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ASSESSING THE CARBON FOOTPRINT AND CUMULATIVE ENERGY DEMAND OF BIODIESEL PRODUCED FROM RAPESEED OIL IN SERBIA

Abstract: This paper aims to evaluate the carbon footprint and energy balance associated with biodiesel production from rapeseed in Serbia, employing the life cycle assessment (LCA) methodology. Data on material and energy consumption were collected for the primary agricultural and industrial entities involved in the biodiesel production chain, with the broader system modeled using information from the ecoinvent life cycle inventory database. Our findings indicate that the carbon footprint of biodiesel (44 g CO_{2eq}/MJ) is significantly lower than that of fossil diesel (86 g CO_{2eq}/MJ) when not considering the potential impacts of indirect land-use change (iLUC). However, inclusion of iLUC impacts could result in a higher carbon footprint for biodiesel than fossil diesel. The life-cycle fossil energy inputs for rapeseed biodiesel are estimated at 0.53 MJ per one MJ of biodiesel, while fossil diesel requires approximately 30% more fossil energy than is present in the fuel.

Keywords: biodiesel, rapeseed, carbon footprint, energy efficiency, life cycle assessment.

1. INTRODUCTION

Biofuels are being advocated as environmentally friendly substitutes for fossil fuels because they derive from renewable biomass sources. Unlike fossil fuels, the carbon dioxide released when biofuels are burned is considered neutral for global warming because it originates from the atmosphere, having been absorbed by plants during photosynthesis. However, the production chain of biofuels involves various processes that emit greenhouse gases (GHGs) and consume non-renewable energy sources. Therefore, to accurately assess the environmental impact of biodiesel, it's crucial to adopt a life cycle approach, encompassing every stage in its complex life cycle from resource extraction to final combustion. The life cycle assessment (LCA), outlined in ISO 14040 and ISO 14044 standards, is a standardized environmental management tool recommended by the European Commission and mandated by the Directive of the European Parliament and Council (EU) 2018/2001, also known as the Renewable Energy Directive 2018. This methodology offers a systematic framework for evaluating the environmental footprint of products, including biofuels, ensuring that all associated impacts are thoroughly considered. By employing LCA, policymakers and stakeholders can gain a holistic understanding of the environmental implications of biofuel production and use, enabling informed decision-making towards sustainable energy solutions.

The objective of this study is to conduct a LCA of biodiesel manufactured in Serbia using locally sourced feedstock, such as rapeseed. Additionally, the aim is to identify environmental hotspots throughout the complex life cycle of biodiesel and propose measures for minimizing both its carbon footprint and non-energy resource demands.

2. METHOD

The life cycle assessment of biodiesel was conducted in accordance with ISO 14040:2006 standard, with adherence to the principles of attributional LCA (Ekvall, 2019). The LCA methodology comprises four main steps: goal and scope definition, inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation.

2.1. Goal and scope

This study aims to evaluate the carbon footprint (CF) and cumulative energy demand (CED) of rapeseed biodiesel, commonly referred to as rapeseed methyl ester (RME), produced in Serbia. The functional unit (FU) is defined as 1 TJ of energy, equating to 26,316 kg of biodiesel, based on a lower heating value (LHV) of 38 MJ/kg. System boundaries encompass all pertinent stages in the biodiesel life cycle, including the entire production chain of RME and its subsequent combustion in the internal combustion engine of a road vehicle. Primary and secondary data were employed to establish the inventory of key processes in foreground system (refer to Fig. 1), while the background system was modeled using relevant datasets from the ecoinvent 3.7 (Wernet et al., 2016) life cycle inventory (LCI) database (see Table 1). Processes associated with the production, maintenance, and end-of-life treatment of machinery, equipment, buildings, and infrastructure within the foreground system are excluded from the study. Nevertheless, their contribution to the overall results is typically minor, thus their exclusion is unlikely to significantly impact the outcomes. In attributional LCA, system boundaries "ideally contain processes that are actually directly linked by (physical, energy, and service) flows to the unit process that supplies the functional unit or reference flow (Sonnemann&Vigon, 2011)". Therefore, indirect impacts, such as GHG emissions associated with indirect land-use change, are not taken into account when calculating the carbon footprint of biodiesel. Multifunctionality is addressed by allocating the overall impacts of multifunctional processes among their co-products based on economic value. The issue of multifunctionality in LCAs of biodiesel is thoroughly discussed in our previous paper (Kiš&Bošković, 2013), which also outlines the economic allocation procedure utilized in this study.

