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Two birds with one stone: A combined environmental and economic performance assessment of rapeseed-based biodiesel production

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Abstract

Rapeseed is the dominant feedstock for biodiesel production in Germany; however, significant decline in crop yields observed during the 2018 drought in Europe poses economic and environmental risks for its sustained use as a fuel crop. Many Life Cycle Assessment (LCA) studies were conducted to quantify the potential environmental impacts of biodiesel production; however, only a few studies have considered the spatial and temporal heterogeneities of the studied regions. Furthermore, previous studies have usually only focused on the greenhouse gas (GHG) savings of biodiesel and have ignored the environmental burden and economic profits of biodiesel production. For the first time, we combined the Regional Environmental LCA model with an economic analysis to evaluate both the environmental impact and the economic benefits of biodiesel production in Central Germany (CG). Our results showed that emissions from rapeseed cultivation were the largest contributor to both global and regional environmental impact categories. In our study region, we found that GHG emissions were around 56%–71% lower for rapeseed-based biodiesel than for fossil fuels. Due to the drought in 2018, we also observed that the regional rapeseed supply could not meet the demand of biodiesel production in CG. An economic analysis of biodiesel production found significant economies of scale effect in the biodiesel industry. In addition, none of the studied biodiesel plants were able to operate at their designed installed capacities without causing indirect land-use change. Furthermore, the profitability of biodiesel production was closely related to the feedstock cultivation cost. Based on these findings, we concluded that a regionalized LCA model would be able to more accurately evaluate the environmental influence of biodiesel production by taking site-specific conditions into consideration. We also suggest that potential biodiesel plant operators take the regional biodiesel production density and feedstock cultivation conditions into account when deciding on plant size.

KEYWORDS
biodiesel, greenhouse gas emissions, multi-objective optimization, Net Present Value, regional environmental impacts, regional studies, spatially explicit Life Cycle Assessment

1 | INTRODUCTION

The Paris Agreement has been ground breaking in its efforts to obtain global involvement in combating climate change. Its aim is to limit global warming to <2°C above the pre-industrial average (UNFCCC, 2015). The European Green Deal provides an action plan for implementing climate actions for a sustainable, resource-efficient and environmental-friendly economy in Europe (EU Commission, 2019). To achieve these goals, the European Union (EU) commission put forth its proposal in April 2020 to enshrine in legislation the EU's political commitment to be climate neutral by 2050 (EU Commission, 2020). One measure that has already been put into practice is sustainably certified biogenic raw materials and biofuels. For instance, approximately 9.5 million tonnes of CO_2 eq. were avoided in 2018 through the use of biofuels (BLE, 2019).

Biodiesel is a critical type of biofuel that has many advantages over petroleum diesel, such as lower pollution rates, lower greenhouse gas (GHG) emissions and a higher degradability (Firoz, 2017). The feedstocks for biodiesel production are generally oilseed crops, animal fats and microalgae. Of the different oilseed crops, soybeans are the primary feedstock for biofuel production in the United States. In Asia, China's most common feedstocks are used and imported vegetable oils and jatropha, and in Malaysia, Indonesia and Thailand, palm oil is the primary raw material for biodiesel production (Koçar & Civaş, 2013). In the EU, the primary crops are rapeseed, sunflower and soybeans. Among the EU's 27 member countries, France, Germany and Poland were the top three rapeseed producers in 2018, producing 4.9, 3.6 and 2.2 million tonnes, respectively (FAOSTAT, 2018). In Germany, biodiesel is the most produced biofuel (fatty acid methyl esters, FAME), comprising approximately 64% of the total output in 2017, followed by bioethanol at 34% (FNR, 2019). Biofuels made up approximately 5% of the total fuel consumption in the transport sector in 2018, 3.6% of this being biodiesel (FNR, 2020).

However, the production of biofuel is under debate as a result of the potential environmental burdens caused by the cultivation of bioenergy crops. These include land competition with food crops (Muscat et al., 2020; Valentine et al., 2011), nutrient pollution in groundwater (Diaz-Chavez et al., 2011; Nyakatawa et al., 2006; Wu et al., 2018), potential biodiversity loss (Di Fulvio et al., 2019; Immerzeel et al., 2014; Meehan et al., 2010) and decline in soil quality (Wu et al., 2018). The biggest argument against the cultivation of bioenergy crops is direct and indirect land-use change (dLUC and iLUC), which pose both an environmental problem and ethical problem (e.g. crop scarcity, malnutrition). In contrast to dLUC, there is little consensus on the approaches used to evaluate iLUC, making it difficult to quantify. Nevertheless, many studies still report that the emissions from iLUC could offset any GHG savings from biofuels (Lapola et al., 2010). In addition, the Renewable Energy Directive (RED) 2009/28/EC (EU Commission, 2009), as the most crucial policy for promoting biofuel production, is also being criticized for using standard values (default values) to measure GHG savings as part of its sustainability criteria. For instance, when comparing two widely used GHG accounting tools, scholars pointed out the need to include deep harmonization in the calculation processes under the current methodological framework of the RED (Hennecke et al., 2013). Additionally, many researchers believe that Germany's rapeseed biodiesel might fail to reach the 35% GHG reduction goal when weather conditions are unfavourable and actual N_2O field emission values are taken into account (Pehnelt & Vietze, 2012, 2013). Therefore, in 2015, the RED was redrafted to take iLUC effects into consideration and the EU Parliament introduced a cap (ILUC Directive) of 7% on the amount of biofuel crops. Three years later, the RED II re-casted the RED to promote renewable energy utilization and establish a framework for the country's renewable energy policy for the period from 2021 to 2030. Moreover, the RED II proposed differentiating between low-risk and high-risk iLUC feedstocks. Unlike low-risk feedstocks, such as maize, sugarcane and rapeseed, high-risk feedstocks like palm oil will be subject to a sub-cap (below the 7% biofuel crop-based cap) keeping it at 2019 consumption levels from 2021 to 2023 and then phasing it out to 0% by 2030 (Dusser, 2019).

Scholars generally agree that Life Cycle Assessments (LCA) are one of the most effective approaches for evaluating the environmental influences of bioenergy production (Campbell et al., 2011; Krohn & Fripp, 2012; Liang et al., 2013; Rocha et al., 2014; Varanda et al., 2011). The scientific literature includes many LCA studies that evaluate the environmental impact of rapeseed-based biodiesel systems (Table 1). These studies mainly follow the generic LCA approach to enable comparison among the various systems and to utilize such Life Cycle Impact Assessment

TABLE 1 Overview of representative studies on the Life Cycle Assessment of rapeseed-based biodiesel products and the impact categories quantified in that study

Authors	Region	Method	GWP	EP	AP	ADP	POCP	ODP	TETP	FAETP	MAETP	HTP	Land	Rad	Car	Fos
Tsoutsos et al. (2010)	Greece	n.a.	×	×	×			×	×				×	×	×	×
Zah et al. (2007)	Switzerland, Europe, Brazil, USA	Eco-indicator 99	×	×	×				×				×			×
Nanaki and Koroneos (2012)	Greece	Eco-Indicator 99	×	×	×				×						×	×
Ozata et al. (2009)	Turkey	Eco-indicator 95	×	×	×		×								×	
Malça et al. (2014)	Spain, France, Germany, Canada	CML 2001	×	×	×	×										
Sanz Requena et al. (2011)	Spain	Eco-Indicator99	×	×	×			×	×				×	×	×	×
Fridrihsone et al. (2020)	Northern Europe	ReCiPe	×	×	×		×	×	×	×	×	×	×	×		×
Mousavi-Avval et al. (2017b)	Iran	CML-IA baseline v3.01	×	×	×	×	×	×	×	×	×	×				
Khanali et al. (2018)	Iran	CML 2001	×	×	×	×	×	×	×	×	×	×				
Palmieri et al. (2014)	Italy	ReCiPe 2008	×	×	×				×	×	×	×	×	×		×
González-García et al. (2013)	Spain	CML 2001	×	×	×	×	×	×					×			
Queirós et al. (2015)	Central Europe	CML 2000 v2.0	×	×	×	×	×	×								
Schmidt (2010)	Denmark	EDIP97	×	×	×		×	×					×			
Dufour et al. (2013)	Spain	Eco-Indicator99	×					×						×	×	×
Montrimaitė et al. (2010)	EU and Lithuania	IPCC	×													
Gasol et al. (2012)	Southern Europe	CML 2000	×	×	×	×			×	×	×	×				
Kesieme et al. (2019)	United Kingdom	CML 2010	×	×	×											
Ji et al. (2021)	China	ReCiPe 2016	×	×	×					×					×	×
Bai et al. (2021)	China	ReCiPe 2016		×	×				×	×	×	×				
Reijnders and Huijbregts (2008)	EU	IPCC	×													
Iriarte et al. (2010)	Chile	CML 2001	×	×	×		×	×	×	×	×	×				
Myllyviita et al. (2012)	Finland	ReCiPe 2008	×	×	×					×		×	×			×
Forleo et al. (2018)	Italy	CML 2001	×	×	×	×	×	×	×	×	×	×				
Fernández-Tirado et al. (2016)	Southwest Spain	ReCiPe 2008	×		×			×				×	×			×

Abbreviations: ADP, abiotic depletion potential; AP, acidification potential; Car, carcinogenic substances; EP, eutrophication potential; FAETP, freshwater ecotoxicity potential; Fos, fossil energy requirement; GWP, global warming potential; HT, human toxicity; Land, land competition/occupation; MAETP, marine aquatic ecotoxicity potential; ODP, ozone depletion potential; POCP, photochemical ozone creation potential; Rad, ionizing radiations potential; TETP, terrestrial ecotoxicity potential.

(LCIA) methods as CML 2001 (Guinée et al., 2002), Eco-indicator 99 (Goedkoop & Spriensma, 2001), ReCiPe 2008 (Goedkoop et al., 2008), EDIP 1997 (Wenzel et al., 1997) and IPCC (2014) in their evaluations. However, the downside of using generic LCAs is that this model is generally based on averages for material and process flows without including temporal and spatial heterogeneities. Therefore, many researchers dispute the reliability and accuracy of applying generic LCAs (Finnveden, 2000; Hellweg & Milà i Canals, 2014). To better incorporate temporal and spatial heterogeneities, more regionalized LCIAs are needed, since the characterization factors of the impact categories are calculated based on site-specific characteristics, for example, topographical condition, land use, soil types, etc. (Rodríguez et al., 2014), the selected spatial scales (Manneh et al., 2010; Yang, Liu, Wang, et al., 2021) and temporal scales (Yang, Liu, Thrän, et al., 2021). Due to the complexity of geographically differentiated processes on a regional scale, a tool that integrates Geographical Information Systems (GIS) and LCA (GIS-LCA) could enable both spatial and temporal information to be incorporated into the regionalized LCIA (Gasol et al., 2011; Hellweg & Milà i Canals, 2014).

One of the ways GIS-LCA has been successfully applied is the Regional Life Cycle Assessment model (RELCA) which was used to evaluate the GHG emission performance of rapeseed-based biodiesel plants in Central Germany (CG) by capturing the spatial heterogeneity of site-specific conditions (O'Keeffe, Majer, et al., 2016; O'Keeffe, Wochele-Marx, et al., 2016; O'Keeffe et al., 2017). RELCA also includes temporal climatic input and is an interesting way to test whether the widespread drought in central and northern Europe in 2018 influenced regional GHG emissions and caused other environmental burdens. As pointed out by Gonçalves et al. (2020), a decarbonized society and sustainable bioeconomy development can only be achieved if both economic and environmental benefits are balanced. Therefore, there are many studies focusing on optimizing the life cycle costs and environmental impacts of biofuel products by applying the multi-objective optimization tool (Cambero & Sowlati, 2016b; Mousavi-Avval et al., 2017a; Patle et al., 2014). This approach can produce quantitative trade-offs among the objectives and thus enable better decision-making about the biodiesel production processes.

