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Integral Assessment of Organic Fertilization on a *Camelina sativa* Rotation under Mediterranean Conditions

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Abstract: The goal of this study was to provide quantitative agronomic data and environmental performance through a life cycle assessment of camelina in a crop rotation. For this purpose, camelina [*Camelina sativa* (L.) Crantz] was included in a crop rotation (camelina-barley [*Hordeum vulgare* (L.)]-camelina) fertilized with two organic fertilizers (dewatered sludge and composted sludge) during three growing seasons (2015–2018). Three treatments were considered in this experimental study of 0.018 ha: (1) Fertilization with composted sludge (15 t ha^{-1}), (2) fertilization with dewatered sludge (35 t ha^{-1}), and (3) control treatment without fertilization. Results showed that camelina's yield was affected by climatic conditions, ranging from 0.9 to 1.4 t ha^{-1} in the first season (2015/2016) and the third season (2017/2018 and did not present significant differences between treatments. The yield components with a positive response to organic fertilization were number of silicles, number of seeds per plant, and thousand-seed weight, with an average increase compared to the control of 23.7%, 16.5%, and 18.5%, respectively. A negative correlation was observed between organic fertilization and total fat content, contrary to the increase in protein content observed with organic fertilization. The environmental assessment of this crop rotation revealed that fertilization and transport were the main hotspots. Despite the undesirable weather limitations, this study showed a positive response of camelina's yield components and seed quality to organic fertilization. By applying these organic fertilizers, it may be possible to obtain favorable camelina yields and promote waste valorization. To minimize the environmental impacts of this crop rotation with camelina, the main recommendations could be to reduce the distances between the dewatering and composting sites and the field and optimize fertilization rates. Further research is needed to determine the application of these organic fertilizers in the long term.

Keywords: energy crop; agronomic performance; life cycle assessment; yield; sewage sludge; compost

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1. Introduction

Countries worldwide are heading towards more sustainable consumption and production systems. Since the development of the Circular Economy Action Plan in 2015, the European Commission continues to advocate for a low carbon circular economy in which pressures on natural resources and waste accumulation are minimized [1]. Burning fossil fuels is the main contributor to greenhouse gas emissions [2], and substituting them with biofuels can present several benefits [3,4]. In this regard, the agricultural sector has been identified as essential to produce agricultural raw materials, such as oleaginous crops, for biodiesel production.

Camelina sativa (L.) Crantz is an oilseed crop from the Brassicaceae family characterized for its high adaptation to different climatic conditions and high resistance to diseases and pests [5]. A renewed interest in this crop has appeared in recent years due to its numerous uses, mainly for biofuels as an alternative to fossil fuels and feedstock for animal feed [6]. In order to determine the best agricultural practices for growing camelina, different investigations have been carried out. Multi-location trials have determined the productive performance of camelina in different growing conditions showing its agronomic potential as the main crop or intercrop [7]. Camelina's yield has also been studied with different irrigation regimes [8,9].

Nutrient management is also an essential aspect in camelina's cultivation affecting growth, yield, and seed quality [10,11]. Mineral fertilization studies have been performed to determine the rate of mineral fertilizer application [12–14]. Jankowski et al. (2019) investigated the effects of nitrogen (N) and sulfur (S) fertilization on camelina yield and seed quality. It was concluded that N rates higher than 120 kg ha^{-1} were recommended to obtain high protein content and S rates of 30 kg ha^{-1} were recommended for both feed and food purposes. The addition of organic amendments in agricultural fields, such as animal and green manures, sludge, and compost, is a common agricultural practice to include wastes and by-products from industrial, municipal, and agricultural sectors [15]. Limited investigations have focused on studying the response of camelina to organic fertilization. Angelopoulou et al. (2020) determined that the use of vermicompost and compost increased linoleic and palmitic acids, and compost exhibited the highest seed and oil yield [16]. In another study, camelina's seed oil concentration of linolenic and erucic acids, tocopherols, and campesterol increased when organic fertilizer (chicken manure pellets) was applied and highlighted the influence of the season and fertilization in camelina's cultivation [17].

Despite the recent studies conducted concerning camelina production, more research is needed to provide field-based agronomic recommendations. In this sense, agricultural practices used for growing other crops could be investigated on camelina. For instance, the use of composted and dewatered sewage sludge as organic amendments, which have proven to be an effective source of nutrients for crop growth [18,19]. Additionally, crop rotation has been found to be a useful tool to control weeds [20] and enhance soil properties by increasing soil organic carbon and, thus, improving water retention and nutrient supply [21]. Although these are well-documented agricultural practices [21,22], few studies have been carried out investigating organic fertilization combined with camelina crop rotation.

Apart from the agronomic aspects of growing camelina, other considerations should be addressed to its production. Crop production should not only focus on increasing crop yield but should also promote sustainable crop rotations. Life cycle assessment (LCA) is a widely used methodology to quantify the sustainability impacts of a product or service and has been applied extensively to agricultural systems [23]. The traditional LCA methodology consists of completing an inventory of the different processes involved in the production of a good or service and then quantifying the life cycle impacts generated by each process [24]. Several studies applying the LCA tool have been conducted to determine the environmental impacts of camelina. Most of the LCA studies focus on the environmental impacts of camelina on biodiesel production [22,23,25]. Krzyżaniak and Stolarski (2019) concluded that the highest impacts of camelina production corresponded to fossil depletion, climate change, and particulate matter. In another study, Tabatabaie et al. (2018) quantified the environmental impacts of the processes of camelina seed production under two scenarios (no-tillage and conventional tillage), transportation, camelina oil extraction, and transesterification together with an economic analysis. It was determined that the cropping system under the no-tillage system generated lower GHG emissions compared to the conventional tillage system. Few investigations considering the environmental performance of camelina under Mediterranean conditions [26,27], in rotation with winter cereals [28], and considering camelina in multiple cropping systems [29], have been carried out.

Limited data are available regarding the productive and environmental performance of camelina in crop rotation, using organic fertilization and grown under Mediterranean conditions. In this regard, the objective of this study was to provide on-field data from the combined effect of applying two types of organic fertilizers to a crop rotation system on camelina's agronomic performance and soil properties. Complementarily, a life cycle assessment and the quantification of the environmental impacts of camelina production were evaluated. It was believed that the use of organic fertilizers would have benefited camelina's yield with respect to no fertilization and that the fertilization rates would have had a strong influence on the environmental impacts.