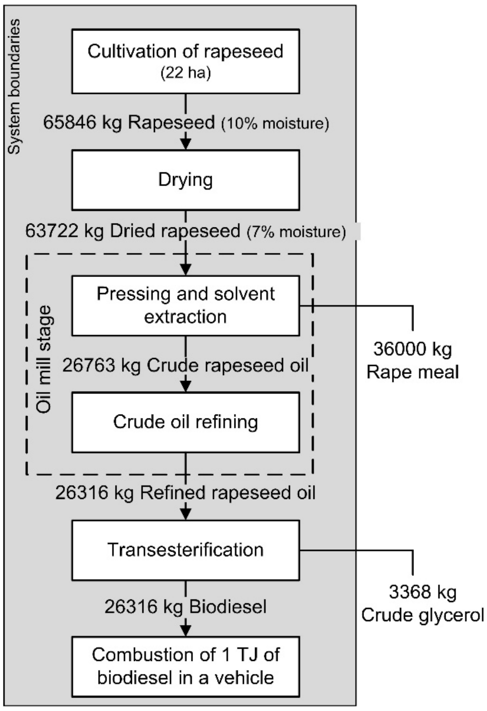

Figure 1: Main material flows in the life cycle of rapeseed biodiesel
Source: authors' own depiction

2.2. Life cycle inventory (LCI) analysis

Inventory analysis involves compiling and quantifying inputs and outputs for the analyzed product system. Below is a brief description of the main processes comprising the life cycle of biodiesel and the associated input/output flows.

Production of oilseed rape. It is assumed that rapeseed is cultivated in the Vojvodina region, which currently accounts for approximately 80% of domestic rapeseed production. The required inputs (fertilizers, pesticides and diesel fuel) for achieving the targeted rapeseed yield of 3,000 kg/ha (with 10% moisture content) were estimated based on recommendations from relevant agricultural advisory institutions, considering the predominant local conditions in

Vojvodina, such as soil types, fertility, and climate. The targeted yield aligns well with the five-year (2018-2022) average rapeseed yields in Vojvodina. Detailed description of the agricultural operations and inputs associated with rapeseed production in Vojvodina is available from Kiš et al. (in press). Greenhouse gas (GHG) emissions occur during diesel combustion in agricultural machinery and fertilization. Tier 2 emission factors from the EMEP/EEA 2019 study (Winter and Dore, 2019) were used to determine the amount of GHGs, such as carbon dioxide (CO_2), methane (CH_4), and dinitrogen monoxide (N_2O), released with the combustion of diesel fuels in agricultural machines (for details see Kiš et al., in press). The only GHG released due to the application of mineral fertilizers is N_2O. The amount of N_2O is estimated using the most recent guidelines of the IPCC (Hergoualc'h et al., 2019) which apart from direct emissions of N_2O from mineral fertilizers and crop residues also considers indirect N_2O emissions from volatisation, leaching and runoff of nitrogen from fertilizers and crop residues (the calculation procedure is described in more details in Kiš et al. (in press). Rapeseed is assumed as the sole marketable output, with crop residues left in the field. After harvest, rapeseed is transported to a dryer, using a tractor equipped with two 8-tonne trailers.

Drying of rapeseed. Rapeseed undergoes drying in an indirect gravity dryer to reduce moisture content to 7%, optimal for storage and processing (Maslać, 2021). The dryer employs natural gas as a heat source, with a specific thermal energy consumption of 5700 kJ per kg of evaporated water (Grbić, Lučić, Bicok, &Đukić, 2020). Electrical energy consumption is estimated at 2.7 kWh per tonne of seed. (Ivan Pavkov, Faculty of Agriculture, University of Novi Sad, pers. commun.).

