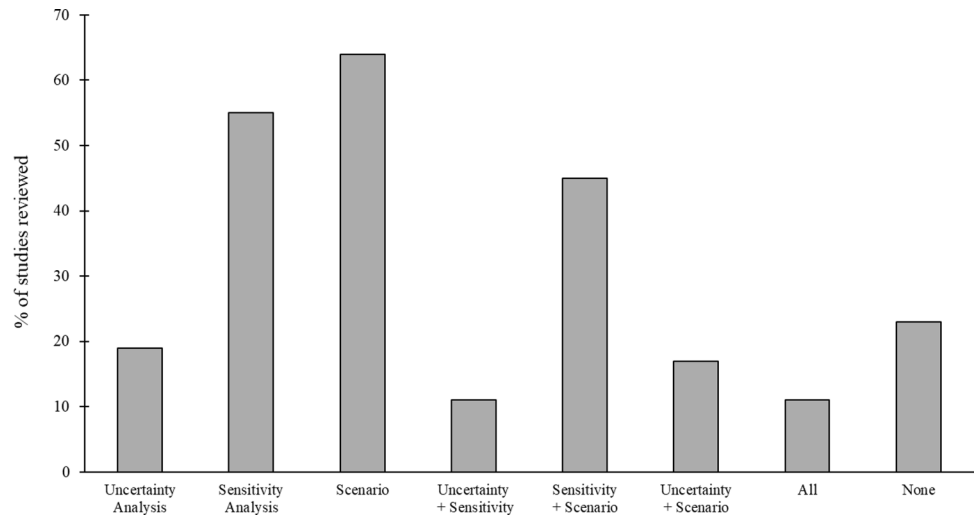


Fig. 5 Details of uncertainty, scenario, and sensitivity analysis in the reviewed studies



The database used for inventory analysis is shown in Table 2. IMPACT 2002+, ReCiPe 2016, EDIP 2003, CML, Ecopoint 97, Eco-indicator 99, and TRACI are the standard methods used to evaluate environmental impacts (ILCD 2010; Owsianiak et al. 2014). Figure 4 shows the no. of different impact methods used in reviewed studies and grouped into midpoint and endpoint impact categories.

Uncertainties and sensitivity analysis

LCA studies are models that are simplified representations of real-world systems and are thus fundamentally uncertain (Wang and Shen 2013). LCA includes trade-offs between numerous competing factors and, sometimes, uncertainty in relevant aspects (Guinée et al. 2017). The distribution of different environmental emissions, resource consumption, or effect categories may represent one of these uncertainties. The LCIA can also lead to uncertainty in the result. Endpoint impact categories have significantly more uncertainty

but can produce more intelligible findings (Bare et al. 2000), whereas the midpoint method is less scientifically challenging and has much lower uncertainty (Gnansounou and Kenthorai Raman 2016). As shown in Fig. 5, only 19% of studies have done uncertainty analysis. These uncertainties can be reduced by using more precise data (Michiels and Geeraerd 2020; Ubando et al. 2022). The uncertainty for each effect category is calculated by dividing the standard deviation by the mean (Sharma et al. 2020). The calculation of uncertainties is performed on a study-specific basis. Each included study has its own mean values and corresponding standard deviations determined by the data and methodology employed in that particular study. Consequently, the uncertainties vary depending on the specific study and the effect category being considered. It considers uncertainties in data, models, and assumptions used in the analysis. The goal is to provide a measure of confidence or reliability in the reported results. Uncertainty analysis involves identifying sources of uncertainty, estimating their magnitude, and

Table 2 Characteristics of LCA research analyzed in the present study

S.No.	Biomass source	Location	System boundary	Functional unit	Software	LCA method	Database	Year	References
1	Used rice bran oil (URBO)	India	CTGa	1 kg biodiesel production	OpenLCA	CML 2001	Ecoinvent 3.5	2022	(Pradhan et al. 2022)
2	Safflower	Turkey	CTGa	Using a new medium-sized car for 100 km	Simapro	Eco-Indicator 99; IPCC	Ecoinvent	2022	(Isler-Kaya and Karaosmanoglu 2022)
3	Rapeseed oil	UK	CTGa	1-ton biodiesel production	n/i	CML 2001	n/i	2022	(Gupta et al. 2022)
4	Used cooking oil	India	CTGa	1 ton of Biodiesel	Simapro	ReCiPe 2016	Ecoinvent	2022	(Bhonsle et al. 2022)
5	Sugarcane bagasse	India	CTGa	1 kg of Bio-CNG	OpenLCA	ReCiPe 2016	n/i	2022	(Munagala et al. 2022)
6	Safflower	Malaysia	CTGa	1 MJ bioethanol produced	Simapro	IMPACT 2002+	Ecoinvent 3.0	2022	(Hosseinzadeh-Bandbafha et al. 2022)
7	Rice straw	China	FTGa	1 metric ton dry rice straw	OpenLCA	CML 2001	Ecoinvent 3.7	2022	(Alengebawy et al. 2022)
8	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)
9	Date palm waste	Tunisia	CTGa	1 GJ synthetic diesel and gasoline	Simapro	ReCiPe 2016	Ecoinvent; PSILCA	2021	(ben Hnich et al. 2021)
10	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)
11	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-Muhtaseb et al. 2021)
12	Borassus flabellifer	India	CTGa	1 kg biodiesel	Simapro v9.0	IMPACT 2002+	Ecoinvent 3.0	2021	(Mukhopadhyay and Chakraborty 2021)
13	Crop residues	China	CTG	1t of crop residues	Gabi	CML2001	GaBi database	2021	(Yang et al. 2021)
14	Estuarine microalgae	India	CTGa	one-hectare area	OpenLCA	CML – IA	Ecoinvent 3.6	2020	(Saranya and Ramachandra 2020)
15	Spent coffee grounds	United Kingdom	CTG	treatment of 1 tonne of SCG	Gabi	ReCiPe 2016	Ecoinvent 3.3	2020	(Schmidt Rivera et al. 2020)
16	Used cooking oil	Greece	CTGa	production of 1 ton biodiesel	Simapro 8	ReCiPe	Ecoinvent 3	2020	(Foteinis et al. 2020)
17	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)
18	Rice husk	Southeast Asia	GaTGa	1 kg of biohydrogen produced	OpenLCA	CML 2001	Ecoinvent 3.5	2020	(Reaño 2020)
19	Rice straw	India	CTGa	1 L of ethanol	OpenLCA	ILCD 2011 midpoint	Ecoinvent 3.3	2020	(Sree Kumar et al. 2020)
20	Forest residues	USA	CTGa	1 MJ of renewable diesel	Gabi	n/i	Ecoinvent; GaBi 9 database	2020	(Spatari et al. 2020)

