agriculture

Article

Life Cycle Assessment of Olive Oil Production in Turkey, a Territory with an Intensive Production Project

Beatriz Ruiz-Carrasco [1], Lázuli Fernández-Lobato [1], Yaiza López-Sánchez [2] and David Vera [1,*]

[1] Department of Electrical Engineering, Linares Higher Polytechnic School, University of Jaén, 23700 Linares (Jaén), Spain; brc00002@red.ujaen.es (B.R.-C.); lflobato@ujaen.es (L.F.-L.)
[2] Department of Applied Economics, University of Málaga, 29016 Málaga, Spain; ylopez@uma.es
* Correspondence: dvera@ujaen.es; Tel.: +34-953-648-582

Abstract: The global warming fight should focus on agriculture, especially on olive crops, due to their potential role in combating it. One of the leading olive oil-producing countries is Turkey; therefore, evaluating and quantifying the environmental impacts of its olive oil production is essential. This is the first analysis of Turkey that encompasses both the farming and the industrial phases through a cradle-to-gate life cycle assessment (LCA). As a representative value chain, it was considered an intensive system, according to the representativeness of rainfed and irrigated areas, with two-phase and three-phase olive oil extraction in Turkey. In the climate change category, analysis results gave a value of 3.04 kg of CO_2 equivalent for 1 kg of unpackaged virgin olive oil. The phase that contributes the most in all impact categories is the farming phase (2.53 kg of CO_2 equivalent), whereas the most impactful activities are fertilization and irrigation (69.5% of impact in this stage). The results have been compared to others obtained by different value chains, revealing an intermediate position in environmental impact. It can be concluded that better agricultural practices should be implemented, including the optimization of energy and water systems, in order to minimize the negative environmental effect of olive oil production.

Keywords: life cycle assessment; environmental impact; olive cultivation; olive oil production; intensive farming; Turkey

check for updates

Citation: Ruiz-Carrasco, B.; Fernández-Lobato, L.; López-Sánchez, Y.; Vera, D. Life Cycle Assessment of Olive Oil Production in Turkey, a Territory with an Intensive Production Project. *Agriculture* **2023**, *13*, 1192. https://doi.org/10.3390/agriculture13061192

Academic Editor: Maria Pergola

Received: 4 May 2023
Revised: 30 May 2023
Accepted: 31 May 2023
Published: 3 June 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

It is scientifically undeniable that climate change (CC) is a global environmental challenge and that it is, to a large extent, due to human activity, including the agricultural sector [1–4]. Within this sector, the olive oil industry has an important role to play in the fight against CC due to the large areas of olive cultivation worldwide, which is approximately 11 million hectares [5], as well as the increasing production. In Mediterranean climate regions, olive trees represent a widespread horticultural crop, becoming the most emblematic tree [6].

Olive oil is produced mainly in the Mediterranean zone, with the European Union (EU) as the world's leading producer, exporter and consumer. Almost 95% of the worldwide production of olive oil (about 3.3 million tons/year on average in the period 2017 to 2022) comes from Mediterranean countries. The most productive countries for such period were Spain (44.0% of the worldwide production), Italy (9.8%), Greece (8.2%), Tunisia (8.0%), Turkey (6.9%), Morocco (5.3%), Portugal (4.2%), Syria (3.9%), Algeria (2.9%) and Egypt (1.1%) [7].

In this context, it is relevant to analyze the contribution of the olive oil value chain towards a more sustainable production system in CC hotspots. This assessment is especially interested in geographical areas (Mediterranean basin) and specific countries where olive oil production is an important part of their agricultural output. This study covers one of these countries, Turkey, which is among the top five worldwide producers of olives and olive oil, and has a long tradition of olive cultivation (Table 1) [7].

Table 1. Turkish olive oil production (2017–2022) [7].

Harvest	2017–2018	2018–2019	2019–2020	2020–2021	2021–2022
Production (thousand tons)	263	193.5	230	193.5	235
% of World Production	7.78	5.86	7.0	6.41	6.92
Total World Production (thousand tons)	3379	3304	3269	3019.5	3398

Turkey has nearly 182 million olive trees, and it annually produces an average of 223,000 tons of olive oil, considering harvests from 2017–2018 to 2021–2022 [7]. Olive orchards are located mainly in the Turkish coastal zone with Mediterranean climatic conditions. Ozturk et al. [8] stated that "nearly 75% of the olive groves in Turkey grow in slopy areas with little soil depth, effectively lacking irrigation facility. Only 8% of the olive cultivation area is irrigable, and this is closely related to the yield". Cooperative companies are very few, and the most representative value chain includes the irrigated and non-irrigated systems of the intensive type of agricultural system. Therefore, the system analyzed in this study is a mix of the representativeness of rainfed and irrigated subtypes. As for the industrial phase, Turkish olive oil mills (OOMs) generally consist of two- and three-phase centrifugal olive oil extraction systems (Figure 1). The two-phase system is also known as the traditional or ecological method because it uses only mechanical means of olive oil extraction. It avoids chemical solvents, and it results in a lower yield of olive oil production compared to three-phase method. Conversely, the three-phase system is more efficient because it allows the simultaneous extraction of oil, wastewater and cake (also known as pomace) from the olive paste. The by-products and residues generated are also different between those systems. Two-phase extraction produces wastewater and sludges with moisture up to 70%. Three-phase extraction generates a higher volume of wastewater and a cake, a valuable product, with moisture from 30% to 40% [9]. There are 1250 OMMs with an average total production capacity of 28,800 t/day, of which 1100 are modern two or three-phase facilities. However, the Turkish government has been supporting two-phase factories since the beginning of the century and are striving to transform three-phase factories [10].

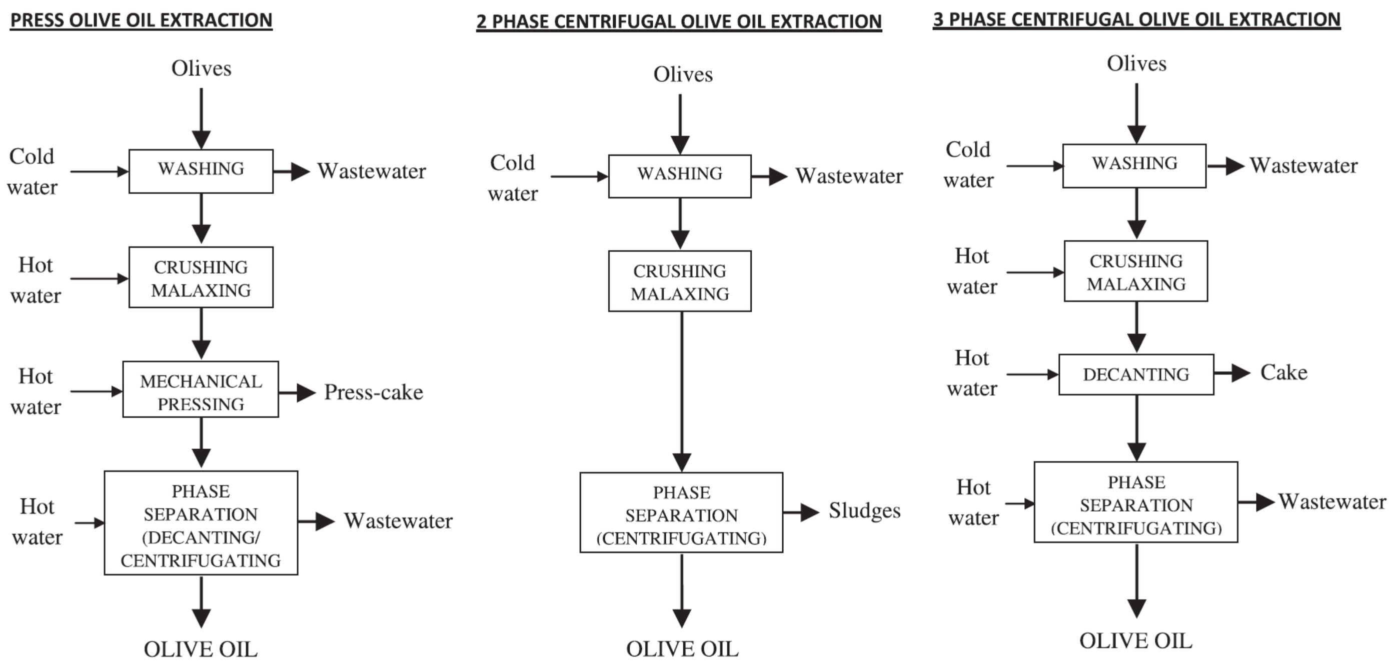

Figure 1. Main olive oil extraction processes [11].

Life cycle assessment (LCA) is a useful instrument to estimate and assess the environmental impact (EI) attributable to the life cycle of a product or process [12]. The importance of its making has increased in recent decades in different fields of study [13]. LCA in the olive oil industry has been widely studied for over a decade, identifying environmental hotspots and proposing recommendations to limit EI [14,15]. The rise of LCA studies for olive oil production was well presented by Blanco et al. [16] in their review, which shows that, within 110 works analyzed from 2008 to 2021, more than 78% were published from the year 2015 onwards. The latest review of LCA of olive oil production [17], which focuses on water use, points out that the farming phase is the most damaged stage since it is where more water is consumed.

Italy is where most LCA studies have been generated, with diverse scopes for the analysis of olive oil production. For example, Guarino et al. [18] evaluated the energy and environmental impact by analyzing different crops with diverse slopes and procedures, thus embracing both the farming and industrial phase. Their study also concluded that the first part of the life cycle is the most relevant one, with the highest impacts produced by fertilizers. Furthermore, within the transformation stage, the production of bottles is the one that more energy requires and therefore, it represents the highest environmental impact. On the other hand, Restuccia et al. [19] compared two- and three-phase systems and they obtained LCA results that revealed lower EI generated by the two-phase method. In addition, this work suggests two possible scenarios, which are also evaluated, for managing pomace: composting and bio-gasification. Regarding waste, Batuecas et al. [20] assessed two methods of treating it: anaerobic digestion and its disposal on the soil. In addition, De Luca et al. [21] conducted a study with a highly specific scope: weeding. For this, the researchers considered three scenarios from zero levels of chemical use, represented in organic systems, to high levels.

Regarding LCA for the Spanish olive oil value chain, most of them are based on the environmental analysis of small olive grove areas. Romero-Gámez et al. [22] assessed the EI of various olive crop system types in Spain (traditional, intensive and super-intensive), concluding that reduction and optimization of fertilization would improve olive growing processes. Navarro et al. [23] studied the influence, not always positive, of regulation updates in packaging olive oil through the LCA technique. Other studies applied the LCA methodology to evaluate pyrolysis and two thermochemical processes as valorization ways of the olive pomace [24,25]. Fernández-Lobato et al. [26] performed a complete LCA to detail how Andalusian virgin olive oil (VOO) production impacts the environment. This study covers both agricultural and industrial stages. The most recent one [27] compares, through LCA, two olive oil production scenarios for their by-products valorization, with and without gasification technology.