Pressing and extraction of rapeseed oil. The dried rapeseed is transported with 28-tonne truck to the oil mill located 80 km from the dryer. The inventory of the oil mill stage is based on reports from a Danish AAK oil mill from Aarhus (Schmidt, 2007). Similar to Serbian oil mills, the production line at AAK comprises seeds pretreatment and pressing plant, along with solvent extraction. Among the materials used, only hexane is utilized in significant quantities, consumed at a rate of 1.19 kg per tonne of pressed and extracted rapeseed oil. The energy supply to the oil mill encompasses electricity and steam. Steam is co-produced with electricity within the mill through a combined heat and power plant (CHP) fueled by fuel oil. Energy consumption associated with both pressing and extraction amounts to 1590 MJ of heat energy (generated by combusting approximately 43 kg of fuel oil in the CHP plant) and 419 MJ of electricity (of which around 90 MJ is produced within the CHP plant) per one tonne of produced oil (Schmidt, 2007). During the process, rapeseed meal is co-produced with rapeseed oil in quantities specified in Fig. 1. Allocation factors were estimated using the average Serbian export prices of rapeseed oil (1195 USD/t) and meal (326 USD/t) in the period 2020-2023 available from the Statistical Office of the Republic of Serbia database.

Rapeseed oil refining. In the crude oil refining process, free fatty acids are converted into soaps by adding sodium hydroxide and removed by centrifugation. Other impurities are removed by filtration using acid-treated bleaching clay. In the refining process, 6.1 kg of light fuel oil and 104 MJ of electrical energy (part of this amount, around 13 MJ, is co-produced with steam in the CHP plant) are consumed per ton of crude oil (Schmidt, 2007).

Transesterification of refined oil into biodiesel. In this study, it is assumed that biodiesel is produced from refined rapeseed oil using a continuous alkali-catalyzed homogeneous process, with methanol as the alcohol for transesterification. This method is also employed at VictoriaOil in Šid, which is currently the largest biodiesel plant in Serbia. The oil mill and the transesterification plant are adjacent to each other; therefore, transportation of refined oil is not included in the inventory. A description of the process, along with a detailed inventory of material and energy flows associated with the production of one tonne of biodiesel, is provided in our previous article (Kiss, Bošković, &Jovanović, 2010). During the transesterification process, glycerol is co-produced with biodiesel at a rate of 128 kg per tonne of biodiesel. Consequently, part of the overall impact is attributed to the glycerol co-product, under the assumption that the market prices of biodiesel and glycerol are 285 USD/t (ChemAnalyst, 2024) and 1170 USD/t (Burgin, Foss, &Gomez, 2023), respectively.

Combustion of biodiesel. In this study, we assume the utilization of biodiesel for providing freight transport services via a lorry with a maximum payload of 28 tonnes, equipped with an engine compliant with EURO3 emission standards. The specific fuel consumption (45.86 g/tkm or 26,316 kg/FU considering LHV of biodiesel as 38 MJ/kg) and GHG emissions from the operation of the lorry (as outlined in Table 1) are estimated based on data from the relevant ecoinvent report (Spielmann, Bauer, Dones, & Tuchschmid, 2007). The life cycle environmental impacts of a biodiesel-fueled lorry are compared with those of a fossil diesel-fueled counterpart, both evaluated based on the same functional unit (1 TJ of delivered energy). Due to the differing LHVs of biodiesel and fossil diesel (38 and 43 MJ/kg, respectively), the impact of biodiesel is evaluated against the equivalent energy content of 23,256 kg of fossil diesel fuel.

Table 1 provides an overview of the material and energy flows associated with each process in the foreground system, along with references to the LCI data used to calculate the impacts associated with them.

