

1 Life Cycle Assessment of the Spanish virgin olive oil 2 production: a case study for Andalusian region

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10 11 **ABSTRACT**

12 Spain is the producer of an average of about 45% of olive oil in the world, with more than
13 80% of its agricultural area dedicated to this tree crop. The goal of this study is to assess
14 the environmental impact of the virgin olive oils production in Spain, attending to the
15 farming and industrial phases. In order to achieve this aim, a Life Cycle Assessment
16 (LCA) is conducted for 5 harvests in approximately 4.000 ha of olive grove in Jaen, the
17 greatest producer of Spain. The type of olive grove analyzed is representative for Spain:
18 conventional (non-organic), with a medium-low slope, extensive (100-150 trees per ha)
19 and about 40% of them counting with an irrigation system. The functional unit chosen for
20 the comparative analysis is 1 kg of unpacked virgin olive oils under a perspective “from
21 cradle to gate”. One of the most representative categories, climate change, places the
22 average environmental impact in 2.43 kg of CO₂ equivalent, while the range is between
23 1.93 and 3.00 depending on the harvest. Huge differences between values are observed
24 in the farming phase and they are mostly caused by the virgin olive oils yield of every
25 harvest, being the most impactful the worst harvest and vice versa. There is considered
26 that to this whole value corresponds a reduction of about 45% of the total by long-term

1 carbon sequestration in soil. The impact hotspots detected in the farming phase, in terms
2 of climate change potential, are the categories of plant protection products and
3 herbicides (24.11% of the average whole value) and fertilizers (20.01%). However, the
4 environmental impact of the industrial phase is relatively constant, with a value of 0.547-
5 0.554 kg of CO₂ equivalent, of which 80.74% is caused by pomace treatment, that
6 translated to the average whole value, represents the 18.56%.

7 **Keywords:** Life Cycle Assessment; Life Cycle Inventory; Virgin Olive Oil; Environmental
8 Impacts; GHG emissions.

9 1. Introduction

10 Europe is the first producer, exporter and consumer of olive oil worldwide (holds a 66%
11 share of the global consumption). In fact, world olive oil production reached an average
12 of 2.86 million tons in the period between 2005/06 and 2017/18, and 71.1% of it was
13 produced in the European Union (EU). In terms of production, three Mediterranean
14 countries cover almost the entire EU production of olive oil, with 2 million tons
15 approximately (94.23% of EU olive oil production in the period 2015/20): Spain, Italy and
16 Greece, with 63.14%, 17.34% and 13.75% of the EU production respectively (European
17 Commission, 2020; International Olive Oil Council, 2019a; Mili and Bouhaddane, 2019).
18 Different issues related to the environmental impact of olive oil production have reached
19 significant institutional and scientific momentum for over a decade (Beaufoy, 2000;
20 Giovenzana et al., 2019; Souilem et al., 2017). In particular, a tool for obtain objective
21 values of the environmental impact produced by the life cycle of a product is the Life
22 Cycle Assessment (LCA) (Curran, 1996), and the olive oil sector analyzed through LCA
23 is becoming increasingly important (Bantias et al., 2017; Espadas-Aldana et al., 2019;
24 Salomone et al., 2015; Salomone and Ioppolo, 2012).

25

26 LCA in the olive oil production sector has been traditionally based on ISO 14040 and
27 ISO 14044 standards. In 2014, following with the development of the environmental

1 footprint framework, the EC launched 11 pilot projects for the elaboration of Product
2 Environmental Footprint Category Rules (PEFCRs) for different consumption products,
3 including olive oil (Benini et al., 2014; Russo et al., 2016).

4 For over 10 years, the olive oil sector has been extensively studied through LCA to
5 identify environmental hotspots and to propose recommendations to limit environmental
6 impacts (Espadas-Aldana et al., 2019). In that line, the most of the studies of LCA in olive
7 groves have been studied in Italy (Rinaldi et al., 2014; Salomone and Ioppolo, 2012).

8 Only few studies have focused their analysis of the environmental impact of olive oil
9 production in Spain. [Romero-Gómez et al. \(2017\)](#) carried out a comparative analysis of
10 the environmental impacts of different olive growing systems existing in Spain (traditional
11 systems, intensive and super-intensive). According to these authors, optimization of
12 fertilization should be the first priority to optimize olive growing. The results showed that
13 dryland organic farming practices are dominant in the cases studied, showing a low use
14 of chemical fertilizers, pesticides and herbicides, low mechanization, bulk packaging and
15 an efficient waste management. Recently, [Navarro et al. \(2018\)](#) analyzed the contribution
16 of the normative changes in packaging olive oil in Spain using LCA methodology, taking
17 average values from technical Spanish information from the years 2000 and 2006. [At the
18 same time, Parascanu et al. \(2018b, 2018a\)](#) performed an LCA of olive pomace
19 valorization through different biomass conversion technologies. The LCA elaborated was
20 based in the data collected from an olive oil mill (OOM) in Toledo (South of Madrid,
21 Spain). From environmental point of view, these theoretical studies were carried out for
22 the olive oil extraction process and the olive pomace valorization. Specifically, in
23 Andalusia, the cradle of olive oil production, Dios-Palomares Rafaela and Martínez-Paz
24 (2011), and Gómez-Limón et al. (2012) applied the Data Envelopment Analysis (DEA)
25 techniques to achieve an environmental approach to olive oil industry and farms
26 respectively.

27 This [study](#) covers the farming phase and the industrial phase, integrated by the
28 extraction of Virgin Olive Oils (VOOs) and the valorization of pomace as the main residue

1 of the olive oil supply chain (European Commission, 2008). This application is carried
2 out in the most representative geographical area worldwide in the production of olive oil,
3 the province of Jaen, in Spain. Consequently, the following is a brief description of some
4 of studies selected for a specific comparative analysis of the results. The main reasons
5 for this selection are, firstly, that these studies apply LCA to the olive grove "from cradle
6 to gate" as this paper do. Secondly, because Italy and Greece are the second and third
7 countries, respectively, with the highest world production of olive oil, after Spain (see
8 "Case study"). In this way, a comparative analysis can be carried out with different cases
9 of the main olive oil producers worldwide. It is important to point out the different
10 processes of olive oil production between countries. In this sense, Spain mainly has a
11 centralized model, with very large OOMs that produce a lot of olive oil from many farmers.
12 On the other hand, Italy, Greece or Tunisia, for example, have a model distributed in
13 smaller OOMs that individually produces less olive oil ([Espadas-Aldana et al., 2019](#);
14 [International Olive Oil Council, 2020](#); [Valta et al., 2015](#)).

15 The study conducted by Proietti et al. (2017) consist in a multidisciplinary study about
16 the Carbon Footprint (CF) of Extra Virgin Olive Oil (EVOO) (European Commission,
17 2008) in Italy. This study aims to promote process innovations by implementing eco-
18 friendly techniques and technologies along a more sustainable value chain. LCA
19 approach was used to quantify the environmental impacts during the entire life cycle,
20 from olive cultivation to transformation processes and packaging. [In another study,](#)
21 [Pattara et al. \(2016\) analyzed the CF of the production of olive oil in Abruzzo \(Italy\). It](#)
22 [was focused in the quantification of the greenhouse gas \(GHG\) emissions for different](#)
23 [cultivation crops and OOMs \(three cooperative and two private\), identifying the drivers](#)
24 [behind these emissions.](#) The study carried out by Avraamides and Fatta (2008) applied
25 a "Cradle to gate" LCA to evaluate the consumption of raw materials and emissions of
26 pollutants from olive oil production in Lythrodontas, a region of Cyprus. It was studied in
27 order to identify the processes which give rise to the most significant environmental
28 burdens. Other studies, as Rinaldi et al. (2014), have concentrated on evaluate the

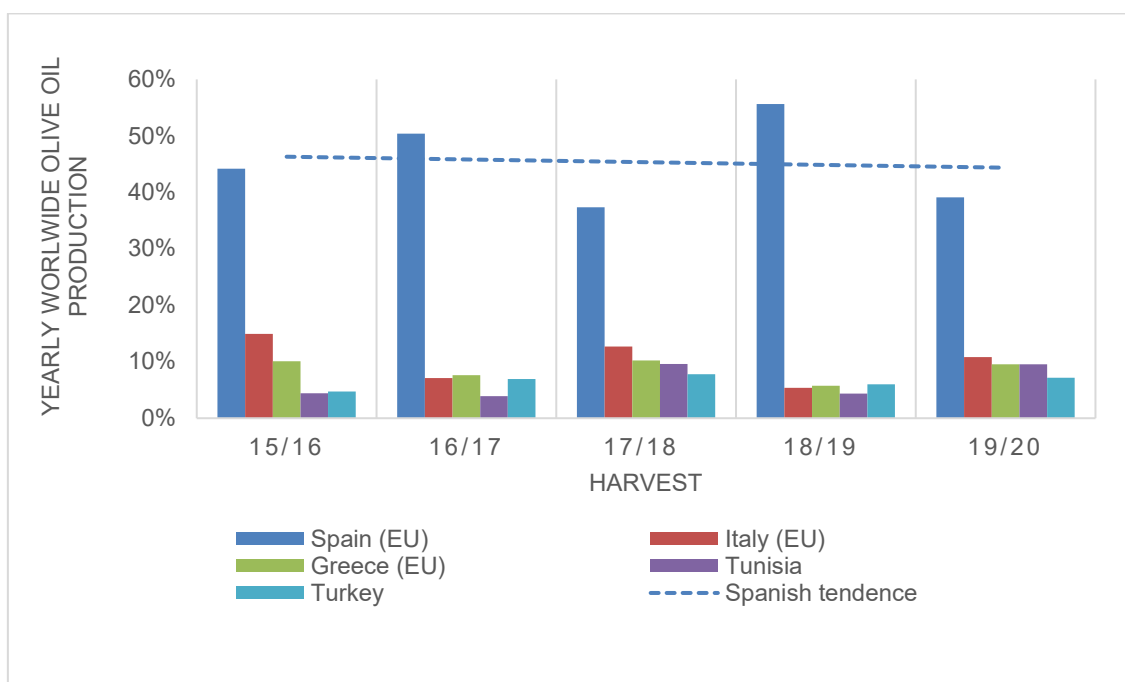
1 cradle to grave CF and energy footprint analysis of EVOO. LCA methodology was
2 employed to quantify the environmental impact of 1L of EVOO produced in the Province
3 of Perugia (Italy) and consumed in the principal importing countries. Results indicated
4 that EVOO distribution was the largest relative contributor to carbon and environmental
5 footprints. Finally, recent studies realized a review of LCA research on olive oil
6 production (Espadas-Aldana et al., 2019) [that represents the current theoretical](#)
7 [framework](#). In detail, the analysis was conducted on 23 publications and 2 review papers
8 between 2008 and 2018, including articles based on six European projects. This review
9 highlights that the environmental hotspots are generally agriculture practices, waste
10 treatment and distribution activities. [It reflects that the study over this topic in Spain has](#)
11 [a relative low representation \(5 studies with different specific approaches\) in scientific](#)
12 [literature, despite being the most important producer in the world.](#)