Concerning Greece, different scopes have also been analyzed through an LCA methodology. Within these LCA studies, the most current one [28] quantitatively points out the environmental yield of Greek olive growing systems under different management techniques while detailing the advantages of smart irrigation application. Tsarouhas et al. [29] conducted a broader study since it analyses 14 subsystems from the entire olive oil production chain. Chatzisymeon et al. [30] and Kalogerakis et al. [31] applied the LCA tool to study the olive mill wastewater. The former estimated the environmental footprint of three oxidation processes for those wastewaters, while the latter focused on studying the recovery yield of compounds from olive mill wastewater.

Although in less quantity, it is possible to find other studies regarding the LCA of the olive oil value chain, from Portugal [32,33], Iran [34,35] or Cyprus [36,37], for example. However, it is also worth noting that there are few studies from Tunisia and Turkey, despite their position as olive oil producers. They are the first and the second worldwide olive oil producers out of the EU.

In Tunisia, the beginning of LCA studies debuted a decade ago with the research of the EI derived from activated carbon manufacturing from olive wastes [38]. Later, Ben Abdallah et al. [39,40] assessed the sustainability of the different olive growing systems in the country, integrating LCA and multicriteria decision analyses. Another work on Tunisia [27] analyzed, for the first time, the EI of Tunisian virgin olive oil production by a cradle-to-gate LCA, covering the agricultural and industrial stages.

Finally, Turkey generates little literature regarding the evaluation of EI in olive oil production. Some recent studies briefly touch on the subject or include a small part of the process. Özilgen and Sorgüven [41] evaluated energy and exergy utilization and carbon dioxide emission in soybean, sunflower and olive oil production. It did not use an LCA methodology, but it calculated thermodynamic values. Another study we can find is the one prepared by Duman et al. [42], which evaluated, in a pioneering way, the impact produced by pomace olive use through LCA. The most recent work [43] investigates the effects of carbon emissions according to different crops, including olive growing, although without using LCA as in the first one mentioned.

The fact that Turkey is the world's second-largest producer of olive oil outside the EU, added to the lack of LCA studies related to EI evaluation of olive oil production, makes it pertinent to choose this country as a case study. Given this, the leading goal of this study is to describe and quantify the EI of the most representative value chain of olive oil production in Turkey (intensive cultivation with two and three-phase oil extraction) for an intermediate productive season through LCA methodology.

2. Materials and Methods

LCA is a helpful analysis technique to evaluate the EI derived from each of the steps in a product life cycle, from feedstock extraction to processing, manufacturing, distribution and consumption [44]. ISO 14040 and ISO 14044 regulations establish the fundamental structure for LCA studies of olive oil production [45,46]. These standards indicate four phases to include in any LCA. In the first phase, goal and scope should be defined. Then, the inputs and outputs of the evaluated system are quantified in the second phase, in which inventory analysis is conducted. The third phase is the impact assessment and, finally, the fourth phase is the interpretation of results. In addition, to be deep into its analysis, an LCA study should follow the rules described in Product Environmental Footprint Category Rules for olive oil—3rd draft (PEFCR) [47]. PEFCR for olive oil is one of the 11 pilot projects that the European Commission (EC) began in June 2014 under the name of Product Environmental Footprint Category Rules (PEFCRs) [15,48] and that, in turn, is an extension and a complement to developing the Product and Organization Environmental Footprint (PEF/OEF) methodology published by the EC in April 2013 [49,50]. PEFCRs can assist in directing attention towards the crucial factors of a PEF study, ultimately reducing the amount of time, effort and expenses required. Russo et al. [51] stated that "LCA and environmental performance of products enter a new daring era with PEF", and this research undoubtedly leads in that way, using LCA in adherence with the data requirement rules established in the PEFCR for olive oil [47].

2.1. Goal and Scope Definition

The primary aim of this research is to evaluate the EI across various impact categories in the agricultural and industrial phases of the most representative system of VOO production in Turkey. The concept of virgin olive oil is understood here in general terms, and refers to those defined by the International Olive Council as: "oils obtained from the fruit of the olive tree (Olea europaea L.) solely by mechanical or other physical means under conditions, particularly thermal conditions, that do not lead to alterations in the oil, and which have not undergone any treatment other than washing, decantation, centrifugation and filtration". This concept includes four subtypes of product, in order of their quality: extra VOO, VOO (understood here in specific terms, as a subtype of VOO), ordinary VOO and VOO not fit for consumption (also known as "Lampante") [52]. This study is the first one on Turkish olive oil production that includes the previously mentioned phases, since it analyzes the principal olive production systems (intensive dryland and irrigated) and the two extraction methods used (3-phase and 2-phase extraction). Furthermore, this LCA study follows the PEFCR directives for olive oil designated by the EC [47].

Figure 2 shows the general system boundaries for a cradle-to-gate LCA of olive oil production [53]. This study with a cradle-to-gate approach includes the following upstream and core activities: production of inputs and energy sources, olive production, oil extraction, use and waste management and emissions involved in the production phases. Upstream processes include in and outflows within the farming phase, while core processes include those in the industrial one. The cradle-to-gate approach excludes packaging and downstream processes, so they are not part of this study [27].

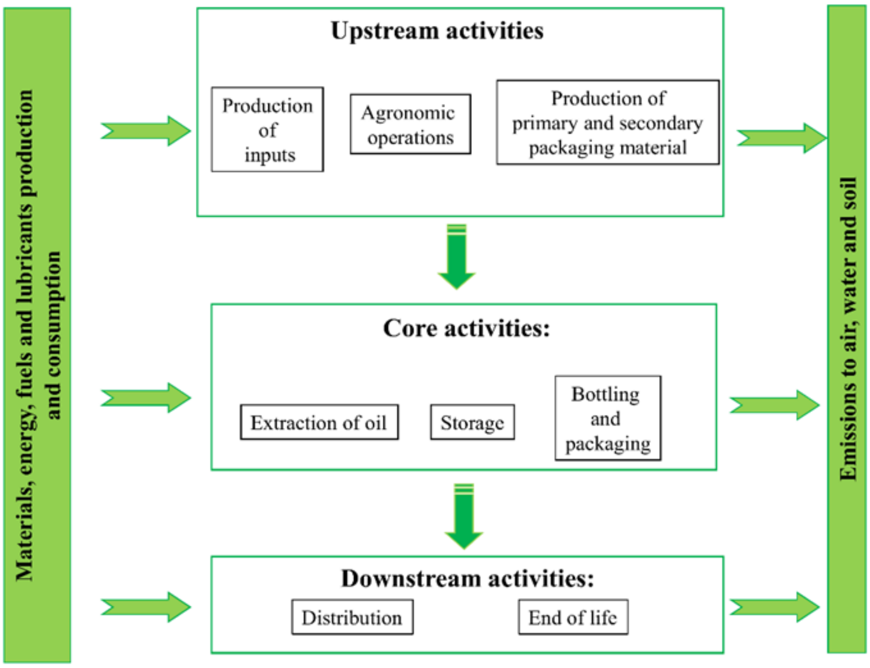

Figure 2. System boundaries for life cycle assessment [53].

The functional unit (FU) must be well defined, measurable and contemplate the commercial product, including the anticipated final packaging [45]. Thus, the established FU is 1 kg of VOO without packaging at the point of production, OOMs. Although some previous LCAs for olive oil production's impact studies considered other FUs related to volume [29,54,55], electing a mass FU seems more appropriate in that it does not depend on temperature and links better with the extraction phase where mass measures are applied. Other authors, such as El Hanandeh and Gharaibeh [56] or Fotia et al. [28], chose mass units.

Data Collection

Both surveys of farmers, and surveys of OOM managers provided primary data for this research. A total of 36 farmers from different regions (Aegean, Marmara, Mediterranean and Southeastern Anatolia), with different productive systems and sizes of olive crops, generally of more than 25 years of age, were taken into account. In the same way, 14 OOMs with different extraction methods were analyzed, being representative examples of the features of VOO production in Turkey. PEFCR guidelines led the design of the questionnaires, which included qualitative and quantitative data on factors, such as the characteristics of farms or OOMs, the processes involved, input and output products, and energy and waste management [47]. Moreover, specialists with extensive experience in cultivating olives and scholars with lengthy research careers in the same field pre-tested the questionnaires to ensure the validity of their content. Furthermore, these had open-ended questions to acquire critical comments that cannot be obtained only with quantitative surveys. The supplied information was verified by conducting the polls in person, over the phone and, in some instances, going to crops and installations, as Rajaeifar et al. [57] and Guarino et al. [19] did in their studies.

Afterwards, a statistical treatment of surveys allowed for discarding false or unrepresentative values on the data quality requirements defined in the PEFCR. The inventory has been built with weighted averages based on the representativeness, depending on whether it was olive cultivation or OOM from the 19/20 harvest. Although the main source of inputs/outputs was the survey, some information included in the PEFCR was incorporated as secondary data. Table 2 shows the source of the primary group of activities considered in the model. Finally, data extracted from literature and other available life cycle inventory (LCI) databases (i.e., Ecoinvent and Agribalyse) were related to activities incurred at the background procedure (i.e., agrochemicals production, fertilizers, machinery, and their transport).

Table 2. Source of information of the items in the Life Cycle Inventories.

Farming Phase		Industrial Phase	
Activity	**Data Source**	**Activity**	**Data Source**
Harvesting	Survey	Olive oil extraction	Survey
Cutting	Survey	Crude pomace olive oil extraction	PEFCR
Irrigating	Survey	By-products generation	Survey/PEFCR
PPP and Herbicides	Survey	Residues Generation	Survey
Soil Management	Survey		
Pruning	Survey/PEFCR		
Fertilizing	Survey		

The typical Turkish value chain includes the irrigated and rainfed systems of the intensive type of agricultural system. Due to that, the prototypal system is a mixture of the percentage of these two subtypes' representativeness in a cultivated area (58% rainfed and 42% irrigated). However, extensive cases, and a particular super-intensive case, were also assessed to broaden the analysis. Processes of 2- and 3-phases characterized the industrial phase in Turkey. As these are representative processes in the olive oil value chain, an industrial mix in proportion to their representativeness included them. The volume they represent in the value chain is approximately 55% and 45%, respectively [58].