Table 1: Flows associated with the life cycle of rapeseed biodiesel (per FU) and source of LCI data

Life cycle phase	Processes/Flows	Unit	Amount (a)	Amount (b)	Source of LCI data
Rapeseed cultivation	Seed	kg	88	62	ecoinvent 3.7
	Diesel, low-sulphur	kg	2,269	1,606	ecoinvent 3.7
	Lubricating oil	kg	14	10	ecoinvent 3.7
	NPK (6:12:24)	kg	10,974	7,771	ecoinvent 3.7 (c)
	AN (33.5% N)	kg	6,585	4,663	ecoinvent 3.7
	Pesticides, unspecified	kg a.i.	30	21	ecoinvent 3.7
	Water for diluting pesticides	kg	39,508	27,975	ecoinvent 3.7
	GHG emissions from the combustion of diesel fuel	kg $CO_{2eq.}$	7,367	5,217	Winter and Dore (2019)
	N_2O emissions from the application of N fertilizers	kg N_2O	38	27	based on Hergoualc'h et al. (2019)
	Transport (tractor with trailers)	tkm	658	466	ecoinvent 3.7
Seed drying	Electricity	kWh	178	126	ecoinvent 3.7
	Heat, from natural gas	MJ	12,107	8,573	ecoinvent 3.7
Oil pressing and extraction	Hexane				ecoinvent 3.7
	Electricity	MJ	32	23	ecoinvent 3.7
	Heat, from light fuel oil	MJ	8,788	6,223	ecoinvent 3.7
	Tap water	kg	48,724	34,501	ecoinvent 3.7
	Heat, from natural gas	MJ	5,106	3,616	ecoinvent 3.7
	Transport (16-32 t truck)	tkm	54	38	ecoinvent 3.7
Oil refining	Electricity	MJ	2,398	2,326	ecoinvent 3.7
	Heat, from light fuel oil	MJ	6,810	6,605	ecoinvent 3.7
	Tap water	kg	714	692	ecoinvent 3.7
	Heat, from natural gas	MJ	8	8	ecoinvent 3.7
	Phosphoric acid	kg	21	20	ecoinvent 3.7
	Sodium hydroxide	kg	55	54	ecoinvent 3.7
	Sulfuric acid	kg	50	49	ecoinvent 3.7
	Activated bentonite	kg	237	230	ecoinvent 3.7
Transesterification	Heat, from natural gas	kg	32,545	31,568	ecoinvent 3.7
	Electricity	MJ	2,018	1,958	ecoinvent 3.7
	Deionised water	MJ	9,211	8,934	ecoinvent 3.7
	Sodium methoxide	kg	132	128	ecoinvent 3.7
	Sodium hydroxide	kg	39	38	ecoinvent 3.7
	Methanol	kg	2,526	2,451	ecoinvent 3.7
	Hydrochloric acid	kg	263	255	ecoinvent 3.7
	Tap water	kg	3,803	3,689	ecoinvent 3.7
Combustion of biodiesel	CO_2, biogenic, to air	kg	70,510	70,510	based on Spielmann et al. (2007)
	CO_2, fossil, to air (d)	kg	3,917	3,917	
	CH_4, to air	g	397	397	
	N_2O, to air	g	695	695	

Note: (a) before co-product allocation; (b) after co-product allocation; (c) modified ecoinvent 3.7 process (see Kiš et al., in press); (d) a portion of the carbon in RME originates from methanol, which accounts for CO_2 emissions of fossil origin.

Source: authors' own compilation

2.3. Life cycle impact assessment (LCIA)

The carbon footprint (measured in kg CO_2-equivalent emissions, CO_{2eq}) of biodiesel was computed using the ReCiPe 2016 Midpoint (H) LCIA method, which aligns with the IPCC methodology and characterization factors (Huijbregts et al., 2017). In this study, it is assumed that carbon emissions originating from biomass (i.e., biogenic CO_2 emissions) are neutral in terms of global warming and therefore are excluded from GHG emissions. Likewise, the biodiesel fuel chain does not receive credit for carbon sequestered during plant growth. The cumulative energy demand is assessed using the CED LCIA method (Frischknecht et al., 2007). Implementation of life cycle impact assessment methods.), which considers all relevant non-renewable and renewable energy sources utilized in the analyzed product system. Both LCIA methods and the ecoinvent 3.7, which provided most of the LCI data for background processes, are integrated into the OpenLCA v. 13 LCA software, which was utilized for the calculation process.

