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A Comparative Cradle-to-Gate Life Cycle Study of Bio-Energy Feedstock from *Camelina sativa*, an Italian Case Study

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Abstract: Growing energy needs and medium-term weakening of fossil energy reserves are driving forces towards the exploitation of alternative and renewable energy sources, such as biofuels from energy crops. In recent years, *Camelina sativa* (L.) Crantz has been rediscovered and is gaining popularity worldwide. The present work reports the results of a study on the life cycle, from cradle-to-gate, of *C. sativa* oil as a raw material for the production of biofuels in northern Italy, considering two scenarios, namely, the production of biodiesel (BD) and the extraction of pure vegetable oil (PVO). The functional unit was 1 megajoule of biofuel. A life cycle impact assessment (LCIA) was calculated according to the ILCD2011 procedure. Focusing on the global warming potential, the PVO scenario performs better than the BD scenario, with around 30 g CO_2eq MJ^{-1}. The net energy ratio (NER) exceeds unity for BD (approximately 1.4) or PVO (approximately 2.5). The same general trend was recorded for all calculated LCIA indicators; the common evidence is a generalized worse performance of the BD scenario, with indicators always scoring higher than the PVO. In particular, the two human toxicity indicators—carcinogenic and fresh water—eutrophication represent a significant difference, attributable to the refining process. Uncertainty and sensitivity analyses, respectively, underline the generalized importance of agricultural performances in the field and of allocation choices. Specifically, the importance of the grain yield and seed oil content in determining the environmental performance of the two scenarios was evident. As far as allocation is concerned, mass allocation provides the most favorable results, while on the other hand, the expansion of the system was the most penalizing alternative.

Keywords: LCA; energy crop; GWP; biofuels

1. Introduction

In recent years, concerns about the mid-term weakening of fossil energy reserves, coupled with the growing energy requirements and the related environmental issues, have been driving forces motivating the exploitation of alternative and renewable energy sources. According to Elbersen et al. [1], under the current European scenario, including in Italy, this relies on the exploitation of dedicated energy cropping based on rotational crops supplying feedstock, such as sugar, starch, and oils, which are second generation biofuels from lingo-cellulosic material, far from becoming economically viable at a large scale in the short term. Oil-crops, at present, are predominant, covering about 82% of the European land used for biofuel production and almost entirely processed into biodiesel. In Italy, the more important oil-crops are sunflower and rapeseed. In fact, the concept of environmental safety associated with the potential impact of alternative energy sources has become of crucial importance. This drove the development of quite a lot of environmental management computing tools and procedures, e.g., environmental auditing, risk assessment, environmental performance evaluation, and the so-called life cycle assessment (LCA). The latter is probably the most comprehensive framework, being thought of as a cradle-to-graveassessment of the potential environmental impacts of a product or a service, therefore including the input and output throughout life (the cycle), i.e., from raw material extraction and supply to use, end-of-life, recycling, and final disposal. Moreover, a dedicated international standard, the ISO14040:2006, provides guidelines to perform an LCA study, by four main sequential steps: (1) the goal and scope definition; (2) the inventory analysis; (3) the impact assessment; and (4) interpretation [2]. The target of an LCA study can be extremely variable, so within this broad structure, there may be cases where a simple inventory analysis it is enough to reach the desired goal (without impact assessment), or cases where a partial life-cycle, the so-called cradle-to-gate studies, can satisfy the requirements (with impact assessment). The impact assessment step aims to quantify the environmental impact in terms of a dedicated scale (the impact indicator) which relates to a specific and well defined impact category, i.e., an environmental matter of trouble that gathers the already collected entries and emission of the compiled inventory. A relevant example of impact category in the contest of agriculture and bio-energy is the climate change which relates to the radiative forcing of greenhouse gases (i.e., their capacity of trapping heat on the Earth's surface by absorbing infrared radiation), and whose indicator is the global warming potential (GWP). This deserves importance also for energy crops though they have a nearly-shut cycle of carbon dioxide. This is because all the agricultural practices aimed at crop establishment require the manufacture and use of production means, such as fertilizers, machinery, and fossil fuels combustion. Hence, this translates to a carbon footprint, along with a pattern of other environmental loads belonging to other specific impact categories.

At global level, beside the common energy crops cited above, an ancient oilseed plant, *Camelina sativa* (L.) Crantz (family Brassicaceae) (common names camelina or false flax), was rediscovered a few years ago and is gaining popularity especially in Canada, USA, and eastern Europe, where new large camelina plantations were established. However, also in Italy, camelina seems to have a great potential, owing to numerous interesting traits. First, camelina seeds contain oil in comparable amounts with other widely grown oilseed crops, such as rapeseed (30–40%). Furthermore, camelina is a short-season crop with resilient traits for some environmental conditions such as low temperature during germination and drought stress conditions. Therefore, it can be suitably cultivated on difficult marginal lands and/or as rotation crop in typical fallow-cropping systems. Finally, camelina is a low-input crop, requiring a low amount of agricultural inputs, fertilizers, and pesticides, contributing to a potentially reduced environmental load. These aspects of camelina have been widely studied [3].

Besides this, an updated literature review of camelina environmental performances sums up to no more than eight works around the world in the last 5 years, to the best of our knowledge. Table 1 provides an overview of this literature [4–11].

Five out of the eight works were from the USA. Three works were from Europe: specifically, Spain, Poland, and Italy. The assessed product was camelina grain in five cases, with a GWP which ranged from 0.53 to 1.47 $kgCO_2eq\ kg^{-1}$ of grain. The same indicator ranged from 25 to 150 gCO_2eq per megajoule of biodiesel. Extending the analysis to the 2010-2014 period, adds four more papers; however, none of these were from Europe. Therefore, this literature examination shows that camelina exploitation in Europe requires further and deeper study.

Table 1. Overview of literature concerning camelina environmental performances in the last 5 years.

Reference	Year	Location	Assessed Product	Main Indicator #	Range
Martinez et al. [4]	2020	Spain	grain	GWP	0.530–1.470 $kgCO_2eq\ kg^{-1}$
Krzyzaniak et al. [5]	2019	Poland	grain	GWP	1.152–1.528 $kgCO_2eq\ kg^{-1}$
Tabataie et al. [6]	2018	USA	biodiesel	GWP	56.0–60.0 $gCO_2eq\ MJ^{-1}$
Bacenetti et al. [7]	2017	Italy	biodiesel	GWP	0.150 $kgCO_2eq\ MJ^{-1}$
Berti et al. [8]	2017	USA	grain	GWP	0.53–0.84 $kgCO_2eq\ kg^{-1}$
Moeller at al. [9]	2017	USA	grain	GWP/NER	0.451 $kgCO_2eq\ kg^{-1}$—3.91–4.12 $MJ\ MJ^{-1}$
Dangol et al. [10]	2015	USA	biodiesel	GWP/NER	25.0 $gCO_2eq\ MJ^{-1}$—3.6 $MJ\ MJ^{-1}$
Keshavarz-Afshar et al. [11]	2015	USA	grain	GWP/NER	0.134 $kgCO_2eq\ kg^{-1}$—3.7–10.4 $MJ\ MJ^{-1}$

GWP = global warming potential, indicator of the impact category "Climate Change"; NER = ratio among of energy needed for product production and energy content of the product.

The present work is based on the results of previous experiments carried out in Italy [12–14]. In particular, Masella et al. [12] studied the agronomic performance of camelina in response to different growing areas, sowing periods, and genotypes. An approximate average grain yield of about 1360 kg ha^{-1} was reported. The same experimental plan was studied by Pecchia et al. [13] who assessed a camelina seed oil content spanning from 27.5% to 37.2% (% w w^{-1} dry matter). Similarly, Colombini et al. [14] characterized the composition of camelina meal obtained from seeds after extracting the oil with a solvent. They concluded that camelina meal can be used in ruminant rations as a high-quality protein source, being the crude protein average content greater than 340 g kg^{-1} dry matter. Hence, an environmental evaluation is presented here, with a comprehensive analysis starting from a detailed inventory compilation.

A wide base of already published data for the crop cultivation has been used, including and considering the effects of variability in the grain and oil yield. Moreover, several impact indicators have been considered beside global warming potential, with insights in the matter of uncertainty and sensitivity.

2. Materials and Methods

The environmental assessment of the present work was based on a cradle-to-gate life cycle study, i.e., a partial product life cycle dealing with all the flows entailed from resource extraction (cradle) to the factory gate (camelina biofuels). The choice of the cradle-to-gate approach, stopping the product system chain at the stage of the biofuel production, was driven by the main consideration that the final fuel delivery and subsequent use generally account for only a negligible part of the total impact. The standardized LCA procedure was followed as closely as possible, covering the four main steps of goal and scope definition (1); inventory analysis (2); impact assessment (3); and interpretation (4) [2]. The work was performed by OpenLca software, a free modular framework for sustainability assessment and life cycle modeling.

The matter of allocation has been faced by a partitioning method, where the environmental burdens of a process are mathematically assigned among the arising co-products using a specified criterion. Partition was based on the criterion of co-products energy content (Table 2).