It is relevant to point out that these amounts do not fluctuate excessively from one year to another, since procedures and actions, both in the farming and industrial phases, almost persist unaltered over the years. Accordingly, the average values describe the overall pattern in the studied stages. On the other hand, olive yields, within the agricultural phase, can vary noticeably year-to-year, principally owing to changing weather conditions besides the olive grove's biological character, a crucial element in the EI of the FU [15,55,57]. To these, it is worth adding that variation is higher in the extensive and intensive rainfed systems because of its dependency on the weather, while in irrigated crops, the olive yield is nearly constant. It means that the EI assessment for an unproductive year would be much higher for every kg of VOO in extensive and intensive rainfed systems. However, for a standard year with intermediate weather conditions, such as the period assessed in this work, the EI would be representative of the general behavior.

For this study, the system used was SimaPro 9.0 ("System for Integrated Environmental Assessment of Products"), which monitors and analyses the EI of any process through a quantitative and systematic method, the ILCD method. This software takes EI values from various scientific databases (ecoinvent 3.5, Agri-footprint 4.0, ELCD, Industry data 2.0, Methods) and provides an environmental model with numerical values for those operations emissions [54,59]. Results show the rate and amount of EI for each activity, input and output of the FU assumed. The 2011 ILCD mid-point+ and IPCC 2013 GWP 100a methods are the base to estimate the EI in the different categories [60]: climate change (CC) in kg CO_2 eq., global warming potential (GWP) in kg CO_2 eq., ozone depletion (OD) in kg CFC-11 eq., human toxicity (HT) in CTUh, particulate matter (PM) in kg PM2.5 eq., ionizing radiation (IR) HH in kBq U235 eq. and E in CTUe, photochemical ozone formation (POF) in kg NMVOC eq., acidification (AA) in molc. H+ eq., terrestrial eutrophication (TE) in molc N eq., freshwater eutrophication (FE) in kg P eq., marine eutrophication (ME) in kg N eq., freshwater ecotoxicity (FET) in CTUe, land use (LU) in Kg C deficit, water resource depletion (WD) in m^3 water eq. and mineral, fossil and renewable resource depletion (MFRD) in kg Sb eq.

2.2. Life Cycle Inventory

Rebitzer et al. [12] defined the LCI as "the compilation, tabulation, and preliminary analysis of all environmental exchanges (emissions, resource consumptions, etcetera)". Along with this, Islam et al. [61] stated: "LCI is the crucial phase of LCA which deals with the quantification and accumulation of a system input and output data." In summary, the LCI is an essential part of the LCA since it collects from various sources and quantifies the values of the flows (inputs/outputs) in each process, which is necessary for its subsequent environmental evaluation. Table 3 shows the LCA inventory of this study with its flows referring to the FU. Processes' traits assessed in the farming stage in Turkey are:

- Soil Managing. It encloses farming machinery used at different times of the year, with its corresponding fuel consumption, to harrowing, tillage, ploughing and mowing by a rotary mower. Additionally, it considers abiding crops in this category.
- Irrigating. Only for irrigated crops, this is done with a system of high- or low-density polyethylene and polyvinyl chloride (PVC). Apart from water, it demands electricity for pumping, which usually comes from the Turkish electric power grid. Some crops, however, have different power supply systems but these are minimal cases.
- Fertilizers. They may be spread directly on the ground through a broadcaster (except for rainfed-extensive crops) or mixed with irrigation water. They are principally phosphate, nitrogen and potassium, but in some crops, others also applied are borax, ammonium, potassium and urea products. It includes their transport, too.
- PPPs and herbicides. They are used to protect crops from pests and diseases. These products could be spread directly on the ground or mixed with irrigation water. Likewise, this trait includes their transport.
- Harvesting. The most common form to obtain olives is by shaking the tree with diesel or gasoline machines called vibrators. In this way, the olives fall on polyethylene nets placed on the ground around the trunk's tree and covering the entire area occupied by its crown. After that, with the aid of machinery or vehicles, the nets are collected, and olives are deposited in trailers, which transport them to the OOM. Finally, tractors with empty trailers, or loaded with remains of leaves and wood, return to the farm. It includes the cutting process, as PEFCR indicates. This activity is generally done manually, either with saws, pruning shears, or both. Typically, pruning occurs annually in irrigated systems and biennially in rainfed ones.
- Pruning. This could be carried out manually (traditional and intensive growing) or with the help of equipment (especially superintensive systems). There are two categories for pruning waste: wood (more than 10 cm in diameter) and branches with leaves of different diameters. The wood is usually sold directly at the farm, mainly for craftsmanship or as firewood, and branches are crushed straightly on the ground or burned. As for extensive and intensive systems, they are mainly hauled to nearby farms for sheep feeding (leaves), leaving the rest to be transformed into coal (branches between 2 cm and 10 cm in diameter) or to be used as combustible in conventional furnaces (twigs smaller than 2 cm in diameter).

Table 3. Farming phase LCI in Turkey (Inventory data per ha).

	Extensive		Intensive		Super-Intensive	Intensive
Activity/Product	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**	**Irrigated**	**Mix**
Olive yield (kg olives)	3125.0	3700.0	3452.4	4495.9	5000.0	3890.7
Harvesting						
Petrol, two-stroke blend (kg)	-	-	-	-	-	-
Transport, tractor and trailer (tkm)	41.6	36.3	48.3	70.6	41.6	57.7
Polyethylene, linear low density (kg)	1.4	1.0	1.4	1.8	2.1	1.6
Cutting						
Petrol, two-stroke blend (kg)	-	-	-	-	-	-
Lubricating oil (kg)	-	-	0.1	-	-	0.1
Irrigating						
Electricity, low voltage (kwh)	-	426.8	-	530.3	723.9	222.7
Water (m^3)	-	2395.2	-	2408.9	2500.0	1011.7
Polyethylene, linear low density (kg)	-	5.5	-	11.1	47.3	4.7
Polyethylene, high density (kg)	-	2.5	-	5.1	21.7	2.1
Polyvinyl chloride (kg)	-	4.0	-	8.2	34.9	3.4
PPP and Herbicides						
Application of PPP (ha)	2.2	4.1	3.4	4.3	0.0	3.8
Water (m^3)	0.2	0.4	0.1	0.1	-	0.1
Insecticide (kg)	-	5.9	0.2	3.4	-	1.5
Fungicide (kg)	16.0	67.9	12.2	19.8	-	15.4
Herbicide (kg)	-	1.6	-	-	-	-
Polypropylene (kg)	0.0	0.1	0.0	0.0	-	0.0
Polyethylene (kg)	1.4	2.6	0.4	0.8	-	0.6
Transport, lorry 7.5–16 t (tkm)	4.0	7.5	1.2	2.3	-	1.7
Transport, tractor and trailer (tkm)	0.4	0.8	0.1	0.2	-	0.2
Soil Management						
Harrowing (ha)	-	0.6	0.4	0.1	-	0.3
Tillage (ha)	1.0	1.8	1.6	3.7	6.0	2.5
Ploughing (ha)	-	0.1	-	0.0	-	0.0
Mowing, by rotary mower (ha)	-	-	-	-	-	-
Transport, lorry 7.5–16 t (tkm)	0.1	0.1	0.1	0.1	0.1	0.1
Occupation, permanent crop (ha)	1.0	1.0	1.0	1.0	1.0	1.0
Pruning						
Transport, tractor and trailer (tkm)	92.4	80.7	107.2	156.9	92.4	128.1
Agricultural machinery (kg)	0.1	0.1	0.1	0.1	0.1	0.1
Fertilizing						
Fertilizing, by broadcaster (ha)	0.0	0.1	0.1	0.1	0.2	0.1
Nitrogen fertilizer (kg)	134.3	199.6	89.9	68.1	-	80.7
Potassium fertilizer (kg)	34.9	19.4	29.1	11.4	-	21.6
Phosphate fertilizer (kg)	101.7	19.4	29.1	11.5	-	21.7
Borax (kg)	-	0.5	-	0.2	-	0.1
Ammonium sulfate (kg)	-	280.9	-	19.2	-	8.1
Potassium nitrate (kg)	-	293.5	31.2	-	-	18.1
Urea (kg)	-	140.5	-	13.7	-	5.8
Potassium chloride (kg)	-	140.5	-	5.8	-	2.4
Polypropylene (kg)	0.6	2.8	2.5	0.3	6.8	1.6
Polyethylene, high density (kg)	23.1	56.0	17.7	12.5	-	15.5
Transport, lorry 7.5–16 t (tkm)	66.9	162.3	51.4	36.2	-	45.0
Transport, tractor and trailer (tkm)	6.7	32.9	29.1	3.6	80.0	18.4

It must be pointed out that there were impediments to the data gathering due to the lack of information or representativeness scarcity. Because of this, it was necessary to assume the following:

- Olive planting operations. According to Salomone et al. [62] and Solomone and Ioppolo [63], olive trees over 25 years of age are not regarded in terms of EI, so these were not considered in the inventory.
- Fertilizers, PPP and herbicides. To standardize criteria at the time of its measuring, information collected related to fertilizers, PPP and herbicides has been split up into basic elements or chemical compounds.
- Land use (LU) change. Since, in most cases, olive cultivation is established and unchanged in terms of LU for more than 100 years, it is considered a permanent crop occupation.

- Pruning waste management. Pruning scraps are usually delivered to nearby local growers, either as animal feed or as an energy source. The most common practice is to convert the wood into coal or use it as a combustible, which is this commodity's end-life phase considered in this study. Since the carbon and carbon dioxide released by this activity is part of the short carbon cycle, they are not included in the LCA analysis [64].
- Transport. It is an approximate route from the most representative site to the major industrial cities and ports, assuming it is done by a diesel truck weighing from 7.5 to 16 metric tons. Regarding products consumed at crops and OOMs, that distance is estimated at 100 km. Once there, a diesel tractor would complete the transport between the olive grove, the supplying warehouse and the OOM.
- Infrastructure. Small infrastructures such as installations or storehouses, and their power consumption, are irrelevant to an LCA study of VOO production [62].
- Emissions. This refers to the atmosphere, water or land emissions the farming phase produces. These were taken into account as set by PEFCR.