Table 2 (continued)

S.No.	Biomass source	Location	System boundary	Functional unit	Software	LCIA method	Database	Year	References
21	Oleaginous yeast	India	CTGa	300 L biodiesel	SimaPro v8.0	ReCiPe End-Point (H); IMPACT 2002+	Ecoinvent 3.1	2020	(Chopra et al. 2020)
22	Desmodesmus	China	CTGa	1 kg microalgae	n/i	n/i	n/i	2020	(Li et al. 2020)
23	Waste cooking oil	Malaysia	CTGa	1000 kg of biodiesel production	SimaPro	CML 2001 and Eco-indicator 99	Agribalyse; NEEDS	2019	(Chung et al. 2019)
24	Microalgae	Taiwan	CTGa	100 MJ petrofuel produced; 1 kg biofuel	SimaPro	ReCiPe	Ecoinvent 3.5	2019	(Wu et al. 2019)
25	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)
26	Biowaste	EU-27	CTGa	1 MW of Biomethane	SimaPro	IMPACT 2002+	Ecoinvent 3.2	2019	(Ardolino and Arena 2019)
27	Palm oil	Malaysia	GaTGa	1 tonne of anhydrous bioethanol produced.	SimaPro	CML 2 baseline 2000	SimaPro database	2019	(Mohd YUSOF et al. 2019)
28	Jatropha	Cameroon	WTT; WTT	1 MJ of Jatropha vegetable oil	SimaPro	n/i	Ecoinvent 2.0; JEC E3-database	2019	(Vrech et al. 2019)
29	Sweet potato	Brazil	CTGa	1 MJ of bioethanol produced	SimaPro	CML IA Baseline	Ecoinvent 3.1	2018	(Costa et al. 2018)
30	Phormidium Autumnale	Brazil	CTGa	1 kg biodiesel	Chromatography Station T2100p (Plus Edition) v9.04 software	n/i	n/i	2018	(Siqueira et al. 2018)
31	Sweet potato	China	CTGa	1000 L of 99.5% bioethanol production	Microsoft Excel 2013	CML - IA 2000	CML database	2017	(Zhang et al. 2017)
32	Microalgae	Europe; Brazil	CTG	1 MJ of Biofuel	-	IMPACT 2002+	Ecoinvent; ELCD	2017	(Carneiro et al. 2017a)
33	Beef tallow	Brazil	CTGa	1 MJ of biodiesel	GaBi	CML 2001	GaBi 6.3 database	2017	(Sousa et al. 2017)
34	Pulp and paper sludge	n/i	CTGa	1 MJ of bioethanol produced	SimaPro	CML - IA	Ecoinvent 3.1; Agri-footprint	2016	(Sebastião et al. 2016)
35	Microalgae	India	WTT; TTW	1 kg biodiesel	SimaPro	ReCiPe midpoint (E)	SimaPro database	2016	(Gnansounou and Kenthorai Raman 2016)
36	Soybean; Rapeseed oil	Spain	CTGa	1 GJ	SimaPro	ReCiPe	Ecoinvent 3.1; PestLCI; MAGRAMA	2016	(Fernández-Tirado et al. 2016)
37	Rice straw	India	CTG	1 MJ of transportation fuel	Excel	n/i	NREL reports; Lab experiments	2016	(Soam et al. 2016)

Table 2 (continued)

