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Environmental impact of the most representative Spanish olive oil farming systems: a Life Cycle Assessment Study

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ABSTRACT

Agricultural production is an essential activity in the global economy, which must advance towards the design of sustainability projects hand-in-hand with consumers, companies, and policymakers. An exhaustive study in line with the guidelines set by government entities is required to quantify this impact in an ample spectrum of environmental categories. The Life Cycle Assessment (LCA) is a powerful tool that enables obtaining such information, as other authors have already done in different sectors. This study uses the LCA to determine the environmental impact of the production of virgin olive oils, considering different agricultural and industrial production systems in Spain. For this purpose, a wide range of cultivated olive tree crops and various types of olive oil mill facilities have been studied in Andalusia, the territory of Spain with the highest dedication to olive oil production. This area has a special consideration for developing projects within this economic sector. The study focuses on olives, virgin olive oil and hectares of cultivation land, adopting a "cradle-to-gate" approach and including economic allocation, considering the main processes related to its production in the agricultural and industrial phases. The study period covers the five most recent harvests (2017/18 to 2021/22) to obtain appropriate and updated environmental impact values. The results from the study time indicate that higher densification, irrigation, and slope crops lead to a higher environmental impact. Specifically, the climate change category of the functional unit range between 1.90 (low yield crops) and 6.09 kg of CO_2 equivalent (super-intensive irrigated), while in the most representative cases, extensive crops, it results in 2.90 (rainfed) and 3.49 (irrigated) kg of CO_2 equivalent.

Keywords: Life Cycle Assessment; Environmental Impact; Climate Change; Olive oil production.

List of abbreviations

EI	Environmental impact
LCA	Life cycle assessment
LCI	Life cycle inventory
OOM	Olive oil mill
PM	Particulate matter
PPP	Plant protection products
PEFCR	Product environmental footprint category rules
VOO	Virgin olive oil

1. INTRODUCTION

Agriculture, with an aggregate value of more than USD 4.15 trillion, is one of the main economic sectors in the world (World Bank Data, 2022). Furthermore, olive groves, which constitute 25% of the total permanent worldwide cultivated area (11.6 million hectares) and distribute in 70% rainfed and 30% irrigated, are among the large permanent crops (International Olive Oil Council, 2022).

From ancient times to the present day, olive cultivation has been closely intertwined with the Mediterranean basin's nutrition, culture, and economy. The olive sector is the source of livelihood for many people in the countries surrounding the Mediterranean Sea (Yonar, 2022). In particular, olive tree cultivation plays a crucial role in the European Union (EU) since it is the principal olive oil worldwide producer (around 60%), and within the EU, Spain is its largest producer, far ahead of Italy and Greece. Global consumption of olive oil has nearly doubled from 1.6 million tons in 1990/91 to 3.2 million tons in 20211/22 (International Olive Oil Council, 2022). Regarding upcoming trends, calculations have shown that the global market for olives will grow at a *Compound Annual Growth Rate* (CAGR) of 4.5% from 2019 to 2024 (European Commission, 2018; Mili and Bouhaddane, 2019).

Concerning the distribution of this crop, Spain concentrates the larger area, with 2,507,684 ha (more than 180 million trees), followed by Tunisia (1,746,360 ha) and Italy (1,143,363 ha). Consistently, the most representative producer, according to their virgin olive oil (VOO) production figures from the last harvests (2017/18 to 2021/22), is Spain with more than a million tons, followed by Italy and Greece, which each, produce around 300 thousand tons on average (International Olive Oil Council, 2022).

Worldwide, one of the most representative regions of olive monoculture is the province of Jaén, in Andalusia (southern Spain) (Fig. 1). It holds the highest olive oil production and the largest area of olive groves within Spain. Jaén is the world's largest producer of olive oil as well, so its economy is, to a large extent, based on olive monoculture, making olive production the economic engine of this region (with a value of 300 M€). With more than 66 million olive trees covering 550,000 ha (over 25% of Spain's total olive grove area and 42% of the whole cultivated land in Andalusia), Jaén accounts for 20% of the world's olive oil production (Martínez et al., 2009; Robles-Molina et al., 2014; Rodrigo-Comino et al., 2021; Sánchez-Martínez and Cabrera, 2015). In addition, the olive oil industry is increasingly diversifying into related economic activities, such as olive-oil tourism, an emerging tourism typology in Jaen and the broader Mediterranean basin (Pulido-Fernández et al., 2019).

In light of the above, it seems logical that evaluating the most prominent worldwide olive oil production systems holds great significance for this economic sector.

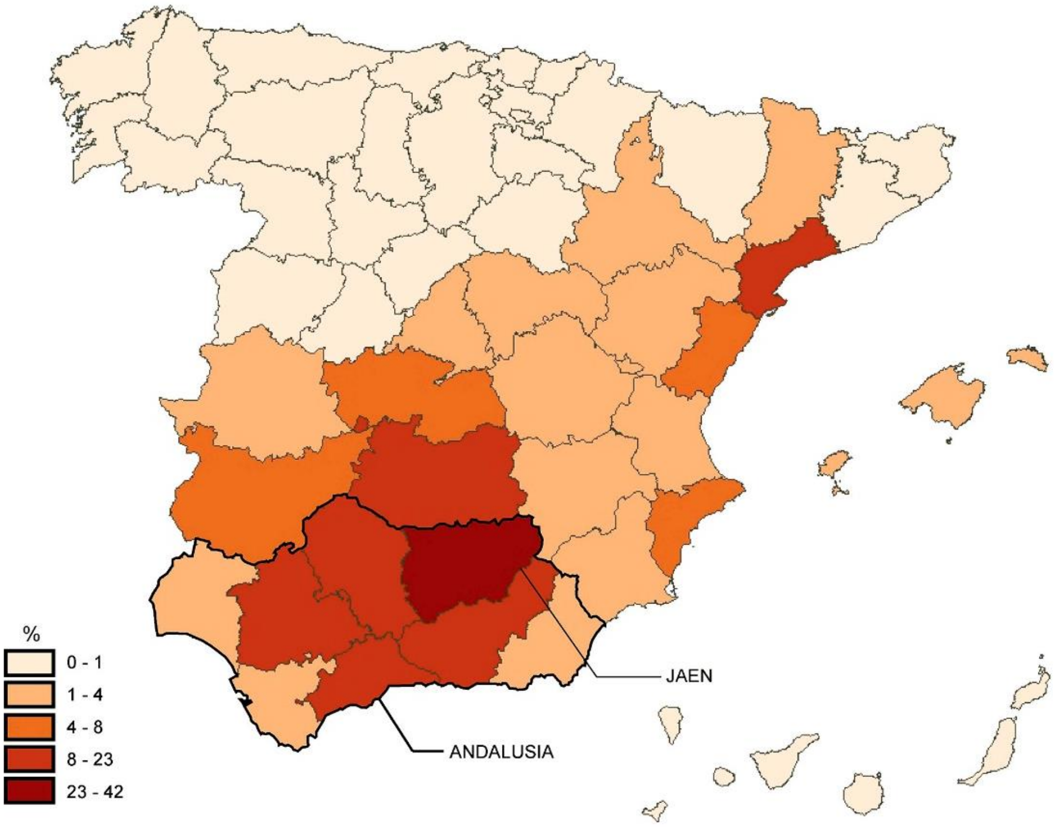

Fig. 1**.** Olive grove surface in every province of Spain (Ministry of Agriculture Fisheries and Food, 2020).

The structure of this paper is as follows. Firstly, the introduction provides a context and background to explain the relevance of this research. Subsequently, it follows a brief analysis of the context where the study happens, Andalusia (Spain), the most significant territory in olive oil production. It continues with the methodological framework of this study, specific data of the life cycle inventory (LCI) of VOO production in Spain and the methods used for data collection. Next to this description, the results of the LCA and the quantification of the EI are detailed. Finally, the paper concludes by summarizing the limitations, future challenges and new research directions in the sustainability of olive oil sector.

2. LITERATURE REVIEW

The notion that life cycle assessment (LCA) has become one of the most important tools for environmental management in recent years is thoroughly acknowledged. In fact, to further improve its effectiveness, the European Commission established a Product Environmental Footprint (PEF) through the Product Environmental Footprint Category Rules (PEFCR)as a necessary document for the more general guidance for LCA studies. Its purpose was to direct the focus toward the most significant parameters of the LCA studies, thus also reducing time, effort, and costs. As Russo et al. (2019: 2025) stated, "*LCA and environmental performance of products enters a new daring era with PEF*". This case study follows that direction by applying the PEFCR to olive oil (Schau et al., 2016).

In the last decade, significant literature reviews have been published on the life cycle assessment of the value chain in olive oil production, among which the following are noteworthy: Banias et al., 2017; Blanco et al., 2022; El Joumri et al., 2023; Espadas-Aldana et al., 2019; Rapa and Ciano, 2022; Salomone et al., 2015, 2010. Most of the works on the LCA of the olive oil sector examined several processes in different countries. However, only a few have provided relevant information on the LCA in Spain, even though it is the most important country in this sector (Fernández-Lobato et al., 2021). None of these studies made an LCA during the agricultural and extraction phases as a whole nor for the most representative olive farm types in Andalusia, either.