Related to the next phase, the industrial one, its flows are classified into three classes (Table 4): olive oil extraction, by-product generation and residues treatment. In Figure 2, it is possible to see the different actions of this phase in Turkey (2- and 3-phase systems). Below, their features are itemized:

- Washing. It is required to remove small limbs and leaves from olives and to clean the dust. This activity generates wastewater that, normally, is discharged at the municipal treatment plant with the rest of the liquid residues.
- Milling and malaxing. These two post-washing processes allow for olives to be transformed into an olive paste suitable for oil extraction. It is useful to raise this paste's temperature to enhance the extraction process.
- Decantation and centrifugation. These are the central processes for acquiring olive oil from the preceding olive paste. They require the highest amount of energy within the industrial phase, in addition to water and heat. In the 3-phase system, 2 centrifugations are usually necessary to acquire all the olive oil. This process produces 3-phase pomace and olive mill wastewater in large quantities. The latter, which contains just 3–6% of organic matter, is habitually deposited in pond storage open to the air to dry naturally. Both for its amount and treatment, olive mill wastewater is one of the most critical issues in the 3-phase system [65]. On the other hand, the 2-phase system produces only 2-phase pomace, thus eliminating the olive mill wastewater problem.
- Pomace production and management. Three-phase pomace is an organic material composed of olive flesh, pebbles, and a degree of moisture content of around 30%, whereas the two-phase pomace is about 70%. They are by-products generally sold to pomace oil extractor plants. Before transporting the two- or three-phase pomace to a pomace oil extractor plant, the OOM could separate olive stones from pomace, since it is a valuable by-product in the biomass market.
- Drying and extraction pomace. Once pomace, either two-phase or three-phase, is at the extractor plant, it is dried until it reaches a humidity level of approximately 12%, resulting in an exhausted pomace. The process of hexane extraction also yields another valuable by-product, crude pomace olive oil, which reaches a high price in the market [42]. The processes require various inputs, including electricity, water, organic solvents and heat.
- Oil Washing and separating in the liquid extraction. This is the last step. After centrifugation, the resulting olive oil undergoes a water-washing process, which completes the production of VOO.

Table 4. Industrial phase LCI in Turkey (Inventory data per 1 kg of VOO).

Type	3-Phase	2-Phase	Mix
Olives (kg)	4941.18	4620.08	4796.68
Electricity, low voltage (kWh)	124.95	114.89	120.42
Gas (kg)	-	-	-
Water (m^3)	3.24	2.19	2.76
Olive stones (kg)	80.00	51.56	67.20
Transport, tractor and trailer (tkm)	-	-	-
Petrol, two-stroke blend (kg)	-	-	-
Lubricating oil (kg)	-	-	-
Soap (kg)	0.18	0.18	0.18
Sodium perborate, powder (kg)	0.83	1.59	1.17
Area of OOM dedicated with an expected lifetime of 50 years (m^2)	0.04	0.05	0.04
Pomace treated (kg)	1941.18	3953.17	2846.57
By-Products Generation			
Olive stones (kg)	450.00	450.00	450.00
Dry organic matter with 10% RH (kg)	1358.82	1581.27	1458.92
Crude pomace olive oil (kg)	-	-	-
Exhausted pomace (kg)	-	-	-
Residues generation			
Water content in pomace (kg)	582.35	2371.90	1387.65
Wastewater (kg)	-	1788.00	804.60
3-phase wastewater (kg)	5240.00	-	2882.00

When preparing this part of the inventory, some assumptions also had to be made based on the PEFCR and accessibility of data:

- Transport distances. In the same way as the farming phase, a distance of 100 km was deemed for the transportation of chemicals consumed in the OOM. This one, together with the pomace transport to the pomace oil mill, is done by a diesel truck of 7.5–16 metric tons. Furthermore, the latest acquires the value considered by the PEFCR.
- Infrastructure. The representative value of OOM per FU is obtained dividing the OOM by the estimated VOO production of 50 years, which is the time considered as their useful life.
- Emissions. As with the cultivation phase, atmosphere, water and land emissions yielded by the industrial one, mainly caused by fuel use, are calculated following the guidelines that PEFCR sets.
- Crude pomace extraction. Although this activity plays a part in the olive oil value chain, and it is necessary to state its EI of the industrial phase, its in-depth assessment does not fall within this research's scope. Hence, pomace generation per FU supplied by the survey is developed was founded on the data that PEFCR provide. It was adjusted to the relative humidity contained in the type of pomace, taking into account different amounts of inputs and outputs.

Data collected from both survey types have been enough to determine the average values of inputs and outputs in the most characteristic value chain (a mix of intensive rainfed and irrigated) and in other alternative systems such as extensive and super-intensive irrigated. Tables 3 and 4 show the average data that the farming and industrial surveys provided, respectively.

Extensive cases present substantial quantities of fertilizers, especially nitrogen and nitrogen compounds. For this reason, the olive yield is high for these types of tree crops. A single questionnaire provides data for the super-intensive case, and it does not reflect the use of chemical fertilizers (only organic matter), PPP or herbicides. It agrees with its olive yield, which is not much higher than the one observed in intensive irrigated systems. Lastly, the most representative value chain, the intensive-mix case, emerges by applying the representativeness of the rainfed and irrigated intensive systems, corresponding to the most representative supply chain.

As in the farming phase, the average data collected from surveys are expressed in a table format (Table 4), both the 2-phase and 3-phase systems, including a column for the mix considered the Turkish prototype system. The values obtained from relevant inputs such as electricity and water usage, apart from by-products and residue production, are comparable to those commonly accepted in the scientific literature [66,67]. The 2-phase system usually has lower water and energy consumption than the 3-phase system. In addition, the 2-phase does not produce as much and as dense oil mill sewage as other techniques, but the pomace has a more elevated level of water volume. Pomace-treated input alludes to pomace with different relative humidity, depending on the system (70% for 2-phase, 30% for 3-phase).

2.3. EI Allocation

In olive oil production, in addition to the main product, by-products and residues are also obtained, as already stated. However, for the allocation, those with an economic value are paid heed—that is, VOO as the main product and olive stones, crude olive pomace and exhausted pomace olive as by-products. Nevertheless, the treatment of the waste generated has an EI on the phase from which it comes, and this should also be taken into consideration. As for residues, pomace is considered a waste of the OOM, but it has to be mandatorily processed whether it provides low earnings or costs, depending on the current year. This process generates an added EI in olive oil production and its by-products.

This aforementioned economic allocation consists of awarding a proportional part of the EI to these products, which have a monetary value, in a percentage of these values and the amount of each one produced [68]. It is achieved by employing the following formula:

$$EA = (EV \times M) / \left(\sum_{n} (EV_n \times M_n) \times 100 \right)$$

where EA corresponds to the EI allocation (%), EV to the economic value per mass unit (€) and M to the total mass of products (kg). The data are obtained to "n" products and by-products considered in the process.

The production of different valuable by-products has been well defined by experts in olive oil production from the Olive Research Institute. The quantity of each item has been collected from the survey completed by the target population. The primary parameters used to compute the economic allocation and results can be found in Table 5.

Table 5. Economic allocation for VOO and by-products production in Turkey (per 1 kg of VOO).

Process		3-Phase		2-Phase		Mix	
Output	**Economic Value 2015–2020 (€)**	**Mass (kg)**	**Economic Allocation (%)**	**Mass (kg)**	**Economic Allocation (%)**	**Mass (kg)**	**Economic Allocation (%)**
VOO	2.720	1.00	97.23%	1.00	96.47%	1.00	96.88%
Exhausted pomace from 2-phase process	0.063		0.00%	1.58	3.53%	0.71	1.60%
3-phase pomace	0.040	1.94	2.77%		0.00%	1.07	1.52%

3. Results

3.1. Farming Phase

As has already been mentioned, the most representative value chain includes the irrigated and non-irrigated systems of the intensive type of agricultural system. Due to that, the most representative system is a mix that considers the representativeness of rainfed and irrigated subtypes (58% and 42%, respectively).

LCA results of the farming phase in Turkey are presented in Table 6 for the CC category. These correspond to 4.80 kg of olives, which is the amount required to produce 1 kg of VOO, considering the most representative case, a scenery with two-phase and three-phase extraction systems. Data indicate the most impactful group is extensive, followed by intensive and, finally, by the super-intensive as the least impactful. Regarding their subtypes, the irrigated option is more impactful than dryland systems.

Table 6. LCA Farming phase (by type and subtype of agricultural system in Turkey, per 1 kg of VOO).

Type	Extensive		Intensive		Super-Intensive	Intensive
Subtype	Rainfed	Irrigated	Rainfed	Irrigated	Irrigated	Mix
Representativeness	-	-	58.0%	42.0%	-	-
Category (Unit)						
CC (kg CO_2 eq)	3.17	7.25	2.31	2.76	1.62	2.53
OD (kg CFC-11 eq)	2.30×10^{-7}	6.21×10^{-7}	1.73×10^{-7}	2.35×10^{-7}	1.47×10^{-7}	2.03×10^{-7}
HT, non-cancer effects (CTUh)	1.47×10^{-6}	2.56×10^{-6}	1.15×10^{-6}	1.24×10^{-6}	8.91×10^{-7}	1.20×10^{-6}
HT, cancer effects (CTUh)	1.52×10^{-7}	3.15×10^{-7}	1.03×10^{-7}	1.59×10^{-7}	1.28×10^{-7}	1.30×10^{-7}
PM (kg PM2.5 eq)	2.39×10^{-3}	5.49×10^{-3}	1.61×10^{-3}	2.56×10^{-3}	2.14×10^{-3}	2.07×10^{-3}
IR HH (kBq U235 eq)	0.309	0.813	0.204	0.421	0.288	0.310
IR E (interim) (CTUe)	2.33×10^{-6}	5.75×10^{-6}	1.60×10^{-6}	2.18×10^{-6}	8.55×10^{-7}	1.89×10^{-6}
POF (kg NMVOC eq)	9.96×10^{-3}	2.00×10^{-2}	8.13×10^{-3}	9.88×10^{-3}	7.54×10^{-3}	8.99×10^{-3}
AA (molc H+ eq)	2.58×10^{-2}	4.98×10^{-2}	1.77×10^{-2}	1.89×10^{-2}	1.06×10^{-2}	1.83×10^{-2}
TE (molc N eq)	7.86×10^{-2}	2.35×10^{-1}	5.78×10^{-2}	5.82×10^{-2}	3.71×10^{-2}	5.80×10^{-2}
FE (kg P eq)	9.55×10^{-4}	2.21×10^{-3}	5.40×10^{-4}	1.23×10^{-3}	1.06×10^{-3}	8.73×10^{-4}
ME (kg N eq)	5.96×10^{-3}	1.04×10^{-2}	4.38×10^{-3}	4.34×10^{-3}	2.75×10^{-3}	4.36×10^{-3}
FET (CTUe)	25.1	180	20.9	90.4	21.1	54.7
LU (kg C deficit)	67.4	61.9	62.1	48.2	41.6	55.3
WD (m^3 water eq)	1.85×10^{-2}	4.80×10^{-1}	6.78×10^{-3}	4.20×10^{-1}	3.84×10^{-1}	2.07×10^{-1}
MFRD (kg Sb eq)	7.19×10^{-4}	7.77×10^{-4}	4.22×10^{-4}	2.68×10^{-4}	8.28×10^{-5}	3.47×10^{-4}

Climate change (CC), global warming potential (GWP), ozone depletion (OD), human toxicity (HT), particulate matter (PM), ionizing radiation (IR), photochemical ozone formation (POF), acidification (AA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET), land use (LU), water resource depletion (WD), mineral, fossil and renewable resource depletion (MFRD).