3. RESULTS AND DISCUSSION

The carbon footprint and cumulative energy demand of biodiesel and fossil diesel are presented in Table 2. The carbon footprint of rapeseed biodiesel is 44 g CO_{2eq}/MJ, and it is approximately 50% lower than that of fossil diesel, which was estimated at 86 g CO_{2eq}/MJ. It's important to note that in this study, we did not consider the rather controversial issue of indirect land-use change (iLUC) induced by biofuel production (see Finkbeiner, 2014). Consequently, the presented LCIA results do not include the potential impacts associated with iLUC, which, according to Directive (EU) 2018/2001, can range between 33 to 66 g CO_{2eq}/MJ, with a mean value of 55 g CO_{2eq}/MJ for oil crops derived biodiesel.

The estimated life-cycle fossil energy inputs (fossil CED) for rapeseed biodiesel were 0.53 MJ/MJ of biodiesel, indicating that the energy in biodiesel is almost two times greater than the fossil-based energy required to produce it. In contrast, fossil diesel requires 30% more fossil energy than is present in the fuel, resulting in an unfavorable ratio of energy output to energy input of 0.76 (calculated from Table 2). The CED LCIA method also accounts for energy sources other than fossil fuel, but given their minor contribution to overall energy usage (Table 2), the following discussion focuses on the fossil energy demand of the investigated product systems.

Table 2: Carbon footprint (kg CO_{2eq}/FU) and cumulative energy demand (MJ/FU) of biodiesel and fossil diesel

Indicator	Seed production	Seed drying	Crude oil extraction	Crude oil refining	Transesterification	Combustion of biodiesel	Total, biodiesel	Total, fossil diesel (c)
Carbon footprint	27,292	739	5,403	1,456	4,850	4,141	43,880	86,216
Cumulative energy demand								
fossil(a)	284,635	12,170	73,671	19,437	136,061	0	525,975	1,310,984
biomass(b)	5,513	7	115	106	245	0	5,986	903
nuclear(a)	12,614	160	1,832	889	2,364	0	17,860	4,668
water(b)	3,475	169	2,017	863	1,216	0	7,740	1,798
wind, solar, geothermal(b)	1,903	18	175	92	288	0	2,475	567

Notes: (a) non-renewable, (b) renewable, (c) estimated based on the ecoinvent 3.7 process, which describes road transport using a lorry with a weight capacity of 16-32 tonnes equipped with an engine compliant with EURO3 emission standards.

Source: authors' own compilation

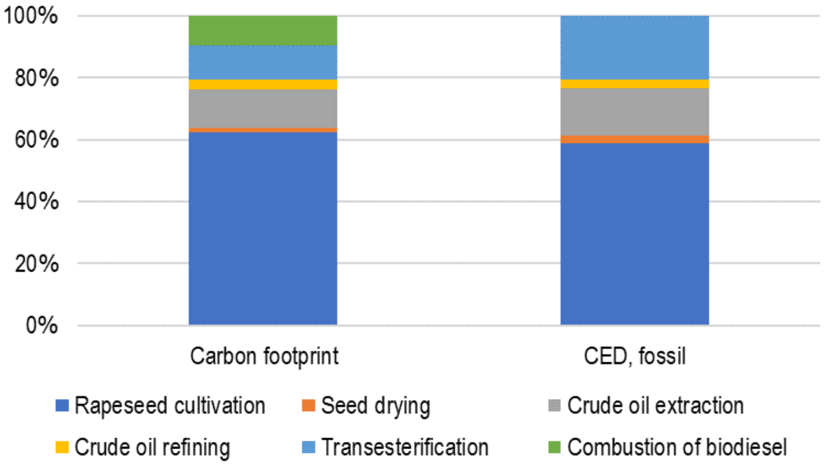

Figure 2: Contribution of life cycle stages to carbon footprint and fossil energy demand of biodiesel