13 In conclusion, although several relevant papers and research projects studied LCA in
14 different phases and levels of the olive oil value chain, most of them focus on the
15 environmental analysis of smaller and different areas of olive groves than those
16 proposed here. On the contrary, this study uses a more global approach, integrating the
17 two main phases of the olive oil production, with the particularities of the most
18 representative case study in Spain. It is remarkable that this analysis is carried out in the
19 geographical area with the highest concentration of olive groves, OOMs and pomace oil
20 mills in the world.

21 In view of that, the main goal of this study is to obtain reference values of the
22 environmental impact in the farming and industrial phases of the VOOs production in
23 Jaen. This province has a strong influence in the olive oil industry and this study aims to
24 provide useful information in order to identify the processes that give rise to the most
25 significant environmental problems. This information will be determinant for taking
26 strategic decisions intended to improve and optimize the olive oil value chain.

27 **2. Case study: Jaen as a leading territory for olive oil production in Spain**

1 Spain produces an average of 1,395 thousand tons of olive oil per year, considering
 2 harvests from 15/16 to 19/20, keeping its influence in the world market with an average
 3 participation rate of 45.07% for that period. As shown in Fig. 1, Spain sustain a
 4 permanence tendency in the first position of market rate in the world, with a minimum of
 5 37.25% in the harvest 17/18 and a maximum of 55.63% in the harvest 18/19.



6
 7 **Fig. 1.** Worldwide market rate of the top olive oil producers from the harvest 15/16 to 19/20
 8 (International Olive Oil Council, 2019).

9 Spain is the country of the EU with more area dedicated to olive growing, with 55% of
 10 the total in the world (Eurostat, 2020). According to Ministry of Agriculture Fisheries and
 11 Food (2020), the olive grove represents 83.83% of the total agricultural area in Spain.
 12 Andalusia registers a total of 1,633,215 ha of this crop, of which 1,538,263 are for olive
 13 oil production. In the last decade, this territory has increased by more than 93,000 ha,
 14 most of which are located in the province of Jaen. In fact, 38.61% of the olive groves of
 15 Andalusia are concentrated in the province of Jaen, followed far behind by Córdoba
 16 (23.28%) and Granada (13.11%) (Table 1). The olive oil production in the Andalusian
 17 region is over 80% of the total Spanish production for the last five harvests. In the case

1 of Jaen, it represents an average production of 36% (Ministry of Agriculture Fisheries
2 and Food, 2020).

3 **Table 1**

4 Olive grove surface and production of olive oil in Andalusia (Ministry of Agriculture Fisheries and Food,
5 2020).

6

	Olive grove Surface (harvest 19/20)		Olive oil production (average from 15/16 to 19/20)	
	Ha	%	Tm	Spanish rate (%)
Jaen	586,921	38.15%	508,380	36.69%
Cordoba	360,880	23.46%	278,889	20.13%
Granada	203,100	13.20%	118,046	8.52%
Seville	174,128	11.32%	111,455	8.04%
Malaga	130,951	8.51%	68,731	4.96%
Rest of Andalusia	738,108	48%	31,634	2.28%
Total in Andalusia	1,538,263	100.00%	1,117,136	80.63%

7

8 The olive oil supply chain in Spain generates four types of residue. Three of them
9 (pomace, stones or pits and leaves) are generated during the olive oil production
10 process, characterized by the 2-phase extraction process in Spain; while the rest is
11 generated in the field as a result of annual or biannual pruning of the olive trees.

12 Summarizing the principal characteristics of olive cultivation in Jaen for the last five
13 harvests, these can be expressed as follows: 43.20% irrigated – 56.80% dryland,
14 conventional (non-organic), with a medium-low slope and extensive (100-150 trees per
15 ha). The industrial phase takes place in an OOM with a 2-phase extraction process, it
16 has an olive oil yield from 10% to 22%. The residues generated in the farming phase that
17 come from the pruning are chopped up and reabsorbed by the field, while olive stones,
18 pomace and leaves obtained in the industrial phase are conveniently transported for their
19 treatment and use out of the OOM.

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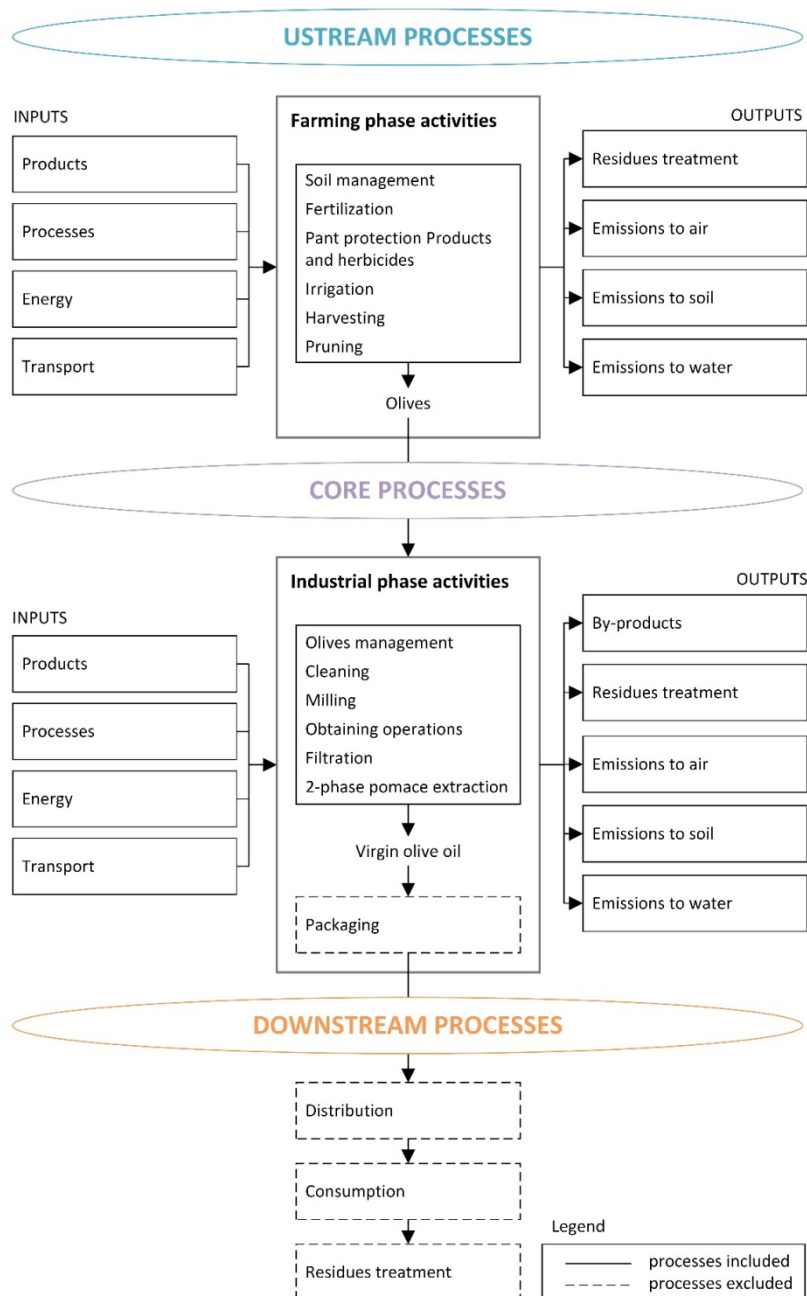
21 **3. Methodology**

1 The methodological approach of this study was divided into four basic stages. In a first
2 step, the functional unit (FU) and system boundaries are exposed. Secondly, after
3 describing the sources and methods used for the collection of data and assumptions, a
4 detailed description of the life cycle inventory of VOOs production in Jaen is presented.
5 In third place, it is shown the information related to the LCA method. The section is
6 concluded by defining the calculation method of the carbon sequestration due to long-
7 term carbon storage in the soil of olive-groves.

8 **3.1. Functional unit and system boundaries**

9 The FU chosen is 1 kg of unpacked VOOs at the point of production (OOM). In previous
10 LCA case studies for the evaluation of the impacts of olive and olive oil production, the
11 FU were related to 1L, 0.75L, 1 ton of olive oil or 1 ton of olives (Belaud and Clarens,
12 2012). Although the most common in these studies is to use the liter as the FU (Proietti
13 et al., 2017; Rinaldi et al., 2014; Tsarouhas et al., 2015), in this case study, the FU has
14 been defined as a unit of mass, in agreement with other authors (El Hanandeh and
15 Gharaibeh, 2016). In this regard, it should be noted that when it concerns to olive oil at
16 a production level, measurements are made in mass units, as opposed to the final
17 product intended for consumption, which is purchased by liters.