2. Materials and Methods

2.1. Experimental Design

Field experiments were carried out in the experimental site La Canaleja (Alcalá de Henares, Spain) (40°30′ N–3°18′ W, 600 m.a.s.l.), during three growing seasons, from 2015 to 2018. The experimental design consisted of the crop rotation camelina–barley–camelina and three fertilization treatments (composted sludge fertilization, dewatered sludge fertilization, and control treatment without fertilization) (Figure 1). As shown in Figure 1, the camelina cultivar [*Camelina sativa* (L.) Crantz] was grown during the first season (2015/2016) and the third season (2017/2018). In *Brassica* cultivars, such as camelina, temperature and rainfall are important environmental conditions affecting camelina's yield and seed quality [30,31]. During the second season (2016/2017), the cultivar of barley [*Hordeum vulgare* (L.)] was grown. Among one of the oldest cultivated crops in the world, barley belongs to the *Poaceae* family and has been cultivated worldwide and in different cropping systems [32].

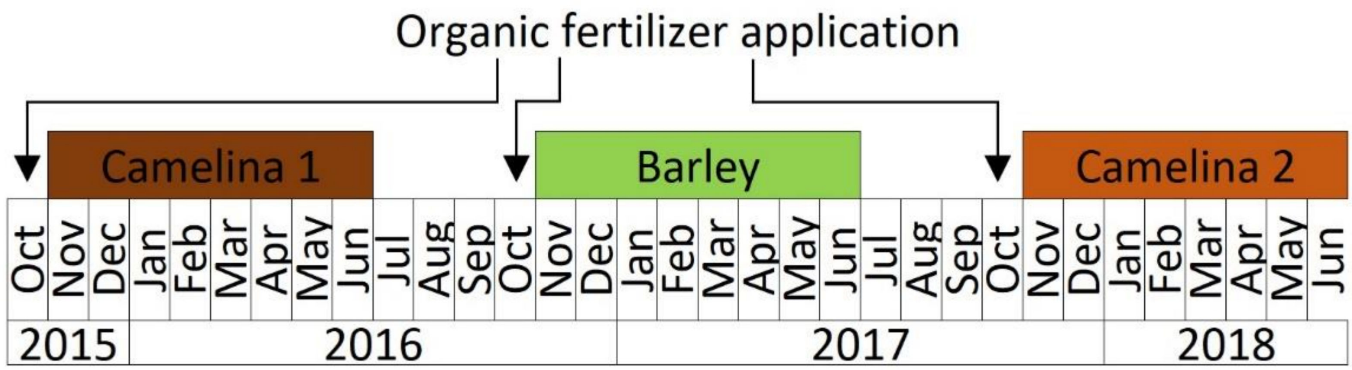

Figure 1. Experimental study of the crop rotation during three seasons considering three fertilization treatments.

Camelina and barley were cultivated in a non-irrigated block design with three replications of each treatment including the control. The total plot size per treatment was 180 m^2 (18 m × 10 m). Climatic conditions correspond to Mediterranean, classified as BSk on the Köppen–Geiger scale [33], characterized by mild winters and hot and dry summers [34]. Meteorological data were collected from a weather station located on the experimental site of La Canaleja belonging to the National Institute for Agricultural and Food Research and Technology (INIA). The average long-term climatic conditions of Madrid were obtained from the statistical weather and climate web page of Madrid [35]. According to the USDA classification, the soil present in the experimental field is a Calcic Haploxeralf [36].

2.2. Crop Management

The processes carried out in the cultivation of this crop rotation are represented in Figures 1 and 2. Soil preparation consisted of chiseling and ploughing to aerate and reduce compaction of the soil without carrying out soil inversion. A straight-point chisel plow was used to break up soil aggregates from 6 to 12 cm depth without significantly mixing the soil layers. Both organic fertilizers were obtained from urban sewage sludge and applied every year before soil preparation. Compost was applied at a rate of 15 t ha^{-1} (wet weight). Composting is an aerated process consisting of the decomposition of organic material to obtain a stable and non-phytotoxic product. Dewatered sludge was applied to the field at a rate of 35 t ha^{-1} (wet weight). Table 1 summarizes the characteristics of both organic fertilizers. Dewatered sludge was obtained from a dewatering process using a filter press and a centrifuge. The application of this type of organic amendments for agricultural purposes is regulated in Spain by a Royal Decree, establishing the parameters to analyze, such as dry matter, organic matter, pH, nitrogen, phosphorus, and other components, and their limits [37]. The organic fertilizers were obtained from the same site, therefore the transport from the composting and dewatering site to the field plots were the same. The distance was 110 km, and it was transported using a trailer. The chemical analyses to determine the organic fertilizers' parameters were carried out in a laboratory located in the National Institute for Agricultural and Food Research and Technology (INIA).

