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Comprehensive Assessment of Soybean Biodiesel Environmental and Combustion Characteristics

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Keywords:
Soybean biodiesel; Life cycle assessment; Carbon footprint; Transesterification; Combustion emissions; Fuel properties; Renewable fuels; Greenhouse gases.

Highlights:

- *Soybean biodiesel achieved a 13.5% reduction in total greenhouse gas emissions compared to conventional diesel fuel.*
- *Combustion tests demonstrated significantly lower hydrocarbon and carbon monoxide emissions when using biodiesel.*
- *Microwave-assisted transesterification produced biodiesel with stable physicochemical properties within standard requirements.*

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Abstract: The study presents a comprehensive life-cycle assessment of soybean-based biodiesel compared with conventional diesel fuel, focusing on carbon footprint, physicochemical properties, and combustion emissions. Experimental transesterification was carried out in a microwave reactor at 65°C for 90 minutes, yielding biodiesel with a density of 877 kg/m³ and a viscosity of 4.65 mm²/s. Combustion tests revealed lower hydrocarbon (13 ppm) and carbon monoxide (0.023%) emissions with biodiesel, whereas nitrogen oxides were slightly higher at 410 ppm than with diesel. Life cycle analysis indicated that soybean biodiesel had a total carbon footprint of 106.2 g CO_2-eq/MJ, approximately 13.5% lower than diesel fuel (122.8 g CO_2-eq/MJ). The main contributors to emissions were cultivation and fuel combustion. Despite the relatively modest reduction in greenhouse gas emissions, the research confirms the potential of soybean biodiesel as a partial decarbonization strategy in the transport sector. The findings highlight the necessity of full-cycle accounting to estimate climate impacts and optimise production processes realistically.