18 The system boundaries are based in an LCA “cradle to gate” (Schau et al., 2016), it
19 studies the products, processes, energy, and transport necessary to obtain VOOs as
20 well as the waste treatment and emissions involved in the production phases. Firstly, the
21 study analyses the upstream processes: inputs and outputs of the system in the farming
22 phase. Secondly, the analysis goes deeper into the core processes: inputs and outputs
23 in the transformation processes of the industrial phase, considering the waste treatment
24 and by-product separation until this point, but not packaging, as it is not relevant for
25 production. Finally, the downstream processes match with distribution, consumption,
26 waste treatment after use, and their respective inputs and outputs, these processes are
27 not part of the study as they are beyond the scope of a “cradle to gate” analysis (Fig. 2).



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Fig. 2. Phases of the virgin olive oil life cycle from cradle to gate.

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3.2. Life cycle inventory

4

To conduct an in-depth analysis of the qualitative and quantitative processes to obtain

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VOOs in the province of Jaen, it was necessary to collect data from the different

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production phases of olive oil (farming phase and industrial phase). These data were

7

obtained from: (1) the survey sent to the olive farmers and OOMs located in the province

8

of Jaen, (2) official documents such as the PEFCR and agriculture reports from the

1 government of Spain, (3) scientific literature related to the production of olives and olive
2 oil, and (4) the product datasheets of the consumed substances. The survey was the
3 principal source of information, with the completion of qualitative and quantitative
4 questionnaires, by face-to-face interviews with farmers, OOM owners and supervisors.

5 Most of the primary data comes from a survey of farmers with different sized agricultural
6 holdings older than 25 years and persons in charge of OOMs, representing the
7 characteristics of VOO production in Jaen for the harvests 2015-16 to 2019-20. The
8 secondary data comes from scientific literature or official sources, with the PEFCR
9 (Schau et al., 2016) as the principal reference. The questionnaires were pre-tested to
10 guarantee the validity of their content by agricultural technicians with experience in olive
11 oil farms and by academics with research experience in this field.

12 Consequently, two surveys were conducted, one to evaluate the farming phase, sent to
13 the farmers, and the other to evaluate the industrial phase, carried out by the OOMs.
14 Both questionnaires were drawn up following the PEFCR indications, including therefore
15 qualitative and quantitative information on farm or OOM characteristics, processes, input
16 and output products, energy and waste (Schau et al., 2016). The questionnaires were
17 open-ended to elicit critical observations that cannot be obtained by solely quantitative
18 surveys. The surveys were carried out face to face, by telephone and in certain cases
19 visiting their crops and facilities to check the information given, following the example of
20 Rajaeifar et al. (2014) and Guarino et al. (2019).

21 A total of thirty-one farmers and twelve OOMs were surveyed, located in different areas
22 of the province of Jaen. The surveys carried out by farmers include the areas and annual
23 production of crops in accordance with Regulation (EC) 543 / 2009 (Ministry of
24 Agriculture, Fisheries and Food 2020, 2019, 2018, 2017, 2016). It is worth noting that
25 the area covered by the surveys is 3,920 ha of olive groves, and the average annual
26 production of VOOs for the period studied is 7,269 tons. The study collected data from

1 farmers with a similar type, systems, densities and conditions of olive grove to the one
2 that is most typical of Jaen (extensive, dryland or irrigated, with a density of 100-150
3 trees/ha and with a low or medium gradient). Data from OOMs were obtained from them
4 with a two-phase extraction process: different ownership structure and sizes. All this
5 allows us to say that the study is representative of the target populations.

6 Having obtained input and output data from five harvests, average values were
7 calculated for each respondent. These values are in relation to the surface of olive
8 cultivation, the mass of olives harvested or the mass of olive oil obtained, as appropriate.
9 A statistical treatment was conducted to discard false or non-representative values
10 (those that are above or below twice the standard deviation), providing a confidence
11 interval of 95%.

12 It should be noted that these quantities do not present significant changes from one year
13 to another because the techniques and activities, both agricultural and industrial, remain
14 practically unchanged over the years. Consequently, the average values represent the
15 general behavior in the phases analyzed.

16 For its part, the olive yield (farming phase) can fluctuate significantly from year to year
17 because of the changing weather conditions and the biological nature of olive groves,
18 and this is a determining factor in the environmental impact of the FU (Pattara et al.,
19 2016; Rajaeifar et al., 2014; Rinaldi et al., 2014).

20 This study, in view of its large scope, was also supported by the yearly government data,
21 that provides information of the olive tree crop surface area in production, olives and
22 VOOs production by provinces (Ministry of Agriculture, Fisheries and Food 2020, 2019,
23 2018, 2017, 2016). Thus, the yearly olive yield faithfully represents the entire field of
24 study, the province of Jaen. A representative value for the whole period of study has also
25 been calculated, resulting from the average of the yearly values weighted by the yearly
26 VOOs production (Table 2).

1 **Table 2**

2 Cases studied: harvests 15/16 to 19/20 in the province of Jaen (Ministry of Agriculture, Fisheries
3 and Food, 2019, 2018, 2017, 2016, 2015), (IDAE, 2019), (Spanish meteorological agency, 2020) and
4 (Olimerca, 2020).

Harvest	15/16	16/17	17/18	18/19	19/20	Weighted average	Source
Tree crop density (trees/ha)	100 - 150						Survey
Type of crop	Traditional						
Irrigated area (%)	46.4	46.3	42.9	40.9	39.5	43.2	
Olive yield (kg/ha)	4,110	4,179	3,050	5,491	3,592	4,086	Government of Spain
VOOs yield (kg/ha)	912.75	879.06	661.53	1,138.85	778.17	874.35	
Annual precipitation (l/mm ²)	297.6	372.9	319.5	686.9	389.2	417.7	
VOOs price (€/kg)	3.206	3.538	2.998	2.324	1.943	2.655	Survey - Olimerca
Crude pomace price (€/kg)	1.429	1.706	1.405	0.838	0.677	1.249	Survey - Olimerca
Exhausted pomace price (€/kg)	0.025	0.015	0.014	0.015	0.017	0,017	Survey - IDAE
Olive stones price (€/kg)	0.065	0.063	0.073	0.056	0.06	0.063	Survey
Extraction process	2-phase						Survey

5 The characteristics of the processes analyzed in the farming phase are:

- 6 – Land management. It consists in the use of tractors and other farm machinery
7 with its respective fuel consumption, to do the work in the field once a year. The
8 tasks defined are harrowing (using a spring tine harrow), ploughing and tillage by
9 rotary cultivator. The occupation of the land as a permanent crop is included in
10 this category.
- 11 – Irrigating. This process only occurs in irrigated crops. It includes a pump system
12 with polyethylene and PVC pipes laid in the ground, which conduct groundwater
13 to the olive trees. Beside water, it requires an electric consumption that generally
14 comes from the Spanish electric grid. Some crops, however, have a diesel-feed
15 or photovoltaic system, but the impact on overall inputs is negligible. Dryland
16 systems only take rainwater.
- 17 – Fertilizers. A wide variety of specialized products is applied to the olive grove.
18 They can be poured directly into the soil by a fertilizer broadcaster, usually once

1 a year, or mixed into the irrigation water. They are mainly phosphorus, nitrogen
2 and potassium-based. However, there are some products based on other
3 compounds, such as borax, ammonium sulfate, potassium nitrate, urea,
4 ammonium phosphate, potassium chloride, potassium sulfate, or phosphoric
5 acid. They have been quantified in the survey and collected in the field inventory.

6 – Plant protection products (PPP) and herbicides. In non-organic tree crops (the
7 most frequent in Jaen), the use of fungicides, pesticides and herbicides to protect
8 olive production is common. The main substances used for these treatments are
9 organophosphorous compounds , glyphosates and pyrethroid-compounds. Other
10 minority substances mentioned in the survey are also included in the inventory;
11 they are generic herbicides, phenylurea herbicides, copper oxide, chloroacetic
12 acid, formic acid, sulphonylurea compounds, diphenylether compounds and boric
13 oxide. These products are applied directly to the soil three times a year on
14 average, mixed in the irrigation water or using a field sprayer (usually for crops
15 bigger than 15-20 hectares).

16 – Harvesting. The most widespread method of obtaining olives from the trees is by
17 shaking them with specialized machinery and collecting the olives with a
18 polyethylene net placed on the surface under the tree crown. Consecutively, nets
19 are collected with the help of machinery or, as has recently become usual, with
20 the use of quads. A tractor with a trailer loaded with 400 to 700 kg of olives is
21 used to transport the olives to the OOM (which is usually located within a radius
22 of 20 km) and returns to the crop empty or with waste wood and leaves.

23 – Cutting. This study, as a PEFCR, considers the cutting process part of the
24 harvesting. It records in the inventory machinery such as chainsaws for cutting
25 tree branches, oil lubricant and fuel consumed by them. Additionally, a branch
26 windrower cuts the low branches to add them to the rest of the organic material.
27 This process is generally carried out once a year after the harvesting for irrigated
28 systems, and every two years in the case of dryland crops.

1 – Pruning. Traditionally, the wood from the cutting process was burned directly in
2 the field, but today this practice is banned. Currently, organic material generated
3 in the cutting process is displaced in lines between the trees to be crushed by a
4 wood shredder pulled by a tractor. The resulting organic matter reaches a value
5 of 2,000 – 2,500 kgs/ha (de Mena et al., 2017; Malheiro et al., 2013) and lies on
6 the ground to be partially absorbed as natural fertilization for the crop.

7 Despite the information obtained, there were limitations on the data collection due to a
8 lack of information or its low representativeness. For these reasons, it was considered
9 appropriate to make the following assumptions:

10 – Olive planting processes. Olive trees over 25 years of age (which is the case of
11 this study) are not considered in the inventory because they do not cause an
12 environmental impact (Salomone et al., 2015; Salomone and Ioppolo, 2012).

13 – Fertilizers, PPP and herbicides. The information collected with respect to
14 fertilizers, PPP and herbicides has been broken down into primary elements or
15 chemical compounds in order to use the same criteria in their quantification.
16 These products are mandatorily contained in returnable polyethylene bottles and
17 polypropylene bags, as shown in the inventory.