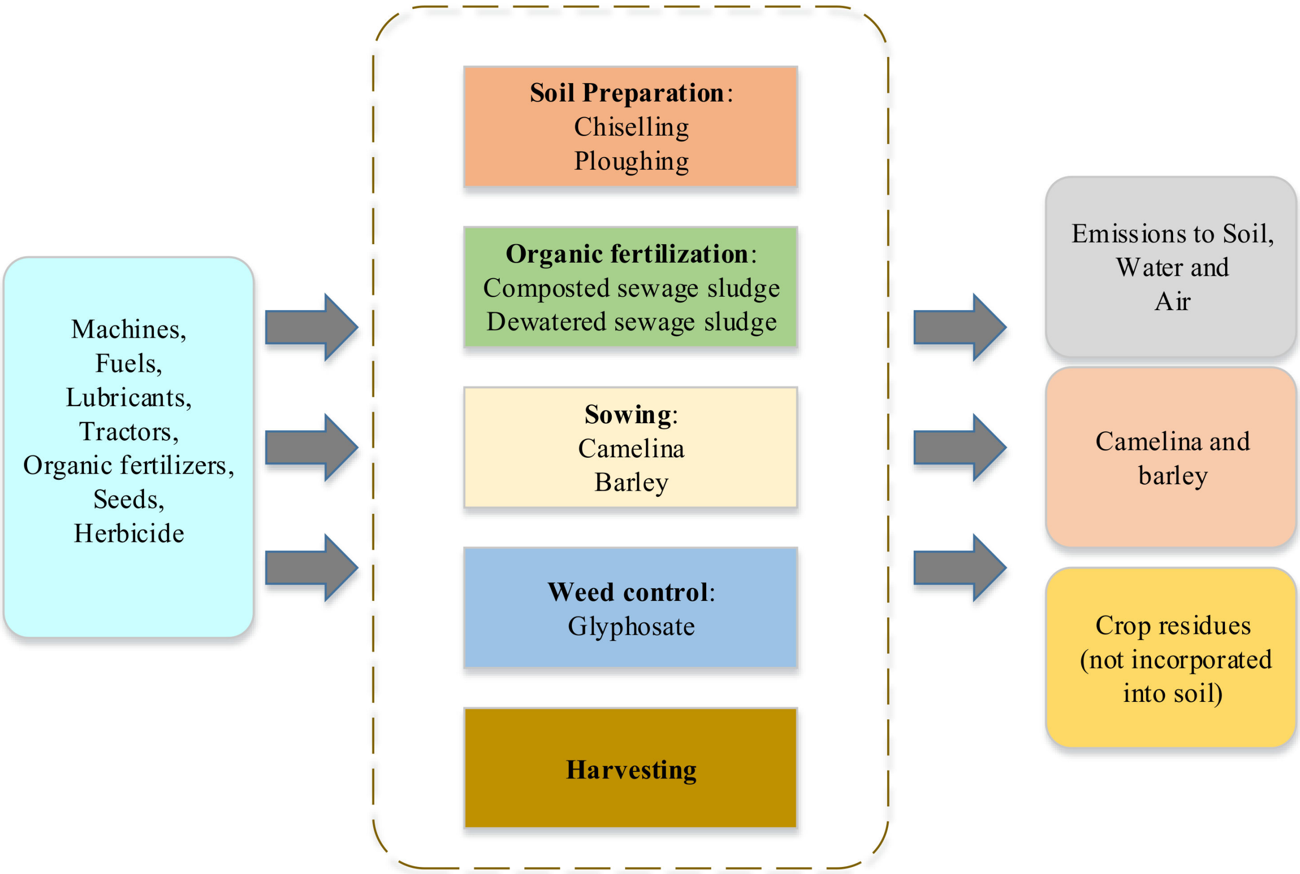

Figure 2. System boundary for camelina-barley-camelina crop rotation fertilized with composted sludge and dewatered sludge.

Table 1. Characteristics of dewatered sludge and composted sludge used as organic fertilization (dry matter).

Parameter	Sewage Sludge		Applied per Year	
	Dewatered	**Composted**	**Dewatered (35 t ha^{-1})**	**Composted (15 t ha^{-1})**
pH, 1:2.5 H_20	7.7	8.1		
E.C., 1:5 H_2O (dSm^{-1})	3.5	4.2		
	%		kg ha^{-1}	
Dry mater	21.2	77.4	7420	11,610
Humidity	78.8	22.6	27,580	3390
Total carbon	16.5	18.2	1224	2113
Organic matter	29.1	31.4	2159	3646
N Kjeldahl	5.5	1.2	408.1	139.3
N-NH_4^+	1.6	0.2	118.0	23.2
N-NO_3^-	0.08	0.05	6.1	5.2
P_2O_5 total	4.9	3.1	363.6	359.9
K_2O total	0.6	0.4	44.5	46.4
CaO total	6.3	7.1	467.5	824.3
MgO total	1	1.5	74.2	174.2
	mg kg^{-1}		kg ha^{-1}	
Zn	473	451.1	3.51	5.24
Cu	298	152.2	2.21	1.77
Cr	25.3	52	0.19	0.60
Ni	27.8	18.7	0.21	0.22
Pb	35.2	25.8	0.26	0.30
Cd	0.9	0.6	0.01	0.01

The sowing consisted of 8 kg ha^{-1} of camelina and 200 kg ha^{-1} of barley, and it was done using a conventional seeder. Seeds of camelina were provided by Camelina Company Spain, and barley seeds were obtained from the seed bank located in the National Institute for Agricultural and Food Research and Technology (INIA). The weed control, immediately after sowing but before emerging, consisted of the application of glyphosate at a rate of 2 L ha^{-1} in each plot (Roundup®). Finally, the harvest was performed in June using a self-propelled combine harvester.

These field operations were the same every year and it only varied the type of crop seed depending on the season. A summary of the field operations and inventory data is found in Appendix A (Table A1) and Appendix B (Table A2). After each agricultural season, crop residues were removed from the field and not incorporated into the soil. Therefore, there was no addition of N from the preceding crop residue [2]. Before the start of this investigation, the plots were fallow plots, without cultivars.

2.3. Crop and Soil Analysis

Each replication was harvested, and camelina's and barley's yield was determined per plot considering a 1 m^2 area from the center of each plot. Seeds were weighed for each plot and treatment to determine yield. Camelina's seeds were then dried to constant mass at 65 °C in a laboratory dryer to determine the percentage of moisture. Seed yield components (number of branches, number of silicles plant^{-1}, thousand-seed weight, and number of seeds plant^{-1}) were evaluated at harvest considering also a 1 m^2 area from the center of each plot. Plant height was taken from 5 plants in the 1 m^2 area from each plot before harvesting.

Crude protein and total oil content of camelina were determined in sub-samples, scanned in the near-infrared spectroscopy (NIRS) Systems 6500 monochromator (FOSS NIR Systems Inc., Eden Prairie, MN, USA) [38]. The fatty acids profile was obtained through gas chromatography. Soil samples down to a depth of 30 cm were collected after the three years of the experiment to determine the chemical properties variation of the soil. Soil samples were left to dry at ambient temperature, passed through a 2 mm sieve, and homogenized.

Standard methods were used for the determination of the physicochemical parameters. Soil pH was measured with the glass electrode (pHmeter BASIC20 [39]) based on a soil water suspension of 1:2.5 (w/v). Soil nutrients (potassium, phosphorus, calcium, magnesium) and heavy metals (iron, copper, zinc, lead, nickel, chromium, and cadmium) were extracted with acids and determined using inductively coupled argon plasma emission spectrometry (ICPES) [40] in the chemical laboratory located in the National Institute for Agricultural and Food Research and Technology (INIA).

2.4. Statistical Analysis

The effects of the type of crop (camelina and barley) and the type of organic fertilization (composted sludge, dewatered sludge, and control), as well as the interaction between them, were estimated using a two-way analysis of variance (ANOVA). In order to evaluate significant differences between camelina's yield components, one-way ANOVA was performed. For the parameters with a significant difference ($p < 0.05$), a post hoc analysis using the Duncan test was also carried out. To determine the significant differences in the soil, a two-way ANOVA considering the type of organic fertilization and the sampling time (at the beginning of the study and at the end of the study), as well as the interaction between them, was carried out. For the soil parameters with a significant difference ($p < 0.05$), a post hoc analysis using the Duncan test was also carried out. All the statistical analyses were performed with IBM SPSS software [41].