S.No.	Biomass source	Location	System boundary	Functional unit	Software	LCIA method	Database	Year	References
38	Lignocellulosic	UK	CTG	1 L of ethanol	GaBi	CML 2	Ecoinvent 2.2	2015	(Jeswani et al. 2015)
39	Palm oil	n/i	CTG	n/i	SimaPro	CML 2000	Ecoinvent 2.1	2015	(Arpornpong et al. 2015)
40	Sugarcane	Brazil	WTT; TTW	1 ton of sugarcane; 1 km of car operation	SimaPro	ReCiPe midpoint (E)	Ecoinvent 3.0	2015	(Gnansounou et al. 2015)
41	Rice husk	India	CTGa	1 L of ethanol	-	-	NREL	2015	(Mandade et al. 2015)
42	Wheat; Rapeseed	Spain	WTT	1 MJ biofuel energy content	SimaPro	CML 2000	Ecoinvent 2.0	2015	(Gallejones et al. 2015)
43	Sugarcane; Soybean; and Palm oil	Brazil	WTT	1 MJ of energy released by combustion of bioethanol, biodiesel	SimaPro	CML 2 Baseline 2000	n/i	2014	(Rocha et al. 2014)
44	Microalgae	US	CTGa	2 million gallons of microalgal biodiesel per year	n/i	TRACI 2	Ecoinvent 2.0; LCA Food DK; EIA; DOE; ERS; USDA	2014	(Soratana et al. 2014)
45	Palm oil; Jatropha; Rapeseed oil	n/i	CTGa	1 MJ of produced renewable diesel	GaBi	n/i	GaBi database	2014	(Uusitalo et al. 2014)
46	Maize; Sugar beet; Sugarcane; Wheat	n/i	CTGa	1 kg of ethanol	SimaPro	ReCiPe	SimaPro database	2014	(Muñoz et al. 2014)
47	Palm oil	Malaysia	WTW	1 kg of palm oil methyl ester (PME)	GaBi	Eco-Indicator-99	Ecoinvent	2013	(Lee and Ofori-Boateng 2013)
48	Sweet potato	China	CTGa	1000 L of bioethanol produced	Microsoft Excel 2003	CML-IA	n/i	2013	(Wang et al. 2013b)
49	Rapeseed oil	Spain	CTGa	1 ton of biofuel	SimaPro	CML	Ecoinvent	2013	(González-García et al. 2013a)
50	Wheat straw	UK	WTW	to drive 1 km in a Flexible-fuel vehicle (FFV)	SimaPro	CML Baseline 2000	Ecoinvent 2.2	2013	(Wang et al. 2013a)
51	Jatropha	India	CTG	1 ton of biodiesel produced	n/i	n/i	CEA database; IPCC	2012	(Kumar et al. 2012)
52	Wheat straw	n/i	WTGa	1 km distance by a passenger car; 1 kg of ethanol produced	SimaPro	ReCiPe midpoint	Ecoinvent	2012	(Borrion et al. 2012)
53	Microalgae	n/i	WTW	8.94 10 ¹⁰ MJ/year of biodiesel	GREET	IMPACT 2002+; TRACI	ETH-ESU; Ecoinvent 2.0; BUWAL250; IDEMAT	2012	(Soratana et al. 2012)

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

propagating them through the LCA model to determine their impact on the final results.

The LCA performs a sensitivity analysis by varying a parameter's upper and lower limits and running simulations with different combinations of parameter values. This method is used along with scenario analysis to evaluate how uncertain factors may affect the results (Eggemann et al. 2020). Sensitivity analysis determines which step in the biofuel manufacturing life cycle is directly responsible for the negative environmental impacts.

In LCA, a scenario refers to a specific situation or future projection that is represented through a defined set of assumptions and choices. These scenarios encompass the system boundaries and assumptions about the inputs and outputs of the analyzed product or system (Arguelles-Arguelles et al. 2021). They serve as a means to capture distinct conditions and provide a foundation for analysis and comparison. Scenario analysis entails evaluating the environmental impacts under various hypothetical scenarios or alternative future pathways (Yang et al. 2021). It allows for the exploration of different configurations, technologies, materials, or strategies within the system to gain insights into their potential effects on the overall environmental performance. As shown in Fig. 5, the majority of the reviewed studies (64%) have considered scenario-based analysis. By comparing different scenarios, decision-makers can assess the consequences of different choices and make well-informed decisions.

Interpretation

The interpretation phase considers the impact assessment results and the inventory analysis outcomes (ISO 2006a). The analysis results, together with all the decisions and assumptions made during the process, are examined and analyzed, and broad conclusions are drawn (Osman et al. 2021b). The aim is to arrive at conclusions that back up a decision or produce an LCA result that is easy to comprehend.

Environmental sustainability of biofuels

Carbon footprint

Most LCA biofuel studies focus on GHG emissions and reductions compared to fossil fuels. Biofuel LCA studies also consider other environmental impact categories, such as acidification, eutrophication, photochemical smog, human toxicity, and ecotoxicity. LCA studies show inconsistent conclusions for Global Warming Potential (GWP), ranging from favorable to unfavorable, even for the same feedstock. This is due to assumptions, data sources, allocation procedures,

and LUC variations. GHG emissions are converted to g CO₂ eq. per MJ to compare data from different studies. The lower heating values are assumed to be 27 MJ/kg and 38 MJ/kg for bioethanol and biodiesel, respectively (Yan and Crookes 2009), whenever these statistics are not stated in the original research. The use phase of the biofuel is not considered in the subsequent analysis.

First-generation biofuels

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 Fig. 6a and b, respectively. When the average values are taken into account, the GWP of most of the first-generation biofuels is less than those of conventional gasoline (72.8 to 96 g CO₂ eq. / MJ (González-García et al. 2010a, b; Ou et al. 2009) and diesel (80 to 120 g CO₂ eq. / MJ (Ou et al. 2009; Shirvani et al. 2011; Passell et al. 2013), except for Rapeseed biodiesel.

Some LCA studies that have been analyzed show rapeseed biodiesel emits 2.8 to 350 g CO₂ eq. / MJ of energy (González-García et al. 2013b; Uusitalo et al. 2014; Gupta et al. 2022). 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 drying and cooling of seeds, oil extraction, and refining was minimal. According to the study by (Arguelles-Arguelles et al. 2021), GHG emission was negative for biodiesel production from palm oil because of the amount of carbon dioxide captured during the cultivation phase being more than biofuel's GHG emission. Most studies on palm oil, soybeans, and sugarcane (Lee and Ofori-Boateng 2013; Rocha et al. 2014; Arpornpong et al. 2015; Fernández-Tirado et al. 2016; Munagala et al. 2022) indicated lower GHG emissions than conventional gasoline. The growing and harvesting phase (Phase 1, Fig. 2a) 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 3. Most reviewed studies show a reduction in GHG emissions for first-generation biofuel compared to conventional diesel and gasoline.