18 – Land use change. The olive growing system is consolidated in Jaen and the use
19 of the land has not changed for more than 100 years, so the land use is
20 considered a permanent crop occupation.

21 – Burning pruned waste. The burning of organic olive residues from pruning is
22 prohibited but it still continues in a decreasing number of cases. The carbon and
23 the corresponding carbon dioxide emitted by this activity are considered to belong
24 to the short carbon cycle and are therefore not counted in the LCA (The British
25 Standards Institution, 2011).

26 – Transport distances. The transport distance of the products consumed in the
27 farms and OOMs of Jaen takes a value of 300 km. This distance is an

1 approximate distance from this province to the main industrial cities (Seville and
 2 Madrid) and ports of Andalusia such as Algeciras, Motril and Almeria. This
 3 transport is assumed to be carried out using a 7.5 to 16 metric ton diesel-fueled
 4 truck, in accordance with the European EURO 5 emission standards. Once in the
 5 province of Jaen, it is assumed that a diesel-fueled tractor completes the
 6 transportation within the olive grove and between the supply depot, the olive
 7 grove and the OOM.

8 – Infrastructure and related energy consumption. Infrastructure such as buildings
 9 or warehouses and their energy consumption is negligible for the study of the
 10 production of VOOs in LCA (Salomone et al., 2015).

11 – Emissions. Emissions to air, water or soil produced by agricultural processes
 12 were factored in, keeping the same relation to products and activities set by the
 13 PEFCR.

14 The main processes, inputs and outputs of the farming phase are shown in Table 3.

15 **Table 3**

16 Life cycle inventory of olives production in Jaen.

Inventory data per ha				
Process	Activity / Product	Unit	Quantity	Data source
Harvesting	Petrol	kg	12.936	Survey
	Transport with tractor and trailer	tkm	30.185	Survey
	Polyethylene	kg	1.330	Survey
Cutting	Petrol	kg	1.636	Survey
	Lubricating oil	kg	0.531	Survey
Irrigating	Electricity	kwh	298.536	Survey
	Water	m3	303.438	Survey
	Polyethylene	kg	2.415	Survey
	Polyvinyl chloride	kg	1.222	Survey
PPP & Herbicides	Application of PPP	ha	2.272	Survey
	Water	m3	2.272	Survey / PEFCR
	Transport with tractor and trailer	tkm	0.004	Survey
	Glyphosate	kg	1.625	Survey / Product datasheets
	Copper oxide	kg	1.916	Survey / Product datasheets
	Phenylurea herbicides	kg	2.317	Survey / Product datasheets
	Other PPP & Herbicides	kg	0.501	Survey / Product datasheets
	Polypropylene	kg	1.936	Survey
	Polyethylene	kg	78.593	Survey
	Transport with lorry 7.5-16 ton	tkm	26.066	Survey
Soil Management	Harrowing	ha	1.000	Survey

	Ploughing	ha	1.000	Survey
	Tillage	ha	1.000	Survey
	Transport with lorry 7.5-16 ton	tkm	0.081	PEFCR
	Occupation	ha	1.000	PEFCR
Pruning	Transport with tractor and trailer	tkm	0.131	Survey
	Agricultural machinery	kg	0.070	PEFCR
Fertilizers	Fertilizing by broadcaster	ha	0.040	PEFCR
	Nitrogen fertilizer	kg	24.305	Survey / Product datasheets
	Potassium fertilizer	kg	10.828	Survey / Product datasheets
	Phosphate fertilizer	kg	10.828	Survey / Product datasheets
	Ammonium sulfate	kg	31.370	Survey / Product datasheets
	Potassium nitrate	kg	7.664	Survey / Product datasheets
	Urea	kg	12.972	Survey / Product datasheets
	Ammonium phosphate	kg	4.617	Survey / Product datasheets
	Potassium chloride	kg	4.798	Survey / Product datasheets
	Potassium sulfate	kg	1.123	Survey / Product datasheets
	Phosphoric acid	kg	1.298	Survey / Product datasheets
	Other fertilizers	kg	0.029	Survey / Product datasheets
	Polypropylene	kg	0.132	Survey
	Polyethylene	kg	5.349	Survey
	Transport with lorry 7.5-16 ton	tkm	48.154	Survey
	Transport with tractor and trailer	tkm	0.792	Survey

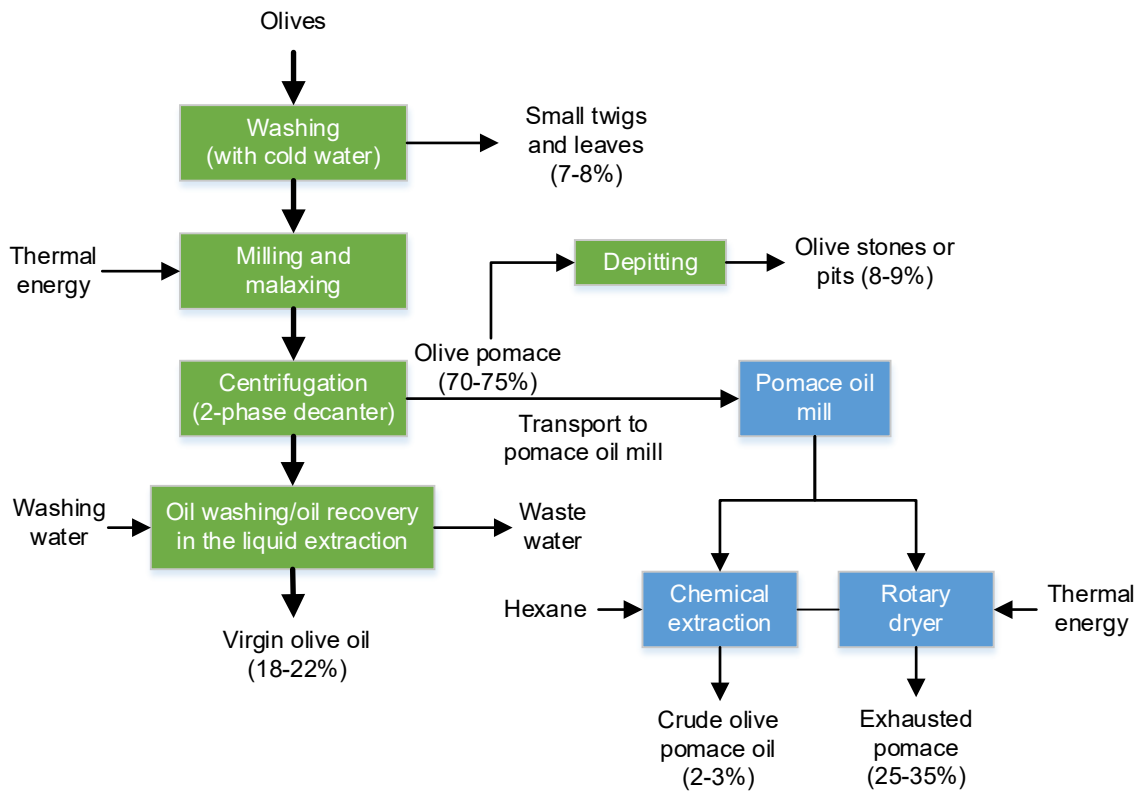
1

2

1 The processes of the industrial phase are shown in Fig. 3 and their characteristics are
2 described below:

- 3 – Washing. When the olives are received at the OOM, it is necessary to separate
4 the olives from all the small branches, twigs, leaves and dust, using water. This
5 produces a natural waste that farmers usually return to their olive crop. In the
6 process, the water consumed is also channeled to the municipal treatment plant.
- 7 – Milling and malaxing. The olives go through this process to be transformed into
8 an olive paste ready for the extraction. To facilitate this work, it is necessary to
9 raise the temperature of the product.
- 10 – Centrifugation. The two-phase decanter is the main process for transforming
11 olives into olive oil. It requires the highest energy consumption in the industrial
12 phase, as well as an additional use of water and heat. The centrifugation
13 facilitates the separation of a residual paste composed by organic matter that will
14 not be converted into olive oil.
- 15 – Extraction of olive pomace and depitting. From the residua paste generated, the
16 OOM usually separates the olive stone and the pomace with a depitting machine
17 to sell them separately. The olive stone is a by-product generated in this process,
18 valuable in the biomass market, and the olive pomace is a waste product that, in
19 Spain, must be processed by law, in spite of its low economic value.
- 20 – Pomace drying and chemical extraction. The pomace resulting from an OOM is
21 transported to a pomace oil mill to extract two by-products: the main by-product
22 is crude pomace, a raw material for the olive pomace oil industry, and exhausted
23 pomace, which has a lower value than olive stones on the biomass market. The
24 inputs needed to obtain these by-products are electricity, water, hexane and a
25 part of the produced exhausted pomace, which is used for heating in a rotary
26 dryer.

- 1 – Oil washing and recovery in the liquid extraction. In the final process, the olive oil
- 2 is washed with water and the process of obtaining virgin olive oils is complete.



3
4 **Fig. 3.** 2-phase olive oil production system in Spain (Vera et al., 2019).

5 Some assumptions based on PEFCR and data availability have also been made in
6 drawing up the inventory:

- 7 – Transport distances. Following the same reasoning as for the products used in
- 8 the farming phase, it is considered that the chemical products used in the OOM
- 9 are transported from a distance of 300 km. The transport of the pomace from the
- 10 OOM to the pomace oil mill assumes the value considered by the PEFCR. In both
- 11 cases, the mode of transport used is a diesel truck of 7.5 to 16 metric tons,
- 12 according to the European emission standards EURO 5.
- 13 – Infrastructure. The representative value of OOMs per FU is the relation between
- 14 the number of OOMs considered and their production, divided by its lifetime, set
- 15 at 50 years.