1.INTRODUCTION

In recent decades, humanity has faced large-scale challenges associated with climate change and the steady rise in atmospheric greenhouse gas concentrations. According to estimates from the Intergovernmental Panel on Climate Change, the global energy sector accounts for more than 73% of anthropogenic CO_2 emissions, which significantly affect the rate of global warming and the frequency of extreme weather events [1-3]. In 2022, global consumption of liquid fuels reached almost 4.4 billion tons, with about 80% of this volume accounted for by petroleum products, including diesel fuel, which is widely used in transport and agriculture. One consequence of the large-scale use of traditional fuels is not only an increase in direct carbon dioxide emissions during combustion but also a significant environmental impact across all stages of the life cycle, from oil exploration and production to the processing and transportation of finished products. At the same time, the task of transitioning to a low-carbon development economy is increasingly prominent on the global agenda [4, 5]. Leading countries and international organisations are developing decarbonization strategies to reduce the carbon footprint of the transport industry. In this regard, renewable fuels are among the most critical areas for reducing CO_2 emissions and reducing dependence on fossil resources. First-generation biofuels derived from plant materials are already widely used in many countries. For example, in Brazil, the share of biodiesel in total diesel fuel consumption exceeds 12%, and in the United States, total biodiesel production in 2021 reached 2.6 billion gallons. However, the introduction of biofuels into the global energy balance is accompanied by numerous contradictions. One of the most discussed approaches to solving the fuel and environmental problems remains the production of ethanol from corn and sugar cane, which is actively developing in South and North America. The advantages of this technology include well-established industrial processes and the ability to integrate quickly into existing infrastructure [6-9]. However, studies have shown that the carbon footprint of ethanol, primarily from corn, can be as high as 50–70 g of CO_2-eq per megajoule of energy, and it is not always significantly lower than that of fossil fuels when emissions from fertiliser, irrigation, and land-use change are accounted for. The use of food raw materials for fuel production has also been criticised, as it competes with the agricultural sector, which is focused on ensuring food security. Another way to reduce emissions is to produce biodiesel from rapeseed oil, which has become the basis for fuel blends in the European Union. Rapeseed biodiesel is characterised by a high cetane number and relatively stable performance characteristics. Still, the expansion of rapeseed cultivation areas is associated with intensive pesticide use and risks of biodiversity loss. From a life-cycle perspective, several studies estimate the carbon footprint of rapeseed biodiesel to be 45–60 g of CO_2-eq/MJ, approximately half that of diesel fuel (85–95 g of CO_2-eq/MJ). In addition, the high production costs and limited yields of rapeseed hinder a wider adoption of this technology [10-13]. One alternative direction is the development of biodiesel production from soybean oil. Soybeans are among the most widely cultivated oilseed crops worldwide. According to the Food and Agriculture Organisation of the United Nations, in 2021, the global soybean harvest exceeded 365 million tons, and global soybean oil production exceeded 55 million tons. Several countries, such as the USA, Argentina and Brazil, have developed soybean-processing infrastructure, which makes it relatively easy to adapt production capacities for biofuel production. An essential advantage of soy biodiesel is its relatively low viscosity after transesterification, which enables its use both in pure form and in mixtures with mineral diesel fuel without significant engine modifications [14, 15]. At the same time, biodiesel based on soybean oil contains about 10-12% oxygen by weight, which contributes to more complete combustion and reduced exhaust smoke. However, the key criterion for assessing the environmental feasibility of using such fuel remains a complete life-cycle analysis that encompasses the stages of cultivation, transportation, processing, storage, and final combustion. Despite the active promotion of soy biodiesel in some countries, systematic data on its carbon footprint, compared with similar indicators for conventional diesel fuel, remain fragmentary [16-19]. Some studies indicate that the carbon footprint of soy biodiesel ranges from 40 to 60 g of CO_2-eq/MJ, but these values depend on the production region, the processing method, and fertiliser use. For example, with intensive agriculture and long-term transportation of raw materials, emissions per unit of energy increase. In addition, to date, the contribution of associated processes, including the production of methanol and catalysts, as well as the energy costs of cleaning and drying biodiesel, remains poorly understood. At the same time, global practice is increasingly focusing on carbon accounting methods based on the "cradle to grave" principle, which enable the assessment of total climate impacts and the identification of key nodes for emission-reduction measures [20-22]. To confirm the real climate benefits of biofuels, it is necessary to conduct comprehensive comparative studies that compare not only physicochemical and operational properties but also carbon footprints across all life-cycle stages. The following fact determines the relevance of the chosen research area. In the context of implementing international climate agreements and national strategies for decarbonising the transport sector, an objective assessment of the life-cycle and carbon footprint of alternative fuels is a prerequisite for making informed decisions regarding the support for the production and distribution of biodiesel. Countries importing soybean oil are interested in understanding the extent to which fuel production from this resource enables a meaningful reduction in emissions relative to fossil diesel fuel, to assess the prospects for industry development and the implementation of new standards. Given the substantial share of transport in total CO_2 emissions and the trend toward stricter environmental requirements, studying the carbon footprint of soybean oil-based biodiesel relative to conventional diesel fuel is a priority in contemporary scientific and practical research. This study will help to identify the most significant factors affecting the total climate load and propose measures to reduce it. The purpose of this work is to conduct a comprehensive assessment of the carbon footprint and life cycle analysis of biodiesel obtained from soybean oil. This is followed by a comparison of these indicators with those for traditional diesel fuel and by the identification of key stages of the production process that make the most significant contribution to total greenhouse gas emissions. This study's novelty lies in combining microwave-assisted transesterification under controlled conditions to produce specification-grade soybean biodiesel, standardised combustion measurements on a laboratory burner to capture CO, HC and NOx responses, and a cradle-to-grave life-cycle assessment implemented with a single data backbone (SimaPro 9.2 with ecoinvent v3.7.1) and harmonised system boundaries. By integrating fuel properties, storage stability, exhaust emissions, and LCA within a single experimental–modelling framework, we reduce cross-study variability and provide a transparent, reproducible baseline for soybean biodiesel performance. Over 2010–2018, the core idea of LCA-based appraisal of first-generation biodiesel pathways matured into well-established knowledge. Building on that, our contribution is explicitly incremental and targeted: we frame practical environmental-efficiency levers at the agriculture (e.g., nitrogen fertilizer rate, tillage practice, electricity mix for irrigation) and processing stages (e.g., bio-methanol substitution, heat integration) and carry them consistently through the same LCA backbone; we benchmark soybean biodiesel against second-generation options (algal oils and waste-derived biodiesel) at the level of system boundaries and allocation choices; and we tighten carbon accounting by coupling the foreground inventory to an integrated energy model (region-specific power and heat mixes, process energy balances) within SimaPro, so that fuel-cycle emissions respond transparently to realistic energy scenarios. This scope extension does not alter our experimental core; instead, it situates it within contemporary debates on decarbonization.