Second-generation biofuels

The GHG emissions of second-generation biofuels vary 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 Fig. 6c and d, respectively. These discrepancies result from various factors such as the feedstock used, the production routes, different technological assumptions, and differences in methodology

Table 3 Stagewise GHG contribution of biofuel production

Biomass source	Percentage of GHG Contribution				References
	Cultiva- tion	Transporta- tion	Oil / Juice processing	Biofuel produc- tion	
Jatropha	55–62	8–10	28–32	5–8	(Kumar et al. 2012; Kalaivani et al. 2014; Vrech et al. 2019; Uppalapati et al. 2022)
Soybean	34–40	16–23	18–24	18–26	(Rocha et al. 2014; Fernández-Tirado et al. 2016; Uppalapati et al. 2022)
Calophyllum inophyllum	40	19	21	20	(Uppalapati et al. 2022)
Rapeseed	68–72	8–11	5–7	11	(Uusitalo et al. 2014; Fernández-Tirado et al. 2016; Gupta et al. 2022)
Sugarcane	53–63	6–10	12–15	20–21	(Rocha et al. 2014; Gnansounou et al. 2015; RSB 2020; Munagala et al. 2022)
Palm Oil	40	6–12	7–9	41–46	(Lee and Ofori-Boateng 2013; Uusitalo et al. 2014; Mohd YUSOF et al. 2019)
Microalgae	30–33	–	20–23	43–47	(Pragya and Pandey 2016; Deshmukh et al. 2019; Uppalapati et al. 2022)
Oleaginous yeast	40–43	–	2–6	49	(Jain et al. 2018; Chopra et al. 2020)

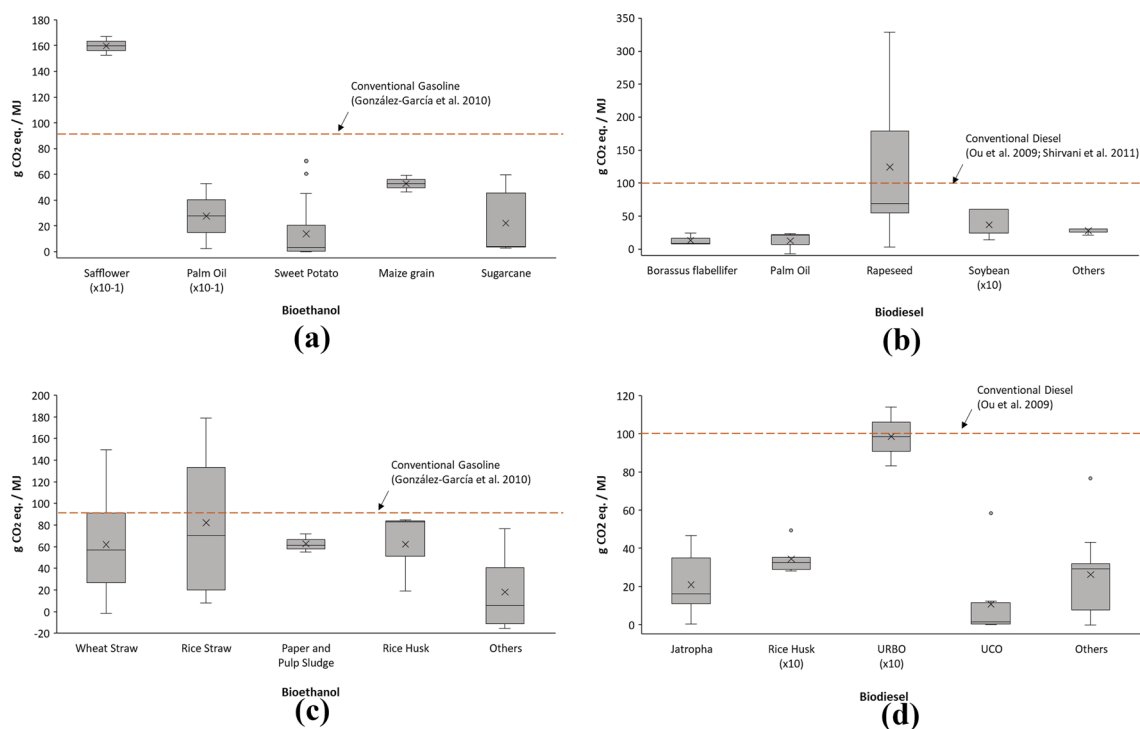
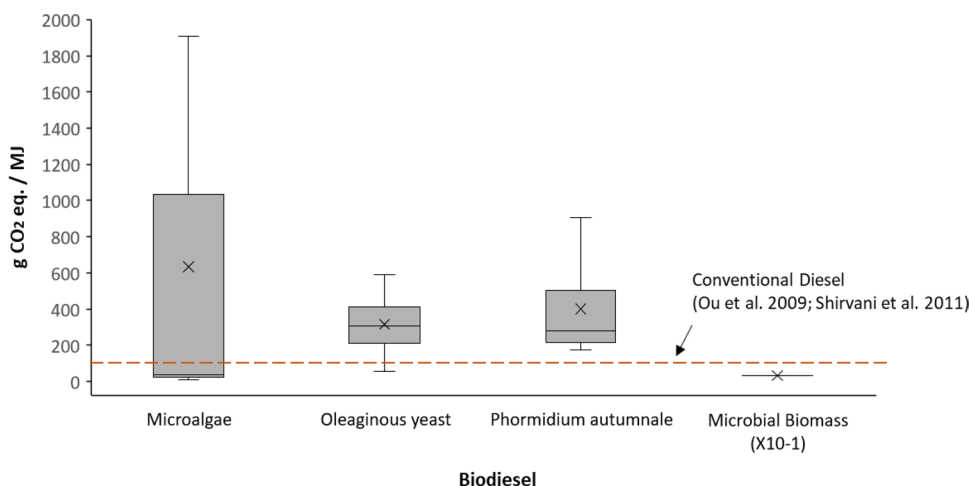


Fig. 6 GHG emissions for **a** bioethanol and **b** biodiesel from first-generation biofuels; **c** bioethanol and **d** biodiesel from second-generation biofuels

used for the analysis. It should be highlighted that technological uncertainties are particularly important when evaluating their potential because advanced biofuels have not yet reached full commercialization. As a result, the quality of the information that is now accessible is not as strong as in the case of the well-known first-generation biofuels