Extensive irrigated, in particular, have the highest impact on the study, which is attributable to the high quantity of inputs resulting in the inventory. The most representative farmers in the survey of this case had a higher consumption than the rest, especially in fertilizers, which is a crucial element to determine the final EI. Irrigating is another one responsible for this high EI, due to the high water and electricity consumption in comparison with the other cases.

Values from both intensives have been mixed in the representative type shown with 42% of the area irrigated, reaching the quantity of 2.53 kg of CO_2 equivalent in the CC category.

Regarding the super-intensive case, its EI is lower than the rest because its inputs are not very substantial. By way of example, the activity of fertilizing uses organic matter, which is not considered an impact, and it does not apply PPP and herbicides in the field. It is one of the reasons why the olive yield is not much higher than the intensive irrigated one. In this case, the LCI considered is not representative of the type of current agricultural practice.

The values of EI in Turkey for the most representative case (intensive non-irrigated and irrigated) are shown by activities in Table 7 and, specifically for the CC category, in Figure 3. Attending to the EI of the mix representative value chain in CC category, fertilizers are responsible for 51.1% of the total EI, being the most impactful activity. They are followed by irrigating (18.6%), PPP and herbicides (11.9%) and soil management (10.3%) at the farming stage.

Table 7. Farming phase LCA of the intensive mix (non-irrigated and irrigated) type in Turkey (per 1 kg of VOO).

Category (Unit)	Total	PPP and Herbicides	Fertilizers	Harvesting	Irrigating	Pruning	Soil Management
CC (kg CO_2 eq)	2.53	0.299	1.29	0.0204	0.468	0.185	0.260
OD (kg CFC-11 eq)	2.03×10^{-7}	4.30×10^{-8}	8.11×10^{-8}	2.51×10^{-9}	3.36×10^{-8}	6.67×10^{-9}	3.62×10^{-8}
HT, non-cancer effects (CTUh)	1.20×10^{-6}	1.31×10^{-7}	5.11×10^{-7}	5.74×10^{-8}	1.49×10^{-7}	1.66×10^{-7}	1.81×10^{-7}
HT, cancer effects (CTUh)	1.30×10^{-7}	6.51×10^{-9}	5.69×10^{-8}	2.13×10^{-9}	3.79×10^{-8}	6.05×10^{-9}	2.09×10^{-8}
PM (kg PM2.5 eq)	2.07×10^{-3}	1.27×10^{-4}	8.33×10^{-4}	1.95×10^{-5}	6.10×10^{-4}	2.51×10^{-4}	2.33×10^{-4}
IR HH (kBq U235 eq)	3.10×10^{-1}	4.73×10^{-2}	1.13×10^{-1}	1.60×10^{-3}	1.26×10^{-1}	4.04×10^{-3}	1.77×10^{-2}
IR E (interim) (CTUe)	1.89×10^{-6}	7.63×10^{-7}	6.74×10^{-7}	7.51×10^{-9}	3.23×10^{-7}	1.93×10^{-8}	9.88×10^{-8}
POF (kg NMVOC eq)	8.99×10^{-3}	1.09×10^{-3}	3.49×10^{-3}	1.60×10^{-4}	1.15×10^{-3}	5.47×10^{-4}	2.56×10^{-3}
AA (molc H+ eq)	1.83×10^{-2}	2.00×10^{-3}	1.06×10^{-2}	1.63×10^{-4}	2.72×10^{-3}	5.40×10^{-4}	2.28×10^{-3}
TE (molc N eq)	5.80×10^{-2}	3.87×10^{-3}	3.69×10^{-2}	5.56×10^{-4}	4.50×10^{-3}	2.98×10^{-3}	9.19×10^{-3}
FE (kg P eq)	8.73×10^{-4}	2.28×10^{-5}	3.53×10^{-4}	6.15×10^{-6}	4.21×10^{-4}	1.63×10^{-5}	5.46×10^{-5}
ME (kg N eq)	4.36×10^{-3}	4.26×10^{-4}	2.45×10^{-3}	5.15×10^{-5}	4.53×10^{-4}	1.43×10^{-4}	8.43×10^{-4}
FET (CTUe)	54.7	34.3	10.7	0.184	7.39	0.642	1.41
LU (kg C deficit)	55.3	0.567	3.49	0.134	0.374	0.372	50.4
WD (m^3 water eq)	2.07×10^{-1}	6.82×10^{-5}	1.10×10^{-2}	-1.92×10^{-3}	2.04×10^{-1}	-5.42×10^{-3}	-4.39×10^{-4}
MFRD (kg Sb eq)	3.47×10^{-4}	1.48×10^{-5}	2.78×10^{-4}	5.77×10^{-6}	4.50×10^{-6}	1.62×10^{-5}	2.78×10^{-5}

Climate change (CC), global warming potential (GWP), ozone depletion (OD), human toxicity (HT), particulate matter (PM), ionizing radiation (IR), photochemical ozone formation (POF), acidification (AA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET), land use (LU), water resource depletion (WD), mineral, fossil and renewable resource depletion (MFRD).

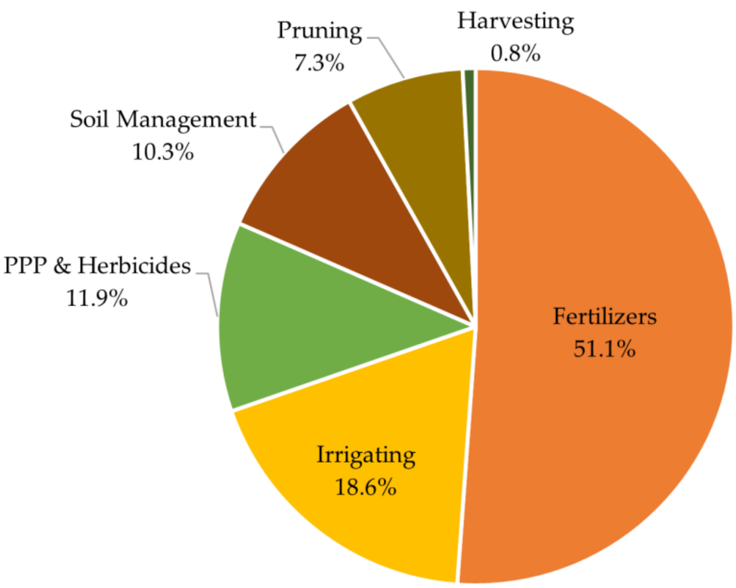

Figure 3. EI in the climate change category of the farming phase for the intensive mix type of tree crop in Turkey.

3.2. Industrial Phase

As already indicated, processes of two- and three-phases make up the industrial phase in Turkey. As they are representative processes in the olive oil value chain, they were both included in an industrial mix in the proportion of their representativeness (45% for the two-phase and 55% for the three-phase).

Thus, and following that rate, the EI due to the industrial phase in Turkey derives from the two- and three-phase mix, in a proportion of 45% and 55%, respectively. Results presented in Table 8 and Figure 4 show an EI in the CC category of 0.51 kg CO_2 eq per FU. The main reason for this high impact is the pomace treatment. Likewise, there are some gains in other categories caused by a rise in the inputs. The oil mill facility, as a significant example, has almost doubled its impact in this country because OOMs in

Turkey are less efficient in terms of m^2 of building per kg of olive oil produced, as the data collection indicated.

Table 8. Industrial phase LCA of the 2- and 3- phase mixes in Turkey, by activity (per 1 kg of VOO).

Type	2-Phase and 3-Phase (Mix)							
Category (Unit)	**Total**	**Oil Mill Facility**	**Management and Cleaning**	**Water**	**Electricity**	**Extraction**	**Pomace Treatment**	**Wastewater Treatment**
CC (kg CO_2 eq)	5.10×10^{-1}	2.68×10^{-2}	4.87×10^{-3}	9.99×10^{-4}	8.75×10^{-2}	4.69×10^{-2}	3.06×10^{-1}	3.76×10^{-2}
OD (kg CFC-11 eq)	1.10×10^{-8}	1.66×10^{-9}	6.19×10^{-10}	1.05×10^{-10}	3.05×10^{-9}	0.00	5.11×10^{-9}	4.98×10^{-10}
HT, non-cancer effects (CTUh)	6.59×10^{-8}	2.49×10^{-8}	1.56×10^{-9}	6.72×10^{-10}	2.57×10^{-8}	3.02×10^{-15}	9.68×10^{-9}	3.47×10^{-9}
HT, cancer effects (CTUh)	2.28×10^{-8}	1.22×10^{-8}	3.95×10^{-10}	4.68×10^{-10}	6.92×10^{-9}	1.19×10^{-14}	2.11×10^{-9}	7.12×10^{-10}
PM (kg PM2.5 eq)	2.51×10^{-4}	2.66×10^{-5}	5.01×10^{-6}	6.46×10^{-7}	1.96×10^{-4}	3.39×10^{-7}	1.25×10^{-5}	9.89×10^{-6}
IR HH (kBq U235 eq)	5.49×10^{-3}	1.36×10^{-3}	3.97×10^{-4}	3.54×10^{-4}	1.42×10^{-3}	0.00	1.52×10^{-3}	4.38×10^{-4}
IR E (interim) (CTUe)	2.35×10^{-8}	5.44×10^{-9}	1.48×10^{-9}	9.28×10^{-10}	4.78×10^{-9}	0.00	8.94×10^{-9}	1.89×10^{-9}
POF (kg NMVOC eq)	5.05×10^{-3}	1.07×10^{-4}	1.67×10^{-5}	3.05×10^{-6}	2.14×10^{-4}	1.95×10^{-6}	4.59×10^{-3}	1.68×10^{-5}
AA (molc H+ eq)	1.23×10^{-3}	2.19×10^{-4}	2.96×10^{-5}	6.09×10^{-6}	5.26×10^{-4}	1.54×10^{-6}	1.42×10^{-4}	3.07×10^{-4}
TE (molc N eq)	3.39×10^{-3}	7.01×10^{-4}	6.59×10^{-5}	1.16×10^{-5}	7.80×10^{-4}	8.95×10^{-6}	4.93×10^{-4}	1.33×10^{-3}
FE (kg P eq)	1.03×10^{-4}	1.28×10^{-5}	1.95×10^{-6}	7.64×10^{-7}	8.11×10^{-5}	0.00	4.27×10^{-6}	2.08×10^{-6}
ME (kg N eq)	2.05×10^{-4}	3.44×10^{-5}	8.91×10^{-6}	1.11×10^{-6}	8.38×10^{-5}	8.11×10^{-7}	4.56×10^{-5}	3.02×10^{-5}
FET (CTUe)	2.87	0.525	4.47×10^{-2}	1.58×10^{-2}	1.63	2.57×10^{-9}	0.611	4.86×10^{-2}
LU (kg C deficit)	0.858	0.624	1.17×10^{-2}	1.34×10^{-3}	3.67×10^{-2}	0.00	0.158	2.53×10^{-2}
WD (m^3 water eq)	-5.67×10^{-4}	-9.30×10^{-4}	3.46×10^{-5}	4.51×10^{-4}	1.42×10^{-4}	0.00	-1.39×10^{-4}	-1.26×10^{-4}
MFRD (kg Sb eq)	4.76×10^{-5}	4.12×10^{-5}	3.18×10^{-7}	7.99×10^{-8}	7.13×10^{-7}	0.00	5.20×10^{-6}	1.38×10^{-7}

Climate change (CC), global warming potential (GWP), ozone depletion (OD), human toxicity (HT), particulate matter (PM), ionizing radiation (IR), photochemical ozone formation (POF), acidification (AA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET), land use (LU), water resource depletion (WD), mineral, fossil and renewable resource depletion (MFRD).