Providing scientific literature on how the LCA application affects different countries is crucial due to their diverse oil production processes, planting densities, and mill distribution. Regarding the latter, as will be justified in the following section, Spain has a more centralized model, i.e., significantly large mills that produce a substantial amount of oil from many farmers. In contrast, countries such as Italy, Greece, and Tunisia possess a more distributed model in small cooperatives or oil mills that process only a few hectares of olive groves (Espadas-Aldana et al., 2019; International Olive Council, 2023; Valta et al., 2015). Thus, the selected papers will provide relevant information on how these structural and productive differences affect the measurement of environmental impact (EI) through LCA.

In this regard, it is worth noting that most studies of LCA in olive oil production have been conducted in Italy (Guarino et al., 2019; Rinaldi et al., 2014; Salomone and Ioppolo, 2012), while only a few have provided information on LCA in Spain (Navarro et al., 2018; Parascanu et al., 2018b, 2018a; Romero-Gámez et al., 2017; Russo et al., 2016a). These studies focus on specific topics such as packaging, olive pomace valorization, or olive growing systems. None of them, however, jointly analyze the agricultural and industrial phase of VOO production in the most important country, Spain, for the most representative crops under different production conditions.

In an interesting study carried out by Pattara et al. (2016), the carbon footprint of a range of farms, olive oil mills (OOM), and cooperatives was determined in the Abruzzo region, Italy. Such a study identified the most impactful production hotspots for that value chain. Subsequent research by Proietti et al. (2017), assessed the carbon footprint of different cases of VOO production in the Italian region of Umbria. This study incorporates long-term carbon sequestration in the soil. The final balance shows how the techniques used to treat organic waste during the agricultural and industrial phases minimize the impact produced by their activities.

Romero-Gámez et al. (2017) conducted a general EI assessment of various olive Spanish production value chain. It considered 11 systems differentiated by crop type, mechanization, irrigation and crop management. According to these authors, intensive and super-intensive systems tend to have a higher EI than traditional systems, so fertilization optimization should be a priority to optimize olive cultivation.

Recently, Sales et al. (2022) undertook a life cycle assessment methodology to compare the EI of different olive production techniques in Portugal: traditional rainfed, intensive, and super-intensive systems (with time boundary of 50 years, the entire agricultural life cycle). The authors defined the functional unit (FU) as “*1 ha of olive growing area*’”. The results of this study confirmed that “super-intensive production systems resulted in higher environmental impacts for all categories (from 2.1 to 135.6 times higher when comparing with traditional rainfed systems and 1.2 to 2.8 times higher when comparing with intensive systems) and fertilization was the agricultural practice with the highest contributions for the environmental impacts in most of the categories, in the three systems under study” (Sales et al., 2022).

A lack of studies exists that focus on impact assessment in the current Spanish process of olive oil production cases using LCA with an integrated approach. Considering this knowledge gap, this work aims to conduct a comparative assessment of the EI derived from VOO production from different case studies of traditional and intensive value chains in Andalusia (Spain). This study intends to provide relevant information to develop diverse production systems improvement in the farming phase and to analyze the influence of density, productivity and management among the case studies on the overall impacts. It is worth stressing that the results of this study enrich the understanding of the application of LCA in the olive oil value chain and provide a unique scenario for future comparative analyses of LCA in this agricultural sector. Finally, it is significant to highlight that the scope of this paper fits within the following *Sustainable Development Goals* (SDGs) of the United

Nations Agenda for 2030: Goal 7 (*Affordable and Clean Energy*), Goal 9 (*Industry, Innovation and Infrastructure*) and Goal 13 (*Climate Action*).

3. METHODS

3.1. Case studies: different farming and industrial systems in Andalusia (Spain).

This section justifies why Andalusia is a unique scenario for assessing olive oil production. Considering Jaen is the world's largest producer of olive oil, it is worth noting that while the scientific literature presents several studies applied to different aspects of olive oil in Jaen, such as olive residues (Cruz-Peragón et al., 2006), olive oil and health (López-Miranda et al., 2010), olive grove monoculture (Galiano Parras, 2017; Sánchez-Martínez and Cabrera, 2015), among others, they do not perform an LCA on different systems in a highly producing region like Andalusia. This point is especially important since, as indicated above, Andalusia has an undisputed weight in olive oil production worldwide. In this sense, not only is the relevance of Andalusia in the olive sector one of the strengths of this study but also the fact that it applies the LCA methodology to the biggest area of olive tree crops existing to date since the vast majority of previous LCA approaches in this field only include specific plots of smaller extension.

The average olive oil production in Spain has been over 1,000 thousand tons between 2017 and 2022. The average contribution rate concerning the world total corresponds to approximately 43%. Fig. 2 shows the continuity of its productive supremacy. However, it is worth noting the decrease in participation in the 17/18 and 19/20 harvests as well as the top position in the 18/19 harvest (55.63% with 1,789 thousand tons). This fact demonstrates and guarantees its leadership and presence in the market for the coming years (International Olive Oil Council, 2022). Regarding the destination of production, at the national level, 93% is destined for oil and only 7% for table olives (Ministry of Agriculture Fisheries and Food, 2022).

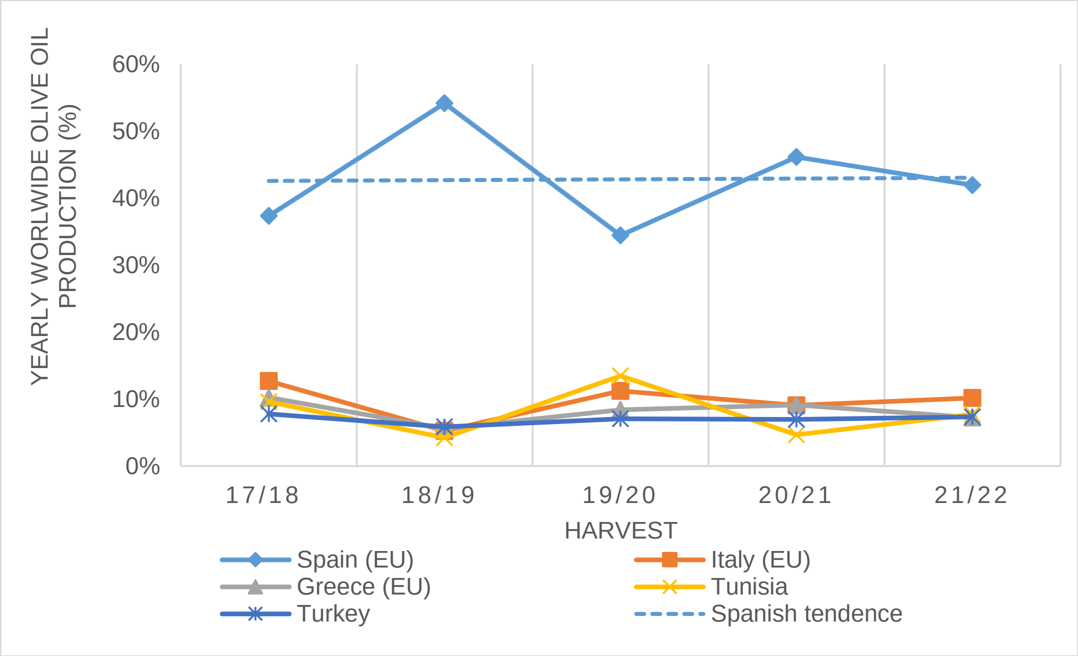

Fig. 2. Top five olive oil producers and yearly participation rate in worldwide production from the harvest 17/18 to 20/22 (International Olive Oil Council, 2022).

As can be seen in Fig. 3, VOO production in Andalusia has reached almost 80% of the total production in Spain recently. Consequently, just this region alone owns an average annual output rate of 36% worldwide, being over the national production of countries such as Italy or Greece, usually close to 15% (Ministry of Agriculture Fisheries and Food, 2022).

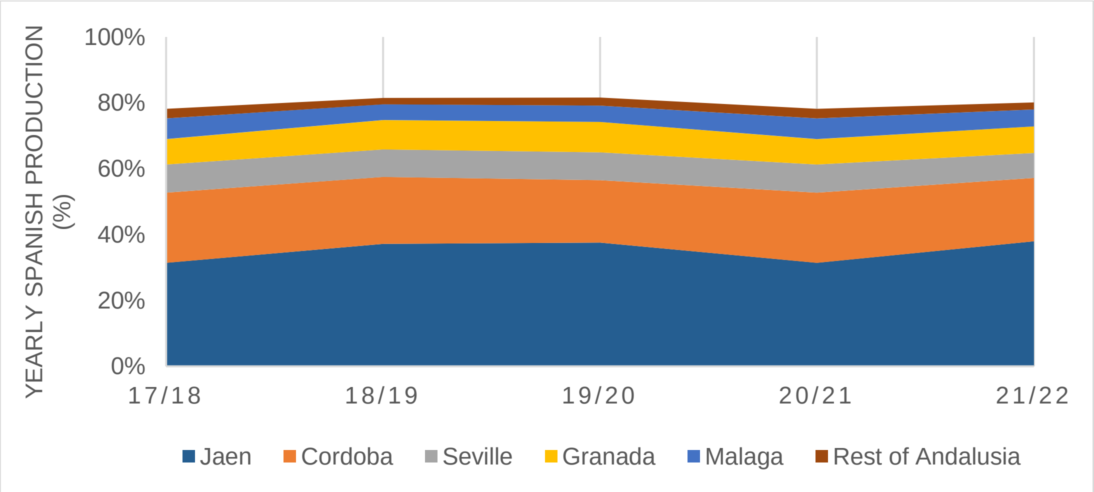

Fig. 3. Andalusian olive oil producers and yearly participation rate in Spanish production from the harvest 17/18 to 21/22 (Ministry of Agriculture Fisheries and Food, 2022).