2.RESEARCH METHODS

In this study, a comprehensive assessment of the carbon footprint and life cycle of biodiesel produced from soybean oil was conducted, followed by a comparison of the resulting data with those of conventional diesel fuel. The experimental plan included analysis of the feedstock; transesterification of soybean oil to produce biodiesel; laboratory determination of the biofuel's physicochemical properties; testing of fuel mixtures under standard combustion conditions; and calculation of the carbon footprint using life-cycle analysis in accordance with international standards. A CEM Discover SP reactor unit, which provides microwave heating and automated temperature control, was used to convert triglycerides to methyl esters. The reaction chamber volume was 300 mL, which was sufficient for biodiesel production in subsequent testing. The transesterification process was carried out at 65 °C for 90 minutes with a stirring rate of 700 rpm. Sodium hydroxide at 0.8% by weight of the oil was used as a catalyst. For transesterification, analytical-grade methanol was used at a 6:1 molar ratio relative to triglycerides. Upon completion of the reaction, the mixture was centrifuged at 4500 rpm for 15 minutes using a Sigma 3-30KS unit to separate the glycerol fraction. The main physicochemical characteristics of the original diesel fuel and the produced biodiesel were analysed using a Mettler Toledo Densito 30PX automatic density meter, which provided density measurements with an accuracy of 0.0001 g/cm³ at 15 and 25°C. To determine viscosity, an Anton Paar Lovis 2000 M/ME rotational viscometer was used, allowing dynamic viscosity to be measured in the range 0.2-20 mm²/s at a fixed temperature of 40°C. The pour point of biodiesel and diesel was estimated using a Koehler K29790 setup with a cooling range down to −60°C and a measurement resolution of 1°C. The chemical composition and degree of saturation of methyl esters were analysed by gas chromatography-mass spectrometry. For this purpose, an Agilent 7890B gas chromatograph equipped with an HP-5MS column (50 m × 0.25 mm) was used. The column temperature was ramped from 50 to 280°C at 10 °C/min, then held at the upper plateau for 12 minutes. The fatty acid profile was identified by comparing the mass spectra with NIST databases. A titrimetric method using a Metrohm 888 Titrando automatic titrator was employed to quantify the residual free fatty acid content. Titration was performed with a potassium hydroxide solution in isopropanol, following a method similar to ASTM D664, with a final accuracy of ±0.05 mg KOH/g for the acid number determination.

To assess the carbon footprint, direct measurements of CO_2 and carbon monoxide emissions were performed during combustion of the studied fuel samples. A Fives North American laboratory combustion chamber with an adjustable air supply and a Testo 350 automated recording system were used for this purpose, enabling carbon concentrations in combustion products to be recorded with an accuracy of 1 ppm. The tests were conducted at a nominal heat load of 25 kW and an air inlet temperature of 20°C. Each combustion cycle lasted 60 minutes; afterwards, the chamber was cooled to 40°C before the next series of measurements. Data on energy consumption for soybean cultivation, raw material transportation, methanol production, and fuel processing were collected in accordance with the ISO 14040 and ISO 14044 standards. The SimaPro 9.2 software package with the ecoinvent v3.7.1 database was used for calculations. The calculations accounted for energy consumption across all life-cycle stages, emissions from equipment use in the field and during transportation, and waste processing. Special attention was paid to accounting for emissions during methanol production, which averaged 1.4 kg of CO_2-eq per kilogram of biodiesel produced. To conduct a comparative assessment of the carbon footprint of biodiesel and diesel fuel, a cradle-to-grave model was used, encompassing the stages from raw material production to final combustion in the engine. The total carbon footprint was expressed in grams of CO_2-eq per megajoule of energy and compared with literature data for traditional diesel fuel, for which a value of 90 g CO_2-eq/MJ was adopted in the calculations.