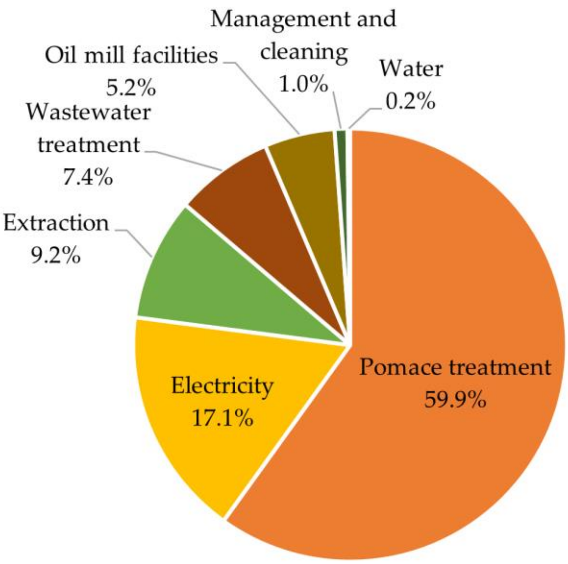

Figure 4. EI in the climate change category of the industrial phase (2- and 3-phase) in Turkey.

The CC category does not take into consideration the carbon emission source to establish the EI. The single impact category, "Global Warming Potential" (GWP), assumes that the biogenic carbon emitted does not impact the environment for that category since those carbon emissions (combustion of biomass, for example) were previously caught from the atmosphere along the growth of a plant or a tree.

In the farming phase, there are no considered biogenic carbon emissions in the LCI, and the GWP category offers values slightly higher than the CC category, resulting from a different method of analysis (IPCC 2013 GWP 100a vs. ILCD2011 Midpoint+ respectively). Table 9 includes, apart from the ILCD categories, the single-issue impact category GWP, which does not consider the impact of the biogenic carbon. The EI of the extraction processes differs depending on whether or not the biogenic carbon (GWP) is taken into account.

Table 9. Global LCA shown by phases and total EI, for every impact category (per 1 kg of VOO).

Impact Category (Unit)	Farming Phase	Industrial Phase	Farming + Industrial Phases
	Intensive Mix	2/3 Phase Mix	
CC (kg CO_2 eq)	2.53	0.510	3.04
OD (kg CFC-11 eq)	2.03×10^{-7}	1.10×10^{-8}	2.14×10^{-7}
HT, non-cancer effects (CTUh)	1.20×10^{-6}	6.59×10^{-8}	1.27×10^{-6}
HT, cancer effects (CTUh)	1.30×10^{-7}	2.28×10^{-8}	1.53×10^{-7}
PM (kg PM2.5 eq)	2.07×10^{-3}	2.51×10^{-4}	2.32×10^{-3}
IR HH (kBq U235 eq)	0.310	5.49×10^{-3}	0.315
IR E (interim) (CTUe)	1.89×10^{-6}	2.35×10^{-8}	1.91×10^{-6}
POF (kg NMVOC eq)	8.99×10^{-3}	5.05×10^{-3}	1.40×10^{-2}
AA (molc H+ eq)	1.83×10^{-2}	1.23×10^{-3}	1.95×10^{-2}
TE (molc N eq)	5.80×10^{-2}	3.39×10^{-3}	6.14×10^{-2}
FE (kg P eq)	8.73×10^{-4}	1.03×10^{-4}	9.76×10^{-4}
ME (kg N eq)	4.36×10^{-3}	2.05×10^{-4}	4.57×10^{-3}
FET (CTUe)	54.7	2.87	57.6
LU (kg C deficit)	55.3	0.858	56.2
WD (m^3 water eq)	0.207	-5.67×10^{-4}	0.206
MFRD (kg Sb eq)	3.47×10^{-4}	4.76×10^{-5}	3.95×10^{-4}

Climate change (CC), global warming potential (GWP), ozone depletion (OD), human toxicity (HT), particulate matter (PM), ionizing radiation (IR), photochemical ozone formation (POF), acidification (AA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET), land use (LU), water resource depletion (WD), mineral, fossil and renewable resource depletion (MFRD).

From a more widespread vision to a more particular one of the EI behavior of olive oil production in Turkey, the data are shown in the following figures. In Figure 5, it is possible to observe the distribution of EI between the different phases for 1 kg of VOO expressed as a percentage. It reveals farming phase is the most impactful stage for all categories of EI, where freshwater ecotoxicity and LU are those with the highest values. On the other hand, within the industrial phase, ozone depletion and water resource depletion are the categories with the lowest values. Indeed, the latest (water resource depletion) has a negative value in this phase, which means that it does not negatively impact the environment.

Figure 5. EI rate in the farming phase and the industrial phase for 1 kg of VOO. Climate change (CC), global warming potential (GWP), ozone depletion (OD), human toxicity (HT), particulate matter (PM), ionizing radiation (IR), photochemical ozone formation (POF), acidification (AA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET), land use (LU), water resource depletion (WD), mineral, fossil and renewable resource depletion (MFRD).

Focusing on each phase separately, Figures 6 and 7 extensively show how each activity contributes to the EI of the most representative value chain in Turkey in all categories. Figure 6 refers to the activities of the agricultural phase for the intensive irrigated–rainfed mix, and Figure 7 alludes to the activities of the industrial one for the two- and three-phase mix.

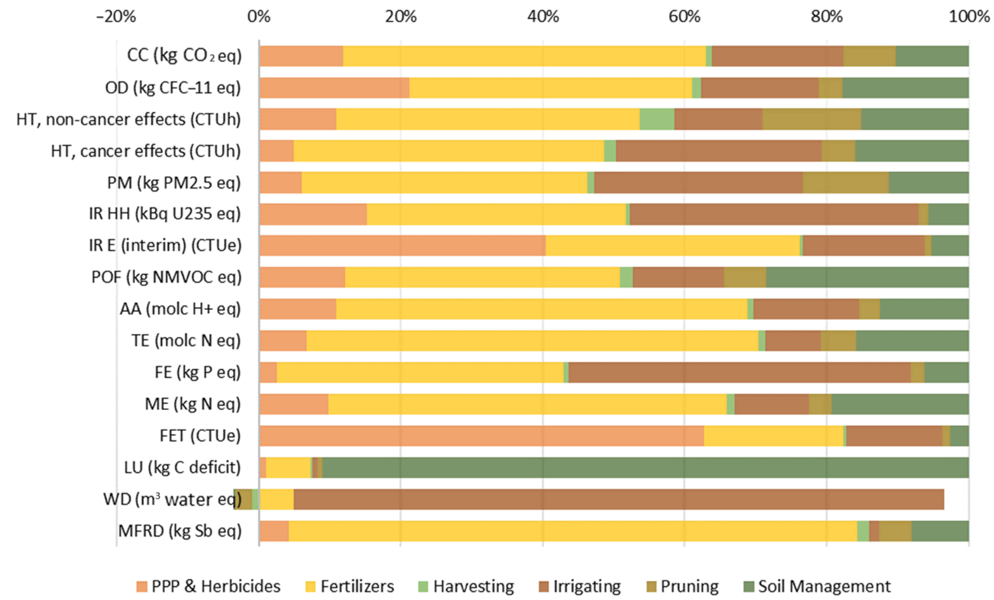

Figure 6. Contribution of farming phase activities. Climate change (CC), global warming potential (GWP), ozone depletion (OD), human toxicity (HT), particulate matter (PM), ionizing radiation (IR), photochemical ozone formation (POF), acidification (AA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET), land use (LU), water resource depletion (WD), mineral, fossil and renewable resource depletion (MFRD).

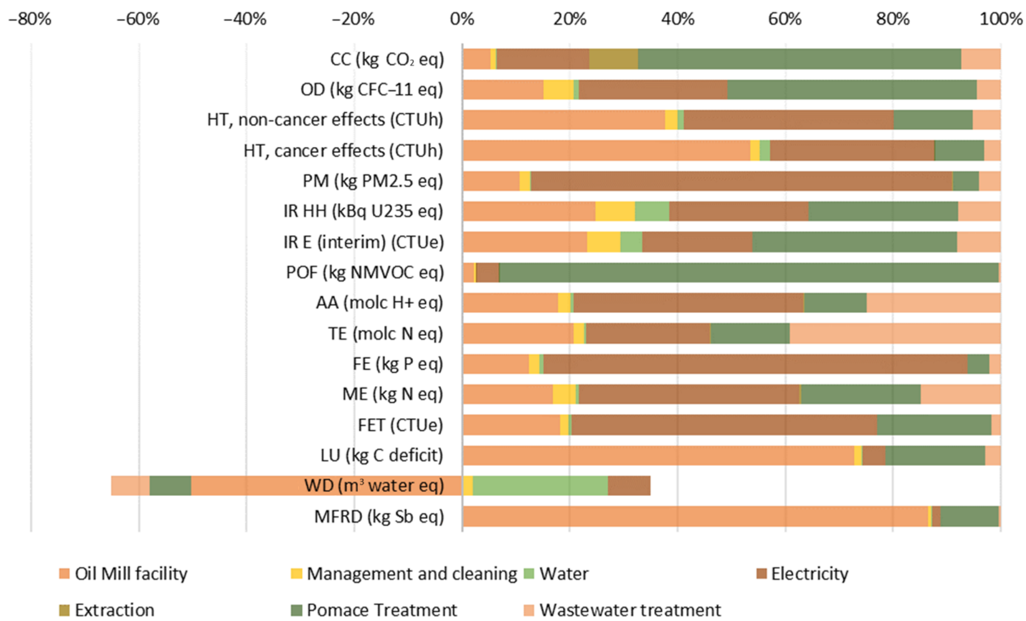

Figure 7. Contribution of industrial phase activities. Climate change (CC), global warming potential (GWP), ozone depletion (OD), human toxicity (HT), particulate matter (PM), ionizing radiation (IR), photochemical ozone formation (POF), acidification (AA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET), land use (LU), water resource depletion (WD), mineral, fossil and renewable resource depletion (MFRD).