2.5. Environmental Impact Assessment

This analysis was conducted from a cradle-to-gate perspective, from the preparation of the soil until the crop harvest (Figure 2). The total environmental impacts were quantified for the two crops cultivated in the three growing seasons: First season camelina, second season barley, and third season camelina. In addition, the experimental field was previously dedicated to investigating camelina production, so carbon sequestration into the soil and environmental impacts due to land-use change were negligible [42].

The functional unit was established as a mass-based functional unit [43] defined as 1 ton of crop produced expressed in cereal unit (CU). To be able to evaluate two different crops in a crop rotation, the cereal unit (CU) was established as a common unit [44]. Therefore, final results were expressed per CU as functional unit. As established by Brankatschk and Finkbeiner (2014), 1 kg of barley equals 1 kg CU and 1 kg of rapeseed, assumed for camelina, equals 1.3 kg CU [45].

Direct nitrogen emissions, such as nitrous oxide (N_2O), ammonia (NH_3), and nitrate (NO_3^-) into the air, soil, and water due to the organic fertilizers' application were estimated considering the type of organic amendment, yield, and nitrogen content of the crop, soil properties, and climatic conditions. These emissions were modeled using the software EFE-So (2015) based on the algorithms defined in Brentrup et al. (2000). Regarding phosphate (PO_4^{-3}) emissions, the SALCA model was used considering the phosphorous leaching to groundwater and the phosphorous run-off to surface water [46,47]. Correction factors of 0.07 kg P ha^{-1} year^{-1} and 0.175 kg P ha^{-1} year^{-1} were used for phosphorous leaching to groundwater and phosphorous run-off to surface water, respectively. Additionally, water, air, and soil emissions from the herbicide glyphosate were estimated considering 10% of the herbicide was released to the air, 8.5% to water, and 76.5% to the soil, and the rest was kept on the crop [48,49].

Background data for the production of camelina and barley seeds, composting and dewatering sludge processes, transport, and agricultural operations (ploughing, chiseling, crop management, sowing, and harvesting) were obtained from the Ecoinvent database v.3 [50] and adapted to our study. This database is a well-known database that has been widely used for agricultural systems [51,52] (Appendix A Table A1).

The environmental performance of crop rotation with camelina and organic fertilization was quantified using the ILCD 2011 Midpoint + method released by the European Commission Joint Research Centre in 2012 [53]. LCA was performed with SimaPro 8.0.5 software analyzing the following categories: Climate change, human toxicity, terrestrial acidification, freshwater eutrophication, terrestrial eutrophication, and abiotic depletion [54].

3. Results

3.1. Weather Conditions and Crop Yield

The monthly variations in air temperature and precipitation were recorded for each growing season. In the first experimental year, the maximum temperature throughout the year and the minimum temperature in autumn exceeded the long-term average temperature (1990–2018) (Figure 3). Annual precipitation in the experimental site was 283 mm, 30.5% lower than the annual precipitation for the long-term period (Figure 3). The second experimental year was also characterized by low precipitation, in particular during June and December. Although the annual precipitation for 2016–2017 (311 mm) was higher than for the first season, it was 23.6% lower than the long-term annual precipitation. Regarding the average temperatures recorded for the second season, the maximum average temperature was higher throughout the year in comparison with the long-term average temperature. The third season was the driest season, with the lowest annual precipitation (224 mm) and the highest annual maximum temperature, 62.9% higher than the highest annual maximum temperature for the long-term period.

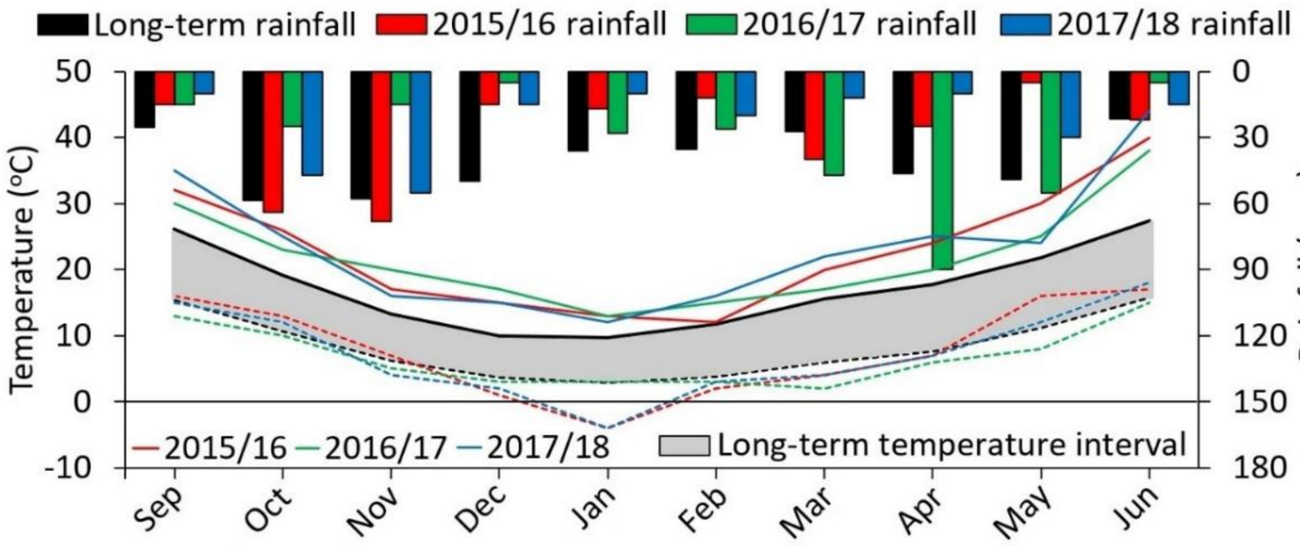

Figure 3. Comparison of the climatic data registered in Madrid from 1990 to 2018 and the three studied seasons (2015/16, 2016/17, and 2017/18). For each season, continuous lines represent maximum temperature, and dash lines are the minimum temperature.

The analysis of the yield of camelina during the first season did not reveal any differences between the fertilization with composted sludge and dewatered sludge (Table 2). Lower yields were obtained for camelina in the third season. A similar trend as with the first season was observed during this experimental year. The composted sludge fertilization presented the highest mean yield. However, the correlation coefficient between the yield and the type of organic fertilization did not show significant differences in both crops, camelina, and barley.