Source: authors' own depiction

Rapeseed cultivation and its associated processes contribute to 62% of the biodiesel's carbon footprint and account for 76% of the fossil energy consumed throughout its life cycle (Fig. 2). GHGs related to fertilizers contribute to 75% of the total carbon footprint of rapeseed production. Around two-thirds of the carbon footprint of mineral fertilizers is due to the emissions of GHGs in their production chain, while the rest is attributed to N_2O emissions after the application of nitrogen fertilizers (Fig. 3). The remaining portion of the carbon footprint during the agricultural stage is primarily attributed to GHG emissions associated with diesel fuel used in agricultural machinery (Fig. 3). Similarly, the fossil energy requirements of rapeseed production are predominantly associated with the usage of mineral fertilizers and diesel fuel (Fig. 3).

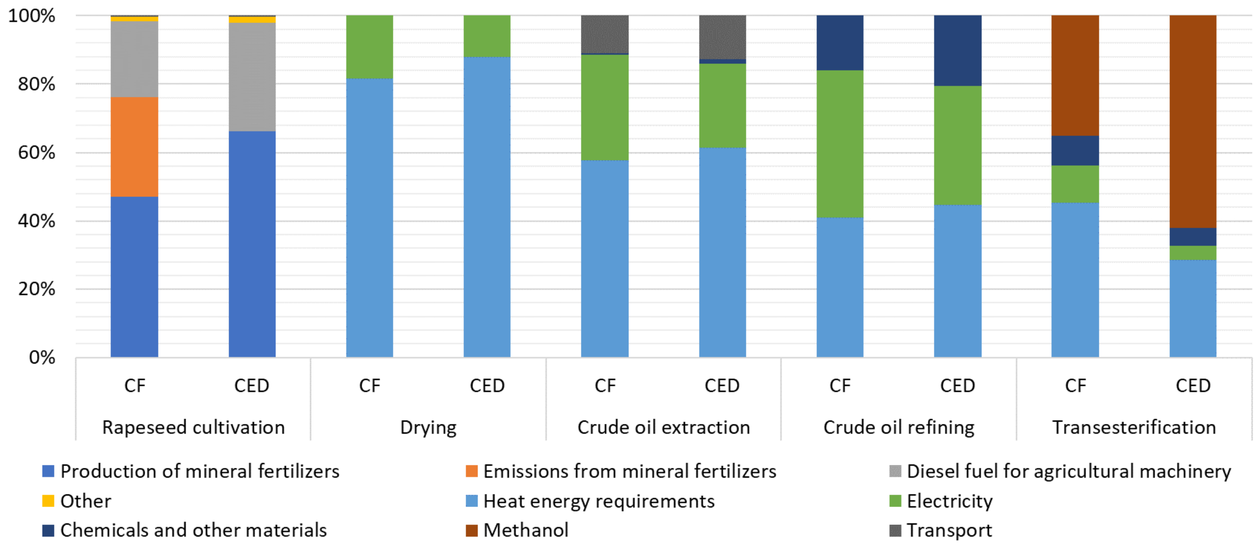

Figure 3: Contribution of processes to carbon footprint and fossil energy demand of biodiesel
Source: authors' own depiction

Processes within the oil mill stage (crude oil extraction and refining) contribute with 15%, while the transesterification stage is responsible for 11% of the GHG emission impacts in the biodiesel's life cycle (Fig. 2). In the oil mill stage, activities related to the production and utilization of heat energy and electricity required by the plant contribute significantly to both impact categories investigated (Fig. 3). Chemicals utilized during solvent extraction and the refining process exert a minor influence on the results. The notable share of transport-related impacts in crude oil production is due to accounting for impacts associated with the transport of dried rapeseed in the oil mill stage rather than in the seed drying stage.

In the transesterification process, the production of methanol and other chemicals used in the process contributes to 44% of the carbon footprint and 67% of the fossil CED of the process, followed by the production and utilization of energy required by the plant (Fig. 3). The significant portion of global warming impacts associated with chemicals in the transesterification stage primarily arises from the substantial GHG emissions released during methanol manufacturing. Environmental impacts linked to the grain drying stage are relatively minor, mainly driven by the heat and electricity requirements of the process (Figs 2 and 3).