The first of those figures brings to light one more time that PPP and herbicides and fertilizers together entail more than 50% of the EI for almost all categories and not only for CC, except for land use and water resource depletion. The second one, for its part, has a varied distribution pattern. Even if focusing on the CC category, pomace treatment would be mainly responsible for the EI in the industrial phase.

4. Discussion

It is possible to compare these results with those obtained for Spain (the worldwide largest olive oil producer) or Tunisia (the principal worldwide olive oil producer outside of the EU) since similar studies with the same methodology have been performed in these countries [26,27]. The farming phase also obtained higher values than the industrial one. Specifically, for the CC category, Spain reached 2.28 and 0.62 kg of CO_2 equivalent for the farming and the industrial phase, respectively, and Tunisia, for its part, acquired 3.14 and 0.39 kg of CO_2 equivalent for their most representative value chains. Furthermore, Tunisia is the only country with the most representative olive oil value chain that does not negatively impact water resource depletion because its representative cultivation method is rainfed. In other words, most of the Tunisian crops only obtain water when it rains, without appreciable impacts in water resources.

The values of impact obtained vary depending on the impact category, region, countries' particularities and type of tree crop. According to the farming phase, Tunisia is, on average, the most impactful one among those three countries. Turkey and Spain produce an EI that, depending on the category, may be higher for one or the other cases. The main difference among them is the system used, which has more consumption and olive yield in the case of Turkey, and apparently more land use in the case of Tunisia. Focusing on the most important category, CC, Tunisia is also the most impactful. On the other hand, with regard to the industrial phase, the LCA values are in the same order for most categories. Particularly in the CC category, the values are highly influenced by the quantity of exhausted pomace burned to dry the pomace from two- or three-phase systems.

In Figures 8 and 9, it is possible to observe the rate of EI that every country produces in the different categories for 1 kg of VOOs. They correspond to the farming phase and industrial phase, respectively.

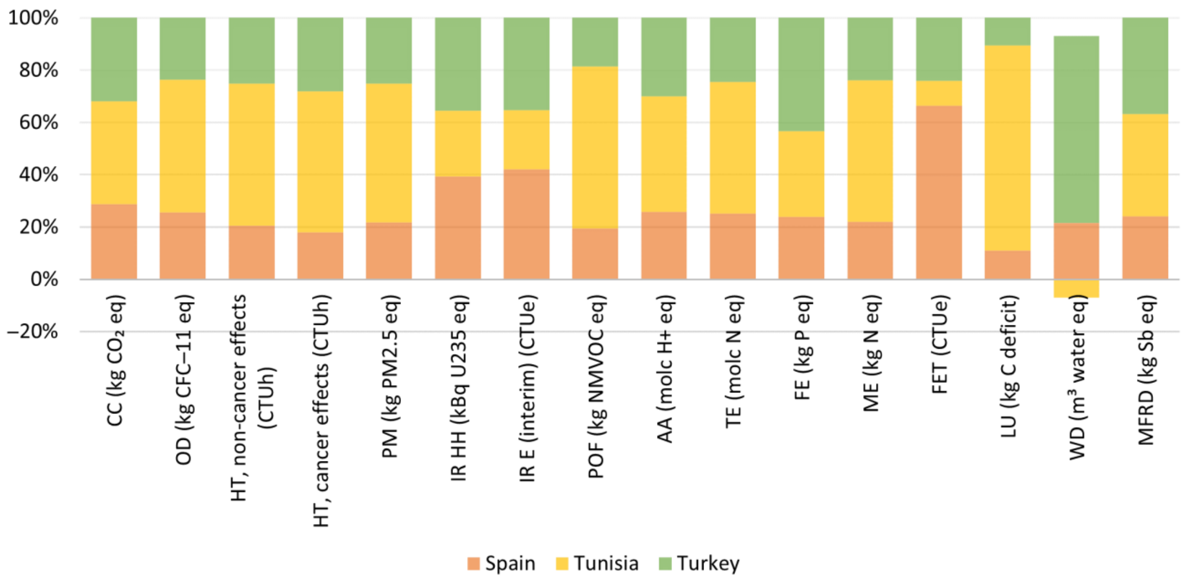

Figure 8. Rate of EI in the farming phase for 1 kg of VOO. Climate change (CC), global warming potential (GWP), ozone depletion (OD), human toxicity (HT), particulate matter (PM), ionizing radiation (IR), photochemical ozone formation (POF), acidification (AA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET), land use (LU), water resource depletion (WD), mineral, fossil and renewable resource depletion (MFRD).

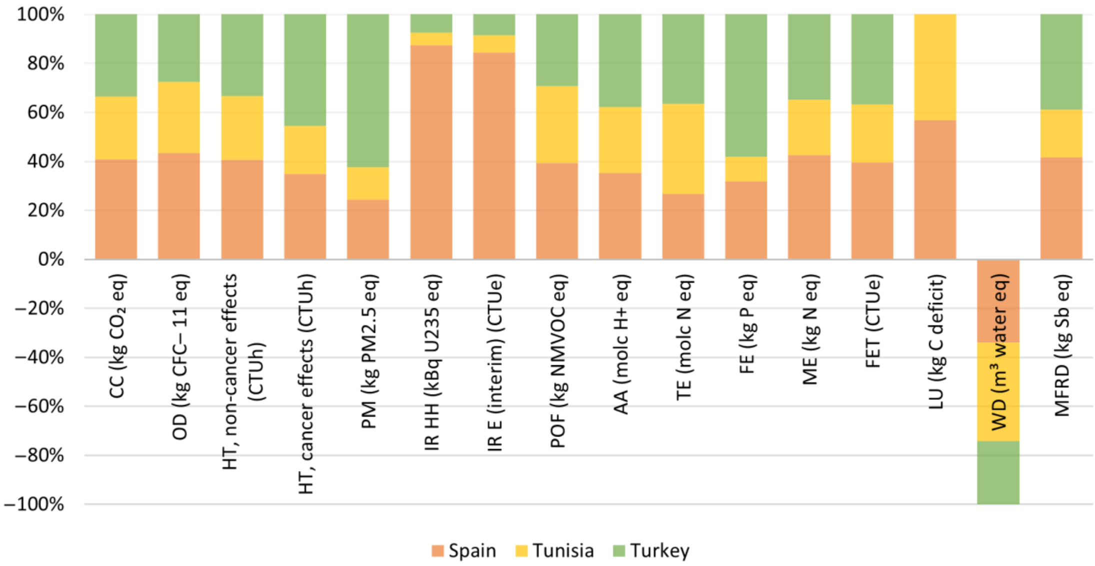

Figure 9. Rate of EI in the industrial phase for 1 kg of VOO. Climate change (CC), global warming potential (GWP), ozone depletion (OD), human toxicity (HT), particulate matter (PM), ionizing radiation (IR), photochemical ozone formation (POF), acidification (AA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET), land use (LU), water resource depletion (WD), mineral, fossil and renewable resource depletion (MFRD).

Summarizing, the global behavior in all categories of those three countries' EI has been compared with a logarithmic scale in Figure 10. In this graphic, it can be observed how Tunisia is, by far, the most impactful country in most categories (14 of 16 categories), while Spain and Turkey have more similar values between them. It is a consequence of the high importance of the farming phase, which is responsible for most differences between values.

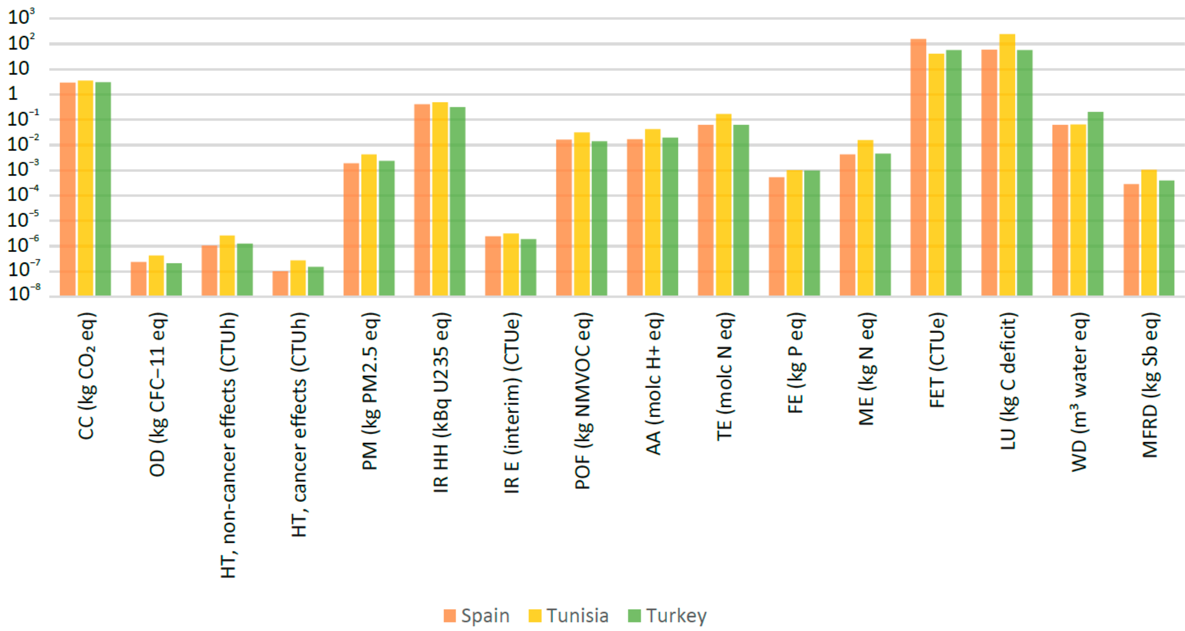

Figure 10. Environmental impact of Spain, Tunisia and Turkey, for all impact categories (per 1 kg of VOO). Climate change (CC), global warming potential (GWP), ozone depletion (OD), human toxicity (HT), particulate matter (PM), ionizing radiation (IR), photochemical ozone formation (POF), acidification (AA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET), land use (LU), water resource depletion (WD), mineral, fossil and renewable resource depletion (MFRD).