- 1 – Emissions. As was done in the farming phase, the emissions to the air, water or
 2 land produced by industrial processes, derived principally from the use of fuel,
 3 are calculated in the same ratio indicated by the PEFCR.
- 4 – Harvested olive residues. The small twigs and leaves resulting from the cleaning
 5 of the harvested olives are gathered together with the help of blowers. The same
 6 farmers that transport the harvested olives to the OOM usually bring them back
 7 to the plantation to chop them up and use the organic material as a fertilizer.
- 8 – Olive stones. From the olive stones produced in the process, about 15% is used
 9 to generate heat, according to Vera et al. (2019). Its combustion generates
 10 emissions to air that produce an additional environmental impact included in the
 11 simulations.
- 12 – Crude pomace extraction. The crude pomace extraction process is part of the
 13 olive oil value chain in Spain, due to the obligation to process the pomace as
 14 waste. Although it is necessary to reflect its environmental impact as part of the
 15 industrial phase, the detailed study of this process is not part of the scope of this
 16 research. Therefore, the generation of pomace per FU is provided by the survey
 17 and its processing is based on the data provided by the PEFCR.

18 The survey provided information of the overall values of inputs and outputs. For this
 19 reason, the different inputs and outputs of the industrial phase are grouped by categories
 20 that constitute the whole transformation process.

21 The main categories, inputs and outputs of the industrial phase are shown in Table 4.

22 **Table 4**

23 Life cycle inventory of VOOs production in Jaen.

Inventory data per 1.000 kg of VOOs				
Process	Activity / Product	Unit	Quantity	Data source
Olive oil extraction	Olives	kg	4,850.872	Survey
	Electricity	kwh	157.250	Survey
	Water	m3	1.828	Survey

	Cellulose fiber	kg	1.127	PEFCR
	Olive stones	kg	62.328	Survey
	Transport with tractor and trailer	tkm	83.545	Survey
	Petrol	kg	0.016	Survey
	Lubricating oil	kg	0.006	Survey
	Cleaning products	kg	0.298	Survey
	Dedicated portion of facilities (average)	u	5.70E-06	Survey
Crude pomace olive oil extraction	Exhausted pomace	kg	658.120	Survey / PEFCR
	Electricity	Kwh	77.039	Survey / PEFCR
	Water	kg	196.387	Survey / PEFCR
	Transport with lorry 16-32 ton	tkm	78.555	Survey / PEFCR
	Hexane	kg	6.131	Survey / PEFCR
	Dedicated portion of facilities (average)	u	8.43E-07	Survey / PEFCR
By-products generation (outputs)	Olive stones	kg	415.522	Survey
	Crude pomace	kg	157.409	Survey / PEFCR
	Exhausted pomace	kg	1,887.692	Survey / PEFCR

1

2 **3.3 Life Cycle Assessment applied to olive oil production**

3 The processed data is operated by the software SimaPro 9.0 (“System for Integrated
4 Environmental Assessment of Products”), which takes representative values of
5 environmental impact from different databases (ecoinvent 3.5, Agri-footprint 4.0, ELCD,
6 Industry data 2.0, Methods) and gives values for the emissions and effluents of the
7 processes. This software creates an environmental model with inputs and outputs based
8 on scientific databases, monitoring and analyzing the processes through the ILCD
9 method, which is quantitative and systematic (Desideri et al., 2014; Proietti et al., 2017).
10 Results are monitored showing the percentage and quantity of environmental impact in
11 different categories for every process, input and output of the FU considered. The
12 method of calculating the environmental impacts in different categories is based on the
13 2011 ILCD Mid-point (CML - Department of Industrial Ecology, 2016).

14 The main product studied and the by-products generated during the studied phases have
15 an economic value and they would receive an allocation of the environmental impact
16 based on these values and the quantity of every product generated (Notarnicola et al.,
17 2015). The waste generated in the studied phases requires a treatment that produces
18 an impact over the phase in which they have been generated. In relation to this, the
19 production of pomace in the two-phase extraction process is considered a waste for the

1 OOM. Moreover, its treatment is obligatory despite the fact that its economic balance
2 could fluctuate between small profits or costs depending on the year. This treatment
3 produces an additional environmental impact on the production of olive oil and the rest
4 of the by-products.

5 The by-products resulting from the core process are those that have an economic value
6 at the point of production: olive stones in the first instance, and, as a result of the pomace
7 treatment, crude olive pomace and exhausted olive pomace. The environmental impact
8 of the processes has been assigned to the products and by-products in proportion to
9 their respective mass and economic value at the point of production according to the
10 following formula:

$$11 \quad EI = (EV \times M) / (\sum_n (EV_n \times M_n) * 100) \quad (1)$$

12 Where *EI* represents the environmental impact (%); *EV* is the economic value per mass
13 unit (€); *M* represents the total mass of the products (kg). The values are obtained for
14 the “*n*” products and by-products considered in the process.

15 The economic values of the main product and by-products generated in the studied
16 processes have followed a strong downward trend in the last four harvests. The main
17 product, VOOs fetched prices in the province of Jaen from 3.54 €/kg for the 2016-
18 2017harvest to 1.94 €/kg for the 2019-2020 harvest, and crude pomace from 1.71 to 0.68
19 €/kg in the same period. The secondary by-products kept their prices between 0.056 and
20 0.073 €/kg in the case of olive stones and between 0.014 and 0.025 €/kg in the case of
21 exhausted pomace.

22 **3.4 Carbon sequestration in olive oil production**

23 In order to determine the long-term carbon sequestered in the soil, it was necessary to
24 identify the production of each biomass waste generated in the olive oil supply chain.
25 They are olive grove pruning during the farming phase, and the small twigs and leaves
26 separated from the olives in the industrial phase (García-Maraver et al., 2012; Vera et

1 al., 2019, 2018b, 2014). The biomass properties are described in Table 5 (de Mena et
 2 al., 2017; Malheiro et al., 2013).

3 **Table 5.** Carbon sequestration parameters.

	Olive grove pruning	Small twigs and leaves
Carbon content (% weight)	47.12	45.71
Moisture (% weight)	38.83	24.4
Iso-humic coefficient (%)	35	20
Total wet matter (kg/ha)	2500	100
Total dry matter (kg/ha)	1529.25	75.6
C in soil (kg/ha)	720.58	34.56
C released as CO ₂ in 100 years (kg/ha)	468.38	27.65
Hummus (kg C/ha)	252.20	6.91
Hummus (kg CO ₂ /ha)	923.07	25.30

4 Once the production of each waste has been determined, it is important to identify the
 5 carbon composition (Garcia-Maraver et al., 2015a), moisture content (Brunori and
 6 Proietti, 2013; Garcia-Maraver et al., 2015b) and iso-humic coefficient (López-Bellido
 7 Garrido, 2017; Sofo et al., 2005). The first two properties are obtained from the elemental
 8 analysis (CHNS) and the rest from the proximate analyses of residues.

9 According to the iso-humic coefficient, 35% of the olive pruning carbon content and 20%
 10 of the small twins and leaves carbon content remain in the soil in the long term. The rest
 11 are released to the atmosphere in the form of CO₂ over a period of 100 years. This
 12 fraction depends on the clay and silt content in the soil and the average annual
 13 temperature. This value is based on the organic carbon content in the first 30 cm of soil
 14 which in turn is obtained from the percentage of organic carbon in the soil (top 30 cm)
 15 and the bulk density. From the application of this fraction, the amount of CO₂ emitted by
 16 the soil per hectare and year is derived (López-Bellido Garrido, 2017).

17 Taking into account these considerations, [it is possible to estimate the total carbon that](#)
 18 [would be sequestered in soil and humus](#) (carbon fixed in soil for more than 500 years
 19 [\(Schau et al., 2016\)](#)). The conversion of 1 g C = 3.66 g CO₂ equivalent was used to
 20 obtain the sequestered CO₂ (Sofo et al., 2005). The CO₂ equivalent derived from long-

1 term carbon sequestration shows the amount of CO₂ that would be retained by the return
 2 of the pruning of olive trees and small twigs and leaves to the soil.

3 **4. Results and discussion**

4 The LCA results for the global impact (farming and industrial phases) of the five harvests
 5 and weighted average (based on yearly olive oil production) are shown in Table 6 for 16
 6 different impact categories, following the FU selected and justified above. As can be
 7 seen, the values of environmental impact change significantly for every harvest. These
 8 variations are mainly due to the different yearly olive yield, since the rest of the variables
 9 are without significant variations. Olive harvests have a high variability between years
 10 due mainly to the different meteorological conditions of each period, in which the annual
 11 precipitation is especially important. These differences can be observed especially for
 12 dryland olive tree groves, which represent around 60% of the total area in Jaen. The
 13 number of square meters needed to produce 1 kg of olives ranges from 1.82 (2018-2019
 14 harvest) to 3.28 (2017-2018 harvest). All agricultural products and processes are carried
 15 out on the cultivation areas in a similar way for every harvest because they depend on
 16 the number of trees. Thus, a low olive yield would be related to the use of more products
 17 and processes for its production, and therefore, more environmental impact per FU.

18 The values for the "climate change impact" category obtain a weighted average value of
 19 2.39 kg CO₂ eq. For the 5 years studied, its value is between 1.93 kg CO₂ eq. (18/19
 20 harvest) and 3 kg CO₂ eq. (17/18 harvest). It should be noted that the lower impact is
 21 consistent with the harvest of greater production of VOOs (664.81 tons in Jaen) while
 22 the value of greater impact (3.00 kg CO₂ eq.) is consistent with the harvest of lower
 23 production (383,302 tons in Jaen).