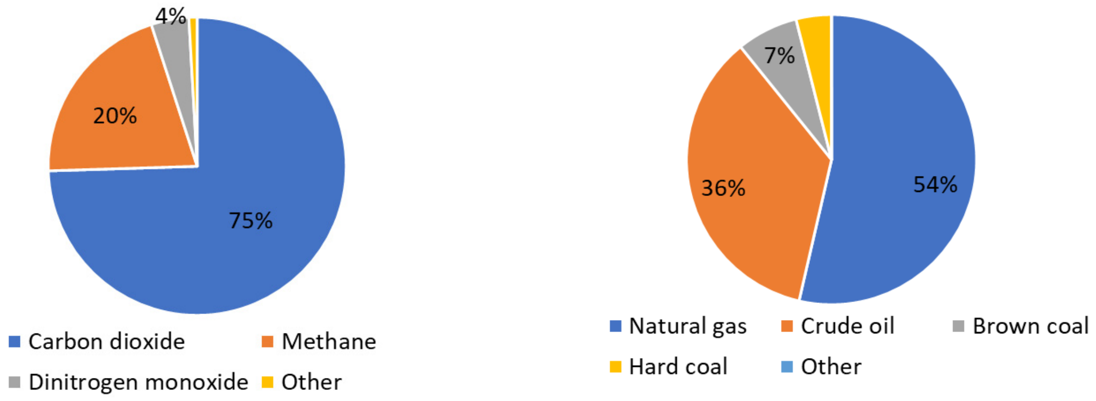

Figure 4: Contribution of elementary flows to category indicator results (left: CF, right: fossil CED)
Source: authors' own depiction

As observed in Fig. 4, only a select few GHGs and fossil energy resources significantly contribute to the estimated carbon footprint and fossil energy consumption of biodiesel. Carbon dioxide stands out as the primary contributor to biodiesel's carbon footprint, followed by CH_4 and N_2O. Processes linked to the production chain of mineral fertilizers and the life cycle of diesel fuel used in agricultural machinery collectively account for roughly half of the total fossil CO_2 and CH_4 emissions in the life cycle of RME, as illustrated in Fig. 5. Additionally, the combustion of fossil fuels for heat generation and electricity production represents another notable source of CO_2 and CH_4 emissions.

The significant contribution of methanol to CH_4 emissions (exceeding 30%, as depicted in Fig. 5) is attributed to the primary method of methanol production, which relies on steam reforming of natural gas. N_2O emissions in the life cycle of RME are predominantly associated with the application of nitrogen fertilizers.

Crude oil and natural gas consumption collectively account for approximately 90% of the fossil CED of biodiesel. Processes driving natural gas consumption closely parallel those contributing to CH_4 emissions (see Fig. 5), underscoring the strong correlation between natural gas consumption and CH_4 emissions. Predictably, diesel consumption in agricultural machinery constitutes the primary factor contributing to the depletion of crude oil reserves. Furthermore, heat generation also contributes to crude oil consumption mainly because light fuel oil is used as the primary fuel in the oil mill stage (Fig. 5). Brown coal (often referred to as lignite) consumption contributes around 7% to the total fossil CED of biodiesel and is closely related to electricity consumption, since electricity generation in Serbia relies heavily on lignite fuel power plants.