Against this backdrop, we attempted to address the following questions by applying the GIS-RELCA approach in our study: (1) Which life cycle stage of biodiesel production acts as a main contributor to global and regional environmental impacts? (2) Can RELCA detect the environmental profile changes of rapeseed-based biodiesel production under the drought conditions of 2018? (3) What is the optimized operating capacity of each biodiesel plant in terms of the minimum environmental impact and maximum economic benefit and which plant is most efficient in CG? To answer these questions, we conducted a case study of CG. The LCIA method CML 2001 was employed in this study to detect environmental impacts along the value chain of biodiesel production. A sensitivity test was applied to compare the environmental impacts evaluated by various LCIA methods, that is, CML 2001, ReCiPe 2008 and EDIP 1997/2003. To test whether RELCA can capture the quantitative and spatial differences in regional rapeseed supply, as well as the associated GHG emissions among biodiesel plants, we compared the RELCA result of 2018 with the result of 2010 reported by O'Keeffe et al. (2017). Additionally, a multi-objective optimization analysis was conducted to find the optimal operating capacity of a biodiesel plant after maximizing the economic benefits and minimizing the environmental burdens. Moreover, we also calculated both the Net Present Value (NPV) and the pro unit production profit of each biodiesel plant at its optimized capacity to identify the most efficient biodiesel plant. Based on these findings, we provided suggestions for the size of future biodiesel plants in CG.

Our study systematically evaluated the environmental and economic aspects of the rapeseed-based biodiesel production system to shed new light on holistic bioenergy management. The method adopted in the current study captures regional spatial–temporal heterogeneity. This method can be applied to study other regions by updating the site-specific data. Moreover, the spatially explicit results can support stakeholders in their decisions surrounding sustainable bioenergy management.

2 | MATERIALS AND METHODS

2.1 | Study site

Our study region was the region of CG, which comprises the German federal states of Saxony, Saxony-Anhalt and Thuringia. The total administrative area is approximately 55,105 km^2 with Saxony comprising 18,450 km^2, Saxony-Anhalt 20,454 km^2 and Thuringia 16,201 km^2. There are a total of 50 counties (German: Landkreise und Kreisfreie Städte) in the study region. The climate varies enormously from north to south: the northern area is generally warmer, with a mean annual temperature of around 9°C, and drier with annual rainfall ranging from 450 to 600 mm. On the other hand, the mean annual temperature in the more mountainous south is about 6°C, with average annual rainfall between 600 and 1000 mm (O'Keeffe et al., 2013). Elevations range from 9 m to 1.211 m a.s.l. (USGS, 2014), which is suitable for the cultivation of various economically important crops, such as rye, corn, barley, rapeseed, wheat and sugar beet (Wochele et al., 2014). Out of the 72 different soil types in Germany, 44 are found in the study region (BÜK, 1000, 2007). The field value (Ackerzahl), which is based on soil fertility, slope, elevation and climate, ranges from 31 to 90. This indicates relatively high soil fertility for arable land and other vegetation growth. According to the Corine land cover map from 2018 (CLC-2018, 2019), there are 34 land-use types in the study region. We aggregated the land-use/cover types into eight categories following Yang, Liu, Wang, et al. (2021; Figure 1). As shown, the landscape is dominated by arable land, which comprised approximately 42% of the total administrative area in 2018, followed by forests at 29% (BMEL, 2015).

2.2 | Methodologies

2.2.1 | RELCA

Goal and scope

This study aims to establish the environmental profile of rapeseed-based biodiesel production by utilizing a regionalized LCIA to quantitatively and spatially compare the environmental burden associated with biodiesel production. We applied the RELCA model developed by O'Keeffe et al. (2017). The major modules of RELCA are rapeseed cultivation, harvested rapeseed transportation, rapeseed oil extraction and rapeseed processing in a biodiesel plant. According to Ferreira (2011), the estimated total energy consumption associated with infrastructure is <2% of the total energy consumed during the entire lifecycle of the equipment. Thus, we followed the approach suggested by Malça et al. (2014) and did not include in our study the materials and energy consumed during the construction and demolition of the relevant infrastructure. In the rapeseed-based biodiesel production system studied here, a functional unit was defined as the emissions associated with producing 1 tonne of rapeseed (t). In addition to the global environmental impact factor, namely the GHG emission potential assessed by O'Keeffe et al. (2017), we also included local environmental impact indicators, which play an essential role in the context of the regionally based study (Figure 2).

Agronomic practices in rapeseed cultivation

The potential diesel consumption for field operations in each pixel was calculated using the online KTBL tool. It calculated the approximate diesel consumption within a field area of 20 ha and based on the average farm-to-field distance of 2 km (KTBL, 2012). Since soil type is a factor that vitally influences the diesel consumption of farm machinery, we classified the soil into heavy (clay content >25%), medium (clay content ≤25% but ≥12%) and light (clay content <12%) types. The primary field operations of fertilizing, ploughing, sowing, crop protection, harvesting, liming and ploughing back were considered when estimating fuel consumption during rapeseed cultivation. The rapeseed production module contains several steps. RELCA carries out Crop Allocation Modelling (CRAM) to identify the location and production of rapeseed, then links the agronomic activities to available biomass through Biomass Inventory Modelling (BioMod). Field operations include direct regional flows, such as fertilizer application, diesel consumption of machinery, change in soil carbon stock as well as indirect emission flows, namely imported pesticides, additional seeds, diesel products, etc. from other regions. Details about using the CRAM model to identify dominant crops distribution in CG and about applying BioMod to establish the mass and energy balances relating to rapeseed cultivation are found under Supporting Information.

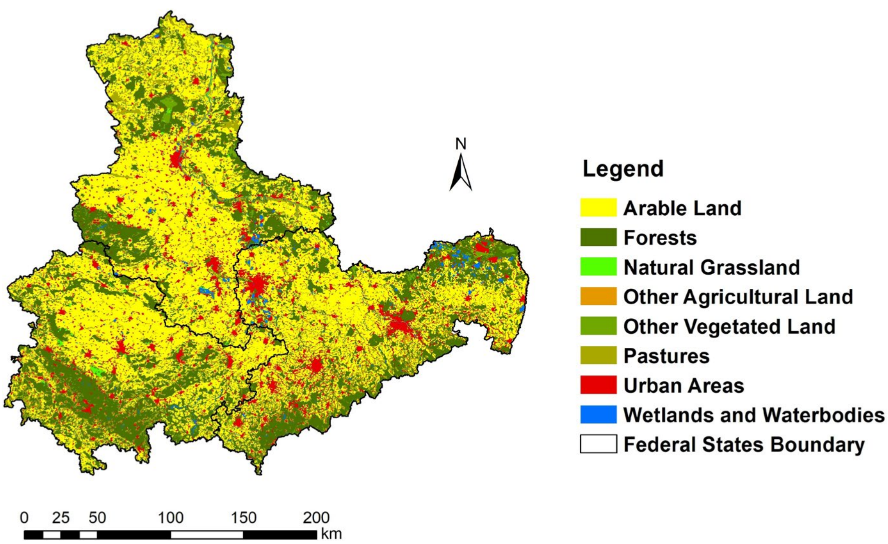

FIGURE 1 Aggregated Corine land cover types in the study region. The spatial data were originally derived from Copernicus Land Monitoring Service

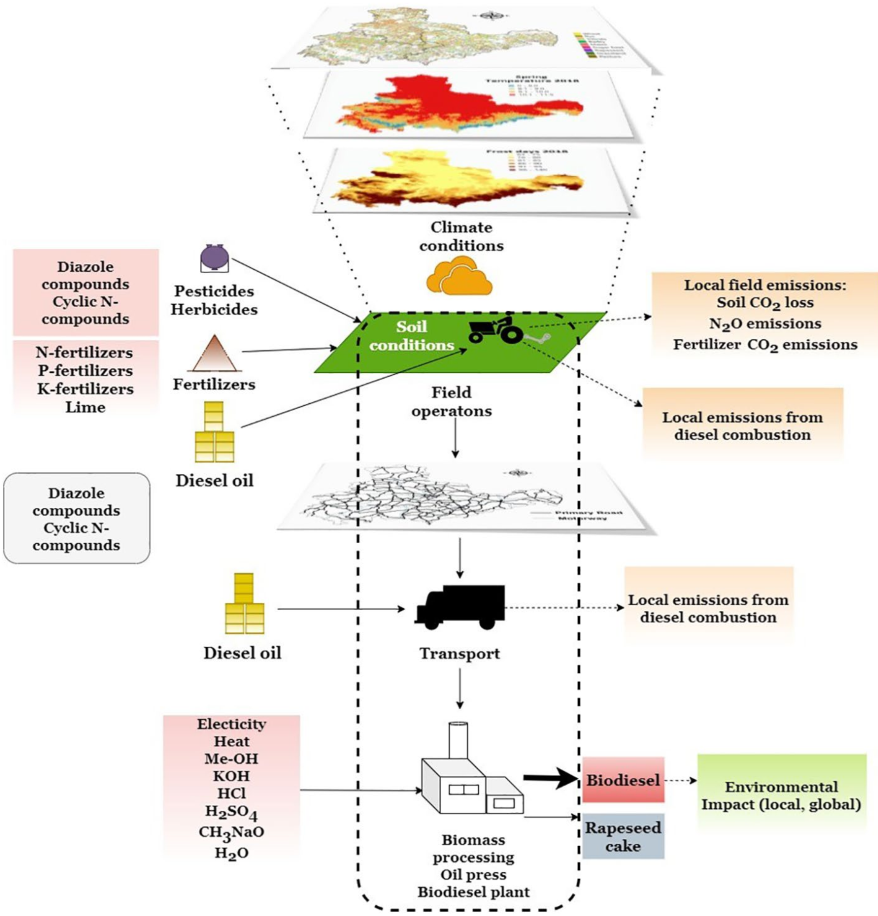

FIGURE 2 System boundary for the production of biodiesel from rapeseed. *Note*: The foreground is the region with agricultural crop cultivation. The geospatial maps of dominant crop distribution, regional climatic conditions and soil types are used to characterize the site-specific condition of rapeseed cultivation areas. The left side shows inputs for rapeseed cultivation, transportation to biodiesel plants and transesterification processing. The middle segment illustrates the major life cycle process of rapeseed-based biodiesel production, and the corresponding environmental impacts are shown on the right

Rapeseed transportation

The linear distance ('hypothetical travel distance' between rapeseed field and biodiesel plant) was calculated using the Euclidean distance function. This enables us to estimate the emissions associated with the transportation of the harvested rapeseed to the biodiesel plants. The data on lorry emissions reported in Ecoinvent 2.0 (CH: operation, lorry 20–28 t, full, fleet average [street]) were used to estimate emissions from rapeseed transportation.

Rapeseed oil extraction

Rapeseed oil is commonly used for cooking, in animal feed and by industry. The high-protein press cake has received increasing attention as an attractive by-product of the rapeseed oil extraction process. It is often used as a soybean replacement in livestock feed (Hanczakowska & Świątkiewicz, 2014). Depending on the processing method, rapeseed cakes can be divided into cold-pressed, hot-pressed and solvent-extracted rapeseed press cakes. Of these, the cold-pressed rapeseed cake yields the highest protein recovery and has good emulsifying properties (Östbring et al., 2020). According to previous studies, we identified 14 oil mills operating within the boundaries of CG (BLE, 2011; FNR, 2013; LfULG, 2009; O'Keeffe et al., 2017).