Table 2. Coefficients used for partitioning allocation.

	Product	LHV # (MJ kg^{-1})	Energy Allocation	Mass Allocation
BD # scenario	biodiesel	37.2	0.95	0.90
	glycerol	16.6	0.05	0.10
	camelina oil	37.2	0.56	0.28
	meal	11.3	0.44	0.72
PVO # scenario	pure camelina oil	37.2	0.34	0.21
	meal	11.3	0.66	0.79

LHV = Low Heating Value; BD = biodiesel scenario; PVO = pure vegetable oil scenario.

2.1. Case Study

The goal of this work is to compare the environmental performances and energy demands of pure vegetable oil vs. biodiesel production, when camelina crop is used as energy feedstock in North Italy. Taking into account that camelina oil, although edible, can be considered as a non-food feedstock, such an estimation is an important issue in view of the concerns about the food-for-fuel dilemma, and information about the environmental impact of the possible use of camelina could be useful. The scope of the study is the Italian Lombardy region (Figure 1), a heterogeneous area with three quite different natural zones: mountains, hills, and plains. Of these, the plains, characterized by temperate continental climate, are almost entirely devoted to agricultural activities. The plain examined in this study is part of Pianura Padana, the largest Italian plain, covering about 4.7 10^{10} km^2, and belongs to the three Italian regions of Piemonte, Emilia-Romagna, and Veneto.

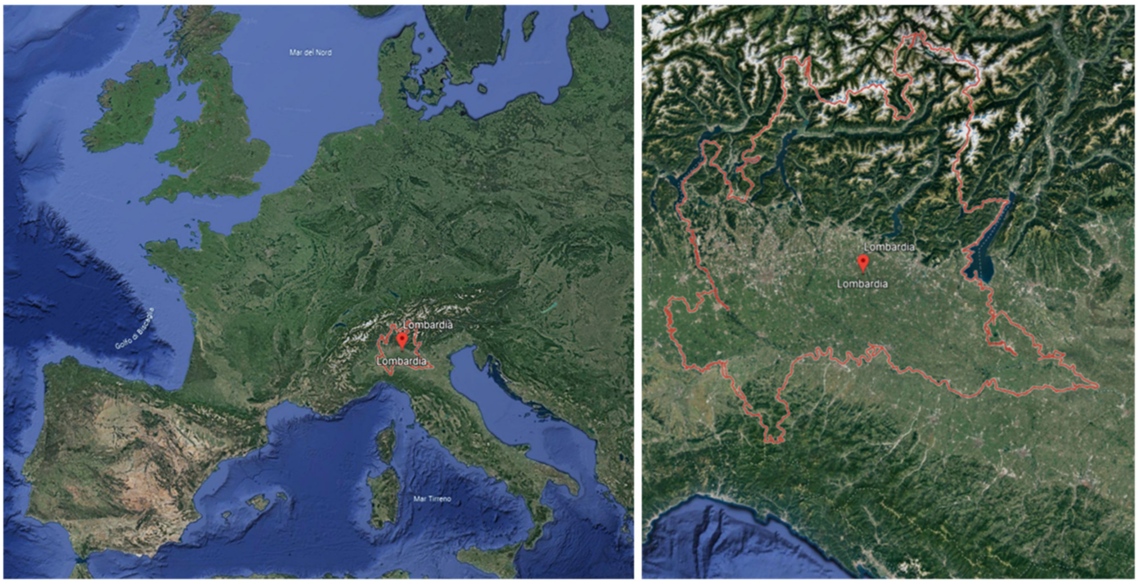

Figure 1. A map of the region under study: Lombardia, Italy, Europe (45.4628327, 9.1075212).

In the contest of Lombardy agriculture, as well as for the more extended area of Pianura Padana, camelina introduction appears to be a practicable solution. In fact, the fallow-cropping approach is common in the region and camelina fits well in this system because of its short season coupled with the low requirements in moisture and nutrients. In this way, lands dedicated to food production should not be affected. Additionally, camelina could replace the current cultivation of rapeseed, which is the main industrial non-food crop for oil production. Furthermore, camelina could be suitably cultivated on marginal agricultural lands, owing to its resilient character.

Two main scenarios were considered, both based on the common stage of camelina grain production. First, the most widespread solution for the production of biofuels from oil crops in Italy is the production of biodiesel, coupled with extraction with solvents. This pathway was selected as the base scenario (namely, BD). Miller at al. [15] and Krohn at al. [16] studied the same solution, and a comparison with their results is proposed in the Results section.

Secondly, the mechanical extraction of camelina oil, coupled with direct use on the farm, was considered as a possible viable scenario, in view of the potential advantages of this solution, including the closed cycle use of products and raw materials and the simpler processing technology (namely, PVO). The technical feasibility of this solution has been proved by Paulsen at al. [17], who studied the use of cold pressed, non-refined camelina and rape PVO in diesel engines, properly adapted and with a proper management of engine control intervals.

2.2. System Boundaries and Functional Unit

The background system, common to both BD and PVO scenarios, entails all the processes and flows of materials and energy required to hold up the foreground system. This includes inventories for resources extraction, energy carries, and related technology (electricity, crude oil-based fuels, coal- and lignite-based fuels, and natural gas-based fuels), transports, etc. The BD foreground system entails the three main processing steps of camelina cultivation (associate main product camelina grain), oil extraction (associate main product camelina oil), and oil conversion to methyl-esters (associate main product biodiesel). The PVO scenario mainly entails camelina cultivation (associate main product camelina grain) and oil mechanical extraction (associate main product camelina pure vegetable oil). The system expansion allocation requires further processes to address soybean meal production (and related sub-processes, such as pesticides production) and glycerol production (and related sub-processes). Processes for the production of materials input needed for oil extraction and processing (e.g., hexane) were included in the foreground system. In the case of BD, the scenario has been assumed that installation for seed drying, oil extraction and refining, and biodiesel production (transesterification) are co-located. Several plants are present in the region under study, but to account for the possible processing in a more extended area than Lombardy, such as Pianura Padana, a transport distance of 200 km between the farm and the seed processing plant has been hypothesized. The basic idea which underlies the case of PVO scenario is the small-scale production of biofuels for a self-supply agriculture, where the production cycle was closed at local scale. Assuming that the single farm unlikely provides itself with equipment for seed drying and mechanical oil extraction, a form of a cooperative association appears feasible, where a single but common installation could serve several local farmers. Therefore, an average distance of 50 km between the farm and the processing installation was supposed for the PVO scenario.

The functional unit (FU) chosen for the life cycle impact assessment (LCIA) computation was 1 megajoule of produced biofuels, whereas inventory analysis referred to 1 kg of produced biofuels. A flow-chart of the LCA model was presented in Figure 2 as example (PVO scenario: camelina oil mechanical extraction; BD scenario: camelina oil chemical extraction).

2.3. Primary Data and Indicators

Camelina could be suitably cultivated in Lombardy and more in general in north Italy as rotation crop, replacing rapeseed or in fallow cropping systems. This implies that either spring or autumn plantation is virtually feasible. Accordingly, the parameters describing camelina performances in the region (seed yield, oil, and protein content of seed) were assumed as the averaged values across spring and autumn plantation of replicated trials, performed in the region over 2 consecutive years and in two different locations. These data have already been published [12–14] and the corresponding statistics of the entire available raw dataset are summarized in Table 3.

Table 3. Statistics of source dataset compiled during camelina field trials conducted from autumn 2008 to spring 2010. Data were recorded over spring and autumn plantations, two different locations, and several genotypes.

Statistics	Grain Yield (kg ha^{-1} at 9% Seed Moisture)	Seed Oil Content (% w w^{-1} Dry Matter)	Meal Protein Content (% w w^{-1} Dry Matter)
Number of Cases	84	84	84
Minimum	133	21	242
Maximum	3945	37	407
Range	3812	16	165
Median	1262	32	339
Arithmetic Mean	1361	32	341
Standard Error	93.2	0.3	3.6
95.0% Lower Confidence Limit	1175.2	31.5	334.2
95.0% Upper Confidence Limit	1546.0	32.6	348.5
Standard Deviation	854.5	2.6	32.8
Coefficient of Variation	0.63	0.08	0.10