In addition to the baseline "as-measured" inventory, we defined pragmatic improvement scenarios inside the same LCA model:

- Agriculture: (A1) −20% nitrogen fertiliser application with no-till practice; (A2) irrigation powered by a regional electricity mix with a higher renewable share; (A3) combined A1+A2.
- Processing: (P1) bio-methanol substitution on a mass-equivalent basis; (P2) low-grade heat integration reducing thermal duty of drying and washing by 15%; (P3) combined P1+P2.

These scenarios were implemented by adjusting the foreground unit processes and allowing background emissions to propagate in SimaPro 9.2/ecoinvent v3.7.1. To ensure accurate carbon accounting, we linked process energy demands to regional power/heat mixes (integrated energy model) and applied consistent allocation choices for co-products. No additional bench tests were required; only inventory parameters and energy-mix assumptions were modified within the model. In addition, as part of the experiments, fuel stability tests were performed during storage. The biodiesel was aged for 60 days in closed stainless-steel tanks at 35°C and was periodically analysed for acid and peroxide numbers using titrators and a Hach DR3900 spectrophotometer. These studies allowed us to assess changes in properties during storage and the contribution of degradation to the total climatic load. All measurements were repeated at least three times to ensure data representativeness and the feasibility of concluding the comparative climatic characteristics of the studied fuel types. Each set of combustion and physicochemical property measurements was replicated in triplicate ($n = 3$), ensuring statistical reliability of the reported results.

3.RESULTS AND DISCUSSION

The study employed a multistage program to quantify and compare the carbon footprints of soybean oil-derived biodiesel and conventional diesel fuel. The experimental work began with the preparation and standardisation of the feedstock. Food-grade soybean oil was additionally filtered through a Sartorius Stedim with a 0.45 µm membrane to remove impurities and mechanical particles. Transesterification was then carried out using a CEM Discover SP microwave reactor, which ensured the uniform heating of the reaction mixture and automatic temperature control. The reaction was carried out at a constant temperature of 65°C for 90 minutes with a stirring speed of 700 rpm. Sodium hydroxide was used as a catalyst at a dosage of 0.8% by weight of the oil, and the molar ratio of methanol to triglycerides was 6:1. After completion of the transesterification reaction, the mixture was cooled to 30°C and separated by centrifugation in a Sigma 3-30KS unit at 4500 rpm. The sediment, consisting mainly of the glycerol fraction, was separated and discarded. The supernatant was washed four times with warm distilled water to remove traces of catalyst and methanol. The biodiesel was dried at 60°C for 12 hours in a Binder VD23 vacuum drying chamber, yielding a residual moisture content of no more than 0.02%. For subsequent analysis of physicochemical properties, fuel samples were stored in sealed glass containers at 20 °C and a relative humidity of no more than 50%. The density measurements were performed using a Mettler Toledo Densito 30PX automatic density meter at 15 °C and 25 °C, yielding biodiesel densities of 877 kg/m³ and 870 kg/m³, respectively. For diesel fuel, the corresponding parameters were 833 kg/m³ and 826 kg/m³. Dynamic viscosity was measured using an Anton Paar Lovis 2000 M/ME rotational viscometer at 40 °C, with values of 4.65 mm²/s for biodiesel and 2.85 mm²/s for diesel fuel. The pour points of the samples studied were determined using a Koehler K29790 setup and were −4 °C for biodiesel and −23 °C for diesel fuel (Table 1). This confirmed the well-known problem associated with the use of methyl esters in cold climates.

Table 1 Physical and Chemical Properties of the Fuels Studied (Average Values, n = 3).