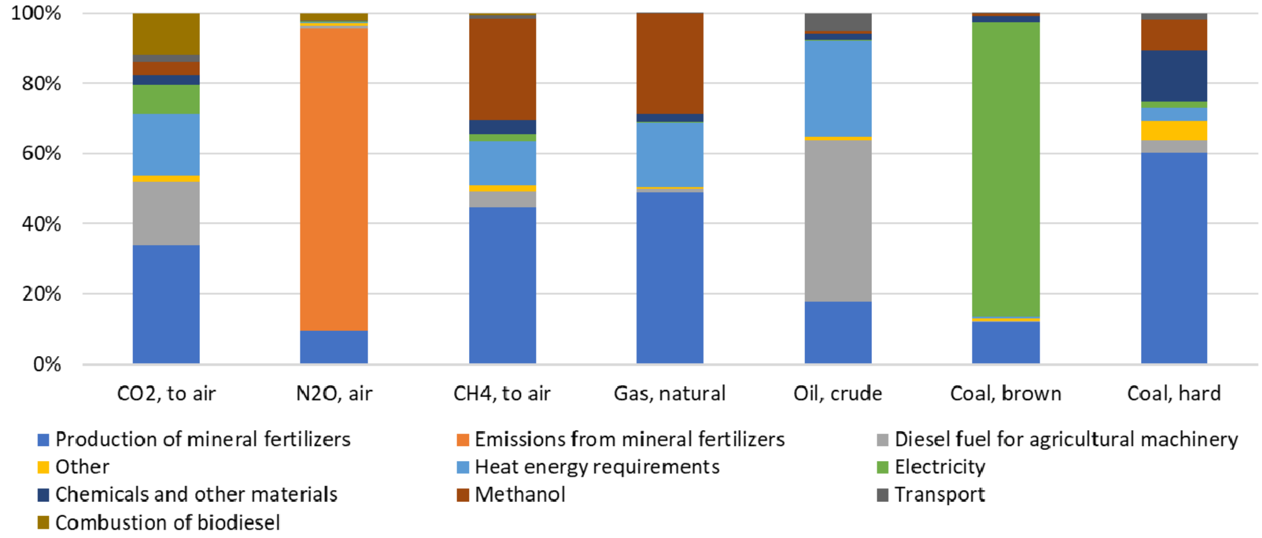

Figure 5: Contribution of specific processes to emissions and resource use in the life cycle of biodiesel

Source: authors' own depiction

4. CONCLUSIONS

The analysis of carbon footprint and cumulative energy demand provides valuable insights into the sustainability of biodiesel derived from rapeseed oil compared to fossil diesel. The results demonstrate a clear advantage for rapeseed biodiesel, with an approximately 50% lower carbon footprint than that of fossil diesel. Moreover, the analysis reveals that rapeseed biodiesel exhibits a favorable energy balance, with almost twice the energy content compared to the fossil energy inputs required for its production. However, it's crucial to acknowledge that the assessment does not consider the potentially significant global warming impacts of indirect land-use change (iLUC) induced by biofuel production, which could cast doubt on the sustainability of biodiesel production.

The cultivation of rapeseed and associated processes contribute substantially to its environmental footprint, predominantly due to GHG emissions and fossil energy use in the life cycle of fertilizers and fuels used in agricultural activities. Furthermore, processes within the oil mill and transesterification stages significantly contribute to GHG emissions and energy consumption. Notably, the production of methanol and chemicals in the transesterification process emerges as a major hotspot, primarily due to GHG emissions released during methanol manufacturing. Additionally, crude oil and natural gas consumption drive the majority of fossil energy demand, emphasizing the need for efficiency improvements in energy-intensive stages.

To enhance the sustainability of rapeseed biodiesel production, several strategies can be pursued. Firstly, optimizing agricultural practices to minimize fertilizer usage and diesel fuel consumption per unit of yield can substantially reduce emissions and energy demand in the cultivation stage. Similarly, improving energy efficiency and transitioning to renewable energy sources in oil extraction and chemical processing stages can mitigate environmental impacts. Furthermore, innovation in production methods, such as utilizing alternative feedstocks (e.g. using bioethanol instead of methanol) or implementing advanced conversion technologies, holds potential for reducing emissions and energy consumption throughout the biodiesel production chain.

Overall, while rapeseed biodiesel offers environmental benefits over fossil diesel, addressing key hotspots in its life cycle is essential for realizing its full potential as a sustainable energy source. Continued research, technological innovation, and policy support are crucial for driving improvements and ensuring the long-term viability of biodiesel production in contributing to global energy needs while minimizing environmental degradation.

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