Transesterification process and biodiesel configuration

Biodiesel is produced via the triglyceride transesterification process with rapeseed oil as the feedstock. In this process, the triglyceride molecules of rapeseed oil react with methanol in the presence of an alkaline or acid catalyst, for example, sodium hydroxide or potassium hydroxide, to produce FAME (biodiesel) and glycerol. Glycerine is a valuable co-product that is increasingly used in feeding digesters and in other industrial applications, as it has a high energy density (Bacenetti et al., 2017; Ma & Hanna, 1999). However, we did not consider expanding our system boundary to include glycerine as a co-product in the current study for the following reasons: (1) glycerine is produced on a much smaller scale and has a lower economic value than biodiesel (Luque et al., 2010); (2) the co-product credits of glycerine remain controversial among LCA researchers due to the range of credits given despite the same co-product function (Malça et al., 2014).

The RELCA included a two-step analysis of the biodiesel configuration. The first step was Conversion Plant Modelling (CPMod), which calculates the theoretical biodiesel production based on the regional conversion efficiency. The base year for biodiesel production is assumed to be from the point of harvest in autumn 2018 to the next autumn in 2019. We assumed that the 10 biodiesel plants studied by O'Keeffe et al. (2017) for the year 2010 were still running at the same operating capacity in 2018. This is because no technical changes were implemented during this time period. Prior research has shown that the biodiesel plants in Germany generally run at approximately 50% of their full installed capacity. Thus, we set a 52% operating capacity for our research (UFOP, 2010). This operating capacity is also in line with O'Keeffe et al. (2017) to enable a comprehensive comparison. We further divided these biodiesel plants into small scale (<10,000 t/year), medium scale (10,000–150,000 t/year) and large scale (>150,000 t/year) according to their designed installed capacities. Table 2 lists the biodiesel production and rapeseed demand of the studied plants in CG. In the second step, the biomass is assigned to the closest conversion plant using Catchment Allocation Modelling (CAMod) to estimate the biodiesel plant's spatial configuration. The model stops assigning rapeseed fields to the nearby plant once the feedstock demands of all the observed biodiesel plants have been fulfilled. The final output of CAMod is a combination of the biomass and the biodiesel plant's inventories for biodiesel configuration, which also set the boundary for foreground flow aggregation on a spatial level.

After calculating the direct emissions based on the foreground activities, the RELCA submodule Non-Regional Modelling (NoRIodM) was employed to evaluate the associated indirect upstream emissions outside of the studied region. The main upstream emission sources we analysed were the fertilizer products and the plant protection products (e.g. pesticides) used in the crop cultivation process. Other indirect emissions could also come from the import of feedstocks due to a shortfall in biomass, diesel consumption tied to field operations and transportation, and the energy and materials used in biodiesel production. The amount of indirect emissions from each of these sources was calculated and assigned to the corresponding rapeseed pixel.

TABLE 2 Biodiesel production and rapeseed demand of the studied plants

Plant	Biodiesel production[a] (t/year)	Rapeseed demand (t/year)	Clustering
1	1040	3088.8	Small scale
2–4	2080	6177.6	Small scale
5	2860	8494.2	Small scale
6	28,600	71,500.0	Medium scale
7	52,000	130,000.0	Medium scale
8–9	104,000	252,720.0	Large scale
10	132,600	322,218.0	Large scale

[a]52% installed capacity.

2.2.2 | Environmental impact assessment

LCIA evaluation with mid-point indicators

The goal, scope, inventory development and impact assessment of the LCA were defined and conducted in accordance with the ISO 14040:2006 standard using the GaBi8 LCA software and the Ecoinvent 2.01 database. The explicit material flows and process flows are shown in Figure S1. The LCIA method used in our study was the CML 2001 characterization model with the following mid-point indicators: global warming potential (GWP), marine aquatic, freshwater aquatic and terrestrial ecotoxicity potentials, acidification (land and water) potential, eutrophication potential (EP), human toxicity potential and photochemical ozone creation potential (POCP; Table 3). The impact categories were selected based on the indicators commonly adopted by existing literature which is presented in Table 1, and cover both global and local impacts. In addition, the catchment area of each biodiesel plant included in the study was delineated according to its capacity, demand for rapeseed, as well as the distance between the plant and the nearest available feedstock. After determining the catchment area of each plant, the environmental impacts indicated by the selected characterization factors were further spatialized to each catchment. As our functional unit is the total emissions from 1 t of rapeseed production, we calculated the catchment-level environmental impacts of rapeseed production by multiplying the rapeseed yield (t/ha) by the characterization factor of each pixel. This process was facilitated using the ArcMap 10.7 software.

Sensitivity assessments of LCIA method selection

We followed the sensitivity assessment approach suggested by Bueno et al. (2016) to test whether there were large discrepancies in the evaluation results of the same environmental impacts when different LCIA methods were used. Considering that the same environmental impacts could be expressed differently due to the variations in the respective units, conversion factors were employed to facilitate harmonization of metrics between methods (Bueno et al., 2016; Table 4). Among the different LCIA methods listed in Table 1, we selected the EDIP 97/2003 (midpoint) and ReCiPe 2008 (midpoint) for comparison with the CML 2001 (midpoint). Here we selected ReCiPe 2008 rather than ReCiPe 2016 due to following reasons: (1) the ReCiPe 2008 has been the most commonly adopted characterization factor data on the European context; (2) there

TABLE 3 The environmental impact categories considered in our study

Impact category	Abbreviation	Unit	Methodology	References
Acidification potential	AP	kg SO_2 eq.	CML 2001	Huijbregts, Schöpp, et al. (2000)
Eutrophication potential	EP	kg PO_4 eq.	CML 2001	Huijbregts, Schöpp, et al. (2000)
Global warming potential	GWP	kg CO_2-eq.	CML 2001	Baitz et al. (2016)
Marine aquatic ecotoxicity potential	MAETP	kg DCB-eq.	CML 2001	Huijbregts, Thissen, Guinée, et al. (2000); Huijbregts, Thissen, Jager, et al. (2000); Pant et al. (2004)
Freshwater Aquatic Ecotoxicity Potential	FAETP	kg DCB-eq.	CML 2001	Huijbregts, Thissen, Guinée, et al. (2000); Huijbregts, Thissen, Jager, et al. (2000); Pant et al. (2004)
Terrestric ecotoxicity potential	TETP	kg DCB-eq.	CML 2001	Haye et al. (2007); Huijbregts, Thissen, Guinée, et al. (2000); Huijbregts, Thissen, Jager, et al. (2000)
Human toxicity potential	HTP	kg DCB-eq.	CML 2001	Hertwich et al. (2001); Huijbregts, Thissen, Guinée, et al. (2000); Huijbregts, Thissen, Jager, et al. (2000)
Photochemical ozone creation potential	POCP	kg C_2H_4 eq.	CML 2001	Andersson-Sköld et al. (1992); Derwent et al. (1998)

TABLE 4 Conversion factor to harmonize metrics between Life Cycle Impact Assessment modelling frameworks

Impact categories and harmonization unit	CML 2001	ReCiPe	EDIP 97/2003
Acidification potential (kg SO_2 eq.)	1.0	1.0	1.0
Eutrophication potential (kg NO_3 eq.)	10.44	32	1.0
Global warming potential (kg CO_2-eq.)	1.0	1.0	1.0
Marine aquatic ecotoxicity potential (kg DCB-eq.)	1.0	1.0	0.0112 (water)
Freshwater aquatic ecotoxicity potential (kg DCB-eq.)	1.0	1.0	0.0112 (water)
Terrestric ecotoxicity potential (kg DCB-eq.)	1.0	1.0	1.43 (soil)
Human toxicity potential (kg DCB-eq.)	1.0	1.0	0.000014 (air) 0.0112 (water) 1.43 (soil)
Photochemical ozone creation potential (kg NMVOC eq.)	1.7	1.0	1.7

Source: Bueno et al. (2016).

have been some changes in the updated ReCiPe 2016 in comparison with ReCiPe 2008; and (3) the goal of the current study was to compare the results of our methods with the results of previously published works, thus we decided to use the ReCiPe 2008. The Eco-Indicator 95/99 was not used because it does not include environmental impacts such as EP, marine aquatic ecotoxicity potential (MAETP), freshwater ecotoxicity potential (FAETP) and POCP, which were the focus of our study.

2.2.3 | Economic analysis of biodiesel production in CG

We optimized the biodiesel plant production capacity by employing the generalized reduced gradient non-linear optimization method. By applying this approach, we aimed to maximize the economic benefits while minimizing the environmental burdens (Lasdon et al., 1974). Of the different constraints, we stipulated that the biodiesel plants included in our study could only consume the feedstock harvested in their corresponding catchment areas. This enabled us to minimize the negative impacts of iLUC caused by the import of rapeseed from other areas, which are difficult to quantify (Plevin et al., 2010).

After determining the optimal operating capacity of each biodiesel plant, we then calculated the economic and environmental benefits generated at the optimized biodiesel operating capacity of each plant. By employing the traditional NPV method, the profits of operating a biodiesel plant for the next 10 years were discounted to today. The NPV method applied in our study was as follows:

$$\mathrm{NPV}_i = \sum_{t=0}^{10} \frac{\mathrm{CF}_{i,t}}{\left(1 + r_{\text{discount factor}}\right)^t}, \quad (1)$$

with i = environmental and economic.

To simplify the optimization, we monetarize the benefits and costs generated from the production and consumption of biodiesel to cash flow (CF_t) from both an environmental perspective and economic perspective. The detailed calculations of the environmental and economic cash flows ($\mathrm{CF}_{\text{environmental}}$ and $\mathrm{CF}_{\text{economic}}$) are presented in Sections 2.2.3.1 and 2.2.3.2.

To stay as close to real conditions as possible, we carefully selected the discount factor ($r_{\text{discount factor}}$) indicating the opportunity cost of capital by applying the following calculation formula:

$$r_{\text{discount factor}} = r_{\text{risk free return}} + r_{\text{risk premium renewable energy}} + r_{\text{inflation rate}}. \quad (2)$$

The risk-free return ($r_{\text{risk free return}}$) was the benchmark interest rate and the inflation rate ($r_{\text{inflation rate}}$) was proxied by the Consumer Price Index.

To determine the risk premium of the overall renewable energy industry ($r_{\text{risk premium renewable energy}}$), we first estimated the market risk of the renewable energy branch (β_{RENIXX}) using the Capita Asset Pricing Model (Lintner, 1965a, 1965b; Mossin, 1966; Sharpe, 1966):

$$R_{\text{RENIXX},t} = R_{\text{risk free},t} + \beta_{\text{RENIXX}}\left(R_{\text{market},t} - R_{\text{risk free},t}\right) + \epsilon_{\text{RENIXX},t}. \quad (3)$$

$R_{\text{RENIXX},t}$ was the variable used to proxy the profit performance of the renewable energy branch. It tracks the performance of the world's leading listed companies in the renewable energy industry. $R_{\text{risk free},t}$ was the risk-free return and $R_{\text{market},t}$ the index that reflects the overall market performance.