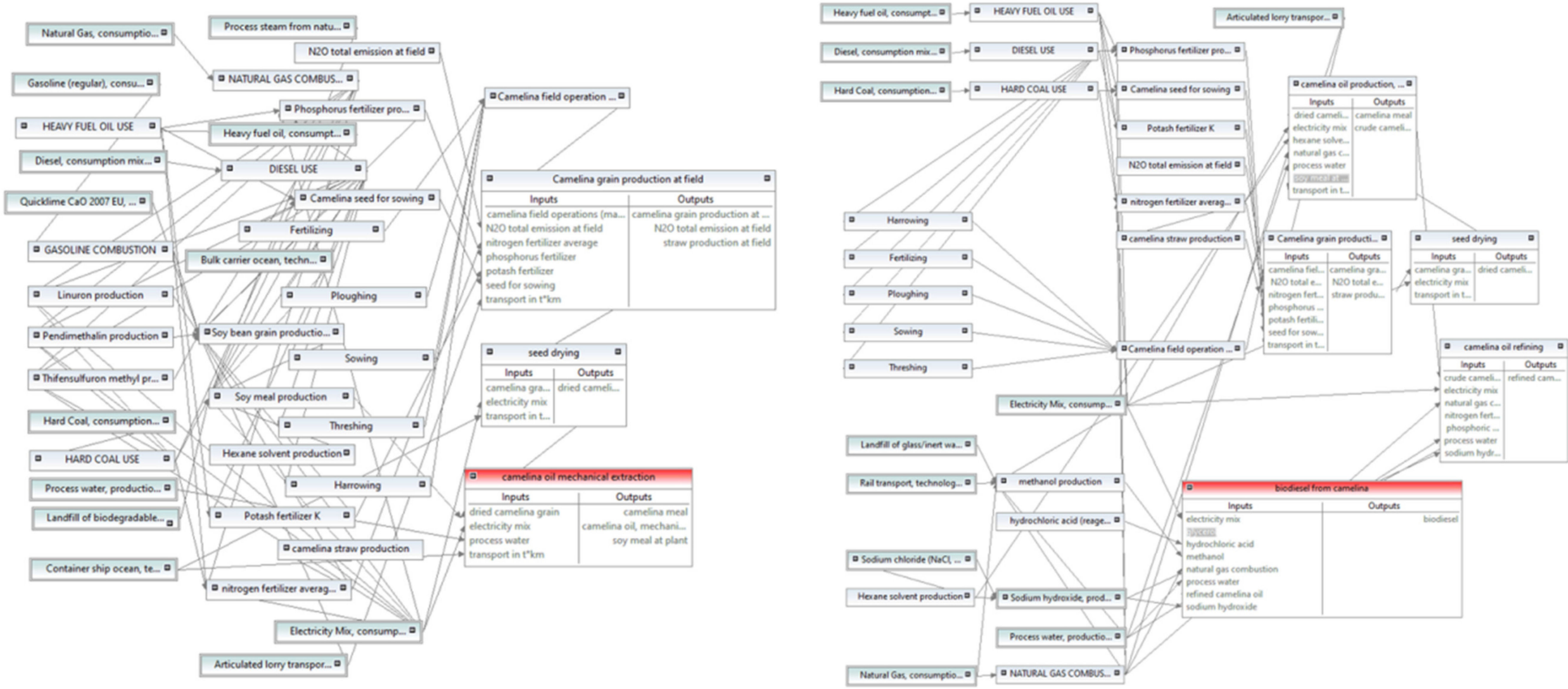

Figure 2. Example flow chart of the life cycle assessment (LCA) models built for pure vegetable oil (PVO scenario) and biodiesel (BD scenario) production from camelina.

This reasonably describe the potentiality of camelina exploitation regardless the cultivation system (crop rotations). A low-input approach was applied in all the trials, with a reduced rate of applied fertilizer, where no pesticide was used. Specifically, phosphorus and potash fertilizers were applied at the seedbed preparation, with a rate of 50 kg ha^{-1} of P_2O_5 (as TSP), 50 kg ha^{-1} of K_2O (Potassium sulphate), respectively. Nitrogen fertilization (30 kg ha^{-1} as ammonium nitrate) was applied immediately after sowing. No manure, irrigation, and pathogenic treatments were applied during cultivation. For the study, inventory data were needed for unit processes from raw material extraction and energy supply, to the production of biofuels (pure camelina vegetable oil and camelina biodiesel). Data for the background system, including fossil energy and electricity, transport, and resource extraction, were mainly derived from the ELCDIII database [18]. The database comprises life cycle inventory (LCI) data from front-running EU-level business associations and other sources for key materials, energy carriers, transport, and waste management, providing special attention on data quality, consistency, and applicability. The respective datasets are officially provided and approved by the named industry association. When this database was missing for some processes, it was supplemented by the CPM (Centre for Environmental Assessment of Product and Material Systems) LCA Database of the Swedish Life Cycle Center [19], the US NREL (National Renewable Energy Laboratory) Database of Federal LCA Commons [20], and the pertinent available literature.

Specifically:

- Data about camelina cultivation (rate of fertilizer, seed for sowing, grain yield, and oil and protein content of seed) were directly derived by camelina field trials performed in the region under study, whereas diesel input for machinery use was from Buratti et al. [21]; this agricultural stage is common to the two studied scenarios;
- Main processes for BD scenario are the oil extraction, oil refining, and transesterification. For these processes, data were taken from Buratti et al. [21], where actual values were from Italian operating biodiesel facilities;
- The main process for PVO scenario is the oil mechanical extraction. For this process data were taken from Esteban et al. [22], referring to conditions close to those under study (e.g., processing plants placed in Spain); data for seed drying were from the same source and also used for BD scenario;
- For electricity use, the Italian mix was always considered as structured in the ELCDIII [18]; the dataset represents the country/region specific situation, focusing on the main technologies, the region-specific characteristics, and import statistics;
- The ELCDIII database does not comprise inventories of fossil fuels use (e.g., natural gas, coal, or diesel combustion) stopping the related inventories at the stage of extraction/production; therefore, data on fuels use processes, comprehensive of transport, were derived from the CPM LCA Database and adjusted to the case study (transport) [19];
- Processes for the production of fertilizer are lacking in the ELCD, so they were derived from the CPM LCA database (nitrogen and phosphorus) [19] and from the US NREL database (potash) [20];
- Data about the following products are absent in the ELCDIII and were derived case by case as below specified: ammonia production (US NREL database); hydrochloric acid (US NREL database); methanol (US NREL database); nitric acid (CPM LCA Database); phosphoric acid (CPM LCA Database); and sulfuric acid (CPM LCA Database);
- Processes for soybean meal production, as well as glycerol production and the relative sub-processes used in the system expansion allocation were derived from the US NREL database, with the exception of pesticides production derived from Audsley et al. [23];
- Hexane is the main material input of oil solvent extraction process. Data for hexane are missing in the considered databases. Assuming the similarity of this substance with pentane, the relative complete production inventories data were taken from CPM LCA Database.

The N_2O emissions related to the agricultural stage were estimated by means of BioGrace GHG calculation tool (freely available at https://www.biograce.net/home). The tool follows the Tier 1 (Equation 11.6) of the IPCC Guidelines [24], computing the total field N_2O emission as the sum of direct emissions related the use of nitrogen fertilizer and crop residues degradation (assumed to be zero in the present work), and the indirect emissions related to leaching and volatilization phenomena.

2.4. Insights on Computational Methods and Environmental Impact Assessment

Figure 3 provides a glimpse of an overview of the methodological framework adopted in the study. It is possible to describe two sets of overlapping and interlinked computations:

1. Databases related computations, common to both the background system and part of the foreground system. In this case, the computation follows rules and procedures adopted in the specific database so that, process by process, the incoming (input) materials, energy and resources are quantified, as well as the out-coming (output) products, by-products, wastes, and emissions (in air, in water, in soil). Therefore, in this case, the so-called emission factors (i.e., rates of a given emission per unit of produced–used item) are precompiled in the database. As described above, the main data belonging to the ELCDIII database were used in the present study [18]. In a few cases, the database was integrated with external datasets as already reported.
2. Agricultural dedicated computation. This set of computations depends on the evidence that agricultural activity implies the soil management, where a common issue is the addition of nitrogen (mineral or organic) to enhance its availability for the crops. This determines a boost of nitrification and denitrification rates, which then increase the production of N_2O, an important greenhouse gas (GHG).

This latter problem is well described in the IPCC Guidelines [24], where a solid indication for an estimation of N_2O emission from managed soils is also provided. The main assumption is that the N_2O emission can occur either by a direct pathway, i.e., from the soils where N is applied, or indirectly according to two different pathways:

1. N volatilization in the form of NH_3 and oxides of N (NO_x), and their deposition in soils and waters surfaces along with their products NH_4^+ and NO_3^-;
2. Leaching and runoff of N: this potentially occurs from synthetic and organic fertilizer, crop residues, N mineralization due to land use change (loss of carbon), and dejection of grazing animals.

IPCC provides a clear methodological structure based on some equations belonging to three tiers, from Tier 1 to Tier 3 [24]. Bearing in mind that a tier stands for a level of methodological complexity, the first tier (Tier 1) represents the basic method, while further tiers require more and complex data.

In the present work the Tier 1 has been used by means of BioGrace GHG calculation tool (freely available at https://www.biograce.net/home) which integrates in particular Equation (11.6) and Equation (11.9) (and sub-equation) as defined in the IPCC Guidelines, for direct and indirect emissions computation. Here, among entries considered, only those ascribed to N input were accounted for and among these was only the emission deriving from the application of synthetic fertilizer, with the organic addition being absent (no manure or compost or sewage sludge) and the emission related to N mineralization being negligible, whereas crop residues were removed from the field. An emission factor of 0.01 (uncertainty range 0.003–0.03) was used for direct emission computation, while 0.0075 (uncertainty range 0.0005–0.025) for indirect contribution due to leaching/runoff and 0.01 (uncertainty range 0.002–0.05) for indirect contribution due to volatilization and re-deposition.