Olive groves occupy a total of 2,468,464 ha in Spain, of which 1,556,394 ha are located in Andalusia, making olive groves the main crop in this region (Table 1) (Ministry of Agriculture Fisheries and Food, 2021). The surface area of Andalusian olive groves for mills has increased by more than 93,000 ha in the last decade, especially in Jaen. This province has around 64 million olive trees (588,095 ha), being the largest olive grove area in Andalusia and Spain (Ministry of Agriculture Fisheries and Food, 2022).

Table 1. The total area of the olive grove for the harvest 21/22 (Ministry of Agriculture Fisheries and Food, 2022).

Province	**Area**		**Olives' production**		**VOO production**	
	(ha)	**(%)**	**(t)**	**(%)**	**(t)**	**(%)**
Cádiz	30,810	1.2%	60,720	0.8%	11,120	0.7%
Huelva	21,456	0.9%	52,351	0.7%	11,978	0.8%
Almería	21,944	0.9%	72,658	0.9%	13,368	0.9%
Málaga	133,808	5.4%	347,988	4.5%	57,353	3.8%
Granada	206,661	8.4%	568,100	7.4%	118,671	8.0%
Sevilla	184,798	7.5%	781,478	10.2%	138,750	9.3%
Córdoba	368,822	14.9%	1,633,325	21.2%	298,510	20.0%
Jaén	**588,095**	**23.8%**	**2,402,301**	**31.2%**	**499,322**	**33.5%**
Andalusia	**1,556,394**	**63.1%**	**5,918,921**	**77.0%**	**1,149,072**	**77.0%**
Spain	**2,468,464**	**100.0%**	**7,687,565**	**100.0%**	**1,492,069**	**100.0%**

It should be noted that olive cultivation continues growing in Spain. Therefore, given its economic weight, and especially its influence on the regional economy, it is essential to improve sustainability practices within its value chain. According to data from the *Survey of Surface Areas and Crop Yields of Spai*n (Ministry of Agriculture Fisheries and Food, 2020), the olive tree crops have not stopped growing in 2022, and throughout the year, 16,669 ha have been planted since the previous harvest.

The latest relevant report on the olive grove sector in Andalusia (Regional Government of Andalusia, 2019) analyzes this region's density planting based on the information collected during the *Survey on Crop Surfaces and Yields* development. According to the data in this report, although, in absolute terms, the olive groves with the highest surface growth are those between 200 and 600 trees/ha (which have increased by 64,196 ha), it is the high-density olive groves that have experienced the highest surface increase in relative terms, and within these, those between 1,000 and 2,000 trees/ha. These latter ones have increased from 17,659 to 43,013 ha, representing an increase of 144%. Most of the intensive olive groves are irrigated, in a higher proportion of irrigation as density increases. However, the presence of rainfed olive groves with high density is not negligible. For example, over 25% of plantations between 1,000 and 2,000 trees/ha are rainfed. In relation to the distribution of densities by age of the olive grove, this study reveals that the intensification of olive grove density to values higher than 1,000 trees/ha is a recent fact: 65% of plantations from 1,000 to 2,000 trees/ha are less than four years old (and also 60% of those exceeding 2,000 trees/ha). According to the Ministry of Agriculture Fisheries and Food (2022) only 22.5% of Spain's olive groves in production are irrigated at present (28.13% in Andalusia). Regarding the province of Jaén, as shown in Table 2, the irrigated production area has progressively decreased from 270,862 ha (2015/2016) to 230,156 ha (2021/2022).

Table 2. Dry and irrigated olive grove cultivation area in Jaen (Ministry of Agriculture, Fisheries and Food, 2022, 2021, 2020, 2019, 2018, 2017, 2016, 2015).

Harvest	**15/16**	**16/17**	**17/18**	**18/19**	**19/20**	**20/21**	**21/22**
Irrigated (ha)	270,862	266,433	248,703	238,780	231,217	231,264	230,156
Dryland (ha)	313,214	308,657	330,710	345,031	353,578	356,245	357,939
Irrigated area of the total (%)	46.37	46.33	42.92	40.90	39.54	39.36	39.14

It should be noted that about 60% of the annual olive oil production in Jaén comes from olive trees with irrigation systems, even though irrigation is not the majority system in the province. Irrigated accounts for approximately 40% of the surface of Jaén, while the rest (60%) of production comes from rainfed olive tree crops. Summarizing, the main parameters of this supply chain are: 40% of the area is irrigated (it accounts for 60% of the VOO production), is mostly conventional, with a low slope, and with extensive tree crop plantations (with an average concentration of 100-150 olives per hectare).

The milling process is usually structured in medium-large private companies or cooperatives, resulting in the association of many producers. According to the Food Information and Control Agency (2022), Spain has 1,828 active OOMs (harvest 2021/2022), and the number of active OOMs in Andalusia was 840 (about 50% of the VOO production of Spain), of which 326 belong to Jaén (39% of OOM in Spain).

3.2. Goal and scope definition

A FU of 1 kg of VOO, elaborated through the 2-phase olive oil extraction process, generated the LCA for the farming phase. While the product bottled and ready for consumption is commonly measured (and purchased) in liters, this study considers production level rather than consumption. Therefore, it is justified to use a mass unit as FU. In addition, choosing a mas unit has more scientific rigor since it does not depend on temperature. In that sense, it should be stressed that the great majority of products in the Environmental databases, such as *Ecoinvent*, are presented in kilograms.

The scope of the LCA is “cradle to gate”, which encompasses both the farming phase and industrial phase. It includes the extraction of raw materials for farming and industrial phases as well as the treatment of the residues in both phases. The industrial phase finishes after the olive oil extraction process, with their residues treated (2-phase pomace) and by-products generated (olive stone, exhausted pomace and crude pomace olive oil). The quantity of those valuable by-products generated has been collected from the survey completed by the target population.

The cases studied derived from the different types and subtypes of agricultural crops in Andalusia, and different types of industry, in accordance with the Regional Government of Andalusia, (2019). The farming crop types are low yield, high slope, extensive, medium density, intensive and super-intensive. All crop subtypes, except low-yield crops normally rainfed, are both rainfed and irrigated. In the case of the industrial phase, it should be noted that in Spain, the 2-phase process is the most representative system, while in other countries, the 3-phase process is the most prominent in some cases. According to Restuccia et al., (2022, p. 14), “the two-phases system resulted to be more sustainable than three-phase extractions with lower values in all considered impact categories”.

3.3. Data collection

Data collection was conducted by gathering inputs and outputs from the agricultural and industrial phases. The information was obtained through questionnaires that covered aspects associated with agricultural activities, such as land (or soil) management, irrigating, fertilizers, plant protection products (PPP) and herbicides, harvesting, cutting, and pruning. In addition, it also contains information related to the industrial phase: extraction of the VOO, oil mill facilities and their consumption; this process produces pomace, in different proportions. After obtaining the specific information, mean values were calculated for each item. The referred data are related to the area of tree plantations (agricultural phase) or the quantity of olive oil obtained (industrial phase).

The questionnaires for the survey were prepared to include both descriptive and numeric data on farming and industrial processes. Thus, all the inputs (activities, sub-processes and energy) and outputs (products, by-products and residues) are obtained according to the PEFCR. In addition, the surveys were designed to be flexible to include any other information not specifically requested but relevant during the processes, adding more quality to the data collection. Moreover, face-to-face interviews, visits to their tree crops and facilities and verification of the information provided complemented the questionnaire, similar to the work of Guarino et al., (2019) and Rajaeifar et al., (2014) and following Regulation (EC) 543 / 2009. The purpose of this Regulation is to establish a standardized framework for the systematic production of Community statistics on the use of agricultural land and agricultural products. The Member States shall compile statistics on the areas and yields of crops produced on their territory and transmit them annually to the Commission within the time limits laid down.

The farmers and olive mills requested are located at different points in Andalusia. The farming survey covers an area of 5,738.64 ha, with a mean production of 36,318 tons of VOO for the seasons analyzed in the olive mills. The study collects data from conventional farms with different characteristics (type, subtype, size, olive tree crop density), as shown in Table 3, and from different sizes and types of OOM with 2-phase extraction process, as presented in Table 4.

Table 3. Main description and representativeness of the farming types and subtypes surveyed.

Type	**Low yield**	**High slope**	**Extensive**	**Medium density**	**Intensive**	**Super-intensive**
Density (trees/ha)	<150	<150	<150	150-180	180-325	>325

Age of trees (years)	>50	>50		>50		>50		>50		5-15	
Aggrupation system	Traditional	Traditional		Traditional		New		New		New	
Cultivation system	Organic	Conventional		Conventional		Conventional		Conventional		Conventional	
Harvesting method	Conventional	Mechanized		Mechanized		Mechanized		Mechanized		Mechanized	
Subtype	**-**	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**
Representativeness	6.3%	19.5%	3.8%	31.0%	16.5%	4.5%	3.0%	5.9%	8.1%	0.3%	1.1%
Olives' production (ton)	0.64	2.27	4.56	3.09	5.39	4.03	6.27	4.34	7.86	4.73	8.56
Farmers surveyed	7	11	8	31	34	6	8	6	9	4	5

Table 4. Main description and representativeness of the OOM type surveyed .