After conducting the ordinary least squares regression, we used the estimated renewable energy sector market beta (β_{RENIXX}) to further calculate the average risk premium factor of the renewable energy industry ($r_{\text{risk premium renewable energy}}$).

$$r_{\text{risk premium renewable energy}} = \beta_{\text{RENIXX}}\left(R_{\text{market},t} - R_{\text{risk free},t}\right). \quad (4)$$

Environmental cash flow

The environmental objective of the optimization was to maximize the total GHG emission savings associated with the biodiesel life cycle. Following Cambero and Sowlati (2016a), the environmental cash flow ($\mathrm{CF}_{\text{environmental}}$) generated through biodiesel consumption was the GHG emission savings, which were estimated by subtracting the GHG emissions from producing the biodiesel ($\mathrm{Env}_{\text{costs}}$) from the GHG emissions savings benefits from consuming the produced biodiesel ($\mathrm{Env}_{\text{benefits}}$; Cambero & Sowlati, 2016a).

$$\mathrm{CF}_{\text{environmental}} = \mathrm{Env}_{\text{benefits}} - \mathrm{Env}_{\text{costs}}. \quad (5)$$

To calculate the environmental benefit of biodiesel consumption ($\mathrm{Env}_{\text{benefits}}$), we multiplied the carbon price (P_{carbon}) by the avoided carbon emission for biodiesel ($Q_{\text{avoided carbon emission}}$).

$$\mathrm{Env}_{\text{benefits}} = P_{\text{carbon}} \times Q_{\text{avoided carbon emission}}. \quad (6)$$

The avoided carbon emission ($Q_{\text{avoided carbon emission}}$) for biodiesel is simply the difference between the carbon emissions from consuming the fossil fuel ($Q_{\text{fossil fuel carbon emission}}$) and from consuming biodiesel ($Q_{\text{biodiesel carbon emission}}$) to produce one unit of energy. To determine the GHG emissions of rapeseed-based biodiesel and fossil fuel, we used the BioGrace GHG calculation tool (BioGrace, 2015) to make the energy allocation for GHG emissions. This calculation tool was based on the RED and the LCA pathway 'FAME from rapeseed'.

$$Q_{\text{avoided carbon emission}} = Q_{\text{fossil fuel carbon emission}} - Q_{\text{biodiesel carbon emission}}. \quad (7)$$

In our study, we defined the environmental cost of biodiesel production ($\mathrm{Env}_{\text{costs}}$) as the cost of the total carbon emissions from the entire biodiesel production chain. The environmental cost was the product of the carbon emissions in biodiesel production ($Q_{\text{biodiesel production carbon emission}}$) and the carbon price ($P_{\text{carbon}}$):

$$\mathrm{Env}_{\text{costs}} = P_{\text{carbon}} \times Q_{\text{biodiesel production carbon emission}}. \quad (8)$$

While the data on the carbon price (P_{carbon}) were downloaded from IHS Markit—Global Carbon Index, we calculated the quantity of the carbon emissions from the biodiesel production chain ($Q_{biodiesel\ production\ carbon\ emission}$) by multiplying the carbon emission coefficient of one unit of biodiesel production ($Coef_{carbon\ emission}$) by the amount of biodiesel produced ($Q_{produced\ biodiesel}$).

$$Q_{biodiesel\ production\ carbon\ emission} = Coef_{carbon\ emission} \times Q_{biodiesel}. \quad (9)$$

Economic cash flow

The economic cash flow from biodiesel production ($CF_{economic}$) was calculated as follows:

$$CF_{economic} = Revenue_{total} - Cost_{total}. \quad (10)$$

The economic benefit of biodiesel production was proxied by the earnings before interest and taxes (EBIT) from biodiesel production ($Revenue_{total}$). The EBIT is the simplified revenues without considering the tax and the interest payments. Therefore, it was composed only of the sales from the produced biodiesel and the oil cake by-product. The total revenue from biodiesel production is calculated by multiplying the corresponding sale price (P) by the amount of sales for each (Q):

$$Revenue_{total} = P_{biodiesel} \times Q_{biodiesel} + P_{oil\ cake} \times Q_{oil\ cake}. \quad (11)$$

Five factors make up the total biodiesel production cost ($Cost_{total}$), namely the cost of rapeseed cultivation ($Cost_{cultivation}$), the cost of the logistics ($Cost_{transport}$), the cost of rapeseed oil extraction ($Cost_{oil\ extration}$), the cost resulting from the biodiesel transesterification process ($Cost_{transesterification}$) and other costs ($Cost_{others}$) such as marketing costs and transaction costs. Due to a lack of data availability, we were only able to derive the variable costs related to production and sales from the whole biodiesel production process. Fixed costs and amortizations of the building, machines, tractors and other equipment were not taken into account. Furthermore, the initial biodiesel production investment cost was also not considered in the cost calculation, as all the 10 biodiesel plants included in our study have been operating since 2010. Therefore, we also assumed that the future free cash flows from these biodiesel plants are not tied to any interest payments. The calculation formula for the total biodiesel production cost ($Cost_{total}$) is thus as follows:

$$Cost_{total} = Cost_{cultivation} + Cost_{transport} + Cost_{oil\ extration} + Cost_{transesterification} + Cost_{others}. \quad (12)$$

For more detailed calculations for each cost factor, please refer to the Supporting Information.

2.3 | Data

2.3.1 | RELCA

The sources of the data collected for each RELCA stage are reported in Table 5. The upstream emissions calculations were derived from the Ecoinvent data, and the emissions from the foreground processes were analysed based on the available statistical records, publications and reports.

2.3.2 | Economic analysis

The variables with the corresponding data sources used in the economic analysis of biodiesel production are presented in Table 6.

3 | RESULTS

3.1 | Mapping of biomass availability in CG for 2018

The results of the CRAM for crop cultivation areas and rapeseed yield are reported in Figure 3. The CRAM performed excellently in allocating crop cultivation areas, as the difference between the modelled cultivation area of each crop and the area reported by the statistical records for that crop was <1%. More detailed information is found in Table S3. In terms of CRAM crop yield modelling, we only show the results for rapeseed in Figure 3b. As the primary feedstock for biodiesel production, rapeseed had fresh matter yields ranging from 1.87 to 3.58 t/ha in CG, which were lower than the rapeseed yields of 2.67–3.94 t/ha in 2010 (O'Keeffe et al., 2017). The lower yields in 2018 might be due to the drought from April to July in the EU. The unfavourable weather conditions directly resulted in severe losses in various crop yields (Beillouin et al., 2020). We also observed that the rapeseed yield in CG was comparably low for Germany. The highest rapeseed yield in Germany reached 5.3 t/ha in 2018. Therefore, apart from the weather conditions, the differences in cultivar capacity, soil type, crop management and agronomic factors could also be the causes of low rapeseed yields (Farré et al., 2001; Zhang et al., 2017).

3.2 | Delineating catchment boundaries using CAMod

As reported above, the feedstock demand of each biodiesel plant in our study was used to assign the rapeseed pixels to

TABLE 5 Life cycle stages during biodiesel production

Life cycle stage	Unit	Amount/Ecoinvent modules	Source
1. Field operations			
Diesel consumption			
Light soil	kg/ha	50.72	KTBL (2012); O'Keeffe et al. (2017)
Medium soil	kg/ha	60.57	KTBL (2012); O'Keeffe et al. (2017)
Heavy soil	kg/ha	84.83	KTBL (2012); O'Keeffe et al. (2017)
2. Rapeseed production			
Fertilizers			
N	kg/ha/year	Calculated by Supporting Information eqs (1) and (2)	O'Keeffe et al. (2017)
P	kg/ha/year	26–29	Witing (unpublished)
K	kg/ha/year	29	KTBL (2012)
CaO	kg/ha/year	1000	KTBL (2012)
Nitrogen fertilizers			
CAN	kg/ha/year	PER: calcium ammonium nitrate, as N, at regional storehouse	Nemecek and Erzinger (2005)
UAN	kg/ha/year	PER: urea ammonium nitrate, as N, at regional storehouse	Nemecek and Erzinger (2005)
Urea	kg/ha/year	PER: urea ammonium nitrate, as N, at regional storehouse	Nemecek and Erzinger (2005)
Mix	kg/ha/year	PER: ammonium sulphate, as N, at regional storehouse/PER: ammonium nitrate, as N, at regional storehouse	Nemecek and Erzinger (2005)
Lime	kg/ha/year	CH: limestone, milled, packed, at plant	Kellenberger et al. (2007); KTBL (2012); Nemecek and Kägi (2007)
Crop protection			
Tebuconazole	kg/ha/year	0.2874	BVL (2013); Roßberg (2013); Roßberg et al. (2002)
Metazachlor	kg/ha/year	0.75	BVL (2013); Roßberg (2013); Roßberg et al. (2002)
Thiacloprid	kg/ha/year	0.072	BVL (2013); Roßberg (2013); Roßberg et al. (2002)
Folicur	kg/ha/year	PER: Pesticide unspecified, at regional storehouse	Jentsch & Grünther, 2020; Sutter (2010)
Nimbus CS	kg/ha/year	PER: Cyclic N compounds, at regional storehouse	Jentsch & Grünther, 2020; Sutter (2010)
Boscaya	kg/ha/year	PER: Diazole compounds, at regional storehouse	Jentsch & Grünther, 2020; Sutter (2010)
3. Rapeseed transportation			
Diesel demand	kg/km	0.297	O'Keeffe et al. (2017)
Field emissions	kg/km	CH: Operation, lorry >28 t, full, fleet average	Spielmann et al. (2007)
4. Rapeseed oil production			
Oil mills			
Electricity input	GJ/t	0.896–0.994	Thrän and Pfeiffer (2015)
Thermal energy input	GJ/t	1.904–3.142	Dones et al. (2007)
Sodium hydroxide	t/t	0–0.003	O'Keeffe et al. (2017)

(Continues)

TABLE 5 (Continued)

Life cycle stage	Unit	Amount/Ecoinvent modules	Source
Phosphoric acid	t/t	0–0.002	O'Keeffe et al. (2017)
Hexane	t/t	0–0.0025	O'Keeffe et al. (2017)
Press cake	t/t	1.43–1.96	O'Keeffe et al. (2017)
Biodiesel plants			
Rapeseed oil	t/t	1–1.01	O'Keeffe et al. (2017)
Electricity input	GJ/t	0.068–0.088	Thrän and Pfeiffer (2015)
Thermal energy input	GJ/t	0.619–1.030	Dones et al. (2007)
Methanol	t/t	0.10–0.13	O'Keeffe et al. (2017)
Potassium hydroxide	t/t	0–0.01	O'Keeffe et al. (2017)
Sodium hydroxide	t/t	0–0.003	O'Keeffe et al. (2017)
Sulphuric acid	t/t	0–0.01	O'Keeffe et al. (2017)
Hydrochloric acid	t/t	0–0.01	O'Keeffe et al. (2017)
Sodium methyloxide	t/t	0–0.016	O'Keeffe et al. (2017)
Biodiesel	t/t	1	O'Keeffe et al. (2017)
Glycerol	t/t	0.093–0.13	O'Keeffe et al. (2017)
FFA	t/t	0.01–0.02	O'Keeffe et al. (2017)
Fertilizer	t/t	0–0.02	O'Keeffe et al. (2017)

the nearest biodiesel plant and to delineate the catchment boundary. Figure 4 illustrates the catchment area of each biodiesel plant and more detailed information on each catchment area is reported in Table 7.