(Mohd YUSOF et al. 2019; Kovacs et al. 2022). The GWP of lignocellulosic biofuel produced from agricultural and forestry wastes is often lower than biofuel produced from energy crops (Gandam et al. 2022). This is mainly caused by N₂O emissions from fertilizers while growing energy crops (Olukoya et al. 2014; Jeswani et al. 2020). Assuming that

Fig. 7 GHG emissions for biodiesel from third-generation biofuels



residues do not have any environmental effects and are solely linked to the primary crop from which the waste is generated, then the adverse effects related to the primary crop can be prevented 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 for the production of biofuels. (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. 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 effects on the environment, including the emission of greenhouse gases (-0.212 g CO₂ eq. per MJ). The high energy output of waste-to-energy conversion technologies and credits for replacing the electricity mix that is dominated by fossil fuels mitigate the negative impacts of these valorization routes. (Pradhan et al. 2022) analyzed biodiesel production from used rice bran oil through esterification and transesterification processes. The GHG emissions were found to be very high (831.5 to 1138.4 g CO₂ eq. / MJ) than conventional diesel (102 g CO₂ eq. / MJ (Ou et al. 2009), which has similar results as the study by (Sun et al. 2022).

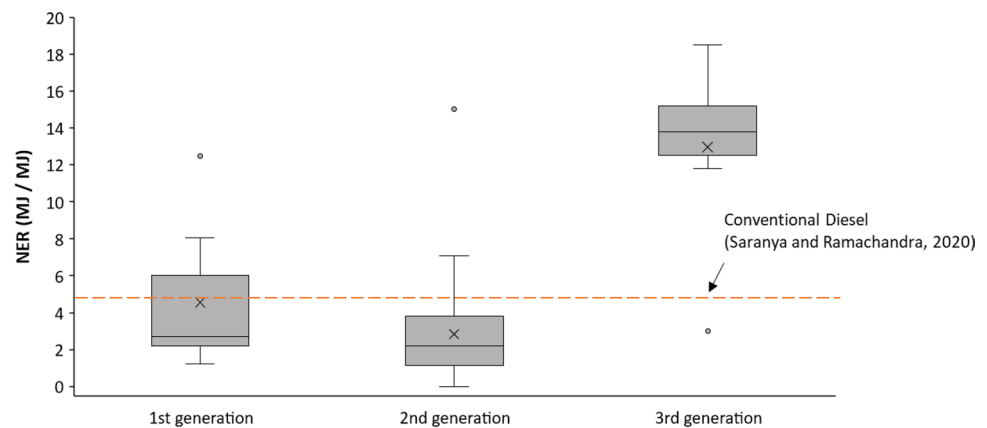
However, the analysis shows that the vanadium-impregnated solid catalyst results in a 26.96% reduction in GWP compared to a commercial hydroxyapatite-supported catalyst, shown in Fig. 6d.

Third-generation biofuels

Among the studies that were evaluated, only 7 LCA studies were found to have calculated the GHG emissions for third-generation biofuels. However, these studies used different approaches, methods, and assumptions when it came to managing feedstocks, nutrients, and co-products, as well as setting system boundaries and process designs. Consequently, the GHG emissions have varied significantly, as indicated in Fig. 7, 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 majorly due to the low algal yield and the substantial energy consumption during the cultivation, harvesting, and drying stages (Mu et al. 2014; Banerjee et al. 2019).

A study by (Saranya and Ramachandra 2020) evaluated the LCA of estuarine microalgae for biodiesel production. The analysis shows that the scenario which uses wastewater as a nutrient has less 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. 2012) shows that none of the four different conditions considered for analysis for biodiesel production meets the Renewable Fuel Standard, which requires a 50% reduction in GHG emissions for advanced biofuels. The analysis shows greenhouse gas

Fig. 8 NER for first, second, and third-generation biofuel



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.

Energy Use

Several indicators, including fossil energy consumption, primary, secondary, or cumulative energy demand, and net energy ratio (NER), are employed in LCA studies to assess energy usage in the life cycle of biofuels (Arvidsson et al. 2012). However, considering that lowering dependency on fossil fuels and ensuring energy security are important goals of national biofuel policies, in addition to mitigating climate change, many concentrated on fossil energy consumption. The NER ratio measures how much energy the biofuel produces in relation to total energy intake. If the NER is less than 1, the system is not advantageous since more energy is needed to produce the biofuel than it contains (Carneiro et al. 2017b). As shown in Fig. 8, most research anticipates that fossil energy use for 1st and 2nd generation biofuels varies across different biofuels ranging from 1.23 to 12.49 MJ / MJ for 1st generation and from 0.003 to 15.04 MJ / MJ for 2nd generation biofuel. Different farming techniques, feedstock production, conversion technology, and allocation strategies are some of the causes of these discrepancies. The assumptions about the type of energy employed in the conversion process also impact the outcomes. The energy demand of LCA of microalgae biofuels is considerably more diverse, ranging from 3 to 18.5 MJ / MJ. The reasons for this variation include technological uncertainty and the range of prospective feedstocks and manufacturing systems.