24 **Table 6**

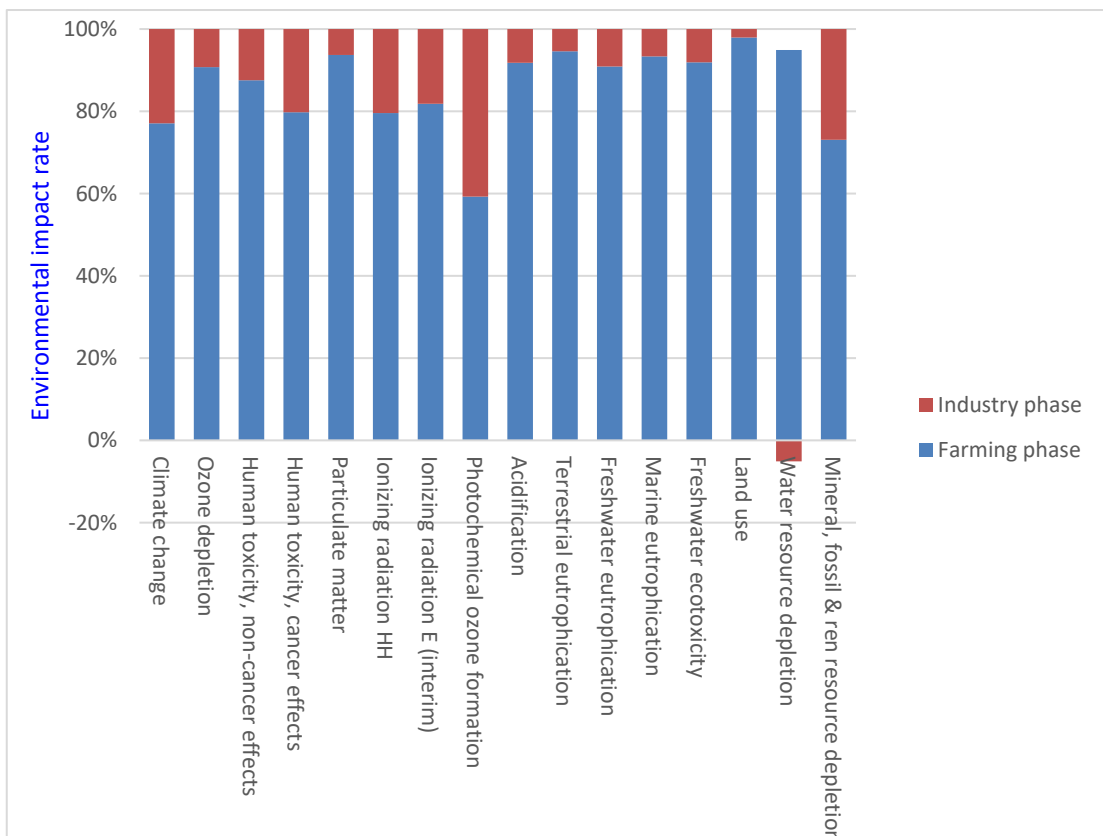
25 Comparative analysis of the LCA (per FU) for five harvests (15/16 to 19/20) in Jaen.

Total impact	Unit	15/16	16/17	17/18	18/19	19/20	Weighted average
--------------	------	-------	-------	-------	-------	-------	------------------

Climate change	kg CO ₂ eq	2.36E+00	2.33E+00	3.00E+00	1.93E+00	2.65E+00	2.39E+00
Ozone depletion	kg CFC-11 eq	1.76E-07	1.73E-07	2.32E-07	1.38E-07	2.01E-07	1.78E-07
Human toxicity, non-cancer effects	CTUh	1.05E-06	1.04E-06	1.37E-06	8.32E-07	1.20E-06	1.06E-06
Human toxicity, cancer effects	CTUh	1.01E-07	9.97E-08	1.29E-07	8.19E-08	1.14E-07	1.02E-07
Particulate matter	kg PM2.5 eq	1.63E-03	1.60E-03	2.16E-03	1.26E-03	1.87E-03	1.65E-03
Ionizing radiation HH	kBq U235 eq	2.46E-01	2.42E-01	3.14E-01	1.99E-01	2.76E-01	2.48E-01
Ionizing radiation E (interim)	CTUe	1.04E-06	1.03E-06	1.34E-06	8.40E-07	1.18E-06	1.05E-06
Photochemical ozone formation	kg NMVOC eq	1.54E-02	1.52E-02	1.86E-02	1.33E-02	1.69E-02	1.55E-02
Acidification	molc H+ eq	1.35E-02	1.32E-02	1.77E-02	1.05E-02	1.54E-02	1.36E-02
Terrestrial eutrophication	molc N eq	5.09E-02	5.00E-02	6.76E-02	3.93E-02	5.83E-02	5.15E-02
Freshwater eutrophication	kg P eq	5.67E-04	5.59E-04	7.47E-04	4.44E-04	6.48E-04	5.74E-04
Marine eutrophication	kg N eq	3.67E-03	3.61E-03	4.86E-03	2.85E-03	4.20E-03	3.71E-03
Freshwater ecotoxicity	CTUe	3.24E+01	3.19E+01	4.28E+01	2.53E+01	3.71E+01	3.28E+01
Land use	kg C deficit	4.80E+01	4.72E+01	6.44E+01	3.67E+01	5.53E+01	4.86E+01
Water resource depletion	m3 water eq	5.22E-02	5.13E-02	7.15E-02	3.89E-02	6.08E-02	5.29E-02
Mineral, fossil & ren resource depletion	kg Sb eq	2.40E-04	2.37E-04	3.01E-04	1.99E-04	2.68E-04	2.43E-04

1

2 As shown in Fig. 4, the distribution of the impact by phases for different categories (in
3 this case for the weighted average) is variable. The farming phase reaches values from
4 59.14% (Photochemical ozone formation) to the whole impact (Water resource
5 depletion), taking the value of 76.99% for climate change. In the category of water
6 resource depletion, it is noteworthy how the industrial phase reduces the impact.



7

1 **Fig. 4.** Distribution of the impact by phases in different categories for the weighted average.

2

3 Fig. 5 shows, for each harvest, the incidence of each phase for climate change category.

4 This data shows that the impact produced by the industrial phase in climate change

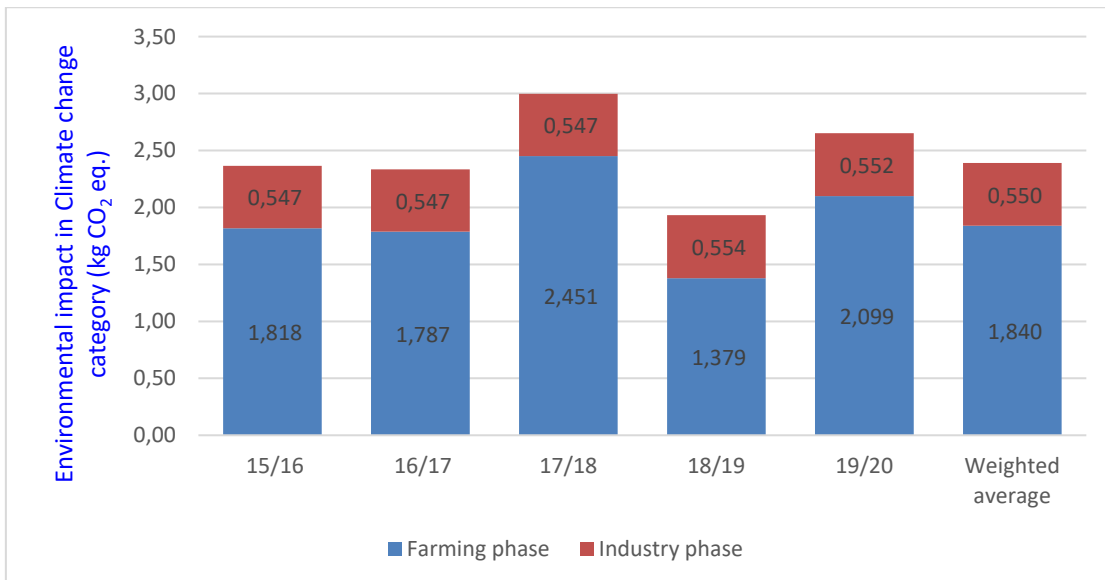
5 remains with a similar value in all the harvests. However, the impact of the farming phase

6 is different for each harvest due to the different yearly olive yield, as described at the

7 beginning of this section. The variability in the farming phase is applicable for each

8 impact category due to the different olive yield between harvests described above.

9



10

11 **Fig. 5.** Phase impact in Climate change category (kg CO₂ eq.).

12

13 The distribution of environmental impact by categories, for the farming and industrial

14 phases, is given in Figs. 6 and 7 respectively. Generally, PPP & herbicides as well as

15 fertilizers are the sub-processes of the farming phase that have the most impact,

16 reaching combined values of between 35% and 65% of the total in this phase for most

17 categories. Specifically, in the weighted average, they take values of 0.58 kg CO₂ eq.