Table 2. Crop yield (kg ha^{-1}) obtained for the crop rotation camelin–barley–camelina considering the three fertilization treatments (dewatered sludge fertilization, composted sludge fertilization, and the control without fertilization).

Fertilization	Crop Rotation		
	Camelina (2015/2016)	Barley (2016/2017)	Camelina (2017/2018)
Control	1249.0 ± 564.1	1069.6 ± 548.5	906.5 ± 324.7
Dewatered sludge	1278.5 ± 282.8	1497.2 ± 306.0	1089.8 ± 181.4
Composted sludge	1415.3 ± 248.3	1270.8 ± 347.9	1199.7 ± 168.0
ANOVA	*p*		
Crop rotation	0.583 (ns)		
Fertilization	0.595 (ns)		
Crop rotation × fertilization	0.464 (ns)	ns: not significant	

3.2. Camelina's Yield Components and Seed Quality

The average yield components and seed quality of camelina were calculated considering the first and third seasons of the experimental study. Although camelina fertilized with both organic fertilizers showed higher height and number of branches than the control, this increase was not significant (Table 3). Regarding the other yield components, composted sludge presented a significant difference with respect to the control and the dewatered sludge in the number of silicles plant^{-1}. In relation to the number of seeds plant^{-1}, the dewatered sludge fertilization presented the highest values, being 17% higher than the control. Results also showed a significant increase of the thousand seed weight in both organic fertilizations with respect to the control. However, the difference obtained between the organic fertilizers was not significant.

Table 3. Camelina's yield components considering the three fertilization treatments (dewatered sludge fertilization, composted sludge fertilization, and the control without fertilization).

Fertilization	Control	Dewatered Sludge	Composted Sludge	
Height (cm)	110.3 ± 4.1	115.0 ± 7.0	115.6 ± 14.8	ns
Nº Branches	12.6 ± 1.5	14.0 ± 1.0	10.6 ± 0.5	ns
Silicles plant^{-1}	48.0 a ± 7.8	54.3 a ± 3.2	71.6 b ± 9.0	*
Nº seed plant^{-1}	2549 a ± 236	3104 b ± 243	3004 b ± 166	*
Thousand seed weight (g)	1.1 a ± 0.1	1.3 b ± 0.1	1.4b ± 0.1	*
Moisture (%)	6.6 ± 0.1	6.6 ± 0.1	6.7 ± 0.1	ns
Total fat (%)	43.2 a ± 1.0	42.3 ab ± 1.67	40.8 b ± 0.5	*
Crude fat (%)	37.0 a ± 1.1	36.1 ab ± 1.6	34.4 b ± 0.4	*
Crude Protein (%)	24.8 a ± 0.9	26.1 ab ± 1.7	27.5 b ± 0.1	*
Palmitic acid C16:0 (%)	6.8 ± 0.1	6.8 ± 0.1	6.9 ± 0.3	ns
Stearic acid C18:0 (%)	2.4 ± 0.1	2.4 ± 0.1	2.7 ± 0.1	ns
Oleic acid C18:1 (%)	9.2 ± 0.3	10.1 ± 0.4	9.3 ± 0.8	ns
Linoleic acid C18:2 (%)	17.0 a ± 0.2	16.3 a ± 0.1	17.9 b ± 0.8	*
Linolenic acid C18:3 (%)	39.0 ± 0.1	39.0 ± 0.4	38.7 ± 0.3	ns
Eicosenoic acid C20:1 (%)	12.3 ± 0.1	12.3 ± 0.3	12.1 ± 0.4	ns
Erucic acid C22:1 (%)	3.6 a ± 0.1	3.5 a ± 0.2	3.0 b ± 0.1	*

Mean values with different letters in the same row vary significantly (*; $p < 0.05$, Duncan test). Results expressed as mean ± standard deviation. ns: not significant.

In relation to seed quality, no significant differences were found in seed moisture (Table 3). The fat and protein content significantly differed between the control and camelina fertilized with the composted sludge. The control showed the highest fat content, while composted sludge fertilization obtained the highest protein content. The fatty acids profile revealed that the predominant fatty acids were the linolenic acid (38.7–39.0%), linoleic acid (16.3–17.9%), eicosanoic acid (12.1–12.3%), and oleic acid (9.2–10.1%) (Table 3).

The application of composted sludge led to a significant increase in the proportion of linoleic acid and a significant decrease in the proportion of erucic acid with respect to the control treatment and the application of dewatered sludge but had no significant effect on the proportion of the remaining fatty acids.

3.3. Soil Effects

The findings of the soils' analysis after the third season are shown in Table 4. No significant changes were observed in the soils' pH and organic matter between both organic fertilizations and the control. After the three-year crop rotation, no significant change was observed in the content of macronutrients (calcium, potassium, phosphorous, magnesium) nor micronutrients (iron, copper) with the exception of zinc. The concentration of heavy metals at the end of the experiment raised significantly (nickel, cadmium, chromium, and zinc: $p < 0.05$), except lead. This raise was not influenced by the treatments with organic fertilizers.

Table 4. Soil parameters at the end of the fertilization with dewatered sludge, composted sludge, and the control without fertilization (dry weight).

Parameter	Control Soil	Dewatered Sludge	Composted Sludge	$p < 0.05$
pH, 1:2.5 H_20	7.9	7.7	7.7	ns
Organic matter, %	3.9	4.4	4.8	ns
P (mg/kg)	492.7	1280.7	1285.7	ns
Ca (mg/kg)	57,427.7	65,506.7	63,409.3	ns
K (mg/kg)	2145.2	2839.3	3054.3	ns
Mg (mg/kg)	6892.7	6468.7	6574.3	ns
Fe (mg/kg)	14,635.0	14,172.7	14,230.7	ns
Zn (mg/kg)	152.3	210.0	199.3	ns
Cu (mg/kg)	23.5	50.2	48.3	ns
Cr (mg/kg)	15.6	25.3	19.5	ns
Ni (mg/kg)	9.0	8.9	10.4	ns
Pb (mg/kg)	23.7	38.3	33.0	ns
Cd (mg/kg)	1.7	2.5	2.0	ns

ns: not significant.