In 2018, most of the biodiesel plants in our study could get enough biomass from their corresponding catchment areas, with plants 8 and 10 being notable exceptions. The reasons why plants 8 and 10 could not run on the feedstock from their own catchment areas varied. As reported in Table 2, plants 8 and 9 were both large-scale biodiesel plants with the same yearly rapeseed demands of 252,720 t. However, as shown in Figure 4, catchment area 9, containing 3570 pixels, was significantly larger than catchment area 8, to which only 416 pixels were assigned. Moreover, Figure 3b shows that the average rapeseed yield in catchment area 8 was much lower than in catchment area 9. According to the results of the CRAM model, the average rapeseed yield in catchment area 8 was 2.25 t/ha while in catchment area 9 it was 2.84 t/ha. Therefore, the feedstock demand of plant 8 could not be met due to the lack of available rapeseed cultivation in the plant's direct vicinity.

Biodiesel plant 10 has a feedstock demand of 322,218 t/year, but due to the unfavourable weather conditions in 2018, catchment area 10 was unable to fully support its plant. Using the self-sufficient plant 9 as a reference, plant 10 had a proportionally larger catchment area due to its higher feedstock demand, as can be seen in Tables 2 and 7. However, the weather in 2018 was significantly drier and warmer than in 2010, with more frost days, warmer temperatures and lower overall precipitation. The lower rapeseed yield in catchment area 10 in 2018 led to a tiny deficit between the supply and demand of rapeseed for biodiesel production. Under more favourable weather conditions, like in 2010, plant 10 would be entirely self-sufficient by consuming the feedstock provided from its own catchment (O'Keeffe et al., 2017).

3.3 | Distribution of greenhouse gas emissions in the landscape

The spatial distribution of direct emissions that led to GWP is displayed in Figure 5a. The amount of indirect emissions and variations across the catchment areas are displayed in Figure 5b. More detailed information is reported in Table S4. As indicated in Figure 5a, the GWP was highly heterogeneous in the CG landscape. GWP values varied strongly from 588 to 1687 kg CO_2 eq./ha. Rapeseed cultivation was the most significant contributor to both direct and indirect emissions. As reported in Table S4, direct emissions from rapeseed cultivation made up 99.55% of the total direct emissions on average, while its proportion in total indirect emission was about 72.05%. The non-allocated characterization factors of GWP ranged from 592.73 to 909.13 CO_2 eq./t rapeseed.

After applying the energy allocation approach, we observed that the GHG emissions ranged from 23.92 to 37.21

TABLE 6 Description of the variables in the optimization

Variable	Abbreviation	Unit	Data source
Panel A: Variables for Net Present Value calculation			
Germany benchmark interest rate on January 1, 2021	$r_{\text{risk - free return}}$	%	Deutsche Bundesbank (2021)
German Consumer Price Index for January 2021	$r_{\text{inflation rate}}$	%	Federal Statistical Office (2021)
Log return of the Renewable Energy Industrial Index World	$R_{\text{RENIXX,t}}$	%	IWR (2021)
U.S. 30-year treasury bond yield on January 1, 2021	$R_{\text{risk free,t}}$	%	U.S. Departmet of the Treasury (2021)
Log return of the MSCI World Index	$R_{\text{market,t}}$	%	Investing (2021)
Panel B: Variables for environmental cash flow			
Weighted carbon price on January 1, 2021	P_{carbon}	€/t	IHS Markit (2021)
Carbon emission of consuming fossil fuel for one unit energy	$Q_{\text{fossil fuel carbon emission}}$	t	RELCA
Carbon emission of consuming biodiesel for one unit energy	$Q_{\text{biodiesel carbon emission}}$	t	RELCA
Carbon emission coefficient of one unit biodiesel production	$\text{Coef}_{\text{carbon emission}}$	t	RELCA
Amount of the biodiesel production	$Q_{\text{biodiesel}}$	t	RELCA
Panel C: Variables for economic cash flow			
Amount of oil cake production	$Q_{\text{oil cake}}$	t	RELCA
Price of biodiesel on January 1, 2020	$P_{\text{biodiesel}}$	€/t	NESTE (2021)
Price of oil cake	$P_{\text{oil cake}}$	€/t	Kucinskas et al. (2014)
Amount of fertilizer N consumed per hectare rapeseed	Fer_{N}	t/ha	RELCA
Amount of fertilizer P consumed per hectare rapeseed	Fer_{P}	t/ha	RELCA
Amount of fertilizer K consumed per hectare rapeseed	Fer_{K}	t/ha	RELCA
Price of fertilizer K on January 1, 2020 in Germany	$P_{\text{Fer}_{\text{N}}}$	€/t	Agrarheute (2021)
Price of fertilizer K on January 1, 2020 in Germany	$P_{\text{Fer}_{\text{P}}}$	€/t	Agrarheute (2021)
Price of fertilizer K on January 1, 2020 in Germany	$P_{\text{Fer}_{\text{K}}}$	€/t	Agrarheute (2021)
Time consumption of fertilizing per hectare rapeseed	$T_{\text{Fer}_{\text{N,P,K}}}$	h/ha	Baquero et al. (2011)
Time consumption of sowing per hectare rapeseed	T_{sowing}	h/ha	Baquero et al. (2011)
Time consumption of herbicide treatment per hectare rapeseed	$T_{\text{herbicide treatment}}$	h/ha	Baquero et al. (2011)
Time consumption of harvesting per hectare rapeseed	$T_{\text{harvesting}}$	h/ha	Baquero et al. (2011)
Germany minimum wage on July 1, 2022	W	€/h	BMAS (2021)
Fuel consumption of fertilizing per hectare rapeseed	$\text{Fuel}_{\text{Fer}_{\text{N,P,K}}}$	l/ha	RELCA
Fuel consumption of sowing per hectare rapeseed	$\text{Fuel}_{\text{sowing}}$	l/ha	RELCA
Fuel consumption of herbicide treatment per hectare rapeseed	$\text{Fuel}_{\text{herbicide treatment}}$	l/ha	RELCA
Fuel consumption of harvesting per hectare rapeseed	$\text{Fuel}_{\text{harvesting}}$	l/ha	RELCA
Petrol diesel fuel price in Germany on January 1, 2020	P_{Fuel}	€/l	Drive Alive (2021)
Cultivation area of rapeseed	$\text{CA}_{\text{rapeseed}}$	ha	RELCA
Total transport distance of each biodiesel plant	$\text{Dis}_{\text{plant}}^{\text{field}}$	km	RELCA
Cost of running 40 t load truck for 1 km	$P_{\text{transport}}$	€/km	Webfleet Solutions (2020)
Machine cost per 1 t produced biodiesel	$\text{Cost}_{\text{machine}}$	€/t	Kucinskas et al. (2014)
Amount of electricity used for producing 1 t biodiesel	$Q_{\text{electricity}}$	Mwh/t	Kucinskas et al. (2014)
Price of electricity	$P_{\text{electricity}}$	€/Mwh	Strom Report (2021)

(Continues)

TABLE 6 (Continued)

Variable	Abbreviation	Unit	Data source
Other equipment cost per 1 t produced biodiesel	$Cost_{other\ equipment}$	€	Kucinskas et al. (2014)
Total transesterification cost per 1 t produced biodiesel	$Cost_{transesterification}$	€	Kucinskas et al. (2014)
Total marketing cost	$Cost_{marketing}$	€	Kucinskas et al. (2014)
Total transaction cost	$Cost_{transaction}$	€	Kucinskas et al. (2014)

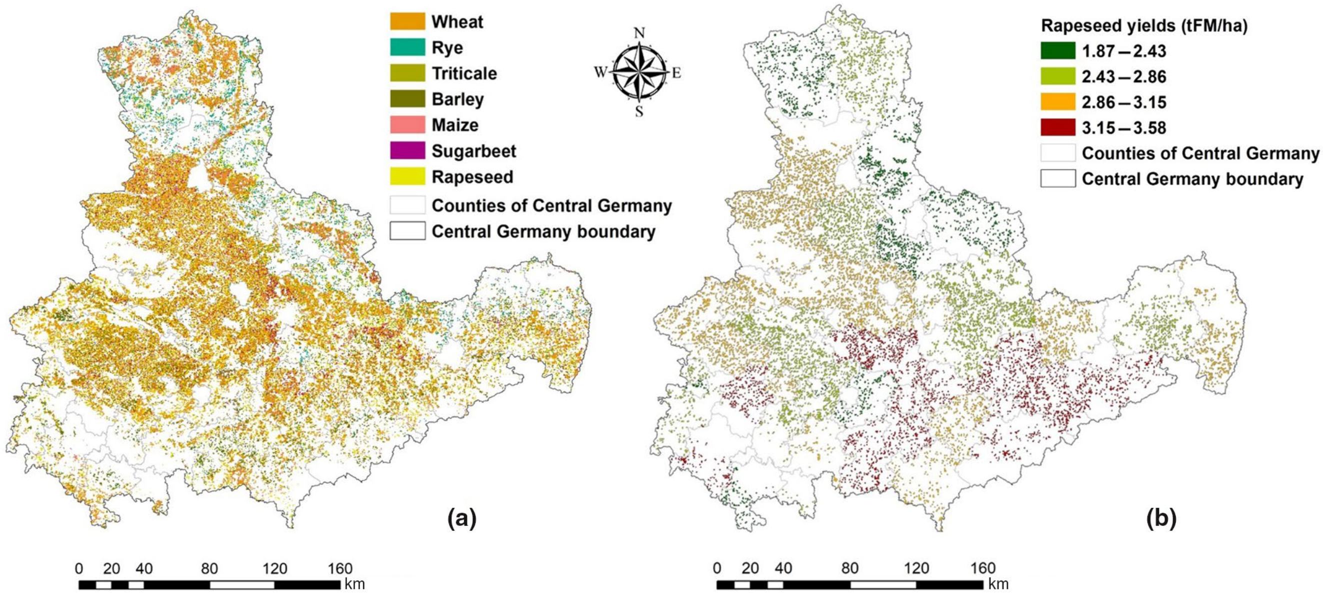

FIGURE 3 The results of the Crop Allocation model (a) agricultural crops distribution and (b) rapeseed yields in Central Germany for 2018

CO_2 eq./MJ across the studied catchment areas in 2018. These emission volumes were lower than the 2010 GHG emission volumes reported by O'Keeffe et al. (2017) which ranged from 32.25 to 39.83 CO_2 eq./MJ. The observed range of rapeseed-based GHG emissions from biodiesel in 2018 indicates that biodiesel could reduce GHG emissions by around 56% to 71% over fossil fuels. This result implies that the rapeseed-based biodiesel produced in CG could meet the 35% GHG reduction goal defined in the RED if the iLUC is not taken into consideration.

The main reason behind the improved GHG savings for biodiesel in 2018 was the decline in rapeseed yields. In addition, arable land areas dropped by 1.19% from 23,351 km^2 in 2010 to 23,072 km^2 in 2018 (Regionaldatenbank Deutschland). Consequently, less agricultural fertilizer and plant protection chemicals were consumed. According to the German Federal Office of Statistics, the total amount of N fertilizer consumed in agricultural crop cultivation in CG declined significantly from 274,832 t in 2010 to 191,916 t in 2018 (Statistiches Bundesamt, 2011, 2020). A similar trend was observed in the consumption of P and K fertilizers, which decreased from 33,539 to 25,226 t and from 41,527 to 34,663 t, respectively.

As with GWP, we also evaluated other regional environmental impacts by distinguishing between direct and indirect emissions. The spatial distribution among the catchment areas of the regional environmental impacts caused by direct and indirect emissions is displayed in Figures S2 and S3, respectively, in Supporting Information. The emissions contributions broken down by direct and indirect emission for the regional environmental impact categories studied here are reported in Tables S5–S11.