OOM Type	**2-phase extraction**
Representativeness	~ 95%
Phases	Olives washing, crushing and malaxing, centrifugation
Main inputs	Olives, electricity, heat sources and water
By-products generated	Olive stones
Residues generated	Wastewater, 2-phase olive pomace (up to 70% moisture), small twigs and leaves
Residues treatment	Wastewater treatment plant, pomace oil extraction plant, animal feeding
Secondary by-products	Crude pomace olive oil and exhausted pomace
OOM surveyed	16

The collected and accepted surveys are more numerous for types and subtypes that are more representative, resulting in a more accurate LCI in these fields. “Traditional mix” consists of High slope and Extensive (rainfed and irrigated), and it is considered the most representative group in Spain (Velasco Gámez, 2009).

The quantification of the inputs and outputs obtained from questionnaires correspond to the average values of the studied harvests. These data are processed to avoid mistakes or low representative indications, and they are used to determine the average values during the input periods, proportionate to the area of tree crop plantations considered, the kg of olives collected and the kg of VOO extracted (FU). These data show no appreciable differences between years due to the fact that agricultural and industrial techniques and processes remain unchanged over time. Thus, the mean values reflect the current behavior within the system considered. However, the yield of the farming phase is highly variable due to the differences in meteorological conditions between years and it is a determinant factor in evaluating the impact of the FU.

3.4. Life cycle inventory

The results in the farming phase cover the entire period between 2017 and 2022, representing an intermediate behavior. Particularly in the industrial phase, it is considered that the conditions and environmental impact related to VOO production are similar throughout the different harvests. Therefore, the inventory considers average values per ton of VOO for the 2017/18 to 2021/22 harvests.

Regarding the general characteristics of the farming phase, they are similar across the different tree crops. However, as shown in Table 5 (LCI of olive production), there are some differences in quantities. The inventory data have been classified into different systems. Generally, the values of inputs increase with the intensification of the cultivation system and when their olive yields are also higher.

- Land management. Agricultural machinery, which requires a fuel input, serves to weed, plow and prepare the land to improve nutrient absorption and soil moisture. This work is usually done once or twice a year, depending on the crop type. However, in those extensive irrigated and intensive crops, it is commonly done more frequently due to the higher dedication to cultivation.

- Irrigation. In irrigated crops, a pumping system is employed to lift water from riverbeds or wells to an elevated reservoir. Then the stored water is distributed through a network of PVC and polyethylene pipes to each tree. This system usually includes fertilizers in the irrigation water to supplement those in the soil. Intensive and super-intensive crops commonly show higher water and electricity consumption per hectare than the traditional cases.

- Fertilizers. Adding a sufficient amount of fertilizers is necessary for the adequate development of the olive tree fruits and in the greatest possible quantity. These fertilizers usually belong to three main groups: nitrogen, phosphorus, and potassium, as well as compounds or materials that include them. Information and quantity of all the active ingredients that fertilizers used in the crops studied contain have been compiled. In integrated systems, farmers who want to obtain the maximum yield from their olive trees use to apply the maximum dose per tree recommended. Fertilizers are transported in a tractor along the rows of olive trees and spread mechanically or manually around the trees. This activity is carried out once or twice a year, depending on the dedication to the crop.

- PPPs and herbicides. They are also called phytosanitary products and include three main groups: fungicides, insecticides, and herbicides. These products are sprayed on the leaves of the trees or on the agricultural soil (two to four times for every harvest in active crops).

- Harvesting. The olives are harvested mainly by vibrating the trees with specialized machinery, which, in the cases studied, uses diesel or gasoline as fuel. The olives are transported to the OOM, where they undergo separation from leaves and, which some farmers return to the cropland.

- Cutting. After harvesting, this activity is carried out to remove dead or dry branches as a kind of tree clearing. The PEFCR considers this a part of the harvesting process, and includes the use of machinery such as mechanical chainsaws, lubricating oil, and gasoline consumed by these tools.

- Pruning. Unnecessary tree elements are cut to revitalize their productive functions since this activity makes sap better distributed. These cut biomass elements (branches, twigs, and leaves) are usually chopped in the agricultural soil to enrich it with organic nutrients.

In the oil mill, the processes follow the next order:

- Reception, cleaning and washing of olives. The harvested olives arrive at the OOM after the prior agricultural phase, where all twigs, leaves, and dust are separated from the olives. A relatively small amount of cold water is used for this purpose.

- Crushing and malaxing. These processes are crucial in the industrial phase. During these, the olives turn into an organic paste that still contains olive stones, pulp, and water. These processes require a significant amount of electricity, heat and water.

- VOO extraction. The 2-phase extraction is the principal olive oil recovery process. It takes place in the 2-phase decanter and involves the highest energy demand of this phase, using a large amount of water, heat and electricity. Along this process, VOO is separated from the rest of the organic paste, also known as virgin 2-phase pomace.

- Separation of wastewater, olive pits and pomace. From the olive oil extraction residue, the industry usually separates olive stones and pomace from olive oil to treat them separately as by-products (olive stones) or residues (pomace).

- Pomace treatment. As a residue, the 2-phase pomace is an organic fluid with a humidity of around 60-70% and usually is transported to the pomace oil extraction facilities for its treatment. At this stage, it is dried to approximately 12%, and that is when it is called dried olive pomace. The application of Hexane enables to extract the crude olive pomace oil from this product, leaving a residue called exhausted olive pomace. Both resulting elements are then considered by-products of the LCA scope.

By considering only the amount of olives required to produce 1 kg of VOO, the most efficient process, according to the surveys, is determined by the type and subtype of the crop since the OOMs have the same extraction systems and similar average olive oil yield. Consequently, this data (olive consumption) is particularly relevant in the industrial phase, as the EI associated with the farming phase is directly proportional to this value. The lack of information in the surveys or their low representativeness caused certain limitations in data collection and, as a result, the following statements were assumed:

- Transport of the collected olives from the field to the OOM usually ranges from 1 to 20 km, so it is considered an average value of 10 km. Transportation of waste from the olive fields or OOM to the waste plant or recycling stations usually ranges from 1 to 40 km, so the value considered is 20 km.

- Emissions from agricultural processes covered by the PEFCR (to air, water or soil) have been established. Calculations of emissions for fuel oil, fertilizers, phytosanitary products and herbicides follow the Guidelines for National Greenhouse Gas Inventories (Intergovernmental Panel on Climate Change - IPCC) (Amstel, 2006).

- The area of active OOM (expected useful life of 50 years) quantifies the m^2 of construction in relation to VOO production.

- Pomace drying. The Aspen Plus simulator software calculated the CO_2 generation in the drying process for a reduction from 70% moisture in the pomace to 12% moisture in the exhausted pomace.

- Crude pomace oil generation. It is part of the extraction process due to the obligation to treat the pomace (calculated from data provided by the PEFCR). The specific analysis of this waste treatment is not a fundamental part of the scope of this research.

The information provided by the survey for the 2017/18 to 2021/22 harvests generated mean data of inputs and outputs based on a weighted average related to crop areas (farming phase) or VOO yield (industrial phase). They are organized into different groups of elements related in Tables 5 and 6.

Table 5. LCI of olives production in Jaen by crop surface of the harvests 2017/18 to 2021/22, based on the survey.

Type	**Low yield**	**High slope**		**Extensive**		**Medium density**		**Intensive**		**Super-intensive**	
Subtype	**Rainfed**	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**
Main data											
Area surveyed (ha)	75.27	460.67	399.25	1,783.52	1,695.56	211.12	287.01	192.39	272.85	140.42	220.58
Olive oil yield (%)	18.95%	20.26%	22.14%	20.20%	23.11%	20.51%	22.78%	19.53%	20.20%	18.56%	19.18%
Harvesting (per ha)											
Olives' production (ton)	0.64	2.27	4.56	3.09	5.39	4.03	6.27	4.34	7.86	4.73	8.56
Oil production (kg)	0.12	0.46	1.01	0.62	1.25	0.83	1.43	0.85	1.59	0.88	1.64
Diesel (kg)	8.50	37.80	158.45	19.68	97.70	31.23	178.41	59.39	245.77	75.84	332.07
Gasoline (kg)	-	13.20	24.78	16.33	11.47	11.30	13.29	7.55	5.44	1.30	4.33
Irrigation (per ha)											
Electricity (kWh)	-	-	841.66	-	1,145.37	-	1,882.76	-	2,124.68	-	2,723.57
Water (ton)			2,192.58	-	1,478.02	-	2,166.13	-	2,228.84	-	2,453.24
Soil management (per ha)											
Diesel (kg)	-	11.90	34.31	3.60	14.33	6.62	20.46	5.40	24.56	5.74	43.68
Ploughing (m^2)	-	0.12	0.34	0.32	0.41	0.38	0.51	0.23	0.18	0.45	0.29
Tillage (m^2)	-	0.45	0.89	1.11	0.95	0.98	1.23	1.42	0.56	1.25	1.62
Harrowing (m^2)	-	0.12	0.21	0.14	0.09	0.42	0.36	0.28	0.74	0.62	0.89
Mowing (ha)	-	-	-	-	1.61	-	1.25	-	1.45	-	1.82
Pruning (per ha)											
Diesel (kg)	0.53	5.18	10.31	1.26	2.79	3.88	5.57	8.03	12.83	9.55	17.77
Gasoline (kg)	0.89	0.06	0.38	2.06	0.95	0.38	2.74	1.67	1.16	0.33	2.53