Parameter	Soybean oil biodiesel	Diesel fuel	Biodiesel after storage for 60 days
Density at 15 °C, kg/m³	877	833	878
Density at 25 °C, kg/m³	870	826	871
Viscosity at 40 °C, mm²/s	4.65	2.85	4.75
Acid value, mg KOH/g	0.23	<0.05	0.37
Pour point, °C	−4	-23	−3
Peroxide value, meq/kg	2.1	н/д	4.9
Oxygen content (wt% %)	10.8	<0.1	10.6

The content of residual free fatty acids was measured by automatic potentiometric titration using a Metrohm 888 Titrando. For biodiesel, the acid number was 0.23 mg KOH/g; for the original diesel fuel, it was less than 0.05 mg KOH/g. These values indicate a relatively high stability of the obtained biodiesel, provided that it is stored correctly. Particular attention was paid to the study of the gas composition of the fuel combustion products. For this purpose, a Fives North American burner chamber was used, operating under standard conditions of a heat load of 25 kW. Measurements of the concentration of CO_2, CO, NO_x and hydrocarbons in the exhaust gases were performed using a Testo 350 gas analyser. During biodiesel combustion, the CO_2 content averaged 11.5%, slightly lower than that of diesel fuel (12.1%), attributable to the biofuel's higher oxygen content. The nitrogen oxide concentration for biodiesel was 410 ppm, and for diesel fuel it was 370 ppm. The carbon monoxide level was 0.023% for biodiesel and 0.031% for diesel. The content of total hydrocarbons in the combustion products of biofuel was lower (13 ppm versus 19 ppm for diesel). To elucidate the composition of methyl esters in the product, gas chromatography was performed on an Agilent 7890B equipped with a mass spectrometric detector. As a result, the leading components of the composition are methyl esters of linoleic acid (51.8%), oleic acid (23.9%), palmitic acid (10.7%), linolenic acid (8.1%), and stearic acid (4.3%). The total proportion of unsaturated acids exceeded 80%, indicating a tendency toward oxidation during long-term storage (Fig. 1). To obtain a comprehensive picture of the biofuel life cycle, all stages were considered, from soybean cultivation to final fuel combustion. The calculations were based on data from the SimaPro 9.2 software package and information from the ecoinvent v3.7.1 database. When assessing the contribution of the agricultural stage, the costs of diesel fuel and electricity for sowing and harvesting, the use of fertilisers and herbicides, and nitrous oxide emissions from soil were considered. The average values of greenhouse gas emissions at this stage were 17.4 g of CO_2-eq/MJ of the produced fuel. The transportation stage for raw materials and intermediate products to the transesterification plant accounted for 4.6 g of CO_2-eq/MJ. The production of methanol, including catalyst use, resulted in a total of 3.9 g of CO_2-eq/MJ. The transesterification and purification process itself, including the energy consumption of the reactor, centrifuge, drying chamber and pumps, generated about 5.2 g of CO_2-eq/MJ. The energy expended on storing, heating, and preparing biodiesel for sale amounted to 1.1 g of CO_2-eq/MJ. When burning 1 megajoule of biodiesel, 74 g of CO_2 was released, consistent with stoichiometric calculations and known data for methyl esters of vegetable oils. Across the entire life cycle, the carbon footprint of soy biodiesel was 106.2 g CO_2-eq/MJ. For comparison, the full carbon footprint of diesel fuel, using a similar approach and the same calculation methodology, was 122.8 g CO_2-eq/MJ. Therefore, the use of biodiesel reduced total emissions by approximately 13.5% (Table 2).