3.4 | Environmental footprint of the rapeseed-based biodiesel system in CG

The overall contributions to each environmental impact category in the primary life cycle stage, that is, cultivation, transportation, oil extraction and transesterification, are shown in Figure 6. More detailed characterization results of the rapeseed system for each environmental impact category are summarized in Table 8. This shows that emissions from the rapeseed cultivation process comprised the largest proportion of total emissions across the studied environmental impact categories, ranging from 48.22% to 91.94%.

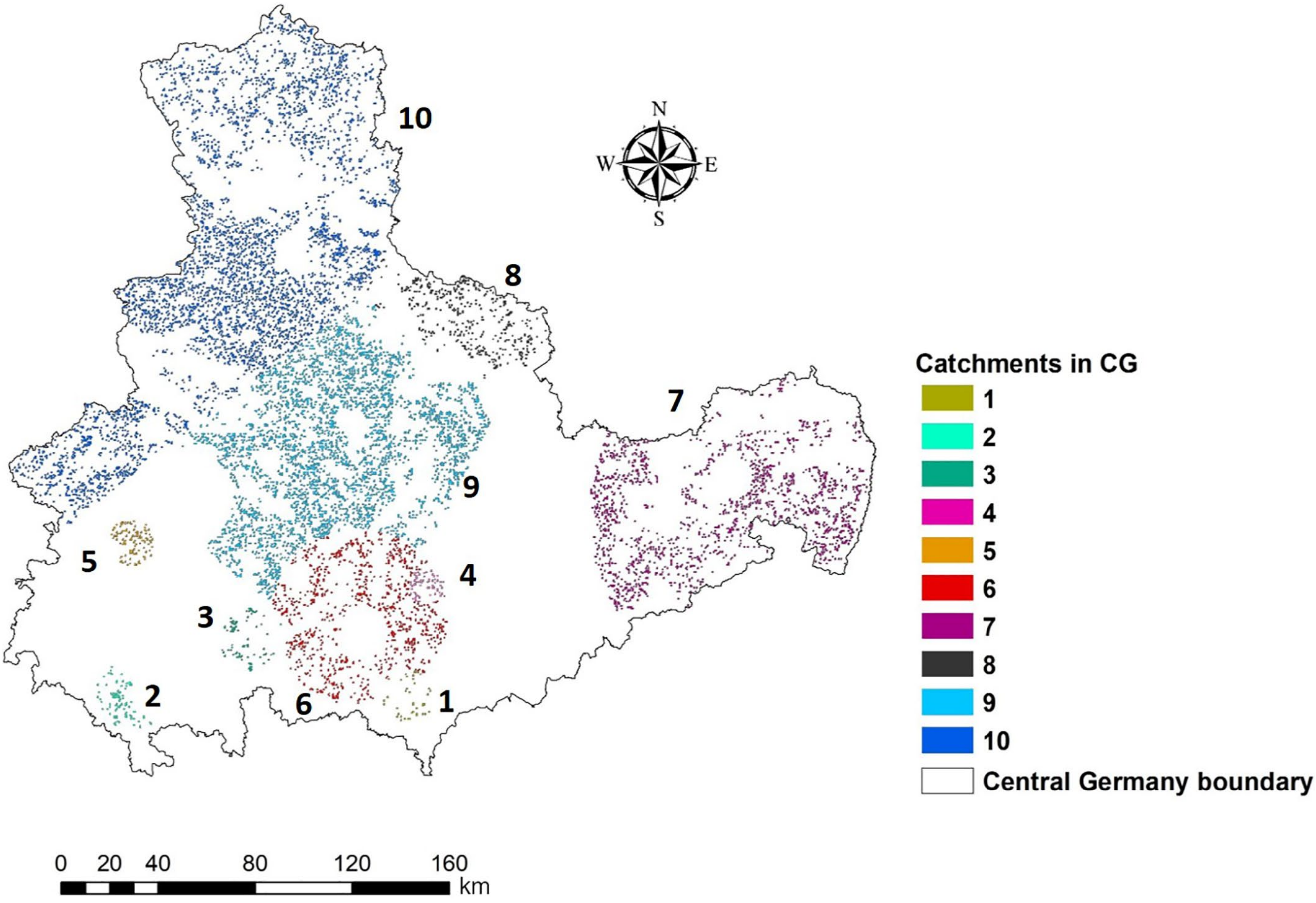

FIGURE 4 Boundaries of the catchment area of each biodiesel plant in the Catchment Allocation Modelling stage. CG, Central Germany

TABLE 7 Biodiesel configuration and information on rapeseed supply and topographic and climatic conditions

Catchment	Area (ha)	DeRep (t/a)	SuRep (t/a)	Az	SL (°)	EL (m)	Cla (%)	DFrost (days)	TSpr (°C)	TAvg (°C)	TotPre (mm/a)
1	1025	3088.8	3157.0	31.4	4.0	497.3	23.7	97	9.2	9.4	616
2	1800	6177.6	6224.5	52.3	2.9	265.9	15.9	80	10.8	11.8	322
3	2125	6177.6	6217.5	30.1	5.2	428.2	32.6	94	9.9	10.5	472
4	2375	6177.6	6178.7	29.6	4.8	415.1	47.8	93	9.0	9.4	626
5	2750	8494.2	8525.7	65.5	2.3	246.7	20.9	83	10.7	11.7	339
6	22,700	71,500.0	71,536.5	41.1	5.0	334.8	19.5	82	10.2	11.0	421
7	42,175	130,000.0	130,000.4	43.5	3.9	276.4	15.0	88	10.6	11.5	356
8	10,400	252,720.0	23,351.2	37.8	0.8	94.2	12.2	75	10.1	10.5	457
9	89,250	252,720.0	252,728.7	66.7	1.6	154.9	17.0	74	10.4	11.1	390
10	113,025	322,218.0	317,971.5	59.0	1.7	132.4	18.7	75	9.9	10.3	482

Abbreviations: Az, Akerzahl; Cla, surface soil clay content; DeRep, demand for rapeseed; DFrost, days of frost; EL, elevation; SL, slope; SuRep, supply of rapeseed; TAvg, average temperature; TotPre, total precipitation; TSpr, spring temperature.

The direct emissions from rapeseed cultivation were CO_2, N_2O, NO_x, CO and dust emitted from tractors. The indirect emissions were mainly from the application of fertilizer and plant protection chemicals in the agronomic processes, as well as diesel consumption, which caused acid deposition of acidifying contaminates in the soil, water and air. Previous studies have also found that cultivation practices contribute significantly to overall emissions (González-García et al., 2013; Malça et al., 2014; Panichelli et al., 2009). However, we found that there were significant discrepancies in the

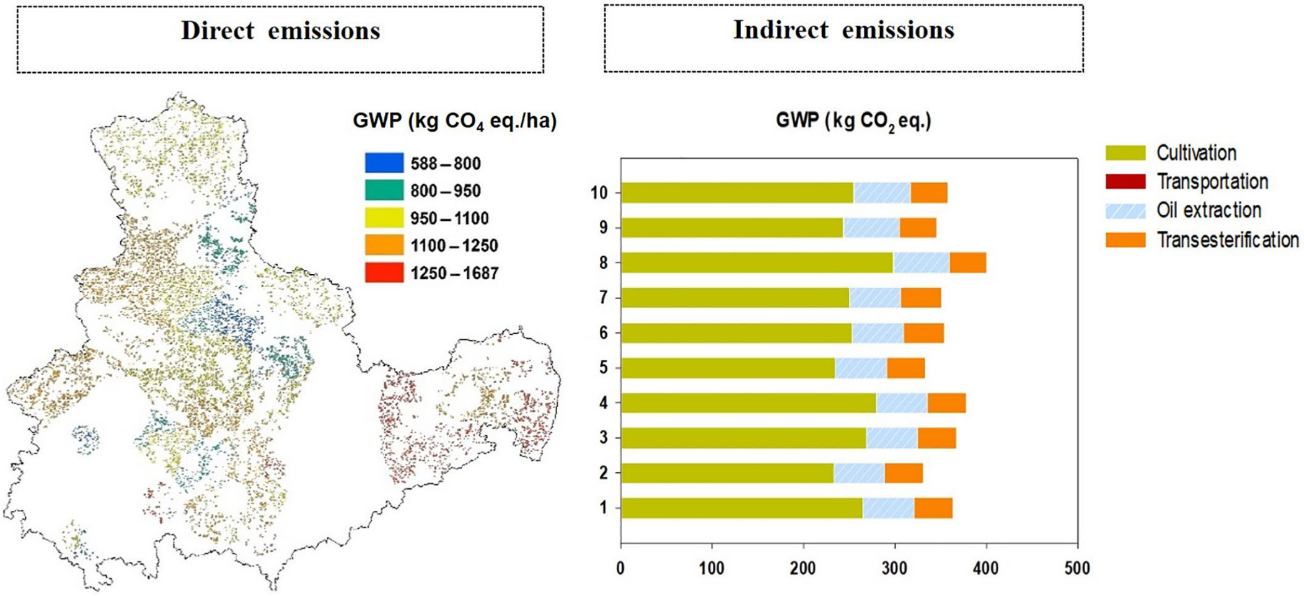

FIGURE 5 (a) Spatial distribution of global warming potential (GWP) caused by direct emissions from producing one hectare of rapeseed and (b) magnitude of GWP resulting from indirect emissions from producing 1 t of rapeseed for catchments 1–10

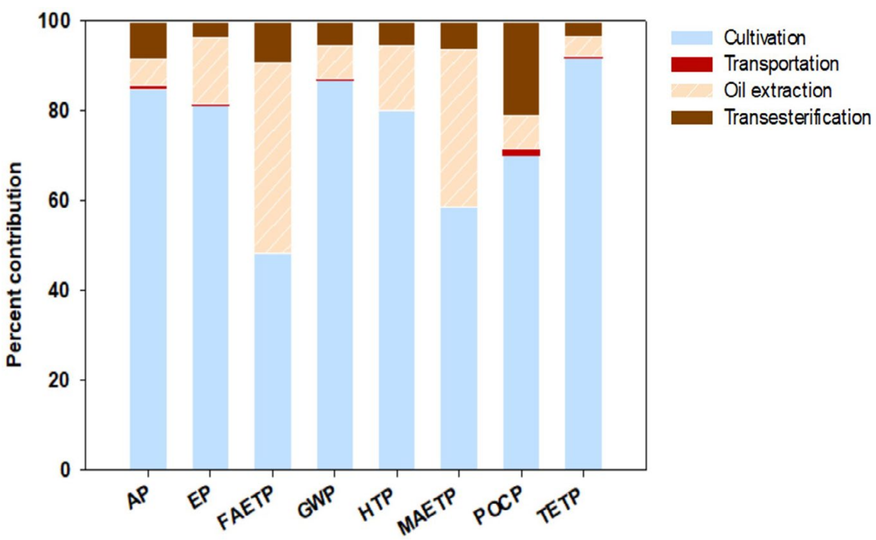

FIGURE 6 Contribution of life cycle steps to the environmental impacts of rapeseed production. AP, acidification potential; EP, eutrophication potential; FAETP, freshwater ecotoxicity potential; GWP, global warming potential; HTP, human toxicity potential; MAETP, marine aquatic ecotoxicity potential; POCP, photochemical ozone creation potential; TETP, terrestrial ecotoxicity potential

magnitude of each characterization factor reported in the literature. For instance, GWP, which is a widely studied environmental impact category, had an average value of 765.43 kg CO_2 eq./t in our study. This is equivalent to a non-allocated energy value of 51.02 kg CO_2 eq./MJ and is lower than the GWP values reported by both Mousavi-Avval et al. (2017b) and Malça et al. (2014), who documented 1181.6 kg CO_2 eq./t rapeseed and 81 kg CO_2 eq./MJ, respectively. The observed differences could be due to the site-specific conditions for rapeseed growth, which strongly influence crop yields. Other reasons might be deviations in the setting of system boundaries, the allocation procedures, the applied weightings, the normalization approaches, as well as the LCIA methods deployed in the analyses (González-García et al., 2013).