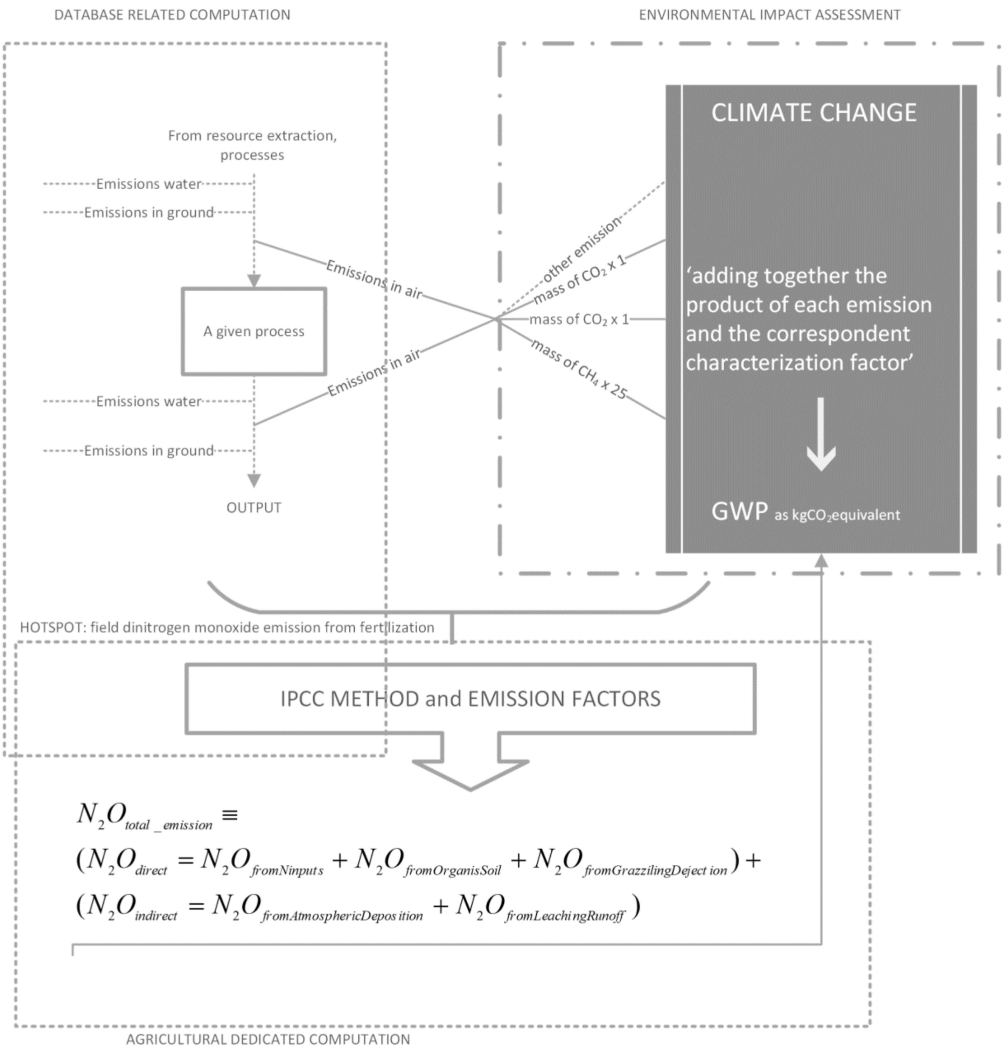

Figure 3. Overview of the methodological framework adopted in the study (GWP = global warming potential, indicator of the impact category "Climate Change").

The impact assessment was performed following the methodology recently proposed by the Joint Research Center, Institute for Environment and Sustainability (JRC-IES), in accordance with the International Reference Life Cycle Data System (ILCD). A detailed description of the analyzed and recommended models and methods, as well as the methodological choices, are available in the ILCD guidance document [25]. In short, the JCR-IES recommendations are based on existing models evaluated in the general framework of the three conventional protection areas: human health, natural environment, and natural resources. A number of existing methods belonging to these protection areas have been selected and recommended for the following impact categories:

- Acidification;
- Climate change (100 years horizon);
- Freshwater (ecotoxicity and eutrophication);
- Human toxicity (carcinogenics and non-carcinogenics);
- Ionizing radiation (ecosystems and human health);
- Land use;
- Marine eutrophication;
- Ozone depletion;
- Particulate matter/Respiratory inorganics;

- Photochemical ozone formation;
- Resource depletion—mineral, fossils and renewables;
- Resource depletion—water;
- Terrestrial eutrophication.

For the climate change category, specifically, the impact indicator is global warming potential (GWP), expressed in kilograms of carbon dioxide equivalent. This method includes up to 93 different items with a variable impact factor. The two important items for agriculture are methane with 25 and dinitrogen monoxide (N_2O) with 298.

Another impact category present in the dataset of available impact assessment methods (OpenLca nexus) is the Cumulative Energy Demand. The method for this category was based on the method developed by ecoinvent association (Technoparkstrasse 1, 8005 Zurich, Switzerland) and extended by GreenDelta (Berlin, Germany) for other elementary flows, available in openLCA 1.4. This impact category includes and takes into account nine different items corresponding to different energy sources:

- Non-renewable resources—fossil (hard coal, lignite, crude oil, natural gas, coal mining off-gas, peat, pit gas, methane, sulfur);
- Non-renewable resources—nuclear (uranium);
- Non-renewable resources—primary forest (wood and biomass from primary forests);
- Renewable resources—biomass (wood, food products, and biomass from agriculture, e.g., straw);
- Renewable resources—geothermal (geothermal energy);
- Renewable resources—solar (solar energy);
- Renewable resources—water (run-of-river hydro power, reservoir hydro power, and energy from waves);
- Renewable resources—wind (wind energy).

Energy flows entailed in each process of the built LCA model were accounted in the corresponding category given above and summed up to give the gross indicator called cumulative energy demand as cumulative energy required per functional unit. Then, this indicator was referred to the energy content of the considered biofuels (BD and PVO) leading to the so-called net energy ratio (NER), an index useful for a prompt understanding the efficiency of energy use in producing a fuel. In summary, on the base of energy entries computed during the study, the net energy ratio (NER) was estimated by comparing the energy obtained from the produced biofuels (PVO and biodiesel) and the amount of energy needed for their production (crop cultivation, seed processing, transport, and all the other related processes) [15].

3. Results and Discussion

3.1. Inventory Analysis

Tables 4–8 provides inventories of the inputs and outputs (products and emissions) of the considered biofuels processing pathway, with reference to the benchmark scenarios of camelina biodiesel (BD) and pure vegetable oil (PVO) without any allocation. The step of camelina cultivation (Table 4) was common to the two scenarios.

Over 98% of emissions in air of this agricultural step, per kilogram of camelina grain, was given by carbon dioxide deriving from fossil fuels use, with diesel accounting for over 40% of total emissions, followed by natural gas combustion (about 27%) and heavy fuel oil combustion (about 15%). The main processes contributing for this are machinery field operation in the case of diesel, and fertilizers production for natural gas and heavy fuel use (mainly the production of nitrogen fertilizer, with over 35% of total carbon dioxide emissions). The same applies for the other in-air emissions, with the exceptions of dinitrogen monoxide, which comes from field emissions due to the use of nitrogen fertilizer (direct emission) and to leaching and volatilization phenomena (indirect emissions). Methane, which deserves to be seen with importance in view of its radiative forcing, mainly derives from fossil fuel production processes: above all, natural gas (about 40%) and diesel (about 25%).

Table 4. Inventory of field inputs and outputs for camelina cultivation. Emissions are divided according to the target compartment of air, water, and soil; only that flows that account for over 0.03% of total mass of outputs have been reported.