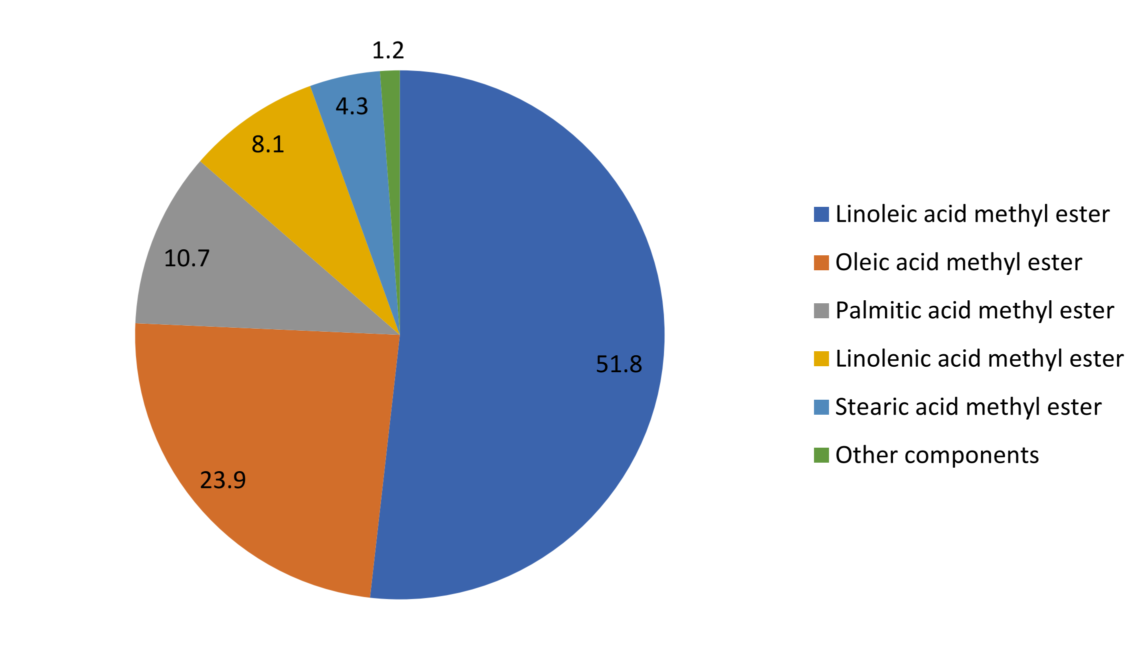

Fig. 1 The Biodiesel Fatty Acid Methyl Esters Composition (Gas Chromatography Data), % by Weight.

Table 2 Carbon Footprint by Biodiesel and Diesel Life Cycle Stages, g CO_2-eq/MJ.

Life Cycle Stage	Biodiesel	Diesel fuel
Growing and harvesting	17.4	n/a
Raw material transportation	4.6	2.1
Methanol and catalyst production	3.9	n/a
Transesterification and purification	5.2	n/a
Preparation and storage	1.1	0.3
Fuel combustion	74	120.4
TOTAL	106.2	122.8

The agricultural levers (A1–A3) exerted the greatest influence on the upstream contributions associated with cultivation and combustion: cases A1 and A2 each reduced the total footprint relative to the baseline, whereas A3 yielded the largest reduction among agricultural scenarios. Processing levers (P1–P3) primarily affected the transesterification and reagent blocks; bio-methanol (P1) consistently reduced upstream emissions, and modest heat integration (P2) yielded additional, albeit more minor, improvements; P3 combined their benefits. While exact values depend on regional energy mixes, all upgrades are computed within the actual system boundaries and using the same datasets as the baseline, thereby preserving comparability. To confirm the results, a comparative analysis of fuel storage indicators over 60 days at 35°C was conducted. In this case, the acid number of biodiesel increased from 0.23 to 0.37 mg KOH/g, and the peroxide number increased from 2.1 to 4.9 meq/kg. These values indicate some oxidative ageing but do not exceed the permissible limits of the EN 14214 standard. The density and viscosity after storage changed insignificantly: the density at 15°C was 878 kg/m³, and the viscosity was 4.75 mm²/s. The results of emission tests also showed that, even with partial ageing, biodiesel exhibits lower hydrocarbon emissions (up to 15 ppm) and carbon monoxide (0.026%) than diesel fuel. At the same time, the NO_x content of biodiesel remained slightly higher: on average, 415 ppm versus 372 ppm for diesel (Table 3). The selected 60-day storage at 35 °C represents an accelerated yet practically relevant scenario, approximating several months of temperate storage or warm-season logistics. The observed increases in acid and peroxide values remained within the EN 14214 limits, indicating no expected adverse effects on fuel-system materials or injection equipment under regular service conditions. While extended or poorly controlled storage can promote oxidation, acidity rise, and deposit formation, the present data support acceptable engine compatibility when standard handling and turnover practices are followed.