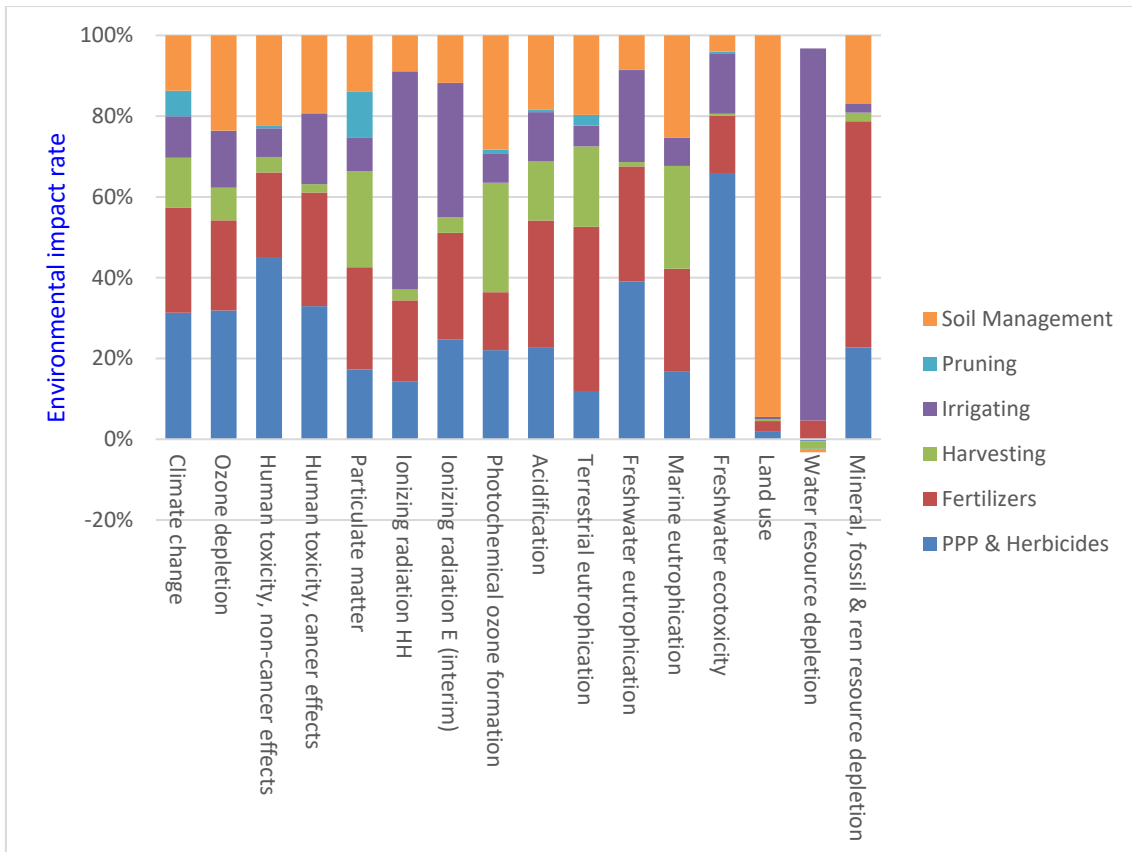
18 (31.31%) and 0.48 kg CO₂ eq. (25.99%) respectively for climate change. This fact is

19 justified by the quantity, type of products and processes used in the traditional olive

cultivation that takes place in Jaen.

1 For the industrial phase, the impact of each of the main inputs and outputs in the olive
2 oil extraction process has been analyzed, as well as the total impact produced by the
3 pomace treatment, which has its own processes and product consumption (based on
4 PEF-CR), as was reflected in the Methodology. One of the inputs that has more impact
5 in most categories is electricity consumption, with habitual values between 20% and 60%
6 of this phase.

7 In general, several representative processes produce the environmental impact for
8 each category. However, for the climate change category in the industrial phase, the
9 pomace treatment produces an impact of 0.44 kg CO₂ eq. (80.74%), while electricity
10 consumption, in second place, reaches the value of 0.05 kg CO₂ eq. (9.21%). The high
11 impact produced by the pomace treatment is mainly caused by the exhausted pomace
12 combustion that takes place in the crude pomace extraction process. On the other
13 hand, the reduction of environmental impact produced in the category of water
14 resource depletion is mainly due to the use of a significant amount of aluminum in the
15 fabrication of the OOM facilities and vehicles.



1

2

Fig. 6. Distribution of the impact of the farming phase in different categories for the weighted average.

3

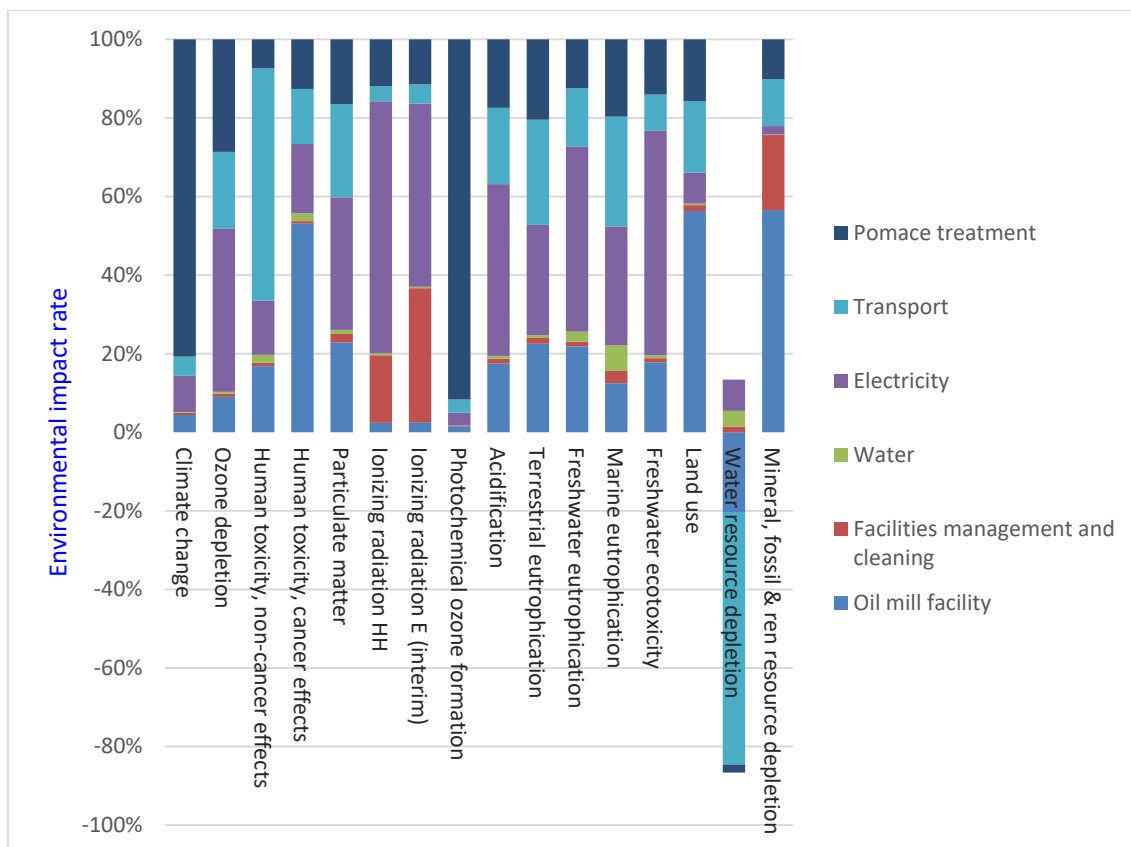


Fig. 7. Distribution of the impact of the industrial phase in different categories for the weighted average.

As can be seen, Table 7 shows the total values of CO₂ removed from the system due to long-term carbon sequestration, calculated per Kg of VOOs for each harvest. Likewise, the values assigned to the FU are shown, by the application of the impact assignment formula described above.

Table 7

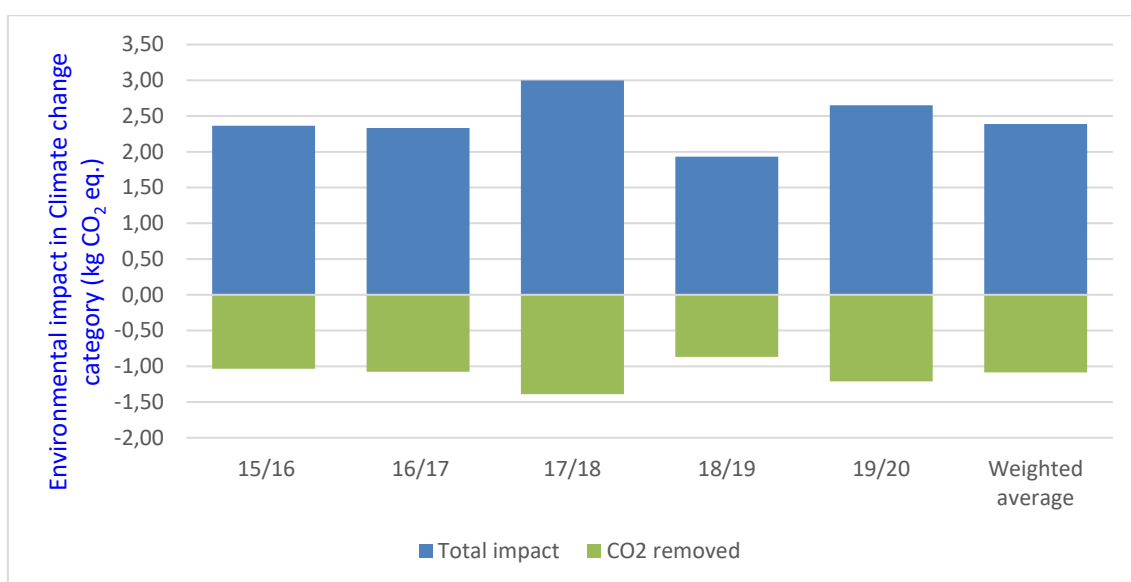
Values of long-term carbon sequestration for returned organic material to soil.

CO ₂ removed (kg of CO ₂ /FU)	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	Average
From pruning	1.011	1.050	1.395	0.811	1.186	1.056
From olives cleaning	0.114	0.120	0.117	0.122	0.117	0.118
Total	1.125	1.170	1.512	0.933	1.303	1.174
Assigned to VOOs	1.035	1.076	1.390	0.869	1.210	1.085

As in the case of the overall impact of olive oil production, carbon sequestration occurs in a greater proportion in the farming stage (from pruning) and its variability is also greater. It depends on the area required for the production of the FU, which varies

1 significantly between harvests. The lowest quantity of CO₂ removed per FU (0.869)
 2 matches with the highest olive yield harvest (18/19), while the highest (1.390) is
 3 consistent with the lowest olive yield one (17/18). Once again, the olive yield determines
 4 the value of carbon sequestration per FU, because they are directly related.

5 Fig. 8 shows the relation between carbon sequestration and the impact produced per
 6 FU, which ranges from 43.78% (15/16 harvest) to 46.36% (17/18 harvest), with 45.41%
 7 for the weighted average. It indicates that the olive oil value chain in Jaen and similar
 8 regions has an overall negative effect on climate change. For that reason, it is very
 9 important to reverse this situation by taking a series of decisions with the aim of reaching
 10 a sustainable position in this sector.



11

12 **Fig. 8.** CO₂ equivalent balance for climate change category based in the long-term carbon
 13 sequestration hypothesis for different harvests and weighted average.