Flows	Unit	Amount	Flows	Unit	Amount
Inputs			emission in water		
camelina field operations (machinery)	MJ	2.29	Chlorides, unspecified	kg	5.18×10^{-3}
nitrogen fertilizer average	kg	6.20×10^{-2}	Particulates, >10 um	kg	4.53×10^{-4}
land occupation, arable	m^2 a	3.13	Sodium, ion	kg	1.81×10^{-4}
phosphorus fertilizer	kg	7.80×10^{-2}	Carbonate	kg	5.88×10^{-5}
potash fertilizer	kg	7.10×10^{-2}	Sulfate	kg	7.31×10^{-5}
seed for sowing	kg	5.39×10^{-3}	COD, Chemical Oxygen Demand	kg	1.69×10^{-5}
Outputs			Oils, unspecified	kg	1.06×10^{-5}
camelina grain production at field	kg	1.00	Sulfide	kg	9.70×10^{-6}
straw	kg	3.00	TOC, Total Organic Carbon	kg	2.20×10^{-6}
emission in air			Decane	kg	1.60×10^{-6}
Carbon dioxide, fossil	kg	4.89×10^{-1}	emission in soil		
Nitrogen oxides	kg	4.05×10^{-3}	Ammonia	kg	7.21×10^{-6}
Sulfur dioxide	kg	1.52×10^{-3}	Strontium	kg	4.56×10^{-6}
Carbon monoxide, fossil	kg	8.67×10^{-4}	Phosphate	kg	4.13×10^{-6}
Methane	kg	7.55×10^{-4}	Chloride	kg	2.48×10^{-6}
Hydrocarbons, unspecified	kg	5.09×10^{-4}	Potassium	kg	1.79×10^{-6}
Particulates, unspecified	kg	3.16×10^{-4}	Sulfide	kg	1.37×10^{-6}
Dinitrogen monoxide	kg	2.95×10^{-4}	Sulfate	kg	2.28×10^{-7}
			Fluoride	kg	7.08×10^{-8}
			Iron	kg	2.03×10^{-8}
			Aluminium	kg	1.56×10^{-8}
			Chromium	kg	1.39×10^{-8}

Among in-water emissions, chlorides (almost entirely deriving from potash fertilizer production process) are predominant covering about 86% of total emissions, followed at a great distance by particulates (>10 µm). Ammonia is the greatest in-soil emission (about 30% of total); however, phosphate, accounting for about 20% of the total, also deserves a certain importance in view of its contribution to the "freshwater eutrophication" LCIA category.

Table 5 show flows (inputs and outputs) of materials and energy requirements of the BD scenario specified process by process in the processing chain, while the consequent cumulative emissions, i.e., per unit of produced biofuel (1 kg of biodiesel), are reported in Table 6.

Within in-air emissions, carbon dioxide account for over 99% of total emissions, where electricity use (about 50%) and natural gas combustion are the main entries. Transports account for only 5%. For electricity use, the main contributing processes are seed drying (about 49%) and oil extraction (about 28%). For natural gas combustion, the important processes are oil extraction (about 58%), oil refining (18%), and transesterification (19%).

Table 5. Inputs and outputs inventory of camelina biodiesel processing chain (seed drying→oil solvent extraction→oil refining→oil transesterification).

Flows	Process	Quantitative Reference	Unit	Amount
Inputs				
grain production	seed drying	per 1 kg of dried grain	kg	1.04
electricity mix	seed drying	per 1 kg of dried grain	MJ	3.18×10^{-1}
transport	seed drying	per 1 kg of dried grain	t * km	2.07×10^{-1}
dried grain	oil solvent extraction	per 1 kg of crude oil	kg	3.57
electricity mix	oil solvent extraction	per 1 kg of crude oil	MJ	6.45×10^{-1}
hexane solvent	oil solvent extraction	per 1 kg of crude oil	kg	1.86×10^{-3}
natural gas combustion	oil solvent extraction	per 1 kg of crude oil	MJ	2.21
Clay, bentonite, in ground	oil refining	per 1 kg of refined oil	kg	1.07×10^{-2}
crude oil	oil refining	per 1 kg of refined oil	kg	1.02
electricity mix	oil refining	per 1 kg of refined oil	MJ	5.52×10^{-2}
natural gas combustion	oil refining	per 1 kg of refined oil	MJ	7.22×10^{-1}
phosphoric acid	oil refining	per 1 kg of refined oil	kg	1.16×10^{-3}
sodium hydroxide	oil refining	per 1 kg of refined oil	kg	6.98×10^{-3}
electricity mix	oil transesterification	per 1 kg of biodiesel	MJ	3.68×10^{-2}
hydrochloric acid	oil transesterification	per 1 kg of biodiesel	kg	1.02×10^{-2}
methanol	oil transesterification	per 1 kg of biodiesel	kg	1.11×10^{-1}
natural gas combustion	oil transesterification	per 1 kg of biodiesel	MJ	7.70×10^{-1}
process water	oil transesterification	per 1 kg of biodiesel	kg	3.90×10^{-1}
refined camelina oil	oil transesterification	per 1 kg of biodiesel	kg	1.02
sodium hydroxide	oil transesterification	per 1 kg of biodiesel	kg	1.06×10^{-3}
Outputs				
camelina meal	oil solvent extraction	per 1 kg of crude oil	kg	2.57
glycerol	oil transesterification	per 1 kg of biodiesel	kg	1.07×10^{-1}

Natural gas combustion is also relevant for methane emission (about 35% of total emissions), as well as electricity use (about 16% of total emissions). Within in-soil emissions ammonia covers about 32% of total emissions, followed by strontium (about 20%) and phosphate, which is relevant for the freshwater eutrophication LCIA category, covering about 19%.

Within in-water emissions, chloride, and particulates (>10 um) are the predominant emissions, covering about 65% and 27% of the total, respectively. Furthermore, in this case, the main contributing entries are electricity use and natural gas combustion for seed drying and oil extraction processes.

The inventory of PVO scenario was summarized in Table 7 (process by process inputs and outputs of materials and energy requirements) and Table 8 (cumulative emissions per unit of produced pure vegetable oil).

As well as the BD scenario, carbon dioxide covers over 99% of total PVO in-air emissions, where about 70% comes from electricity use during camelina seed drying and about 15% from electricity used during mechanical oil extraction. Transport accounts for about 3%. In comparison to the BD scenario, carbon dioxide emission per unit of PVO was noticeably lower (about −40%). Both in-water and in-soil emission of PVO scenario showed the same main entries of BD scenario, where chloride and particulates (>10 µm) are predominant flows for in-water emissions, and ammonia, strontium, and phosphate are the predominant flows for in-soil emissions. As a general trend, the magnitude of all these entries is lower for PVO than BD scenario, mainly because of the simplest processing chain.

Table 6. Cumulative inventory of emissions from camelina biodiesel processing chain (seed drying→oil solvent extraction→oil refining→oil transesterification). Emissions are divided according to the target compartment of air, water, and soil; only that flows that account for over 0.03% of total mass of outputs have been reported.

Flows	Unit	Amount	Flows	Unit	Amount
emission in air			emission in water		
Carbon dioxide, fossil	kg	6.50×10^{-1}	Chloride	kg	1.58×10^{-3}
Methane	kg	1.92×10^{-3}	Particulates, >10 um	kg	6.47×10^{-4}
Sulfur dioxide	kg	1.48×10^{-3}	COD, Chemical Oxygen Demand	kg	9.93×10^{-5}
Nitrogen dioxide	kg	1.04×10^{-3}	Calcium	kg	2.07×10^{-5}
Nitrogen oxides	kg	5.59×10^{-4}	Carbonate	kg	1.99×10^{-5}
Carbon monoxide	kg	2.72×10^{-4}	Iron	kg	1.03×10^{-5}
emission in soil			Sulfate	kg	8.75×10^{-6}
Ammonia	kg	1.47×10^{-5}	Sodium	kg	4.32×10^{-6}
Strontium	kg	9.298×10^{-6}	Fluoride	kg	3.97×10^{-6}
Phosphate	kg	8.436×10^{-6}	TOC, Total Organic Carbon	kg	3.57×10^{-6}
Chloride	kg	5.044×10^{-6}	Sulfide	kg	4.68×10^{-6}
Potassium	kg	3.7×10^{-6}	Ammonia	kg	1.47×10^{-6}
Sulfide	kg	2.836×10^{-6}	BOD5, Biological Oxygen Demand	kg	1.36×10^{-6}
Sulfate	kg	4.727×10^{-7}	Chlorine	kg	1.21×10^{-6}
Calcium	kg	3.453×10^{-7}	Nitrate	kg	1.06×10^{-6}
Sodium	kg	1.533×10^{-7}	Aluminium	kg	8.79×10^{-7}
Fluoride	kg	1.437×10^{-7}			
Decane	kg	6.169×10^{-8}			
Magnesium	kg	5.03×10^{-8}			
Iron	kg	4.128×10^{-8}			
Aluminium	kg	3.25×10^{-8}			
Chromium	kg	2.858×10^{-8}			

Table 7. Inputs and outputs inventory of camelina PVO processing chain (seed drying→oil mechanical extraction).

Flows	Process	Quantitative Reference	Unit	Amount
Inputs				
grain production	seed drying	per 1 kg of dried grain	kg	1.04
electricity mix	seed drying	per 1 kg of dried grain	MJ	3.18×10^{-1}
dried camelina grain	oil mechanical extraction	per 1 kg of pure vegetable oil	kg	4.84
electricity mix	oil mechanical extraction	per 1 kg of pure vegetable oil	MJ	3.30×10^{-1}
process water	oil mechanical extraction	per 1 kg of pure vegetable oil	kg	2.00×10^{-2}
transport in t × km	oil mechanical extraction	per 1 kg of pure vegetable oil	t * km	2.42×10^{-1}
Outputs				
camelina meal	oil mechanical extraction	per 1 kg of pure vegetable oil	kg	3.84

3.2. Impact Assessment

Hereinafter, an LCIA analysis of the two selected scenarios is reported. The climate change category (by means of the GWP indicator) and the energy efficiency (by means of the NER indicator) are treated, firstly, in view of their relevance for biofuels production, and then other LCIA categories are described. For this purpose, for both the two processing pathways (BD and PVO), the assessment was based on energy allocation. Finally, matters of uncertainty and sensitivity are faced.