3.4. Environmental Impact Assessment

The environmental performance of the crop rotation camelina–barley–camelina was quantified following an LCA approach. Figure 4 shows the results of the environmental impact categories according to the type of organic fertilizer and type of crop. Additionally, Figure 5 describes the relative contribution of each of the six processes (soil tillage, seeding, weed control, harvesting, organic fertilization, and transport referred to the organic fertilization transport) to the environmental impact categories associated with the type of fertilization of the overall crop rotation.

For the climate change impact category, the dewatered sludge fertilization exhibited on average 37% higher carbon emissions than with composted sludge. Camelina grown in the third season and fertilized with dewatered sludge exhibited the highest carbon emissions (1735.8 kg CO_2 eq t^{-1}). Similar contributions of the six processes were observed for both organic fertilizations, being the transport the process with the highest contribution, 41% on average. Regarding the impact category human toxicity, the composted sludge fertilization and dewatered sludge fertilization exhibited similar carbon emissions, $2.0 \cdot 10^{-3}$ and $1.9 \cdot 10^{-3}$ CTUh, respectively, corresponding to camelina grown in the third season. For both organic fertilizations, the dominant process was the transport process. Great differences in impacts were obtained for the impact categories acidification and terrestrial eutrophication between both organic fertilizers. On average, the dewatered sludge application was 87% and 61% higher than composted sludge application for acidification and terrestrial eutrophication, respectively. In addition, in both impact categories, the organic fertilization for the dewatered sludge was responsible for almost all the entire impacts.

A similar pattern was obtained for freshwater eutrophication and abiotic depletion, with higher impacts exhibited by camelina grown in the third season. The transport process was identified as the main contributor (44%) to the impact categories freshwater eutrophication and abiotic depletion.

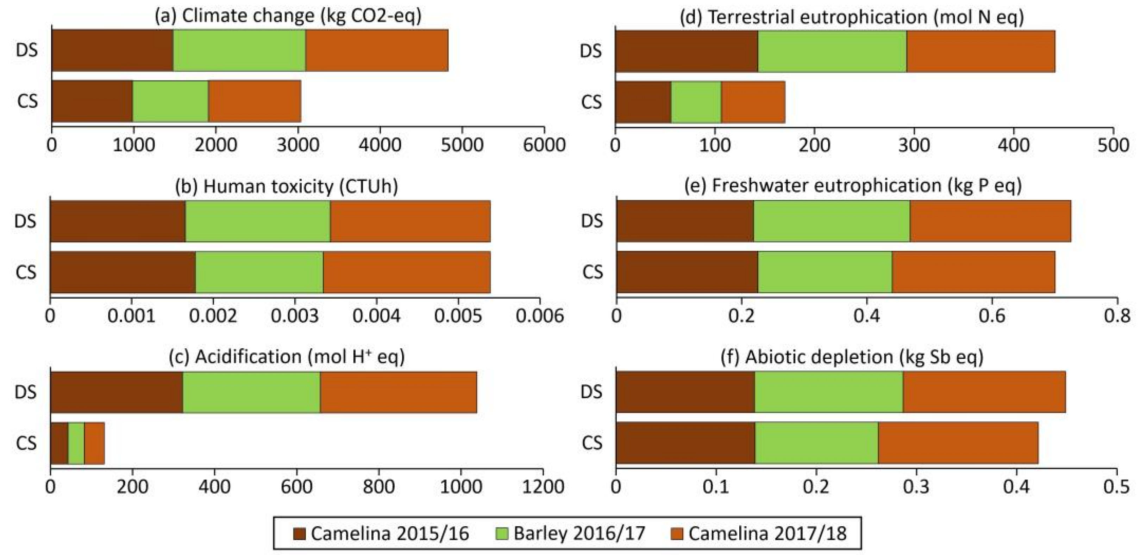

Figure 4. Environmental impact categories comparison (**a**–**f**) concerning the cultivation of the crop rotation camelina-barley-camelina fertilized with dewatered sludge (DS) and composted sludge (CS).

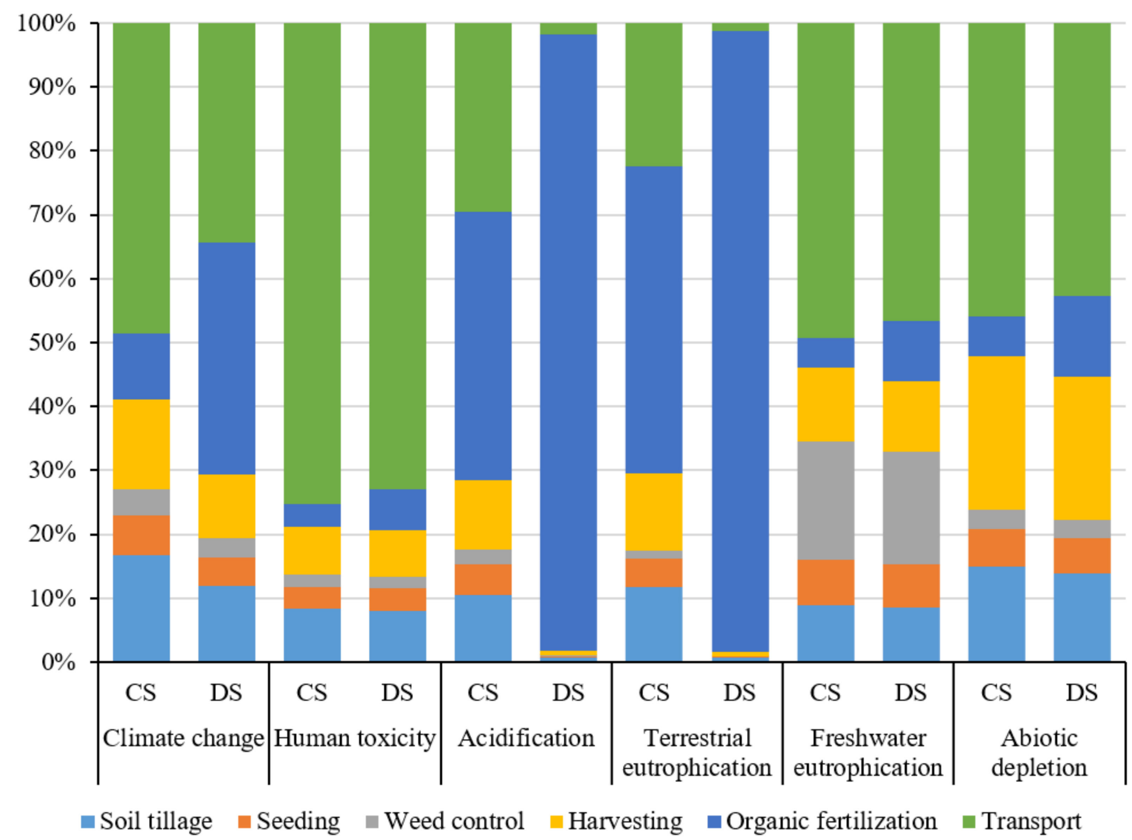

Figure 5. Relative contribution (%) to the environmental impacts categories of each process for the production of 1 t of CU of the crop rotation camelina-barley-camelina fertilized with dewatered sludge (DS) and composted sludge (CS).