3.5 | Economic performance of biodiesel plants at optimized operating capacities

We calculated the NPVs for 10 years into the future (2021–2030) for all the studied biodiesel plants at their optimized biodiesel production capacities. Optimization aimed to maximize the economic benefits and minimize the environmental impact, especially the impact of the iLUC. The results are presented in Table 9.

As shown in Table 9, all of the studied biodiesel plants in CG achieved positive NPVs running at optimized operating capacities, indicating the profitability of biodiesel production in the near future. The optimized operating capacities of the biodiesel plants in CG generally ranged from 51.31% to 53.15%. This finding indicates a vast gap

TABLE 8 Non-allocated life cycle impact assessment for rapeseed-based biodiesel plants in CG. The functional unit here was per 1 t of rapeseed produced

Impact category (unit)	Cultivation		Transportation		Oil extraction		Transesterification		Total	
	D	ID	D	ID	D	ID	D	ID	D	ID
AP (kg SO2 eq.)	0.0002 (0.01%)	1.1844 **(84.79%)**	0.0095 (0.68%)	0.0036 (0.26%)	0.0000 (0.00%)	0.0786 (5.63%)	0.0000 (0.00%)	0.1206 (8.63%)	0.0096 (0.69%)	1.3871 (99.31%)
EP (kg PO4 eq.)	0.3249 **(24.46%)**	0.7542 **(56.77%)**	0.0024 (0.18%)	0.0012 (0.09%)	0.0000 (0.00%)	0.1972 (14.85%)	0.0000 (0.00%)	0.0485 (3.65%)	0.3273 (24.64%)	1.0011 (75.36%)
GWP (kg CO2-eq.)	405.3986 **(52.96%)**	258.8722 **(33.72%)**	1.8457 (0.24%)	0.3035 (0.04%)	0.0000 (0.00%)	57.5240 (7.52%)	0.0000 (0.00%)	42.2800 (5.52%)	407.2442 (53.20%)	358.1881 (46.80%)
MAETP (kg DCB-eq.)	0.0541 (0.00%)	138,607.2153 **(58.45%)**	2.3089 (0.00%)	145.4082 (0.06%)	0.0000 (0.00%)	83,198.2184 **(35.09%)**	0.0000 (0.00%)	15,170.0000 (6.40%)	2.3630 (0.00%)	237,120.8420 (100%)
FAETP (kg DCB-eq.)	0.0000 (0.00%)	34.8722 **(48.22%)**	0.0031 (0.00%)	0.0479 (0.07%)	0.0000 (0.00%)	30.6209 **(42.34%)**	0.0000 (0.00%)	6.7740 (9.37%)	0.0031 (0.00%)	72.3149 (100%)
TETP (kg DCB-eq.)	0.0000 (0.00%)	2.1962 **(91.94%)**	0.0006 (0.02%)	0.0021 (0.09%)	0.0000 (0.00%)	0.1070 (4.48%)	0.0000 (0.00%)	0.0830 (3.47%)	0.0006 (0.03%)	2.3883 (99.97%)
HTP (kg DCB-eq.)	0.0157 (0.01%)	126.9673 **(79.90%)**	0.0398 (0.03%)	0.1552 (0.10%)	0.0000 (0.00%)	22.9834 (14.46%)	0.0000 (0.00%)	8.7510 (5.51%)	0.0555 (0.03%)	158.8569 (99.97%)
POCP (kg C_2H_4 eq.)	0.0000 (0.02%)	0.0704 **(70.01%)**	0.0010 (0.95%)	0.0005 (0.49%)	0.0000 (0.00%)	0.0074 (7.38%)	0.0000 (0.00%)	0.0213 **(21.14%)**	0.0010 (0.97%)	0.0996 (99.03%)

The bold highlighted numbers represent main contributor of total direct- and indirect emissions during rapeseed-based biodiesel production system.

Abbreviations: AP, acidification potential; D, direct emissions; EP, eutrophication potential; FAETP, freshwater aquatic ecotoxicity potential; GWP, global warming potential; HTP, human toxicity potential; ID, indirect emissions; MAETP, marine aquatic ecotoxicity potential; POCP, photochemical ozone creation potential; TETP, terrestric ecotoxicity potential.

TABLE 9 10-year Net Present Value (NPV) for each biodiesel plant at an optimized operating capacity

Plant	Biodiesel production at full capacity (t/year)	Optimized operating capacity (%)	NPV at optimization (Mio €)
1	2000	53.15	6.48
2	4000	52.10	14.59
3	4000	52.34	13.04
4	4000	52.01	11.87
5	5500	52.19	19.49
6	55,000	52.03	222.59
7	100,000	52.02	399.35
8	200,000	4.80	85.79
9	200,000	52.00	996.01
10	255,000	51.31	1247.27

between the rapeseed supply and the rapeseed demand of all the biodiesel plants in CG. If the biodiesel plants in CG ran at their full capacities, severe iLUC might occur because the supply gap must be filled by importing rapeseed from other regions. In particular, plant 8 could only run at about 4.80% of its total installed capacity to avoid the negative impact of iLUC. Each biodiesel plant had an average of around 48% unused production capacity, which represents an enormous loss to all the plant operators.

To identify the biodiesel plant with the best operating performance running at its optimized operating capacity, we further assessed each individual biodiesel plant in a two-dimensional evaluation system to quantify its economic and environmental profits. As shown in Figure 7, plant 6 achieved the best performance from both an economic and an environmental perspective. In contrast, the per-unit economic and environmental profits of the small-scale plants 1, 3 and 4 were significantly lower than all the other plants. In general, the observed performance of each plant also suggests that there was a strong economies of scale effect in the biodiesel production industry.

Since the generation of environmental benefits mainly depends on the biodiesel production technology adopted by the plant, plant 6 might have the most advanced technology in reducing GHG emissions during biodiesel production. This argument is supported by the result of the analysis of the plant's environmental indicators. While plant 6 had the highest avoided GHG emission coefficient (2.12) of all the plants, it also had the lowest coefficient for production of GHG emissions at 0.89.

In terms of economic profit, biodiesel plant 6 should have the lowest per-unit production cost for the entire biodiesel production chain out of all the studied plants since the sale prices for the biodiesel and the by-product were set at a constant for all the plants. Of all the 10 catchment areas, the rapeseed yield of catchment area 6 was the second highest behind catchment area 2. High rapeseed yield led to a significantly smaller feedstock cultivation area. This resulted in lower costs for feedstock cultivation because less fertilizer was applied and less fuel was consumed. Furthermore, the conversion rate of rapeseed-to-rapeseed oil for plant 6 was 2.5, which fell under the second highest category of the 10 biodiesel plants included in our study. Indeed, due to the economies of scales, larger-scale plants, for example, plants 8 and 9, had an even better production efficiency with the conversion rate of rapeseed-to-rapeseed oil being lower than 2.5. However, lower rapeseed yields in some catchment areas strongly raised the cost of field operations and transportation for cultivation. In general, lower cultivation costs along with a higher production efficiency made plant 6 the most efficient biodiesel plant in CG.

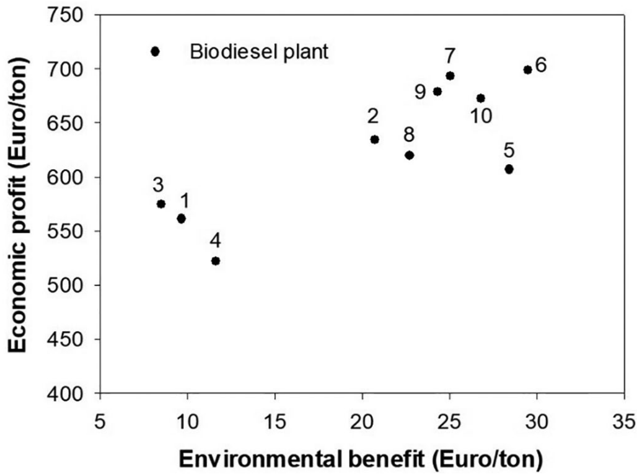

FIGURE 7 Economic and environmental benefits of the studied biodiesel plants

4 | DISCUSSION

4.1 | Raising attention to iLUC and associated emissions

We found that, in 2018, the regional feedstock supply could not meet the production input demands of biodiesel plants 8 and 10 and thus extra feedstock from other regions was needed. In 2018, only 41% of the total 8.9 million tonnes of processed rapeseed were domestically cultivated in Germany, declining from 51% in 2011 (UFOP, 2020). Previous studies reported that the extra rapeseed demand in CG was met by imports from Eastern Europe (O'Keeffe et al., 2017; Tamburini et al., 2020). This raised concerns about dLUC and iLUC (IFPRI, 2011; IINAS & IFEU, 2012).

Between 2010 and 2018, large country-level changes could be observed despite no change in rapeseed cultivation areas at the EU level (Eurostat, 2019). For instance, in Germany, the rapeseed cultivation area declined from 1,457,331 ha in 2010 to 1,322,681 ha in 2016. However, in Poland, cultivated area increased by 19% between 2008 and 2017 (CSO, 2018). These observations suggest that the boom of the biodiesel industry in one country could lead to the expansion of rapeseed cultivation in other countries (Woźniak et al., 2019). Even though rapeseed has a lower iLUC impact than palm oil, researchers have also reported that iLUC emissions from rapeseed-based biodiesel could be significant compared to its potential GHG savings (Baral & Malins, 2016).

4.2 | Sensitivity analysis for selecting various LCIA methods

Table 10 summarizes the results of the sensitivity analysis. The results of the CML 2001, the ReCiPe 1.08 and the EDIP 1997/2003 methods reveal relatively consistent emission rankings for rapeseed-based biodiesel life cycle stages across the environmental impacts categories acidification potential, GWP, MAETP, FAETP, HP and POCP. However, the absolute values for the characterization factors in each of these environmental impact categories vary widely. For instance, the calculated characterization factors for the cultivation process in the MAETP category varied enormously when these three methods were applied. In the MAETP category, the results for the CML 2001 were 138,607.27 kg 1.4-DCB-eq.; however, the ReCiPe 1.08 only reported 2.95 kg 1.4-DCB-eq. for the cultivation process.

In two other categories, namely EP and TETP, both the ranking results and the absolute values for the life cycle stages varied between the three methods. For example, while the CML 2001 and EDIP 1997–2003 found that the emissions generated during the cultivation process made up the most significant proportion of total emission in the EP category, the ReCiPe 1.08 identified the oil extraction process as the major emission source. Furthermore, in the TETP environmental impact category, all the three methods detected that emissions from the cultivation process comprised the largest proportion of total emissions; however, the second largest emission source varied. These observations raised concerns about the uncertainty of the final results of the LCA assessment as they depended on the method used (Bueno et al., 2016). Therefore, there is a need to develop a globally standardized environmental impact assessment method to ensure a consistency of results and facilitate direct comparisons between different studies.