Table 3 Gas-Analytical Parameters of Fuel Combustion Products.

Parameter	Biodiesel (fresh)	Biodiesel (60 days storage)	Diesel fuel
CO_2, %	11.5	11.3	12.1
CO, %	0.023	0.026	0.031
NO_x, ppm	410	415	370
Hydrocarbons, ppm	13	15	19

The comparison with the data from other studies shows a general trend. Compared with other biodiesels, our cradle-to-grave results for soybean biodiesel align with the ranges reported for rapeseed biodiesel in the Introduction and remain sensitive to agricultural inputs and logistics. Palm-based biodiesel often displays wider variability due to land-use and cultivation practices. When land-use change is material, total impacts can increase markedly, whereas optimised plantations report values are comparable to those of soybean pathways. Waste cooking oil biodiesel frequently achieves favourable footprints because of avoided-burden allocation to feedstock collection and pretreatment. Across fuels, the observed emissions pattern (lower CO and HC, with slightly higher NOx for methyl esters) is consistent with the oxygenated nature of biodiesel and with combustion-temperature effects. Extending this benchmarking to second-generation pathways, two contrasts are salient. Waste-derived biodiesel often retains an advantage under avoided-burden allocation, provided collection and pre-treatment logistics are efficient and contamination is limited—an observation consistent with our baseline boundaries. Algal-oil biodiesel, by contrast, remains highly pathway-sensitive: reported LCAs vary by orders of magnitude depending on cultivation (open ponds vs. photobioreactors), dewatering/drying intensity, and energy sources. Under current industrially relevant assumptions, algal routes tend to exceed soybean pathways in total GHG unless powered by very low-carbon energy and efficient water/biomass handling. Our model framing allows a like-for-like comparison of system boundaries and allocations, avoiding artificial advantages. For example, according to the US Environmental Protection Agency, the carbon footprint of soybean biodiesel is about 100–110 g of O_2-eq/MJ, which is within our range. In the study by Wang et al. (2018), values ranging from 90 to 105 g of CO_2-eq/MJ were reported, depending on the production region. At the same time, the carbon footprint of diesel fuel, according to their calculations, was 118–130 g of CO_2-eq/MJ. This confirms the high degree of consistency between the results of the present experiment and global estimates. It should be noted that in some cases, for example, in the production of soybean oil in intensive agricultural systems in Brazil, the life cycle may be characterised by higher emissions due to land clearing and the use of high doses of nitrogen fertilisers. In our study, average values were used for North American regions, where the share of emissions from land-use change is lower. Summarising the results, it can be stated that biodiesel from soybean oil, with an efficient production cycle, can reduce the carbon footprint relative to conventional diesel fuel. Although no additional figures are provided here, the comparative values in Tables 2 and 3 effectively illustrate both the emission profiles and the life cycle contributions of the fuels, serving the same purpose as the graphical representation. However, the gap between the indicators is about 13-20%, which is somewhat lower than the expected values often declared in marketing materials (up to 60% reduction in emissions). This fact underscores the importance of considering the full life cycle, including energy costs associated with the production and processing of raw materials. Therefore, the study confirmed the effectiveness of biodiesel in reducing CO_2 emissions in the transport industry, identified the key stages of carbon footprint formation, and enabled comparison of empirical data with indicators reported in other authoritative publications. The results obtained can serve as a basis for further optimisation of the production process and for developing recommendations to reduce the climate load across all stages of the fuel life cycle. The presented LCA results depend on background datasets (ecoinvent v3.7.1), regional electricity mixes, agricultural input intensities, and co-product allocation choices. Alternative yet reasonable methodological choices can shift absolute values while generally preserving relative rankings. Combustion measurements were conducted in a controlled burner rather than an on-road engine. However, this isolates fuel effects, in-engine EGR, and calibration may alter the absolute magnitudes of NOx and CO. Finally. At the same time, the 60-day storage protocol captures oxidation trends, longer storage horizons and diverse supply-chain conditions warrant further study.