4. Discussion

4.1. Integral Assessment of Organic Fertilization and Crop Rotation

Crop yields in this experimental study were conditioned by the weather conditions recorded for the three seasons. Although camelina was sown in autumn, which has been reported as the best agronomic practice to increase camelina's yield [55], camelina's yield in the first and third seasons was limited by relatively high temperatures and low rainfall, which delayed the crop's growth. Camelina's yield has a significant response to water deficit and this crop's yield can be reduced up to 31.6% with low water availability [8]. In previous studies, the highest yields have been documented to vary between 2.9 and 3.0 t ha^{-1}, found in Southern Ethiopia [56]. In Europe, camelina's yields in France and Germany also showed high values, with a range of 2.3 to 2.8 t ha^{-1} [57,58]. The results in our study are in line with the yields obtained in the Great Plains in the USA, varying between 0.9 and 1.4 t ha^{-1} [59,60]. A similar yield for camelina (1.22 t ha^{-1}) was also observed in the crop rotation camelina–wheat–barley carried out under Mediterranean conditions [20]. However, a higher yield was achieved by barley in the third season of Royo-Esnal et al. (2018) investigation, being 67.7% higher than in our study. In our case, barley was sown in October, and this month and the following months were the driest of the three seasons making the establishment of the crop harder.

With respect to yield components, the number of silicles $plant^{-1}$ is associated with the yield of crops. Camelina yields of 2390 and 1788 kg ha^{-1} exhibited 369 and 271 silicles $plant^{-1}$ [14]. In contrast, our study showed lower values in line with the lower yields obtained. Camelina fertilized with dewatered sludge and composted sludge exhibited similar silicles $plant^{-1}$ as camelina fertilized with nitrogen and sulfur (48–71.6 silicles $plant^{-1}$) [58]. The findings of the thousand-seed weight and plant height were in agreement with studies applying mineral fertilization, being the average values of thousand-seed weight and height 1.3 g and 114.4 cm, respectively [14,58]. The application of composted sludge presented a low increase in the height (4%) with respect to the control treatment without fertilization and there were no significant differences between the dewatered sludge applied and the control. This reinforces the idea that under these Mediterranean conditions, water was a more limiting fact than nutrients [61]. Regarding the seed quality, the results in the present study are within the ranges of protein and fat content obtained for camelina seed quality, with the range of 25.1–38.7% for protein and 19.2–42.4% for total fat [62]. Camelina fertilized with composted sludge and dewatered sludge showed higher protein content but lower fat content than the control. These findings are consistent with other studies that determined that providing nitrogen fertilization enhances protein synthesis in camelina's seeds, for instance applying fertilization of 0.9 g pot^{-1}, provided a protein content of 27.87% [63,64]. In contrast, nitrogen could delay grain filling and maturity [65], explaining the negative correlation between nitrogen fertilization and fat content in camelina seeds [12,60]. The analysis of the fatty acid profile revealed that the most abundant fatty acids were linolenic acid, linoleic acid, eicosanoic acid, and oleic acid. This is consistent with results reported in previous investigations [66,67]. Erucic acid (22:1) can serve as an indicator of camelina's oil use [68]. The level of erucic acid in this study is below the limit established by the European Union for erucic acid levels in edible vegetable oils [69]. In addition, nitrogen fertilization applying organic fertilizers enhances protein synthesis obtaining high protein sources. Therefore, potential use for both camelina oil and meal (camelina after oil extraction) can be animal feed [54].

Soil parameters can play an essential role to promote the plant's growth. In this sense, agronomic practices are key to enhance camelina's productivity. Continuous monocultures promote the depletion of soil's nitrogen and organic carbon, while crop rotations retard this depletion [70]. Additionally, the combination of crop rotations and appropriate fertilization leads to the maintenance of nitrogen and organic carbon at adequate levels [71]. In our study, the initial content of organic matter in the soil could be considered as adequate for the cultivation of crops [72] and this organic matter content in the soils was positively increased with organic fertilization. This positive tendency of increasing soil organic matter is explained by the stimulation of biomass production by adding organic fertilizers, which enhances carbon accumulation [73]. Furthermore, the pH soil was suitable for camelina's growth [74]. Based on the literature, the addition of organic amendments follows the tendency of increasing soil pH [75]. This effect is due to the addition of basic cations with the organic amendments [76] and the chemical reaction of decarboxylation of organic anion and ammonification of organic nitrogen [77]. In our case, no significant differences were observed between organic fertilization and the control. Soil pH in organic fertilization treatments was slightly lower than the control, which may be explained by the protons generated by the nitrification of mineralized nitrogen, which lowers the pH to some extent [78]. In relation to soil nutrients, this soil can be considered fertile soil due to its high content in micronutrients and macronutrients. After the crop rotation, the levels of nutrients had not been negatively affected. Organic fertilization enhances microbial activity, leading to chemical transformations influencing the availability and uptake of soil nutrients [79]. Besides the nutrient content, at the end of the experiment, there were no differences in heavy metal concentrations, but there was a tendency to increase them after the organic fertilization. Although an increasing tendency in heavy metals concentration was observed, the levels remained below the critical values established by the Spanish government for heavy metals in soils [37]. These results need to be interpreted with caution. Longer study periods would be required to monitor the heavy metals concentration in soils, not only considering the total amount of heavy metals but also the concentrations of easily mobile and plant-available forms, even more so when pH tends to be lower after organic fertilization [80].