Lubricant (kg)	0.05	0.02	0.02	0.12	0.07	0.10	0.29	0.08	0.43	0.08	0.34
Fertilizing (per ha)											
Diesel (kg)	-	5.25	14.44	1.77	3.91	5.29	10.80	11.25	13.97	12.83	24.88
Broadcaster fertilizing (ha)	-	1.25	1.76	1.33	1.83	1.42	1.91	1.64	2.12	1.83	2.27
Nitrogen (kg)		27.47	31.14	24.49	56.74	78.74	96.44	96.46	120.45	105.82	177.10
Phosphorus (kg)	-	8.86	26.00	9.37	35.06	41.03	20.27	18.04	48.06	46.14	51.13
Potassium (kg)	-	26.38	36.52	13.96	52.71	63.89	39.62	35.37	81.44	75.34	88.32
Iron (kg)	-	0.51	0.10	1.24	1.15	4.47	7.15	9.25	9.58	3.48	13.90
Water solution (L)	-	45.59	34.71	39.57	240.65	160.30	129.01	144.75	776.40	312.16	522.15
PPP & herbicides (per ha)											
Diesel (kg)	-	5.40	22.69	3.01	6.15	3.42	23.26	6.23	17.67	8.49	39.11
Sprayer (ha)	-	1.45	1.83	2.11	2.26	2.25	2.84	2.48	3.60	3.57	4.45
Water (L)	-	433.00	1,800.00	580.00	1,300.00	620.00	1,800.00	920.00	2,742.92	1,360.00	3,305.79
Fungicides (kg)	-	31.40	62.05	28.07	44.07	55.75	47.13	41.11	41.53	92.36	52.81
Herbicides (kg)	-	3.12	2.73	2.94	5.18	1.45	1.48	1.16	2.70	1.24	1.13
Insecticides (kg)	-	0.28	0.34	0.30	0.36	4.67	0.87	0.95	1.24	3.68	2.89

Table 6. LCI of VOO generation of the seasons 2017/18 to 2021/22.

Activity / Products	Per ton of olives	Per ton of VOO	Source
Olive oil extraction			
Olives input (ton)	1.00	4.70	Questionnaires
Diesel (L)	0.17	0.74	Questionnaires
Gasoline (L)	2.00E-03	8.21E-03	Questionnaires
Electricity (kWh)	30.97	147.33	Questionnaires
Water supply (L)	409.62	1,965.15	Questionnaires
Water treatment (L)	214.20	1,073.49	Questionnaires
Olive stones burned (kg)	11.76	56.15	Questionnaires
Olive stones output (kg)	66.63	318.21	Questionnaires
Facilities surface (m2)	3.38E-02	1.59E-01	Questionnaires
Building surface (m2)	9.46E-03	4.45E-02	Questionnaires
Pomace output (kg)	851.64	3,968.70	Questionnaires
Crude pomace olive oil extraction			
Electricity	1.64E+04	77,039.00	Questionnaires / PEFCR
Water input (L)	4.18E+04	196,387.00	Questionnaires / PEFCR
Transport with lorry (tkm)	1.67E+04	78,555.00	Questionnaires / PEFCR
Hexane (kg)	1.30E+03	6,131.00	Questionnaires / PEFCR
Dedicated portion of facilities (u)	1.79E-07	8.43E-07	Questionnaires / PEFCR
Crude pomace output (kg)	32.68	152.30	Questionnaires / PEFCR
Exhausted pomace burned (kg)	107.19	503.83	AspenPlus simulation
Exhausted pomace output (kg)	180.66	849.14	AspenPlus simulation
Steam output (kg)	561.26	2,615.53	AspenPlus simulation

4. RESULTS

As displayed in Table 7, the EI obtained from the assessment shows that per kg of olives produced, it reaches an overall impact of between 0.15 (low yield crop) and 0.96 kg CO_2 eq. (super-intensive irrigated) for the climate change impact category. It will be translated to the FU (1kg of VOO production), considering the olive oil yield of each type of crop.

Table 7. Environmental impact per 1kg of olives in the farming phase (in bold for the most representative categories, according to PEFCR).

Impact category	Low yield	High slope	Extensive	Medium density	Intensive	Super-intensive
			Rainfed crops			
Climate Change (kg CO_2 eq)	**0.15**	**0.58**	**0.38**	**0.56**	**0.60**	**0.75**
Ozone depletion (kg CFC-11 eq)	**1.46E-08**	**6.78E-08**	**4.44E-08**	**5.57E-08**	**5.78E-08**	**8.02E-08**
Human toxicity, non-cancer effects (CTUh)	3.28E-07	6.22E-07	2.92E-07	3.93E-07	5.45E-07	6.32E-07
Human toxicity, cancer effects (CTUh)	1.23E-08	3.02E-08	1.64E-08	2.53E-08	3.00E-08	3.56E-08
Particulate matter (kg PM2.5 eq)	**5.48E-04**	**4.07E-04**	**2.45E-04**	**3.91E-04**	**4.12E-04**	**5.03E-04**
Ionizing radiation HH (kBq U235 eq)	8.74E-03	6.70E-02	4.18E-02	6.22E-02	5.89E-02	8.77E-02
Ionizing radiation E (interim) (CTUe)	4.23E-08	7.44E-07	4.81E-07	6.40E-07	5.72E-07	9.87E-07
Photochemical ozone formation (kg NMVOC eq)	1.06E-03	2.92E-03	1.95E-03	2.30E-03	2.64E-03	3.15E-03
Acidification (molc H+ eq)	**1.04E-03**	**4.53E-03**	**2.86E-03**	**4.38E-03**	**4.52E-03**	**5.83E-03**
Terrestrial eutrophication (molc N eq)	**3.89E-03**	**2.43E-02**	**1.10E-02**	**1.51E-02**	**1.48E-02**	**1.75E-02**
Freshwater eutrophication (kg P eq)	**3.36E-05**	**1.11E-04**	**6.34E-05**	**1.18E-04**	**1.21E-04**	**1.50E-04**
Marine eutrophication (kg N eq)	3.40E-04	1.29E-03	7.98E-04	1.15E-03	1.19E-03	1.49E-03
Freshwater ecotoxicity (CTUe)	**1.06**	**5.08**	**8.51**	**8.52**	**8.16**	**4.40**

Land use (kg C deficit)	**0.77**	**19.77**	**14.11**	**11.72**	**11.20**	**10.93**
Water resource depletion (m3 water eq)	-1.10E-02	-1.36E-02	-4.35E-03	-3.54E-03	-9.74E-03	-1.06E-02
Mineral, fossil & ren resource depletion (kg Sb eq)	**3.28E-05**	**9.84E-05**	**5.17E-05**	**1.01E-04**	**1.05E-04**	**1.29E-04**
				Irrigated crops		
Climate Change (kg CO_2 eq)	-	**0.82**	**0.60**	**0.77**	**0.75**	**0.96**
Ozone depletion (kg CFC-11 eq)		**9.77E-08**	**6.76E-08**	**8.42E-08**	**7.92E-08**	**9.67E-08**
Human toxicity, non-cancer effects (CTUh)		1.08E-06	6.11E-07	9.05E-07	9.68E-07	1.22E-06
Human toxicity, cancer effects (CTUh)		5.63E-08	3.80E-08	5.19E-08	5.28E-08	6.63E-08
Particulate matter (kg PM2.5 eq)		**6.02E-04**	**4.28E-04**	**5.45E-04**	**5.66E-04**	**7.81E-04**
Ionizing radiation HH (kBq U235 eq)		1.57E-01	1.26E-01	1.57E-01	1.43E-01	1.67E-01
Ionizing radiation E (interim) (CTUe)		9.46E-07	7.03E-07	7.65E-07	6.75E-07	7.95E-07
Photochemical ozone formation (kg NMVOC eq)		4.33E-03	2.85E-03	3.83E-03	3.73E-03	4.95E-03
Acidification (molc H+ eq)		**6.25E-03**	**4.75E-03**	**6.02E-03**	**5.92E-03**	**7.52E-03**
Terrestrial eutrophication (molc N eq)		**1.94E-02**	**1.30E-02**	**1.70E-02**	**1.76E-02**	**2.29E-02**
Freshwater eutrophication (kg P eq)		**2.62E-04**	**1.93E-04**	**2.48E-04**	**2.45E-04**	**2.91E-04**
Marine eutrophication (kg N eq)		1.63E-03	1.18E-03	1.51E-03	1.52E-03	1.98E-03
Freshwater ecotoxicity (CTUe)		**7.97**	**12.98**	**14.15**	**10.49**	**10.88**
Land use (kg C deficit)		**11.88**	**9.49**	**9.11**	**7.99**	**8.29**
Water resource depletion (m3 water eq)		4.95E-02	3.24E-02	3.53E-02	2.29E-02	1.73E-02
Mineral, fossil & ren resource depletion (kg Sb eq)		**1.32E-04**	**9.50E-05**	**1.24E-04**	**1.38E-04**	**1.72E-04**

The harvesting processes and products are the only ones that vary significantly due to the different amounts of olives harvested in each system. Thus, under similar conditions, a lower EI per FU is associated with reduced consumption of products and processes in relation to the amount of VOO produced. From another point of view, an increase in olive yield derived from a higher consumption associated with certain crops (intensive or super-intensive) leads to an increase in EI per ha compared to others with less activity (extensive rainfed). Fig. 4 shows the relative average impact of the different types of olive cultivation in each EI category. It is evident that intensification, irrigation and high slope are parameters linked to higher EI.