Table 8. Inventory of emissions from camelina PVO processing chain (seed drying→oil mechanical extraction). Emissions are divided according to the target compartment of air, water, and soil; only that flows that account for over 0.03% of total mass of outputs have been reported.

Flows	Unit	Amount	Flows	Unit	Amount
emission in air			emission in soil		
Carbon dioxide	kg	3.93×10^{-1}	Ammonia	kg	5.54×10^{-6}
Sulfur dioxide	kg	1.38×10^{-3}	Strontium	kg	3.49×10^{-6}
Nitrogen dioxide	kg	1.08×10^{-3}	Phosphate	kg	3.16×10^{-6}
Methane	kg	7.99×10^{-4}	Chloride	kg	1.92×10^{-6}
Carbon monoxide	kg	2.25×10^{-4}	Potassium	kg	1.45×10^{-6}
emission in water			Sulfide	kg	1.11×10^{-6}
Chloride	kg	1.45×10^{-3}	Calcium	kg	2.40×10^{-7}
Particulates, >10 um	kg	3.74×10^{-4}	Sulfate	kg	1.86×10^{-7}
Sulfate	kg	9.59×10^{-5}	Decane	kg	5.79×10^{-8}
COD, Chemical Oxygen Demand	kg	6.54×10^{-5}	Fluoride	kg	5.46×10^{-8}
Sodium	kg	4.11×10^{-5}	Magnesium	kg	3.31×10^{-8}
Carbonate	kg	2.81×10^{-5}	Sodium	kg	2.10×10^{-8}
Iron	kg	8.84×10^{-6}	Iron	kg	1.58×10^{-8}
Sulfide	kg	5.13×10^{-6}	Aluminium	kg	1.29×10^{-8}
Calcium	kg	3.15×10^{-6}	Chromium	kg	1.11×10^{-8}
Fluoride	kg	2.26×10^{-6}			
TOC, Total Organic Carbon	kg	1.66×10^{-6}			
Chlorine	kg	1.14×10^{-6}			
Ammonia	kg	9.08×10^{-7}			

3.2.1. Global Warming Potential and Net Energy Ratio (for BD vs. PVO Based on Energy Allocation)

Figure 4 provides the results of the GWP computed for the BD and PVO scenarios, along with the so-called fossil fuel comparator, as described in the Renewable Energy Directive 2018/2001/EU (RED II) [26]. This latter figure (vertical dashed line in Figure 4) amounts to 94 gCO_2eq MJ^{-1} of fossil fuel.

Camelina PVO shows better performance against the camelina BD scenario (carbon dioxide equivalent saving of about 30%), while both of the camelina scenarios have GWP values markedly lower than the fossil fuel comparator. This corresponds to a GWP mitigation of about 67% for PVO and more than 50% for BD. The computed values have the same magnitude of other literature reports on camelina derived biofuels, although the pure vegetable oil solution is poorly studied. Shonnard et al. [27] estimated a GWP of about 18 gCO_2eq MJ^{-1} of biofuel in USA. This value is somewhat lower than our estimate. However, in that case, the considered biofuel and the related production technology are quite different, because they refer to hydrogenation-derived renewable diesel. This latter biofuel has also been assessed by Miller and Kumar [15], who calculated a rough averaged value of about 40 gCO_2eq MJ^{-1}, i.e., a value close to our estimate of the BD scenario. Khron and Fripp [16] studied the biodiesel production from camelina in the USA. Their computation amounts to about 40 gCO_2eq MJ^{-1}, less than 10% lower than our value. In contrast, Li and Mupondwa [28] provide GWP values ranging from 7.6 to 24.7 gCO_2eq per megajoule of produced biodiesel. Biodiesel from camelina was also assessed by three more recent studies published in the last 5 years (2015–2020), according to Table 1. Roughly 30 gCO_2eq MJ^{-1} was reported by Dangol et al. [10], while a very large interval was presented by Tabatabaie et al. [6], ranging from about 40 to 80 gCO_2eq MJ^{-1}. Finally, Bacenetti et al. [7] compared biodiesel production from flax and camelina. The latter of these was credited of about 150 gCO_2eq MJ^{-1}, i.e., a much larger number than that reported in this paper (a discrepancy greater than 100 gCO_2eq MJ^{-1}), despite that the country of investigation was the same (Italy). This disagreement is probably due to the lower input approach adopted in the present study. For instance, our nitrogen fertilization amounts to no more than 30 kg ha^1, against 80 kg ha^1 found in the study of [7]. In the same way, the use of no pesticide in our field trials is in contrast to the metazachlor used in the other study.

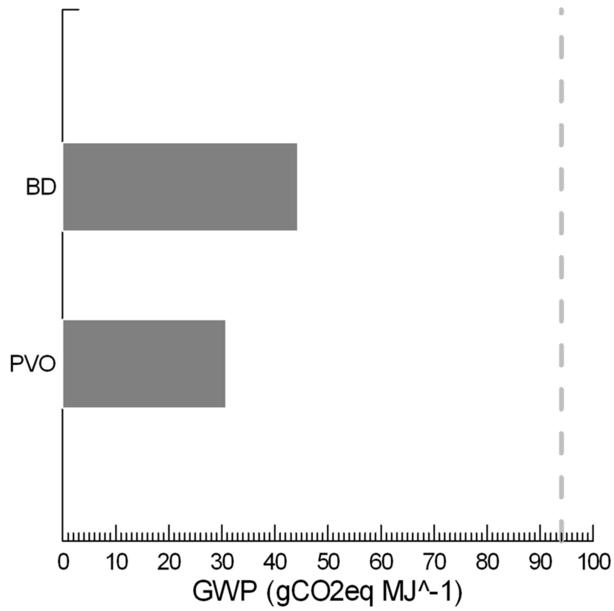

Figure 4. Global warming potential of the two considered camelina scenarios (BD, biodiesel; PVO, pure vegetable oil); the vertical dashed line indicates the benchmark of the fossil fuel comparator, as described in the RED (Renewable Energy Directive 2018/2001/EU (RED II)).

However, the common element that characterizes all of this literature is the importance of the agricultural step and nitrogen fertilization, and in particular, to determine the GWP score.

In the present work, the contribution analysis for GWP showed that, in the case of the PVO scenario, the major contributing processes are seed drying (mainly owing to electricity use which accounts for about 9% of total GWP) and camelina cultivation (agricultural step). The main entries of the latter process are field machinery operation (i.e., diesel consumption) accounting to about 29% of GWP, nitrogen fertilizer production (about 27%), and dinitrogen monoxide emissions at field test (contributing for about 13% to total GWP) as sum of direct emissions related the use of nitrogen fertilizer, and indirect emissions related to leaching and volatilization phenomena. Potash deserves a certain residual importance, as too do phosphorus fertilizer production processes, with GWP contributions of about 11% and 7%, respectively. In the BD scenario, the fuel conversion (transesterification) plus the oil refining together account for about 9% of GWP, the oil extraction for 9%, seed drying for about 7%, and the agricultural step for about 74%. Therefore, in addition to PVO scenario, the cultivation process of camelina crop was the predominant entry for the BD pathway. Furthermore, in this case, the machinery use for field operation and the nitrogen fertilizer production process are the predominant items, accounting for 24% and 23% of the total GWP, respectively, while dinitrogen monoxide emission was slightly lower than PVO, corresponding to about 11% of the total GWP.

Table 9 provides the LCIA indicators, other than GWP.

Comparing the two scenarios, the common evidence is a generalized worse performance of the BD scenario, with indicators always scoring greater than PVO and spanning from a percentage variation of +19% of land use, to +89% of resource depletion (mineral, fossils, and renewable). Beside the latter, two other indicators account for a remarkable difference, i.e., human toxicity—carcinogenics (+87%) and freshwater eutrophication (+78%). All of this must be addressed in the refining process, entailing a greater consumption of energy (mainly electricity and natural gas use) and use of chemicals (methanol, sodium hydroxide, and hexane).

Table 9. Pure vegetable oil vs. biodiesel scenario for some impact categories according to the # ILCD-midpoint recommended methods.