Despite camelina being an alternative energy source to replace the massive use of fossil fuels, the intensification of crop production can lead to adverse environmental impacts [81]. Camelina seed production has been identified to account for more than 90% of the total impacts [26]. Therefore, special attention has been set to agricultural systems. Agronomic use of organic fertilizers as rich sources of plant nutrients is considered a sustainable alternative for the valorization of by-products and wastes [82]. Policies have already been developed concerning the reduction of waste and promoting a circular economy. An example is the circular economy package that the European Commission has established. Among other ambitious targets, it is established that by 2030, 65% of the municipal solid waste should be recycled, and landfilling of these municipal solid waste reduced to a maximum of 10% [83]. In this sense, in the case of Spain, the National Integral Waste Plan aims to reduce the amount of organic waste destined to landfill and encourages its use as organic amendments in agriculture [84]. Additionally, another measure foreseen in the circular economy package related to the use of organic waste is to implement economic incentives for producers who put greener products on the market [85]. Based on our findings, the use of organic fertilizers could be an alternative to mineral fertilizers for camelina's cultivation and promote the recovery and recycling of nutrients.

Although they provide valuable nutrients for plants, organic fertilizers can also exhibit negative environmental impacts due to the leaching and volatilization of these nutrients [86]. This effect was seen in the impact categories of acidification and terrestrial eutrophication for dewatered sludge fertilization. Fertilization processes are the main ones responsible for eutrophication and for acidifying the environment [26] and can result in 90% of the environmental impacts due to the release of compounds, such as SO_2, NH_3, and NO_x [87]. For this reason, it is recommended to apply appropriate rates of organic fertilizers to minimize these nutrient losses and reduce their environmental impacts. For the rest of the impact categories, the hotspot analysis of environmental burdens identified the transport process as the main contributor. Such high environmental impacts were derived from the transportation of organic fertilizers due to the long distance between the composting and dewatering site and the experimental field (110 km). This resulted in high diesel fuel emissions and tire abrasion affecting the impact categories of climate change and resource depletion [88]. In order to minimize the environmental impacts, a possible recommendation could be to locate the composting or dewatering sludge sites nearby the agricultural fields. This will mean reducing direct emissions from diesel consumption and the indirect impacts generated from the supply chain [89].

4.2. Practical Implications

The main challenge faced in this on-field study was the climatic conditions, characterized by high average temperatures and low precipitation, which affected camelina's and barley's yield. Nevertheless, the organic fertilizers achieved a positive response to camelina's growth and yield components.

This study also revealed the increasing trend of soil heavy metal content when applying organic fertilizers. This aspect underlines the importance of adopting adequate agronomic management practices. The implementation of the best management practices is recommended, which would reduce environmental impacts due to crop production. Additionally, the present study has carried out a life cycle assessment on a small scale. Nevertheless, it has been useful to identify the main hotspots of this crop rotation fertilized with composted sludge and dewatered sludge. The results revealed that the transport of organic fertilizers to the experimental field and the fertilization process were the main contributors to the environmental impact categories studied. Therefore, reducing distances between the location dewatering and compositing sites and the field, as well as optimizing fertilization rates, could improve the overall environmental performance of the agricultural system presented in this paper.

Further research could be directed to determine the long-term application of both organic fertilizers, dewatered sludge, and composted sludge. In addition, the application of these fertilizers with different camelina rotation systems could provide information on the best camelina configuration obtaining the highest yields.

5. Conclusions

This research has highlighted that camelina can be cultivated as part of a crop rotation applying organic fertilizers (dewatered sludge and composted sludge). Although climatic conditions (relatively high average temperatures and low precipitation) affected the yield of camelina, the overall yields obtained (from 0.9 to 1.4 t ha^{-1}) resembled those obtained under Mediterranean conditions. In this case, barley's yield was severely affected by climatic conditions reducing this crop's yield to values between 1.1 and 1.5 t ha^{-1}. Despite the undesirable weather limitations, camelina's yield components and seed quality showed, to some extent, a positive response to organic fertilization. The fatty acid profile concurs well with previous findings in the literature. In addition, the correlation between the protein and fat content with respect to fertilization has been shown, highlighting the potential use of camelina as animal feed. Regarding soil effects, the initial soil presented good fertility and there was no nutrient depletion in the soil at the end of the experimental study for none of the three treatments. Although heavy metals' concentration tended to increase with respect to the unfertilized control, the critical levels of heavy metals in soils established by the Spanish government were not exceeded. The life cycle assessment identified the processes of fertilization and transport as the main contributors to the environmental impact categories analyzed.

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Appendix A

Table A1. Data inventory for crop rotation camelina-barley-camelina with organic fertilizations (composted sludge and dewatered sludge).

Input	Unit	Data
Crop yield *	kg ha^{-1}	-
Tillage		
Chiselling	ha	0.018
Ploughing	ha	0.018
Organic Fertilization **		
Composted sewage sludge	t ha^{-1}	15
Dewatered sewage sludge	t ha^{-1}	35
Transport from sewage sludge site to field	km	110
Sowing		
Camelina seed rate	kg ha^{-1}	8
Barley seed rate	kg ha^{-1}	200
Herbicide	L ha^{-1}	2
Sowing	ha	0.018
Harvest	ha	0.018

* Individual yields are summarized in Table 2. ** Composted and dewatered sludge were not applied in the same plots, only one organic fertilizer was used for each experimental plot.

Appendix B

Table A2. Ecoinvent inventory of adapted processes for each season and organic fertilization with composted sludge and dewatered sludge.

Field Operation	Date Performed	Process	Ecoinvent Process
Soil Preparation and Tillage	October	Chiselling	Tillage, cultivating, chiselling {CH} ∣ processing ∣ Alloc Def, U
	October	Ploughing	Tillage, ploughing {CH} ∣ processing ∣ Alloc Def, S
Organic fertilization	October	Transport of organic fertilizers	Transport, tractor and trailer, agricultural {RoW} ∣ processing ∣ Alloc Def, U
		Composted Organic fertilizer	Biowaste {RoW} ∣ treatment of, composting ∣ Alloc Rec, U
		Dewatered Organic fertilizer	Poultry manure, fresh {CH} ∣ treatment of poultry manure, drying, pelleting ∣ Alloc Def, U
		Organic fertilization	Solid manure loading and spreading, by hydraulic loader and spreader {RoW} ∣ processing ∣ Alloc Def, S

Table A2. *Cont.*

Field Operation	Date Performed	Process	Ecoinvent Process
Seeding	November	Sowing	Sowing {RoW} | processing | Alloc Def, U
		Camelina	Rape seed, Swiss integrated production {CH} | rape seed production, Swiss integrated production, intensive | Alloc Def, U
		Barley	Barley seed, for sowing {GLO} | production | Alloc Def, S
Harvesting	June	Harvest	Combine harvesting {RoW} | processing | Alloc Def, U

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