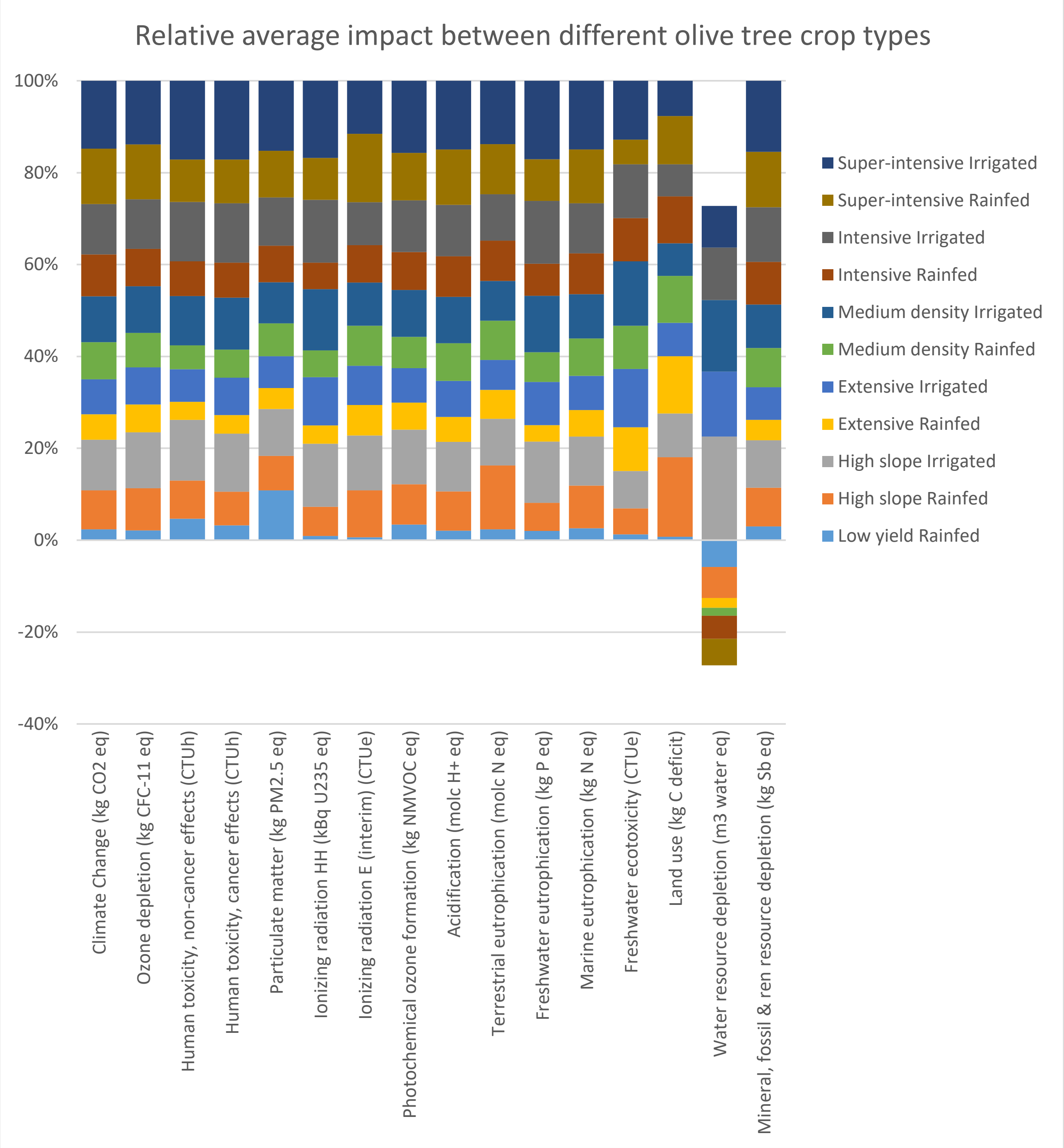

Fig. 4. Relative average impact between different olive tree crop types in the farming phase.

In any case, the average EI of the industrial phase added to the corresponding value of the agricultural phase per kg of VOO represents the total value of the FU production considered. As shown in Fig. 4, the importance of EI by category varies across the different tree crop cases. The lowest EI value in more categories correspond to low yield (13 out of 16). On the other hand, super-intensive irrigated crops have the highest impacts in more categories than the rest (11 out of 16). Rainfed tree crops have negative values in water resource depletion, meaning positive effects in that category, due to certain activities related to metal productions (in transport, buildings, etc.) combined with the fact that they do not require water for irrigation. However, these rainfed crops also have the highest impacts in the land use category.

Table 8 represents the average EI of the assigned industrial phase. For each harvest, while the processes and products consumed in the field remain similar, olive production differs as it is highly dependent on weather conditions, especially rainfall. The olive yield and the type of tree cultivation directly affect the variability in the impact of FU produced in the farming phase, , while the differences in the industrial phase derive from their olive oil yield.

Table 8. Average environmental impact for 1kg of VOO in industrial phase (in bold for the most representative categories, according to PEFCR).

Impact category	Total	Electricity	Transport	Cellulose fibre	Stones burned	Facilities	Pomace treatment	Water supply	Wastewater treatment	Others
Climate Change (kg CO_2 eq)	**9.89E-01**	**5.13E-02**	**5.81E-03**	**1.57E-04**	**8.82E-02**	**2.66E-02**	**8.15E-01**	**7.13E-04**	**7.44E-04**	**8.78E-05**
Ozone depletion (kg CFC-11 eq)	**1.45E-08**	**6.97E-09**	**7.03E-10**	**5.66E-11**	**0.00E+00**	**1.65E-09**	**4.99E-09**	**7.51E-11**	**3.91E-11**	**0.00E+00**
Human toxicity, non-cancer effects (CTUh)	**7.53E-08**	1.86E-08	1.70E-08	1.07E-09	0.00E+00	2.47E-08	1.03E-08	4.80E-10	3.23E-09	3.02E-15
Human toxicity, cancer effects (CTUh)	**1.98E-08**	3.70E-09	6.30E-10	9.59E-11	0.00E+00	1.21E-08	2.75E-09	3.34E-10	1.85E-10	1.19E-14
Particulate matter (kg PM2.5 eq)	**8.81E-05**	**3.57E-05**	**5.36E-06**	**7.88E-07**	**9.72E-14**	**2.64E-05**	**1.81E-05**	**4.61E-07**	**1.00E-06**	**3.41E-07**
Ionizing radiation HH (kBq U235 eq)	**5.10E-02**	3.31E-02	4.24E-04	9.44E-03	0.00E+00	1.34E-03	6.37E-03	2.52E-04	7.49E-05	0.00E+00
Ionizing radiation E (interim) (CTUe)	**1.93E-07**	9.09E-08	2.03E-09	7.08E-08	0.00E+00	5.39E-09	2.31E-08	6.63E-10	2.18E-10	0.00E+00
Photochemical ozone formation (kg NMVOC eq)	**6.57E-03**	2.10E-04	4.63E-05	3.51E-06	8.43E-05	1.06E-04	6.11E-03	2.18E-06	2.38E-06	2.25E-06
Acidification (molc H+ eq)	**9.85E-04**	**4.97E-04**	**4.72E-05**	**6.57E-06**	**3.92E-10**	**2.17E-04**	**2.05E-04**	**4.35E-06**	**6.09E-06**	**1.54E-06**
Terrestrial eutrophication (molc N eq)	**2.30E-03**	**7.97E-04**	**1.62E-04**	**1.30E-05**	**6.01E-09**	**6.95E-04**	**6.01E-04**	**8.28E-06**	**1.72E-05**	**8.95E-06**
Freshwater eutrophication (kg P eq)	**4.85E-05**	**2.50E-05**	**1.69E-06**	**4.51E-07**	**0.00E+00**	**1.26E-05**	**6.88E-06**	**5.45E-07**	**1.23E-06**	**0.00E+00**
Marine eutrophication (kg N eq)	**2.02E-04**	7.61E-05	1.50E-05	1.47E-06	0.00E+00	3.41E-05	5.13E-05	7.93E-07	2.19E-05	8.11E-07
Freshwater ecotoxicity (CTUe)	**2.56E+00**	**1.54E+00**	**5.35E-02**	**2.32E-02**	**0.00E+00**	**5.21E-01**	**3.93E-01**	**1.13E-02**	**1.42E-02**	**2.57E-09**
Land use (kg C deficit)	**9.16E-01**	**7.94E-02**	**3.93E-02**	**8.05E-03**	**0.00E+00**	**6.19E-01**	**1.65E-01**	**9.58E-04**	**4.63E-03**	**0.00E+00**
Water resource depletion (m3 water eq)	**-1.05E-03**	3.30E-04	-5.73E-04	3.66E-05	0.00E+00	-9.22E-04	-8.81E-05	3.22E-04	-1.56E-04	0.00E+00
Mineral, fossil & ren resource depl. (kg Sb eq)	**6.44E-05**	**1.43E-06**	**1.70E-06**	**1.35E-05**	**0.00E+00**	**4.08E-05**	**6.94E-06**	**5.71E-08**	**2.85E-08**	**0.00E+00**

Fig. 5. shows a representative distribution of the different activities or inputs in the EI of the industrial phase of the weighted average for five harvests. Unlike the agricultural phase, the industrial phase impact is sustained over time due to the industrial system used for VOO generation. For example, the average value for the Climate Change impact category is 0.99 kg CO_2 eq. in the industrial phase, ranging from 0.75 (extensive irrigated) to 0.93 (super-intensive rainfed).