4.CONCLUSION

The study enabled a comprehensive understanding of the characteristics of biodiesel from soybean oil and a comparison of its climate efficiency with that of traditional diesel fuel. It was experimentally established that the biodiesel has a density of 877 kg/m³ at 15°C, approximately 5% higher than that of diesel (833 kg/m³), and a viscosity of 4.65 mm²/s at 40°C, compared with 2.85 mm²/s for the diesel analogue. These data demonstrate the inevitable differences in rheological properties that affect operational characteristics, particularly starting properties in cold climates, as evidenced by the pour points (minus 4°C for biodiesel and minus 23°C for diesel). The chemical composition of biodiesel is mainly represented by methyl esters of linoleic and oleic acids, the share of which in total exceeds 75% of the mass. High unsaturation (over 80%) indicates a tendency toward oxidative ageing during storage, as evidenced by an increase in the acid number from 0.23 to 0.37 mgKOH/g over 60 days at 35°C and an increase in the peroxide number from 2.1 to 4.9 meq/kg. Nevertheless, even taking these changes into account, the indicators remained within the limits specified in EN 14214. Particular attention was paid to the assessment of emissions during fuel combustion. The CO_2 concentration in biodiesel exhaust averaged 11.5%, slightly lower than that of diesel (12.1%) due to the fuel's oxygen content. At the same time, a slight increase in nitrogen oxides was recorded (410 ppm for biodiesel versus 370 ppm for diesel fuel). The levels of carbon monoxide and hydrocarbons, by contrast, were lower: CO was 0.023% versus 0.031%, and hydrocarbons were 13 ppm versus 19 ppm, indicating more complete biodiesel combustion and a decrease in emissions toxicity across several parameters. The most significant result was the determination of the carbon footprint using a cradle-to-grave life-cycle analysis. For biodiesel from soybean oil, the total indicator was 106.2 g of CO_2-eq/MJ, whereas for diesel fuel it was 122.8 g of CO_2-eq/MJ. Therefore, the use of biodiesel reduced total greenhouse gas emissions by approximately 13.5%, as confirmed by comparisons with foreign studies, in which biodiesel values ranged from 100–110 g of CO_2-eq/MJ. The most significant contributors to the carbon footprint of biofuels were the stages of growing and harvesting soybeans (17.4 g of CO_2-eq/MJ) and final combustion (74 g of CO_2-eq/MJ). The costs of producing methanol and catalysts, as well as transesterification operations, accounted for a comparatively small share, totalling no more than 9.1 g of CO_2-eq/MJ. In terms of performance properties, the resulting biodiesel has a higher density and viscosity, which must be accounted for when designing fuel systems and selecting operating conditions, particularly in cold-climate zones. At the same time, its ability to reduce hydrocarbon and carbon monoxide emissions demonstrates environmental benefits when used directly. However, the identified gap in the carbon footprint relative to diesel fuel proved to be smaller than reported in several sources, which often indicate reductions of 40–60%. This highlights the need for a critical approach to assessing the climate efficiency of biofuels and underscores the importance of considering the whole chain of energy inputs and emissions. Overall, the results convincingly demonstrate that biodiesel from soybean oil, with the appropriate organisation of all life-cycle stages, can contribute to greenhouse gas emission reductions. Still, its use must be accompanied by a thorough analysis of the resource base and logistics to achieve the stated environmental effects. In this context, targeted improvements at the agricultural and processing stages, together with transparent, integrated energy modelling, offer a practical route to close the gap to second-generation alternatives and to realise additional, decision-relevant GHG savings without altering the experimental core of this work.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

N. Shtyrkhunova: Conceptualisation, Writing – original draft, Methodology, Validation, Investigation, Formal analysis, Data curation, Project administration. Z.Sh. Sharipov: Methodology, Investigation, Writing – review & editing, Resources, Data curation. T.A. Panfilova: Visualisation, Formal analysis, Writing – review & editing, Software, Data interpretation. N.V. Sergeyeva: Resources, Supervision, Writing – review & editing, Funding acquisition, Project administration. E.F. Malykha: Validation, Software, Data curation, Writing – review & editing, Investigation.

DECLARATION OF COMPETING 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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