Impact Category	Reference Unit	PVO	BD
Acidification	Mole H^+ eq.	2.51×10^{-4}	3.26×10^{-4}
Freshwater ecotoxicity	CTUe	3.09×10^{-3}	4.01×10^{-3}
Freshwater eutrophication	kg P eq.	7.64×10^{-8}	1.36×10^{-7}
Human toxicity—carcinogenics	CTUh	1.78×10^{-11}	3.33×10^{-11}
Human toxicity—non-carcinogenics	CTUh	1.21×10^{-10}	1.86×10^{-10}
Ionizing radiation—ecosystems	CTUe	2.99×10^{-9}	4.76×10^{-9}
Ionizing radiaton—human health	kg U235 eq.	3.02×10^{-4}	4.81×10^{-4}
Land use	kg SOC	1.40	1.67
Marine eutrophication	kg N eq.	7.49×10^{-5}	9.69×10^{-5}
Ozone depletion	kg CFC-11 eq.	2.45×10^{-10}	3.91×10^{-10}
Particulate matter/Respiratory inorganics	kg PM2.5 eq.	6.86×10^{-6}	8.89×10^{-6}
Photochemical ozone formation	kg C_2H_4 eq.	2.08×10^{-4}	2.69×10^{-4}
Resource depletion—mineral, fossils and renewables	kg Sb eq.	9.16×10^{-9}	1.73×10^{-8}
Resource depletion—water	m^3	-3.48×10^{-6}	-5.69×10^{-6}
Terrestrial eutrophication	mole N eq.	8.20×10^{-4}	1.06×10^{-3}

ILCD = International Reference Life Cycle Data System.

The net energy ratio indicator (NER) allows a deep understanding of the efficiency of energy employed in producing a given fuel, the ratio being between the output energy and input fossil energy. For both scenarios, the energy performance is positive with NER values greater than unity, specifically 1.4 and 2.5 for BD and PVO, respectively. Furthermore, in this case, the PVO scenario performs better than BD, because of the more intense energy use in the processes involved in biodiesel production. The literature comparison for NER allows consideration and comparison to GWP. Our estimate lies in the gross interval of the studied literature, being included within the NER scoring 1.3 reported by Shonnard et al. [27] and the NER scoring 3.5 of Dangol et al. [10].

3.2.2. Uncertainty and Sensitivity

The data presented in Table 3, whose agronomic implications were already discussed in Masella et al. [12], can now be used to understand the uncertainty and sensitivity of the computed life cycle model. In fact, with all of the agricultural inputs used in those filed trials being constant, the variability showed in the table reflects the uncertainty related to uncontrolled factors, such as the environment and climate. Such variability has the potential to cause uncertainty in environmental impact scores. The field performance variability can be well represented in terms of standard deviation around the mean values, and used to give a reliable estimate of the uncertainty of the computed environmental performances. For this purpose, the mean value and standard deviation computed for the grain yield and seed oil content over the entire set of available data (Table 3) were used. Three levels of both of the parameters were set by subtracting and adding the standard deviation to the mean value (the data being normally distributed in this interval includes up to about 68% of the recorded values). After testing for the absence of a significant correlation between the yield and oil, the three levels of the two parameters were factorially combined, providing nine different combinations of yield–oil pairs. Then, the product systems (the BD and PVO scenarios) were recalculated for each of the nine pair combinations. The results of this procedure are reported in Figure 5, focusing on the most relevant indicators, i.e., GWP and NER, and represented by means of boxplot, i.e., quartile distribution around the median. Clearly, the location of the median values is consistent with the results showed in Table 9; at the same time, however, the partial overlapping of quartiles is evident, which underlines the importance of the grain yield and seed oil content in determining the environmental performances of the two scenarios.

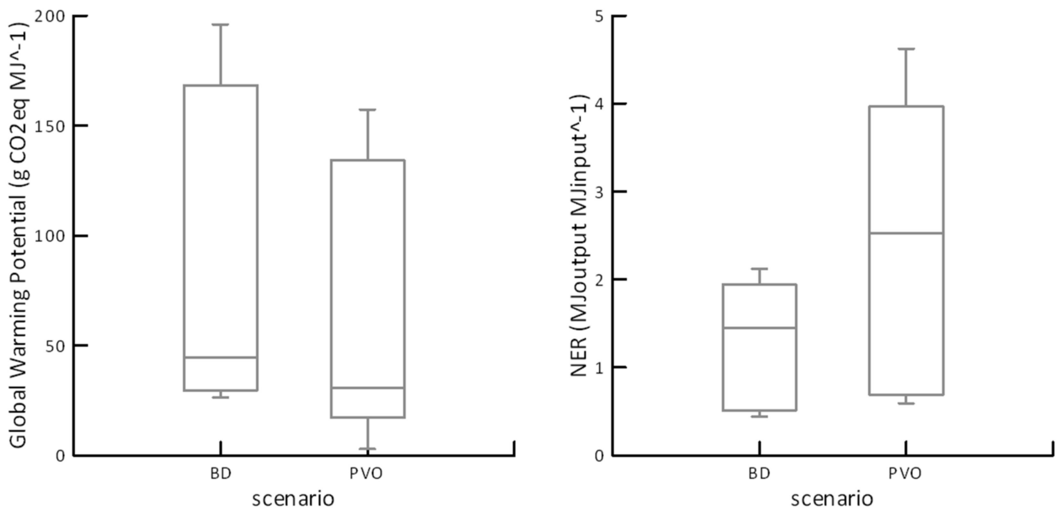

Figure 5. Uncertainty assessment of the two considered camelina scenarios (BD, biodiesel; PVO, pure vegetable oil) for global warming potential and net energy ratio (NER), by means of quartiles distribution around the median values (conventional boxplot) computed by varying grain yield and seed oil content according to the estimated variability of field performances.

Moreover, in the present work, allocation was solved with partitioning based on energy content and selected as a benchmark alternative for both the PVO and BD scenarios. On the other hand, the results of life cycle studies strongly depend on—that is, they are sensitive to—allocation procedures and choices, which occur whenever a process provides more than one valuable product. Hence, to the study of the sensitivity of the systems under investigation with changing allocation procedures and choices deserves interest. Generally, allocation issues are faced in two major procedures, where, besides the already mentioned partitioning methods, the so-called system expansion is a widespread solution. This procedure consists of expanding the product system to include the additional functions related to the co-products. In other words, where a process provides a valuable co-product, the product system is expanded, including a process providing a product with equivalent function (namely, avoided product). In this way, the product system is credited for the impact related to the included avoided product. In contrast, in the partitioning methods, as above cited, the environmental burdens are mathematically assigned among the co-products by a specified criterion. Hence, in order to analyze the sensitivity of PVO and BD to allocation choices, mass partitioning and system expansion were also computed and compared. In the BD scenario, two main valuable co-products raise the issue of allocation, the meal cake resulting from the oil extraction and glycerol resulting from transesterification of camelina oil; however, in the PVO scenario, only the meal cake resulting from the oil mechanical extraction deserves allocation. In both cases, straw produced during camelina cultivation was not included. In fact, the characteristics of camelina straw are poorly studied and its possible uses as animal bedding or for making fiber products can only be defined as potential. Furthermore, owing to the high value of the straw/grain mass ratio (3–4:1), a proportional partitioning of the environmental burdens, either on a mass or energy basis, would not be a correct allocation, since the straw would loaded too much, providing misleading results. The same holds for the option of system expansion, where the system would be over-credited with the environmental burdens of the selected avoided products. All of this does not represent the real causality of the product system under study. In any case, straw removal from the field was assumed. This leads to energy consumption (diesel needed for bailing operation) on one side, and N_2O emission saving due to the avoided straw decomposition in the soil. Both of these points were considered in the inventory computation. Table 2 provides the coefficient used for allocation, based on partitioning method (mass and energy allocation). For system expansion, camelina cake meal allocation was based on its functionality as animal feed, and its similarity with soybean meal, as proposed by [28]. The substitution ratio was based on the protein content of the oilseed cakes, deriving the corresponding value from the literature, in the case of soybean (480 g kg^{-1} dry matter; [29]). For camelina, the average value from the present field trials was used (341 g kg^{-1} dry matter; [14]). Therefore, camelina meal was assumed to replace soybean meal for an equivalent protein content, by including and crediting in the product system the process of soybean meal production. This applies for both the BD and PVO scenarios. With regards to glycerol from transesterification of camelina oil (BD scenario), system expansion was applied by including the process of glycerol production. The latter production process, and also that of soybean meal, was derived from the correspondent processes inventoried in the US NREL database [20].

A common pattern for both the BD and PVO scenarios is evident in Figure 6. Mass allocation provides the best results, either in terms of GWP or NER; however, it is probably the less accurate and reliable choice. By contrast, the most penalizing choice seems to be system expansion, especially for the amount of GWP in the PVO scenario. The same roughly holds for the NER indicator.

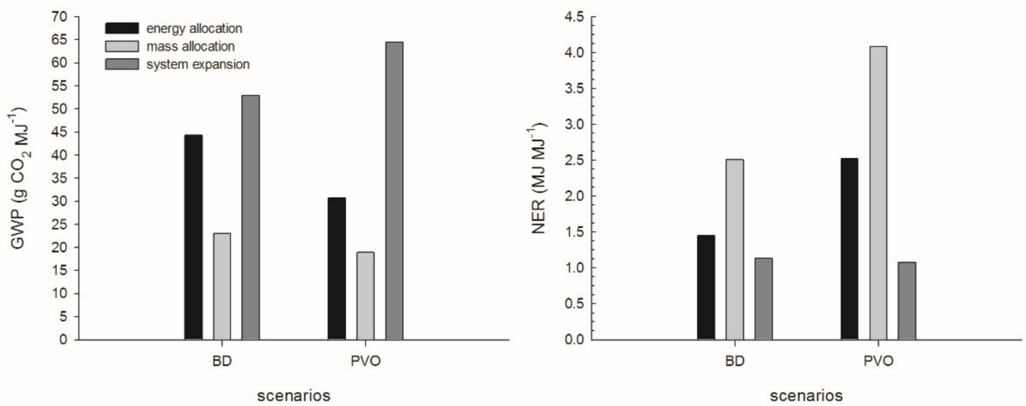

Figure 6. Sensitivity assessment of the two considered camelina scenarios (BD, biodiesel; PVO, pure vegetable oil) as the allocation procedures vary.