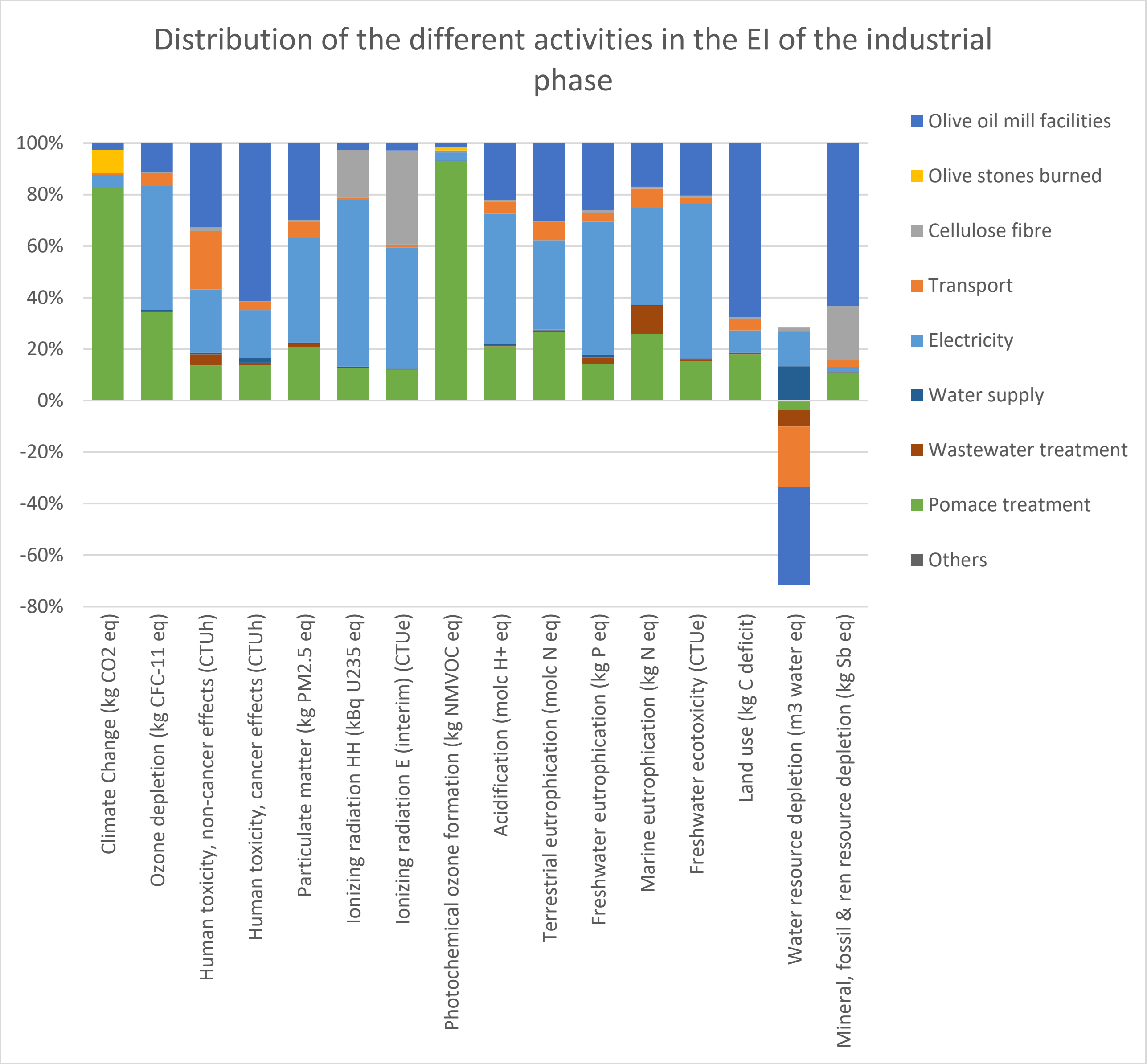

Fig. 5. Distribution of the different activities in the EI of the industrial phase.

When analyzing the climate change category, Fig. 6 shows the distribution of EI by activity for the agricultural and industrial phases together. The farming phase is responsible for most of the EI in all cases, while the industrial phase is only prominent in one of its activities. As can be seen, for the cases studied, under climate change, the least impacting type of tree crops is low-yielding, while the most impacting is super-intensive irrigated, due to the high use of fertilizers, harvesting activities and irrigation, compared to the rest of tree crops.

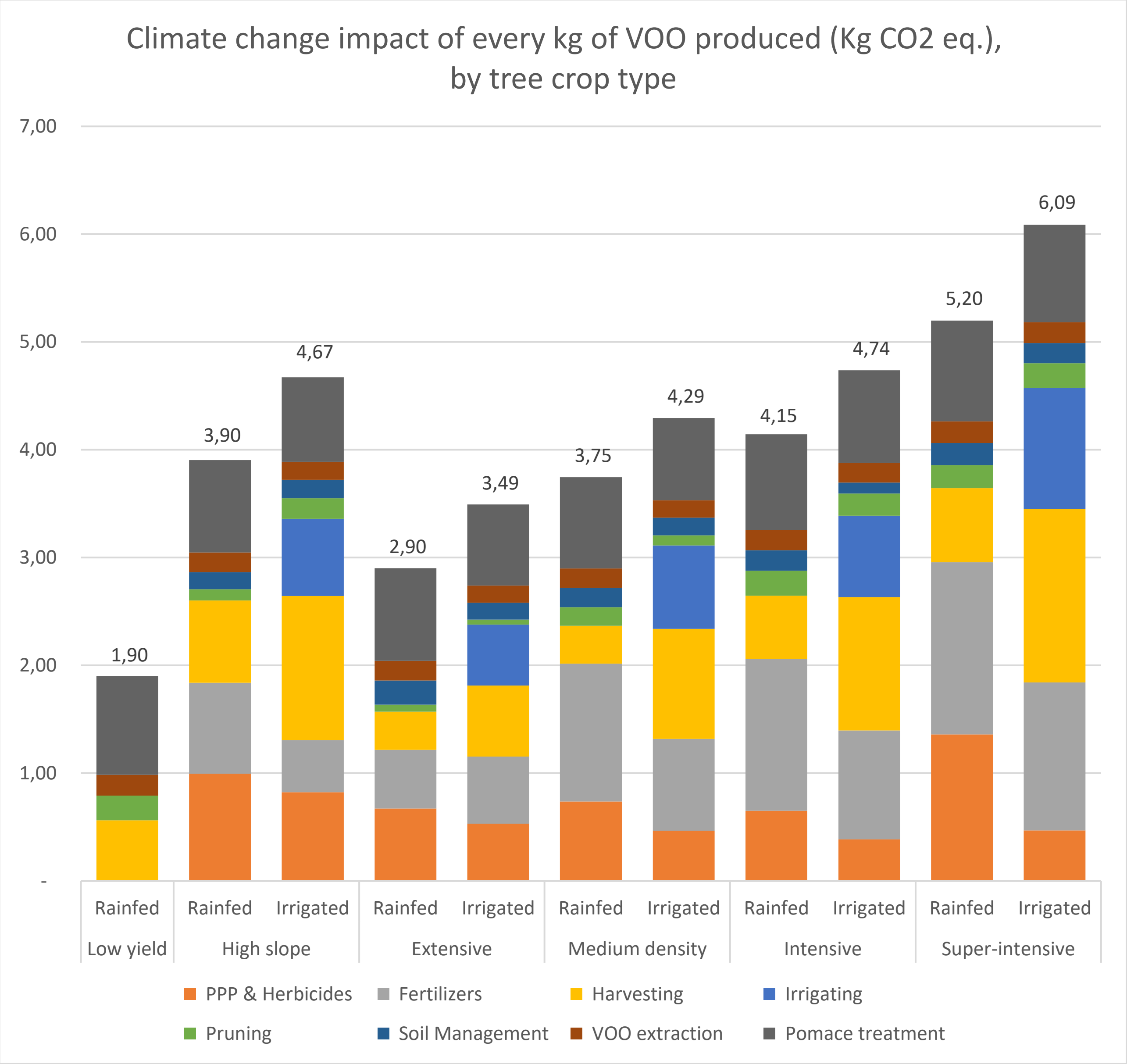

Fig. 6. Climate change impact of every kg of VOO produced (Kg CO_2 eq.), by tree crop type.