(Al-Mawali et al. 2021) estimate a NER of 2.17 MJ / MJ for the generation of biodiesel from waste date seed oil, which is comparable to the energy ratio of 3.15 MJ / MJ reported by (Pleanjai and Gheewala 2009) for palm oil

biodiesel. (Al-Muhtaseb et al. 2021) also reported a similar NER (2.23 MJ / MJ) for waste loquat seed oil biodiesel with an enhanced bifunctional catalytic system. (Uppalapati et al. 2022) estimated the NER for different feedstocks for biodiesel production. The analysis shows that *Jatropha* biodiesel has the highest NER (15 MJ / MJ), which is in line with the study by (Abbas et al. 2016) and (Silitonga et al. 2016) and the lowest for microalgae (3 MJ / MJ). Similar NER was reported by (Pragya and Pandey 2016), (Ajayebi et al. 2013), and (Firoz 2008) for microalgae (2.89 MJ / MJ) and Soybean (12.49 MJ / MJ). (Reaño 2020) and (Sreekumar et al. 2020) analyzed biofuel production from rice husk and straw. The EROI (energy return on investment), similar to NER, ranges from 0.6 to 1.59 MJ / MJ. This shows that the process is net energy positive and hence desirable. Similarly, (Mandade et al. 2015) analyze the lignocellulosic feedstock for ethanol production, and EROI values vary from 2 to 7.1 for different allocation methods.

Water use

Water consumption can be significant in producing bio-feedstocks, especially for first-generation biofuels (Dominguez-Faus et al. 2009). The use of irrigation water for certain feedstocks could pose a problem as it may compete with the water requirements for other purposes like producing food (Gerbens-Leenes et al. 2009). The total amount of water consumed worldwide might drastically increase due to increasing agricultural biomass production for biofuels (Hammond and Li 2016). In regions currently experiencing water scarcity, this extra water demand could significantly worsen the overall environmental effects of biofuels. As shown in Fig. 9, the water consumption of biofuel production ranges from 36.2 to 540 m³ / GJ for first-generation biofuel and from 1.28 to 188.8 m³ / GJ for second-generation biofuel. When scarcity of water in a particular region is considered, not just the amount of water used, the water footprints (WF) of biofuels can be

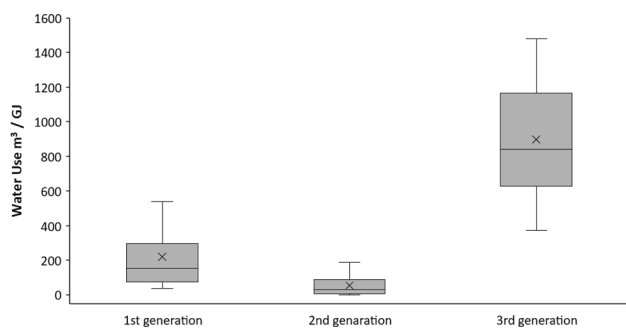


Fig. 9 Water consumption for biofuel production based on reviewed studies

50 to 240 times larger than those of fossil fuels (Berger et al. 2015). This is due to a significant portion of water use in biofuel production in water-stressed regions. In this analysis, the cultivation stage is not included for the second-generation biofuel. It is based on the assumption that the cultivation of feedstock has already been accounted for the LCA of primary food crops or other agricultural products, as they are typically byproducts or residues from those processes (Soam et al. 2016).

(Mandade et al. 2015) analyzed the water life cycle for Indian agro-industrial lignocellulosic biomass-based biofuel production. The analysis shows sorghum stalk biofuel to be more water efficient and sugarcane to be least for biofuel production as it consumes more water for Phase 1 (Fig. 2a) system boundary of LCA of biofuel. (Mathioudakis et al. 2017) analyzed the water footprint of agricultural residues and showed the WF of rice straw to be 129 L / kg. (Xie et al. 2017) analyzed for the ethanol production from cassava and sorghum and reported a WF ranging between 1760 and 5290 L per liter of ethanol, mostly agricultural, contributes towards the WF. Similarly, (Arguelles-Arguelles et al. 2021) show that more than 90% of the water used to produce biodiesel from palm oil ranges from 218 to 540 m³ / GJ was for agriculture of palm plantation. Similar results were shown by (Gerbens-Leenes and Hoekstra 2010).

As shown in Fig. 9, the WF for third-generation biofuel is the highest ranging from 373.4 to 1481 m³ / GJ (Siqueira et al. 2018; Wu et al. 2019). The water footprint of biofuel production from microalgae can vary depending on production methods and water availability in the production region (Banerjee et al. 2019). The WF considers the process water, material inputs for every stage of LCA, and water credit correlated with co-products (Mekonnen and Hoekstra 2011; Siqueira et al. 2018). The total WF comprises both the blue and green WFs, where the blue WF reflects the amount of water needed from local sources such as surface or groundwater for irrigation purposes, while the green WF represents the quantity of rainwater

and soil moisture utilized by plants (Mekonnen and Hoekstra 2011).

Land use change

Land-use change (LUC) either directly or indirectly causes GHG emissions. Since the biomass that powers these systems is produced on the land, land use is a crucial factor in the research of bioenergy systems. LUC is a significant source of GHG emissions, contributing 13 Gt CO₂ – eq globally in 2019 (IPCC 2022). Only 46% of the reviewed studies considered land-use change, as shown in Fig. 3. The lack of attention on advanced LCA studies, such as land-use change, was caused by the unavailability of a significant land-use database (Harris et al. 2015). Based on research conducted by (Fargione et al. 2008; Lapola et al. 2010), it has been found that the amount of GHG emissions resulting from direct and indirect LUC can be considerably higher than the GHG reductions achieved by replacing fossil fuels with biofuels.