14 The results obtained are consistent with those obtained by other authors for different
 15 case studies (Pattara et al., 2016; Proietti et al., 2017), so the present values may
 16 represent the characteristics of olive oil production in Spain's largest production area,
 17 Jaen. In table 8, the characteristics and results of Jaen are compared with those of other
 18 authors with case studies in Italy (the second largest producer worldwide). They also

1 analyze the impact of the production of VOOs "from cradle to gate" with similar boundary
 2 conditions. Moreover, the results of two EPDs (Environmental Product Declaration) are
 3 shown in the comparative analysis, one with respect a brand of olive oil from Spain and
 4 the other for a brand from Greece (the third largest producer worldwide). By comparing
 5 the results of the study with those proposed, it would be possible to observe the
 6 differences in production and climate change impact among the case studies of these
 7 three countries, since there are crucial differences between their olive oil production
 8 systems and volumes. For the comparison between different FUs, the factor proposed
 9 by PEFCR is used: 1L=0.92kg.

10 **Table 8**

11 Comparison of results with different authors and EPDs (EPD Sellas, 2013, EPD Borges, 2015, Pattara et al.,
 12 2016 and Proietti et al., 2017).

	Present work			Pattara et al.		Proietti et al.		EPD Borges	EPD Sellas
Location	Andalusia (Spain)			Abruzzo (Italy)		Umbria (Italy)		Spain	Greece
Harvests studied (years)	5 (2015-2020)			1 (2014-15)		1 (2014-15)		3 (2012-2015)	1 (2012-13)
System boundaries	Cradle-to-gate			Cradle-to-gate		Cradle-to-gate		Cradle-to-grave	Cradle-to-gate
Case studied	Average in Jaen			Case 2 (lowest impact)	Case 5 (highest impact)	Case A (lowest impact)	Case G (highest impact)	-	-
FU	5 L VOO	1 L VOO	1 kg VOO	5 L EVOO		1 L EVOO		1 L EVOO	1 kg VOO
Density (trees/ha)	100-150			± 200	± 200	390	478	-	-
Olive oil yield (L/ha)	950			1,345	1,025	1,172	467	-	-
Global impact	10.99	2.20	2.39	4.48	10.10	0.67	4.48	4.18	2.36
Farming phase	8.46	1.69	1.84	3.34	7.74	0.30	3.33	2.80	1.60
Industry phase	2.53	0.51	0.55	1.14	3.20	0.37	1.14	0.11	0.29
Olive oil extraction	0.51	0.10	0.11	0.44	0.61	0.18	0.14	-	-

13 The study conducted by Pattara et al. (2016) indicates that the impact is between 4.48
 14 kg CO₂ eq./5L oil and 10.10 kg CO₂ eq./5L oil. In that study, the focus is on the cases of
 15 traditional dryland farming, whose density is established at ± 200 trees/ha, far exceeding
 16 the density range studied in this paper (100-150 trees/ha). This fact means that its olive
 17 yield is 5,956 kg/ha in the case of higher impact and 7,180 kg/ha in the case of lower
 18 impact, whereas in Jaen, the average value for the whole study period is 2,376 kg/ha.
 19 The difference of more than twice the productivity of olives is the main reason why the

1 impact of the farming phase in the study by Pattara et al. (2016) only ranges from 3.34
2 kg CO₂ eq./5L oil to 7.74 kg CO₂ eq./5L oil. On the other hand, concerning the industrial
3 phase, its study considers different types of extraction (pressure, 2-phase and 3-phase),
4 and the impact produced by packaging, but not by pomace treatment. Consequently, its
5 impact values are between 1.14 kg CO₂ eq./5L oil and 3.20 kg CO₂ eq./5L oil for this
6 phase. The range of values obtained for olive oil extraction, not considering packaging
7 or pomace treatment, is between 0.44 kg CO₂ eq./kg oil for the 2-phase system and 1.10
8 kg CO₂ eq./kg oil for the pressure system. Thus, it can be concluded that, considering
9 only the 2-phase extraction process, the values obtained for climate change category
10 are also in the same range for the farming phase.

11 The study conducted by Proietti et al. (2017) was carried out considering a FU of 1 liter
12 of EVOO. It obtained values for 7 case studies ranging from 0.67 kg CO₂ eq./L oil to 4.48
13 kg CO₂ eq./L oil. In these cases, the farming phase impact was situated between 0.30
14 kg CO₂ eq./L oil in an organic crop and 3.33 kg CO₂ eq./L oil in a traditional crop. There
15 is a large difference between these cases in VOOs yield, since in the case of lower
16 impact, 1,078.85 l/ha were produced and in the case of higher impact the yield was
17 430.04 l/ha.

18 The fertilization of organic crop only produces an impact of 0.02 L CO₂ eq./kg oil,
19 whereas the same activity in a traditional crop produces an impact of 2.18 kg CO₂ eq./L
20 oil, resulting in the largest contribution to the overall impact. Regarding the industrial
21 phase, its impact is between 0.37 kg CO₂ eq./L oil and 1.14 kg CO₂ eq./L oil being this
22 difference attributable to the different bottling. This study provides carbon sequestration
23 values of between 1.35 and 6.12 kg CO₂ eq./L for cases of minimum and maximum
24 impact respectively. These data, related to the study area, result in 1,456 and 2,631 kg
25 CO₂ eq./ha, being only 948 kg CO₂ eq./ha in the case of Jaen. The lower value of carbon
26 sequestration for the case of Jaen is consequence of a lower density of trees per ha and

1 the fact that pomace does not contribute to the cultivated land, as it does in the Italian
2 case.

3 For the adaptation of the EPDs to the comparison with this study, only those impacts that
4 have been analyzed for Jaen have been considered. Borges' EPD carries out a study
5 with the scope of the whole life cycle ("cradle-to-grave") of 1L of EVOO of a Spanish
6 brand for which it obtains a climate change impact of 2.91 kg CO₂ eq./kg. From that
7 overall figure, 2.80 kg CO₂ eq./kg comes from the farming phase and 0.11 kg CO₂ eq./kg
8 from the industrial phase. In this case, the average impact value obtained in the study is
9 lower than that of Borges' adapted EPD, especially in the farming phase.

10 Sellas' EPD produces an impact value (2.36 kg CO₂ eq./kg) lower than Borges' and very
11 close to the average impact studied for Jaen. It is reduced to 1.89 kg CO₂ eq./kg to
12 consider from it only the activities contemplated for Jaen. 1.60 kg CO₂ eq./kg is derived
13 from the farming phase and 0.29 kg CO₂ eq./kg from the industrial phase, in both cases
14 lower than the impact for Jaen. From this study, the impact of the irrigating process is
15 particularly significant, since it is the only one in the analysis that provides a value, 0.12
16 kg CO₂ eq./kg while for the case of Jaen it is 0.19 kg CO₂ eq./kg.

17 [Beyond the comparison of results with other works, it should be noted that one of the](#)
18 [strengths of this study is the application of the LCA methodology to a representative part](#)
19 [of the largest extension of olive groves to date.](#)

20 **5. Conclusion**

21 Within the scope of sustainable agriculture, contemporary perceptions promote
22 environmentally friendly practices. In this line, this study has been developed to establish
23 which level of impact have the different practices of the VOOs production in the Spanish
24 area with the highest production worldwide. Robust data to characterize the impact
25 generated by the production of VOOs in the most representative case of Jaen have been

1 justifiably calculated. An extensive LCI has been carried out through a deep study of
2 processes and products, in order to develop the LCA of this case study.

3 The results derived from the study show that for the climate change impact category, the
4 production of 1kg of VOOs produces an overall impact between 1.93 (2017/2018) and
5 3.00 kg CO₂ eq. (2018/2019) depending mainly on each year's olive production. The
6 impact of the industrial phase is about 0.55 kg CO₂ eq. for every harvest, but the most
7 significant changes between each harvest occur in the farming phase (it is in a range
8 between 1.38 and 2.45 kg CO₂ eq.).

9 This paper proposes a reduction of the farming phase impact, from the activities with the
10 greatest impact in climate change category, such as PPP & herbicides (31.31%) and
11 fertilizers (25.99%). These values coincide with the analysis of the hotspots shown in the
12 most of relevant literature (Espadas-Aldana et al., 2019). Another valuable part of this
13 study is that the impact for climate change derived from the pomace treatment is
14 responsible for 80.74% in the industrial phase. Therefore, it has been assessed the
15 appropriateness of varying or reducing this treatment, which is linked to the production
16 of pomace in the two-phase extraction system and the subsequent extraction of crude
17 pomace in the pomace oil mill.

18 The reduction of the impact for climate change category by long-term carbon
19 sequestration in soil of the pruning and contribution of twigs and leaves present in the
20 harvested olives is between 0.87 (2018/2019) and 1.39 kg CO₂ eq. (2017/2018). These
21 results are lower than those obtained in the cases studied by Proietti et al. (2017), whose
22 are between 1.35 and 6.12 kg CO₂ eq./L oil. This is explained by factors that include the
23 different tree density and olive yield, as well as the additional contribution produced by
24 the widespread Italian practice of returning pomace to the olive tree crops.

25 This work allows to extend and improve the scientific knowledge on the production of
26 olive oil in terms of sustainability. Furthermore, this study is useful for the EU authorities

1 that are currently regulating the new framework for the support of olive oil production,
2 linked to environmental objectives. In this way, the information provided in the present
3 work could be used to modulate the incentives and subsidies associated to each one of
4 the phases in the production of olive oil. As future lines of research, *it would be very*
5 *significant to analyze different ways of olive cultivation and its differences in residues*
6 *generation and management in Spain and other representative countries. In the same*
7 *direction*, it is proposed to advance in the investigation of technological improvements
8 *such as pyrolysis, biomass gasification, and solar distillation among others (Parascanu*
9 *et al., 2018a; Souilem et al., 2017; Vera et al., 2018a). By their application to the olive oil*
10 *industry, they could reduce the environmental impact produced in this sector.*

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