4.3 | Implications for biodiesel plant size

Based on the findings of the economic performance analysis of biodiesel plants, this section will thoroughly discuss the factors that operators should take into account when deciding on plant size. As shown in Table 9, the calculated NPVs of the studied plants indicate a strong economies of scale effect in the biodiesel production sector. The 10-year NPV prognosis for plant 2, with a productivity of 4000 t of biodiesel per year, was more than twice that of plant 1, which could produce 2000 t of biodiesel per year. The same could also be observed by comparing the NPVs of plants 1 and 7. Compared to small-scale biodiesel plants, a reduction in marginal costs and a higher rapeseed to rapeseed oil conversion rate make large-scale plants more economically efficient. However, as reported, none of the studied biodiesel plants in CG could fully operate at their designed installed capacities without causing negative environmental impacts. Due to the disproportion between rapeseed demand and supply in the CG, large-scale plants with high feedstock demand could only run at their economical operating capacity when the feedstock was imported from other regions. Otherwise, the unused production capacity caused by a lack of feedstock would represent a huge loss to large-scale plant operators. The larger the plant, the higher the feedstock transportation costs that the plant owner must pay. Therefore, in a region like CG with a high biodiesel production density, a large-scale biodiesel plant might not be the best choice when environmental aspects are also considered in the assessment.

Moreover, the regional conditions of feedstock cultivation should also be considered when deciding on plant size. As indicated in Table 9, biodiesel plants 2, 3 and 4 all had a biodiesel productivity of 4000 t/year; however, the NPVs of these three plants varied enormously. In the optimized scenario, plant 3 could run at 52.34% of its

TABLE 10 Sensitivity assessments of CML 2001, ReCiPe 1.08 and EDIP 1997/2003 using harmonized units

Impact	LCIA methods	Cultivation	Transportation	Oil extraction	Transesterification
Acidification (kg SO_2-eq.)	CML2001, acidification potential	1.185	**1.194**	0.013	0.004
	ReCiPe 1.08 Midpoint (H)—terrestrial acidification	1.292	**1.303**	0.014	0.003
	EDIP 1997. Acidification potential	17.270	**17.283**	0.019	0.006
Eutrophication (kg NO_3-eq.)	CML2001. Eutrophication potential	**11.266**	0.039	2.059	0.506
	ReCiPe 1.08 Midpoint (H)—freshwater eutrophication	1.429	0.002	**1.937**	0.316
	EDIP 1997. Nutrient enrichment potential	**10.927**	0.029	2.050	0.422
Global warming (kg CO_2-eq.)	CML2001. Global warming potential	**663.479**	2.149	57.524	42.280
	ReCiPe 1.08 Midpoint (H)—climate change	**663.528**	2.149	57.530	42.307
	EDIP 1997. Global warming	**701.137**	2.161	57.450	42.407
Marine aquatic ecotoxicity (kg 1.4-DCB-eq.)	CML2001 Marine aquatic ecotoxicity potential	**138,607.269**	147.717	83,198.218	15,170.000
	ReCiPe 1.08 Midpoint (H)—marine ecotoxicity	**2.953**	0.004	0.842	0.235
	EDIP 1997. Ecotoxicity water chronic	**5091.584**	4.832	3137.120	572.365
Freshwater aquatic ecotoxicity (kg 1.4-DCB-eq.)	CML2001. Freshwater aquatic ecotoxicity potential	**34.872**	0.051	30.621	6.774
	ReCiPe 1.08 Midpoint (H)—freshwater ecotoxicity	**3.026**	0.003	0.882	0.280
	EDIP 1997. Ecotoxicity water acute	**569.303**	0.536	360.080	68.124
Terrestrial ecotoxicity (kg 1.4-DCB-eq.)	CML2001. Terrestric ecotoxicity potential	**2.196**	0.003	0.107	0.083
	ReCiPe 1.08 Midpoint (H)—terrestrial ecotoxicity	**0.118**	0.001	0.003	0.016
	EDIP 1997. Ecotoxicity soil chronic	**349.067**	21.323	16.631	26.888
Human toxicity (kg 1.4-DCB)	CML2001. Human toxicity potential	126.983	**127.007**	0.195	0.155
	ReCiPe 1.08 Midpoint (H)—human toxicity	68.002	**68.009**	0.092	0.085
	EDIP 1997. Human toxicity air	1384.792	**1366.521**	17.105	1.605
	EDIP 1997. Human toxicity soil	111.060	**111.195**	0.362	0.224
	EDIP 1997. Human toxicity water	93.386	**93.389**	0.052	0.049
Photochemical oxidation (kg NMVOC-eq.)	CML2001. Photochemical ozone creation potential	**0.070**	0.001	0.007	0.021
	ReCiPe 1.08 Midpoint (H)—Photochemical oxidant formation	**0.613**	0.022	0.060	0.111
	EDIP 1997. Photochemical oxidant potential (high NOx)	**0.044**	0.001	0.005	0.019

Note: Functional unit: 1 t rapeseed production. The grey shade level indicates (light to dark) the emission ranking of each life cycle process (weakest to strongest). During various biodiesel production life cycle stages, the bold highlighted numbers represent the highest value of each environmental impact categories under selected LCIA method.

Abbreviation: LCIA, Life Cycle Impact Assessment.

total installed capacity, which was the highest operating capacity level among these plants. Nevertheless, the 10-year NPV for this plant was €13.04 M, which was lower than the NPV of plant 2 operating at 52.10% of the total installed capacity. The 10-year NPV for plant 4 was about 18.64% lower than that of plant 2; however, the difference in the operating production capacity between these two plants was only 0.09%. The reason behind this might be the differences in the rapeseed yields of the respective catchment areas, which were linked to rapeseed cultivation conditions. When yields are high, less area is needed for feedstock cultivation to supply the same amount of rapeseed. Smaller cultivation areas have cost advantages in terms of feedstock field operations, such as the cost of fertilizers and fuel and labour costs. Compared to catchment area 4, with an average rapeseed yield of 2.58 t/ha and a cultivation area of 4606.43 ha, the feedstock cultivation area for plant 2, with a higher average yield of 3.41 t/ha, was only 3483.87 ha. Therefore, the total amount of fertilizers and fuel consumed in catchment area 2 was considerably less than in catchment area 4. In addition, smaller cultivation areas also produce lower transportation costs for field operations and for harvesting in the catchment area. The total transportation distance for catchment area 4 was 4614.28 km, whereas the transportation distance for catchment area 2 was significantly lower at only 2125.55 km.

Therefore, plant owners should not blindly pursue large-scale plants to achieve economies of scales in biodiesel production. As shown in Figure 7, the most efficient biodiesel plant (plant 6) in CG in the optimized scenario is medium sized with a high rapeseed yield in its feedstock consumption area. It is advisable to take both the regional biodiesel production density and feedstock cultivation conditions into account when deciding on plant scale.

5 | CONCLUSIONS AND OUTLOOK

To the best of our knowledge, this was the first paper that evaluated both the environmental impact and the economic benefits of biodiesel production in CG. Our study identified that emissions from rapeseed cultivation are about 48.22%–91.94% of the total emissions across all environmental impact categories in the overall life cycle. The environmental impacts of feedstock cultivation were mainly from the application of fertilizer, crop protection chemicals and agricultural machinery. In addition, our research identified a GHG emission savings of 56%–71% over fossil fuel emissions in CG. This result implied that the rapeseed cultivated in CG could fulfil the 35% GHG reduction goal defined in the RED. Furthermore, in the sensitivity analysis, we noticed the inconsistency of applying different LCIA methods. In terms of the impact that the 2018 drought in Europe had on biodiesel production in CG, we observed insufficient rapeseed supply in CG to meet the demand of existing biodiesel plants. The identified feedstock demand and supply gap could increase the rapeseed imports from other regions outside of CG. This raises doubts about the sustainability of adopting rapeseed-based biodiesel, as the demand for imported rapeseed in CG might lead to iLUC in other regions. An economic analysis of the biodiesel plants in CG indicated that, due to a lack of feedstock supply, none of the studied plants in CG could run at their installed capacity without negatively impacting the environment. We also observed an economies of scale effect in the biodiesel production industry and the cost from feedstock cultivation largely influenced the profitability of biodiesel production. However, economies of scale should not be the highest priority when deciding on plant size. Prospective plant owners should also take both the regional biodiesel production density and feedstock cultivation conditions into account. In the future, it is advisable to cultivate drought-tolerant alternatives to improve resilience to climate change. For example, Schiessl et al. (2020) tested the stress responses to drought of eight winter rapeseed accessions. They found that stress-responsive candidates had better protective mechanisms for adapting to climate change. Moreover, other drought-resistant oil crops, such as safflower and Jatropha curcas, represent alternatives for biodiesel production (Wang et al., 2020; Yesilyurt et al., 2020). However, in addition to feedstock availability, other aspects which cannot be circumvented when promoting the cultivation of these new types of crops include technology feasibility and the planting habits, capabilities and willingness of local farmers.

Based on our research, we suggest that future research on environmental impact assessments should adopt regional LCA modelling tools, such as RELCA, to have a comprehensive understanding of the life cycle of bio-based products in connection with changes in site-specific factors. We found that regional LCA analyses are highly sensitive to environmental changes. Nevertheless, RELCA also has limitations when applied to study regions where regional crop statistics or spatial data are not available or not fine enough. In this case, the RELCA needs to be customized or optimized to adapt to these challenging conditions, which is time-consuming. In contrast, traditional LCAs are more versatile and can be more easily applied in such cases, as fewer input data are required; however, they do not provide a regionalized picture of the environmental effects. Moreover, different LCIA methods could lead to inconsistent results in the same environmental impact category. Therefore, future studies should make attempts to develop a global environmental impact assessment method. Such a method could not only enable a direct comparison to be made between different studies, it could also reduce the complexity of the decision-making process for policymakers.

To reduce environmental burdens, stakeholders could implement some promising measures in their future biodiesel production as proposed by various studies. Such measures include, for instance, optimizing the application of chemical fertilizers (Khanali et al., 2018; Malça et al., 2014; Mousavi-Avval et al., 2017b; Palmieri et al., 2014), promoting organic farming (González-García et al., 2013), conserving soil through management (Malça et al., 2014; O'Keeffe et al., 2017) and improving agricultural machinery (Fridrihsone et al., 2020; Palmieri et al., 2014). Apart from this, we suggest that the stakeholders in biodiesel production pay more attention to the costs derived from feedstock cultivation, which is closely linked to rapeseed yield, and try to improve the cost efficiency of this process, since the feedstock cultivation cost strongly affects the profitability of biodiesel production. Plant operators should also make effective use of the valuable co-products generated in the biodiesel production process. Apart from the press cake mentioned in this study, there are other co-products, such as crop residues (e.g., straw), glycerine and fertilizers derived from the potassium auxiliaries (Smith et al., 2011). Although we did not consider these co-products in our study, we would still expect some promising applications when developing business cases in the future. In doing so, stakeholders could efficiently hedge the volatile biodiesel price and improve the overall profitability of biodiesel production.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

AUTHOR CONTRIBUTIONS

X.Y. designed the research and was in charge of environmental data analysis and interpretation. L.Y. was in charge of economic data assessment and interpretation. X.Y. and L.Y intensively wrote the manuscript and prepared the figures and tables. A.B. and D.T. were involved in revising the manuscript and providing the intellectual content.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the Supporting Information of this article. Additional documentation on data processing and analysis are available at the Helmholtz Centre for Environmental Research (UFZ) internal database under data protection policy. Thus, the full research data underpinning this publication can only be made available subject to the permission from the legal department of UFZ and from the corresponding author under reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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