Studies that include LUC tend to report a higher total environmental impact for biofuel production compared to studies that exclude LUC. This is due to the additional emissions and ecological impacts associated with land conversion. A study by (Isler-Kaya and Karaosmanoglu 2022) reported land use impact on biodiesel production from safflower to be 9.21 and 9.94 PDF*m²*yr (“potential disappeared fraction of species over a certain area over a certain period”) for safflower oil methyl ester (SOME) and ethyl ester (SOEE), which are similar as the study by (Spinelli et al. 2013). Study by (Humpenöder et al. 2013) shows that there was a 50% reduction in GHG emissions without taking LUC into account compared to fossil fuel. (Bhonsle et al. 2022) analyzed biodiesel production from UCO. The analysis shows land use midpoint category was highest for oil boiler use (86.6 m²a crop eq.) for conventional biodiesel and UCO use (6.59 m²a crop eq.) for room temperature scenario. (Chung et al. 2019) also analyzed for the used cooking oil and showed land use impact of 4.72E-01 PDF*m²*yr for catalyst preparation, 4.33E-01 PDF*m²*yr for pretreatment, and 1.26 PDF*m²*yr for the transesterification process. Similar studies were done by (Fernández-Tirado et al. 2016; Gnansounou and Kenthorai Raman 2016; Carneiro et al. 2017a; Vrech et al. 2019). While biofuels can offer advantages in reducing fossil fuel use and associated emissions, the inclusion of LUC-related impacts may diminish these advantages, especially if significant land conversion occurs.

Other environmental impacts

Besides carbon footprint, the environmental impact categories examined in biofuel LCA studies are acidification,

Table 4 Comparison of damage categories using Eco-Indicator 99 and ReCiPe 2016 LCIA method

Feedstocks	Unit	Human health		Ecosystem quality		Resources	
		Eco-Indicator 99	ReCiPe 2016	Eco-Indicator 99	ReCiPe 2016	Eco-Indicator 99	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

eutrophication, and ecotoxicity. About 60% of the reviewed studies analyzed more comprehensive impact categories. Since the reviewed LCA studies employed various methodologies to assess other environmental impacts, comparing them and providing a meaningful range of impacts for 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 the assessments conducted, affecting the comprehensiveness and breadth of the environmental impact analysis (Jolliet et al. 2003). The results of the research are also impacted by the assumptions made regarding the type of vehicle that biofuels are used in. (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 (Borrion et al. 2012; Arguelles-Arguelles et al. 2021; Yang et al. 2021). Figure 10a shows the impact categories of biofuel production from different sources using the IMPACT 2002+ impact characterization. Impact characterization aids in the identification of primary drivers of environmental impacts throughout a life cycle. Through the comparison of impact scores assigned to various inputs or outputs, it allows for the identification of hotspots, which refer to specific stages, processes, or materials that exert a substantial influence on the overall environmental performance (Isler-Kaya and Karaosmanoglu 2022).

Ecotoxicity potential (EP) is mainly attributed to fertilizers and pesticides used in Phase 1 of the LCA system boundary (Fig. 2a). (Lee and Ofori-Boateng 2013; Gallejones et al. 2015) showed similar results for rapeseed biofuel and palm oil, where the use of fertilizers caused 42% and 50% of total

EP. However, the midpoint impacts, such as non-renewable energy and respiratory inorganics, which contributes to human health and resource depletion (González-García et al. 2013b), have the highest single score for biofuel production, shown in Fig. 10b. According to the research conducted by (Kalaivani et al. 2014; Patel and Singh 2023), the ecotoxicity of jatropha biodiesel ranges from 35 to 160 kg TEG (triethylene glycol) per kg of biodiesel. The study found that phosphorus fertilizer accounts for 45% of the total EP, making it the largest contributor, followed by urea, which contributes 20% of the EP. Table 4 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. It allows researchers and practitioners to identify any discrepancies or variations in impact assessment outcomes and evaluate the methodological robustness of each approach. enables informed decision-making by considering different perspectives and approaches to impact assessment. Table 5 shows the environmental impact categories on a relative scale.

Socio-Economic impacts of biofuel production

The socio-economic impacts of biofuels refer to the effects that the production, use, and promotion of biofuels have on society and the economy. These impacts can be positive and negative and vary depending on factors such as the specific biofuel feedstock, production methods, local contexts, and policy frameworks (Kim and Dale 2008). Biofuel production can create employment opportunities across the value chain, including farming, harvesting, processing, transportation, and distribution. This can benefit rural communities and contribute to local economic development. Furthermore, biofuels reduce dependence on fossil fuels, promoting energy security by diversifying energy sources (Cambero and Sowlati 2014; Yang et al. 2015). This can enhance a country's energy independence and reduce vulnerability to price fluctuations and supply disruptions in the global oil market. However, the cultivation of biofuel feedstocks may compete with food production, potentially leading to

increased food prices and reduced food security (Collotta et al. 2019). This can particularly affect regions where land resources are limited or where the agricultural sector is already under stress.

Compared to environmental impacts, economic and social indicators are rarely included in the LCA. Few studies included the socio-economic aspect of biofuel (van Dam et al. 2009; Stephenson et al. 2010; Ekener-Petersen et al. 2014; Ekener et al. 2018; Collotta et al. 2019). Key factors highlighted in these studies encompass indicators such as transportation expenses, food costs, gender equality, health-related diseases, instances of forced labor, and minimum wages., which exert a substantial impact on the broader socio-economic sustainability of biofuel production (van Dam et al. 2009; Yang et al. 2015).

Conclusion

The LCA is a complex technique that is often utilized to compute the GWP and other environmental impacts associated with biofuels. Despite this, it is frequently seen as a tool capable of providing a conclusive response to numerous concerns. This study indicates that there are no concrete solutions, and the conclusions drawn from LCA studies largely depend on factors like the study's goal and scope, the assumptions made, the methodology used, and the tools employed. Therefore, it is essential to acknowledge this and interpret the results accordingly. Furthermore, certain strategies for communicating complexity to policymakers and