According to the type of crop, they obtained an overall value for the five years studied that ranges from 1.90 to 6.09 kg CO_2 eq. It should be noted that the sample size for super-intensive corresponds to a productive stage, so that a future extension of the period analyzed for the entire life cycle of super-intensive crops could provide a further understanding of these data.

When considering the different by-products generated by VOO extraction (olive stones, crude pomace olive oil and exhausted pomace), the most appropriate way to distribute EI to them is through an economic allocation (Notarnicola et al., 2015; Salomone et al., 2015; Schau et al., 2016). In this methodology, the EI of the activities is allocated in proportion to the value of each product, taking into account its mass and price at the point of disposal for the location and period studied (AVEBIOM, 2023; IDAE, 2023; Olive Oil Council, 2023). As can be seen in Table 9, the results of this methodology application assign 92.97% of the EI to VOO, 5.80% to crude olive pomace oil, 0.77% to olive stones and 0.46% to exhausted pomace.

Table 9. Economic allocation for VOO and by-products production (per kg of VOO).

Product	Economic value (€/kg)	Mass (kg)	Economic weight (€)	Economic allocation (%)
VOO	2.47	1.00	2.47	92.97%
Olive stones	0.06	0.32	0.02	0.77%
Crude pomace olive oil	1.01	0.15	0.15	5.80%
Exhausted pomace	0.02	0.85	0.01	0.46%

5. DISCUSSION

An in-depth literature review was conducted, as well as a comparison with selected documents, analyzing their information. First, a comparative analysis has been made between the present study and a recent LCA analysis with similar methodology (same scope and system boundaries) in the same country (Fernández-Lobato et al., 2022, 2021).

The first of the previously mentioned studies, Fernández-Lobato et al., (2021), presented an average climate change impact ranging from 1.93 to 3.00 kg of CO_2 eq. for the most representative value chain in Andalusia (density lower than 150 trees per ha, about 40% of the analyzed area irrigated, with 2-phase extraction). In the current cases, low yield, high slope, and extensive (with their respective subtypes) could fit within its scope. The climate change results obtained for these types range from 1.90 (low yield) to 4.67 (high slope irrigated) kg of CO_2 eq., but the most representative type among them is extensive, with values of 2.90 and 3.49 kg of CO_2 eq.

Fernández-Lobato et al., (2022) conducted a study on various case studies more closely related to the present work, but those cases were not as representative in size and crop types as the one discussed here. The results of their work placed the environmental impacts of climate change in the ranges of 1.80-2.41, 1.59-2.78 and 2.28-3.26 kg CO_2 eq. for traditional rainfed, irrigated and intensive, respectively. Traditional type tree crops also fall within the most representative case in Spain (density less than 150 trees per ha, with 2-phases extraction), although they were studied separately in this case. Additionally, the study introduced a new system, intensive irrigated, as the next most representative after the extensive one.

The EI results of the present study (updated and with larger sample size of studied crops) are slightly higher than those obtained in the previous works, especially in the industrial phase. While in this work, CO_2 derived from the combustion of exhausted pomace in pomace treatment has been modelled using the software Aspen Plus simulator, resulting in 0.82 kg of CO_2 eq., the previous work relied on data from the PEFCR, which considers a mix of 2 and 3-phase pomace from different countries and resulted in 0.44 kg of CO_2 eq. The assumptions made regarding pomace extracted, with higher water content and higher water production than the mixture considered by the PEFCR, lead consequently to a higher EI in the climate change category. This fact drastically increases the pomace treatment EI and, therefore, the total EI. The influence of pomace treatment in the total EI value is 82.45%, outweighing other processes such as electricity, extraction and wastewater treatment in the climate change impact category.

In the cases studied, olive stones, pomace, and exhausted pomace are burned in both the extraction process and the pomace treatment process, both of which considered essential parts of the industrial phase. It should be noted that, currently, the climate change category (*ILCD2011 Midpoint+, version 1.10*) considers biogenic carbon emission to calculate the EI, but, on the contrary, the previous version of climate change category analysis (*ILCD2011 Midpoint, versions before to 1.08*) judged that the biogenic carbon emitted does not impact the environment for that category (European Commission, 2016). Therefore, it is remarkable to pay attention to the chosen method to clarify the EI results and, thus, better compare them with other studies. This kind of CO_2 emission (such as biomass combustion) has been captured equally from the atmosphere during the growing phase of a plant or a tree.

Results from other authors who used similar methodology and scope (farming and industrial phase), such as Proietti et al. (2017), have been adapted to the comparison made in the previous section, producing global values ranging from 0.73 kg CO_2 eq. (Case A) to 4.86 kg CO_2 eq. (Case G). These findings demonstrate that variation in impacts is related to the inputs and olive yield considered in them. Therefore, our results can be considered in line with those obtained by other authors and, as well as including impact values related to new case studies in this work.

The results shown in this study encompass all of the different subtypes of every tree crop in the farming phase studied by Romero-Gámez et al. (2017). To enable comparing results, in the present study, the EI in the climate change category, adapted for 1 ton of olives, ranges between 238-373 kg CO_2 eq. for traditional dryland, between 201-419 kg CO_2 for traditional irrigated, and between 319-469 kg CO_2 for intensive irrigated cases. While Romero-Gámez et al. (2017) consider a long historical period, the harvests considered in this study are more recent. Consequently, the cases studied here have a higher olive yield but with increased dedication and consumption. Therefore, this rise in productivity is accompanied by a more than proportional increase in the consumption of products and activities carried out. For instance, it is noteworthy how the use of fertilizers and PPP has more variety and quantity of products in this study.

In the sustainable agriculture field, contemporary perceptions promote environmentally friendly agricultural practices. In order to demarcate which of those practices have a lower impact on the environment, it is essential to gather representative data of their EI in detail and to compare them with alternative scenarios. In that regard, this study has provided sufficient results to represent the EI produced by the VOO generation through different systems in the world's largest production area, Andalusia (Spain). The study area's specific characteristics have been described, and the impact produced for different crops and impact categories has been shown.

The greatest challenge found in conducting the LCA for this extension has been acquiring representative data to carry out the LCI due to the need for publishing databases that serve as a reference for the elaboration of the inventory (as other authors have pointed out, Espadas-Aldana et al., 2019; Luque et al., 2020). Significantly, this study has made specific adaptations to the LCA methodological requirements, aligning them more closely with scientific articles and the objectives pursued by our research while still following the general framework outlined in the 3rd Draft of the PEFCR developed by the European Union (Schau et al., 2016). For this study, an extensive LCA has been carried out, incorporating and modifying processes, products and values, which represent the characteristics of this case study.

6. CONCLUSIONS

With the increased attention given to the agricultural sector in the context of global climate change and the importance of agriculture for employment and livelihoods, the LCA can help identify more sustainable options in agriculture, in general, and olive groves, in particular. This identification is especially relevant considering that agricultural production is the most impactful in the life cycle of the VOO.

The farming phase is mainly responsible for the EI, accounting for most of the differences between its values. In contrast, the EI values for the industrial phase remain relatively consistent across most categories. Concerning the climate change impact category, the biogenic CO_2 emissions from burning exhausted pomace to obtain dry pomace highly influence its values. Furthermore, dryland systems in the olive oil value chain do not negatively impact in water resource depletion. However, these subtypes of tree crops are changing with the recent implementation of new irrigated systems, such as intensive and super-intensive, in recent years. Intensification and irrigation or high slope increase the EI, in general, while the lack of treatments in low yield olive tree crops reduces significantly most of the EI. According to the results presented in this study, it would be advisable to avoid standard intensification or high slope systems and, instead, embrace dryland, traditional, and low yield systems in order to mitigate GHG emissions. Considering the environment, the current direction of olive oil cultivation is moving in the wrong direction, so it would be beneficial to shift it to alternative systems balanced in VOO production, socio-economically feasible, and environmentally friendly.

The hotspots responsible for most of the EI in the most representative olive oil production systems in Spain are generally harvesting, fertilization, phytosanitary treatments, and irrigation during the farming phase as well as pomace treatment in industrial phase. Through the economic allocation of the EI, it has been determined that approximately 93% of the EI is attributable to VOO, about 6% to crude pomace olive oil, and the remaining 1% to biomass with energetic purposes (olive stones and exhausted pomace). In view of these conclusions, it would be necessary to optimize the inputs in olive groves to reach similar VOO yields, avoiding non-essential elements or processes (especially those identified as hotspots), as followed in most extensive production systems.

There have been limitations in the study related to the scope’s size because it would have been difficult to cover all aspects of a huge number of olive tree crops. Moreover, the draft of the PEFCR is not a final document; it does not cover all types of olive tree crops, and there is limited scientific literature about their LCA. In addition, while some inputs, such as long-term carbon storage in soils, have not been considered because they would require different approaches, methods, and extensions, others and some processes have been adapted to the particular cases in order to improve the study.

This work proposes to reduce the EI in the farming phase by targeting the most impactful activities, such as high emissions methods in harvesting, intensive fertilization and phytosanitary treatments in farming phase. These activities produce impacts on climate change ranging between 69% and 91% of the farming phase. These assumptions agree with the assessment of the value chain covered by the majority of the related authors. According to the industrial phase, the impact generated from the 2-phase pomace management simulation is the cause for more than 80% in this phase, for climate change category. Therefore, a greater EI reduction could be obtained by improving our cultivation techniques and with a different treatment of pomace.

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