4. Conclusions

This study provides reliable estimates of the environmental performance of the camelina crop as a source of biofuels in the Italian context. The calculation is consistent with the relevant literature and underlines the importance of the methodological choice (allocation), on the one hand, and of the field performances (cultivation), on the other, in determining the final environmental performances. For the latter aspect, a large part of the emissions into the air derives from the use of fossil fuels (mainly diesel). This essentially depends on the operation of the machine in the field. In parallel, the combustion of natural gas and the combustion of heavy fuel oil are related to the production of fertilizers (nitrogen fertilizers). A significant item is also dinitrogen monoxide, coming from field emissions (direct emission, due to the use of nitrogen fertilizers, and indirect emissions, due to leaching and volatilization phenomena). Furthermore, in the case of emissions into water, an important contribution comes from the production of fertilizers, especially potash fertilizer.

Hence, the agricultural phase greatly affects the final calculations, both directly and indirectly. The first effect is mainly due to the use of specific crop production means, with significant environmental load. The indirect effect can be identified in the importance of the yield of production in the field, as highlighted by the sensitivity analysis. Therefore, efforts to improve and stabilize camelina field yield should be considered in the future, while maintaining a low-input approach.

Finally, the allocation choices greatly affect both GWP and NER. Specifically, the expansion choice of the system appears to be the most conservative, its GWP being nearly double the mass allocation. The same is true for NER, especially in the case of the PVO scenario.

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References

1. Allen, B.R.; Keegan, D.; Elbersen, B. Biomass and bioenergy in the wider land-use context of the European Union. *Biofuels Bioprod. Bioref.* **2013**, *7*, 207–216. [CrossRef]
2. ISO. *Environmental Management—Life Cycle Assessment—Principles and Frame Work*; Norm ISO 14040:2006; International Organization for Standardization Publication: Geneva, Switzerland, 2006.
3. Eynck, C.; Falk, K. Camelina (*Camelina sativa*). In *Biofuel Crops: Production, Physiology and Genetics*; Singh, B.P., Ed.; CAB International: Wallingford, UK, 2013; pp. 369–391.
4. Martinez, S.; Alvarez, S.; Capuano, A.; del Mar Delgado, M. Environmental performance of animal feed production from *Camelina sativa* (L.) Crantz: Influence of crop management practices under Mediterranean conditions. *Agric. Syst.* **2020**, *177*, 102717. [CrossRef]
5. Krzyżaniak, M.; Stolarski, M.J. Life cycle assessment of camelina and crambe production for biorefinery and energy purposes. *J. Clean. Prod.* **2019**, *237*, 117755. [CrossRef]
6. Tabatabaie, S.M.H.; Tahami, H.; Murthy, G.S. A regional life cycle assessment and economic analysis of camelina biodiesel production in the Pacific Northwestern US. *J. Clean. Prod.* **2018**, *172*, 2389–2400. [CrossRef]
7. Bacenetti, J.; Restuccia, A.; Schillaci, G.; Fiala, M.; Failla, S. Life cycle assessment of flax and camelina for biodiesel production in Sicily (Southern Italy). *Chem. Eng. Trans.* **2017**, *58*, 481–486.
8. Berti, M.; Johnson, B.; Ripplinger, D.; Gesch, R.; Aponte, A. Environmental impact assessment of double- and relay-cropping with winter camelina in the northern Great Plains, USA. *Agric. Syst.* **2017**, *156*, 1–12. [CrossRef]
9. Moeller, D.; Sieverding, H.L.; Stone, J.J. Comparative farm-gate life cycle assessment of oilseed feedstocks in the Northern Great Plains. *Biophys. Econ. Resour. Qual.* **2017**, *2*, 13. [CrossRef]
10. Dangol, N.; Shrestha, D.S.; Duffield, J.A. Life cycle analysis and production potential of camelina biodiesel in the Pacific Northwest. *Trans. ASABE* **2015**, *58*, 465–475.
11. Keshavarz-Afshar, R.; Mohammed, Y.A.; Chen, C. Energy balance and greenhouse gas emissions of dryland camelina as influenced by tillage and nitrogen. *Energy* **2015**, *91*, 1057–1063. [CrossRef]
12. Masella, P.; Martinelli, T.; Galasso, I. Agronomic evaluation and phenotypic plasticity of *Camelina sativa* growing in Lombardia, Italy. *Crop Pasture Sci.* **2014**, *65*, 453–460. [CrossRef]
13. Pecchia, P.; Russo, R.; Brambilla, I.; Reggiani, R.; Mapelli, S. Biochemical Seed Traits of *Camelina sativa*—An Emerging Oilseed Crop for Biofuel: Environmental and Genetic Influences. *J. Crop Improv.* **2014**, *28*, 465–483. [CrossRef]
14. Colombini, S.; Broderick, G.A.; Galasso, I.; Martinelli, T.; Rapetti, L.; Russo, R.; Reggiani, R. Evaluation of *Camelina sativa* (L.) Crantz meal as an alternative protein source in ruminant rations. *J. Sci. Food Agric.* **2014**, *94*, 736–743. [CrossRef] [PubMed]
15. Miller, P.; Kumar, A. Development of emission parameters and net energy ratio for renewable diesel from Canola and Camelina. *Energy* **2013**, *58*, 426–437. [CrossRef]
16. Krohn, B.J.; Fripp, M. A life cycle assessment of biodiesel derived from the "niche filling" energy crop camelina in the USA. *Appl. Energy* **2012**, *92*, 92–98. [CrossRef]
17. Paulsen, H.M.; Wichmann, V.; Schuemann, U.; Richter, B. Use of straight vegetable oil mixtures of rape and camelina as on farm fuels in agriculture. *Biomass Bioenergy* **2011**, *35*, 4015–4024. [CrossRef]
18. Joint Research Center. European reference Life Cycle Database, ELCDIII database, v.3.2. 2015. Available online: https://nexus.openlca.org/database/ELCD (accessed on 15 March 2019).
19. Swedish Life Cycle Center. CPM LCA Database. 2018. Available online: http://cpmdatabase.cpm.chalmers.se/Start.asp (accessed on 15 March 2019).

20. Federal LCA Commons. US NREL Database. 2018. Available online: https://uslci.lcacommons.gov/uslci/search (accessed on 15 March 2019).
21. Buratti, C.; Barbanera, M.; Fantozzi, F. A comparison of the European renewable energy directive default emission values with actual values from operating biodiesel facilities for sunflower, rape and soya oil seeds in Italy. *Biomass Bioenergy* **2012**, *47*, 26–36. [CrossRef]
22. Esteban, B.; Baquero, G.; Puig, R.; Riba, J.R.; Rius, A. Is it environmentally advantageous to use vegetable oil directly as biofuel instead of converting it to biodiesel? *Biomass Bioenergy* **2011**, *35*, 1317–1328. [CrossRef]
23. Audsley, E.; Alber, S.; Clift, R.; Cowell, S.; Cretta, P.; Gaillard, G.; Hausheer, J.; Jolliet, O.; Kleijn, R.; Mortensen, B.; et al. *Harmonisation of Environmental Life Cycle Assessment for Agriculture*; Final Reportconcerted Action AIR3-CT94-2028; European Commission DG VI: Brussels, Belgium, 1997.
24. IPCC. *IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*; Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Eds.; IGES: Kanagawa, Japan, 2006.
25. European Commission-Joint Research Centre—Institute for Environment and Sustainability. *International Reference Life Cycle Data System (ILCD) Handbook- Recommendations for Life Cycle Impact Assessment in the European context*, 1st ed.; EUR 24571 EN; Publications Office of the European Union: Luxemburg, 2011.
26. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC. 2009. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDF (accessed on 15 March 2019).
27. Shonnard, D.R.; Williams, L.; Kalnes, T.N. Camelina-derived jet fuel and diesel: Sustainable advanced biofuels. *Environ. Prog. Sustain.* **2010**, *29*, 382–392. [CrossRef]
28. Li, X.; Mupondwa, E. Life cycle assessment of camelina oil derived biodiesel and jet fuel in the Canadian Prairies. *Sci. Total Environ.* **2014**, *481*, 17–26. [CrossRef]
29. Özdemir, E.D.; Härdtlein, M.; Eltrop, L. Land substitution effects of biofuel side products and implications on the land area requirement for EU 2020 biofuel targets. *Energy Policy* **2009**, *37*, 2986–2996. [CrossRef]