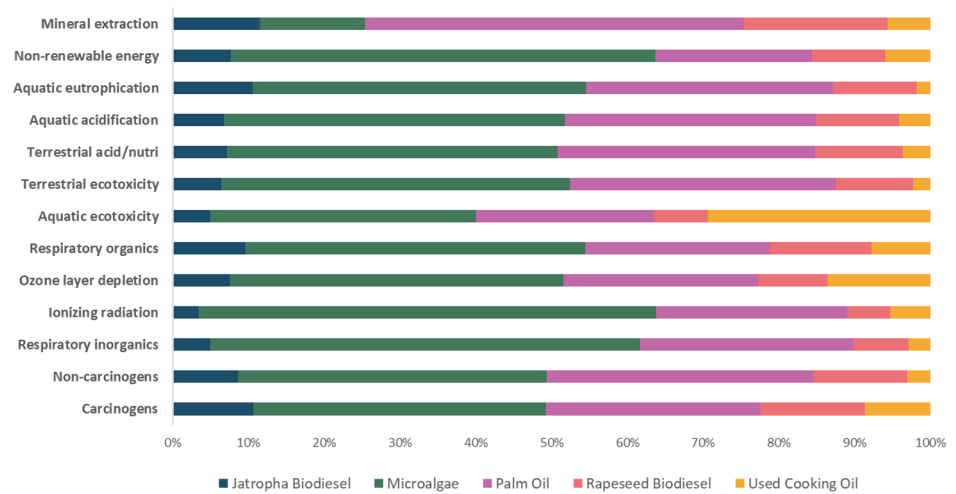
the genpotential disappeared fraction of specieral public are required. This analysis shows that the estimates between the studies differ significantly due to numerous LCA methodological options and uncertainties. Despite this, the available evidence is instructive. To keep up with the latest trends in evaluating the environmental effects linked to biofuel production, we critically reviewed 53 LCA studies published between 2012 and 2022, carefully examining the methodology and conclusions. Our findings suggest that second-generation biofuels have a greater potential to decrease GHG emissions than first-generation biofuels. Third-generation algal biofuels show high GHG emissions than conventional fuels at the current stage of development since their electricity consumption is high. The study critically reviewed the energy use and water use in the production of biofuels, along with several midpoint impact categories, such as acidification and eutrophication associated with biofuel production. Based on the bibliometric mapping from the WoS, we have identified that bioenergy, life cycle assessment, biofuels, and sustainability are more researched areas.

To improve the usability of LCA as an evidence-based tool for assessing the environmental sustainability of biofuels, both attributional and consequential LCA methodology and practical applications must be improved. Uncertainty and sensitivity assessments should be included in all LCA investigations to increase the reliability of the results and improve confidence in making decisions based on LCA studies. Biofuels are not independent entities but a component of much larger systems, such as those related to energy, agriculture, and forestry. Biofuels affect several ecosystem services,

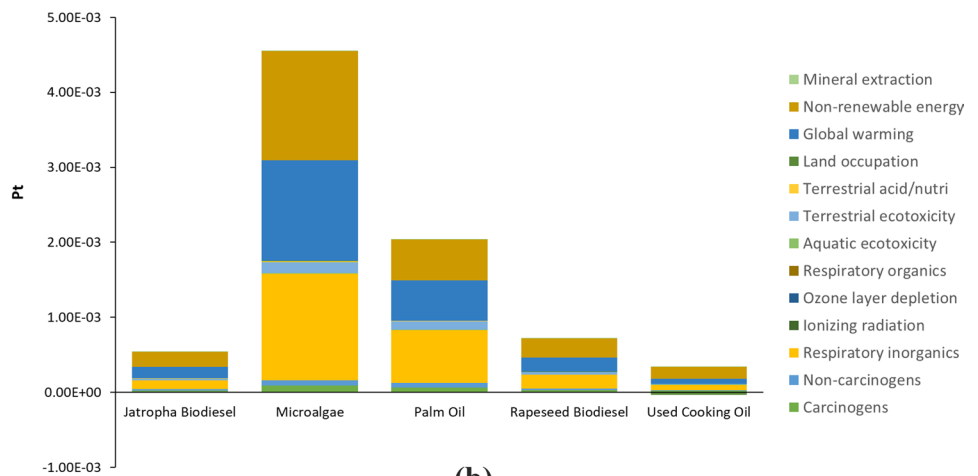
Table 5 Midpoint single score based on IMPACT 2002+LCIA method for biodiesel production

Impact category	Unit	Jatropha biodiesel (Uusitalo et al. 2014; Vrech et al. 2019)	Microalgae (Soratana et al. 2012, 2014; Siqueira et al. 2018)	Palm oil (Lee and Ofori-Boateng 2013; Arguelles-Arguelles et al. 2021)	Rapeseed biodiesel (González-García et al. 2013b; Gallejones et al. 2015)	Used cooking oil (Uusitalo et al. 2014; Bhonsle et al. 2022)
Total	%	100	100	100	100	100
Carcinogens	%	4.63	2.00	3.29	4.50	6.69
Non-carcinogens	%	2.66	1.51	2.92	2.89	1.69
Respiratory inorganics	%	22.65	31.21	34.61	25.62	23.38
Ionizing radiation	%	0.04	0.08	0.08	0.05	0.11
Ozone layer depletion	%	0.00	0.00	0.00	0.00	0.02
Respiratory organics	%	0.02	0.01	0.02	0.03	0.04
Aquatic ecotoxicity	%	0.11	0.10	0.15	0.13	1.21
Terrestrial ecotoxicity	%	3.74	3.23	5.51	4.56	2.40
Terrestrial acid/nutri	%	0.32	0.23	0.41	0.39	0.29
Land occupation	%	0.39	0.16	-0.24	0.40	-10.30
Non-renewable energy	%	36.91	32.09	26.61	35.21	50.43
Mineral extraction	%	0.06	0.01	0.07	0.08	0.05

Fig. 10 Midpoint impact categories **a** Characterization score and **b** Single score of biofuel production



(a)



(b)

including food, water, and land. To prevent biofuels from being disadvantaged compared to other industries or from having advancements in this industry reversed by unsustainable practices in other industries, it is crucial to plan future policy from an integrated systems perspective.

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Data availability Enquiries about data availability should be directed to the authors.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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