Apart from the comparison with other scientific papers, results have been measured according to recent reports and official documents related to LCA in olive oil production. The most indicated documents to stablish relations are Annex III (benchmark and classes of environmental performance) of the PEFCR [47] and supporting studies such as the Environmental Product Declarations (EPDs) of VOO [69]. According to the first, it is possible to grade, on a scale from E (worst case) to A (best case), the EI obtained in every impact category for the FU considered, in a "cradle-to-gate" scope. In this case, every result is placed in grade A, because the scope of the study covers fewer processes than the ones required. However, by comparing with farming and industrial phases of another EPDs, we could confirm that EI values are intermediate in relation to those obtained by commercial VOO [70–73].

Assessing the by-products influence over the LCA needs an analysis of the economic allocation of VOOs in each country. In Spain, in order to make the two-phase pomace profitable, the pomace treatment vaporizes most of the water contents to extract a small amount of crude pomace olive oil, while the leftovers are sold as fuel (exhausted pomace). The three-phase pomace is used as fuel in Tunisia and can be used in Turkey for animal feeding or fertilizer. By the same token as Spain, Turkey produces two-phase pomace, and the exhausted pomace that comes from it is valuable. In Spain, the by-products are becoming more valuable, which makes its value chain more competitive. Meanwhile, in Tunisia, the main derivative product has a low value, and Turkey has an intermediate position since it consumes some generated by-products but it does not have a robust market for crude pomace olive oil. Due to that economic allocation, the EI per FU in the farming and industrial phases could be reduced by 7.64% in Spain, 0.80% in Tunisia and 3.12% in Turkey.

5. Conclusions

The importance of realizing the environmental footprint of olive groves, based on the provisions of the LCA, is crucial to advance the goal of a sustainable olive grove management system. Policies to support adaptation and mitigation of CC will need to be based on quantitative information and, with regard to the Mediterranean basin, it is highly important to know and evaluate olive groves.

The LCA over the VOO production of the most representative value chain in Turkey determines a value of 3.04 kg of CO_2 equivalent per 1 kg of produced VOO in CC category. This value comes mainly from the farming phase (83.2%). Within the farming phase, fertilizers and irrigating become those principal responsible for its impact (69.5 % of the CC in this phase). In the industrial phase, pomace treatment signifies 60% of the CC category in this phase. Due to their respective economic allocation, the EI of the FU can be reduced by 3.12%. Together, PPP and herbicides and fertilizers entail more than 50% of the EI for almost all categories, not only for CC (except for land use and water resource depletion).

Some suggestions regarding sustainability at a farming stage could include long-term carbon sequestration in soils, LCAs to other life cycle stages, biological strategies or technical and technological improvements. Applying good agricultural practices is essential to guarantee the sustainability of Turkish olive groves, besides the fact that it increases yields in rainfed conditions. Nevertheless, optimizing water and energy supplies for irrigated crops in Turkey is also essential to maximize production by employing the minimum possible cultivation area sustainably.

The most notable challenges to face in the industrial phase are the use of energy and the treatment of by-products and residues. It could be improved with some encouraging solutions such as (a) backing renewable sources of energy, for instance, photovoltaic systems; (b) favoring the increasing of two-phase extraction systems over those of three-phase; (c) optimizing transport at all stages of the value chain; (d) including new and original technologies, such as pyrolysis or gasification, to raise energy efficiency.

This work contributes to the research on LCA of VOO production through different agricultural and industrial systems. In such way, it may favor decision making, in an objective manner, to achieve a more sustainable development of the olive oil value chain worldwide.

Author Contributions: Conceptualization, B.R.-C., L.F.-L., Y.L.-S. and D.V.; methodology, B.R.-C. and L.F.-L.; software, D.V.; validation, Y.L.-S. and D.V.; formal analysis, Y.L.-S. and D.V.; investigation, B.R.-C., L.F.-L. and Y.L.-S.; resources, D.V.; data curation, L.F.-L.; writing—original draft preparation, B.R.-C., L.F.-L. and Y.L.-S.; writing—review and editing, Y.L.-S. and D.V.; visualization, B.R.-C.; supervision, Y.L.-S. and D.V.; project administration, D.V.; funding acquisition, D.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research work was supported by the project entitled "Hacia una producción sostenible y sin residuos en la industria oleícola: un modelo de economía circular" (Ref. No. 1381442), cofunded by Programa Operativo FEDER 2014–2020 and Consejería de Economía y Conocimiento de la Junta de Andalucía of the Spanish Government. This work has been supported by the Project "Opportunities for olive oil value chain enhancement through the by-products valorization (OLIVEN)" funded through the ARIMNet2 2017 Joint Call by the funding agency: Agencia Estatal de Investigación (Spain), PCI2018-093255. ARIMNet2 (ERANET) has received funding from the European Union's Seventh Framework Program for research, technological development and demonstration under grant agreement no. 618127.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors deeply appreciate the technical support and assistance of Şahnur Irmak and his research team from the Olive Research Institute (Turkey) during the data collection phase of the olive farming cultivation in Turkey.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cook, J.; Oreskes, N.; Doran, P.T.; Anderegg, W.R.L.; Verheggen, B.; Maibach, E.W.; Carlton, J.S.; Lewandowsky, S.; Skuce, A.G.; Green, S.A.; et al. Consensus on Consensus: A Synthesis of Consensus Estimates on Human-Caused Global Warming. Environ. *Res. Lett.* **2016**, *11*, 048002. [CrossRef]
2. Cook, J.; Nuccitelli, D.; Green, S.A.; Richardson, M.; Winkler, B.; Painting, R.; Way, R.; Jacobs, P.; Skuce, A. Quantifying the Consensus on Anthropogenic Global Warming in the Scientific Literature. *Environ. Res. Lett.* **2013**, *8*, 024024. [CrossRef]
3. Agovino, M.; Casaccia, M.; Ciommi, M.; Ferrara, M.; Marchesano, K. Agriculture, Climate Change and Sustainability: The Case of EU-28. *Ecol. Indic.* **2019**, *105*, 525–543. [CrossRef]
4. McCarl, B.A. Analysis of Climate Change Implications for Agriculture and Forestry: An Interdisciplinary Effort. *Clim. Chang.* **2010**, *100*, 119–124. [CrossRef]
5. FAOSTAT. Available online: http://www.fao.org/faostat/en/#home (accessed on 14 April 2021).
6. Breton, C.; Guerin, J.; Ducatillion, C.; Médail, F.; Kull, C.A.; Bervillé, A. Taming the Wild and "wilding" the Tame: Tree Breeding and Dispersal in Australia and the Mediterranean. *Plant Sci.* **2008**, *175*, 197–205. [CrossRef]
7. International Olive Oil Council World Olive Oil Figures. Available online: http://www.internationaloliveoil.org/estaticos/view/131-world-olive-oil-figures (accessed on 17 October 2022).
8. Ozturk, M.; Altay, V.; Gönenç, T.M.; Unal, B.T.; Efe, R.; Akçiçek, E.; Bukhari, A. An Overview of Olive Cultivation in Turkey: Botanical Features, Eco-Physiology and Phytochemical Aspects. *Agronomy* **2021**, *11*, 295. [CrossRef]
9. Souilem, S.; El-Abbassi, A.; Kiai, H.; Hafidi, A.; Sayadi, S.; Galanakis, C.M. Olive Oil Production Sector: Environmental Effects and Sustainability Challenges. In *Olive Mill Waste: Recent Advances for Sustainable Management*; Elsevier Inc.: Amsterdam, The Netherlands, 2017; pp. 1–28. [CrossRef]
10. IOOC. *General Description of Olive Growning in Turkey*; IOOC: Tehran, Iran, 2012; Volume 20.
11. Zbakh, H.; El Abbassi, A. Potential Use of Olive Mill Wastewater in the Preparation of Functional Beverages: A Review. *J. Funct. Foods* **2012**, *4*, 53–65. [CrossRef]
12. Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Norris, G.; Rydberg, T.; Schmidt, W.P.; Suh, S.; Weidema, B.P.; Pennington, D.W. Life Cycle Assessment Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications. *Environ. Int.* **2004**, *30*, 701–720. [CrossRef]
13. Karkour, S.; Rachid, S.; Maaoui, M.; Lin, C.-C.; Itsubo, N. Status of Life Cycle Assessment (LCA) in Africa. *Environments* **2021**, *8*, 10. [CrossRef]

14. Espadas-Aldana, G.; Vialle, C.; Belaud, J.-P.P.; Vaca-Garcia, C.; Sablayrolles, C. Analysis and Trends for Life Cycle Assessment of Olive Oil Production. *Sustain. Prod. Consum.* **2019**, *19*, 216–230. [CrossRef]
15. Russo, C.; Cappelletti, G.M.; Nicoletti, G.M.; Di Noia, A.E.; Michalopoulos, G. Comparison of European Olive Production Systems. *Sustainability* **2016**, *8*, 825. [CrossRef]
16. Blanco, I.; De Bellis, L.; Luvisi, A. Bibliometric Mapping of Research on Life Cycle Assessment of Olive Oil Supply Chain. *Sustainability* **2022**, *14*, 3747. [CrossRef]
17. El Joumri, L.; Labjar, N.; Dalimi, M.; Harti, S.; Dhiba, D.; El Messaoudi, N.; Bonnefille, S.; El Hajjaji, S. Life Cycle Assessment (LCA) in the Olive Oil Value Chain: A Descriptive Review. *Environ. Dev.* **2023**, *45*, 100800. [CrossRef]
18. Guarino, F.; Falcone, G.; Stillitano, T.; De Luca, A.I.; Gulisano, G.; Mistretta, M.; Strano, A. Life Cycle Assessment of Olive Oil: A Case Study in Southern Italy. *J. Environ. Manag.* **2019**, *238*, 396–407. [CrossRef]
19. Restuccia, D.; Prencipe, S.A.; Ruggeri, M.; Spizzirri, U.G. Sustainability Assessment of Different Extra Virgin Olive Oil Extraction Methods through a Life Cycle Thinking Approach: Challenges and Opportunities in the Elaio-Technical Sector. *Sustainability* **2022**, *14*, 15674. [CrossRef]
20. Batuecas, E.; Tommasi, T.; Battista, F.; Negro, V.; Sonetti, G.; Viotti, P.; Fino, D.; Mancini, G. Life Cycle Assessment of Waste Disposal from Olive Oil Production: Anaerobic Digestion and Conventional Disposal on Soil. *J. Environ. Manag.* **2019**, *237*, 94–102. [CrossRef]
21. De Luca, A.I.; Falcone, G.; Stillitano, T.; Iofrida, N.; Strano, A.; Gulisano, G. Evaluation of Sustainable Innovations in Olive Growing Systems: A Life Cycle Sustainability Assessment Case Study in Southern Italy. *J. Clean. Prod.* **2018**, *171*, 1187–1202. [CrossRef]
22. Romero-Gámez, M.; Castro-Rodríguez, J.; Suárez-Rey, E.M. Optimization of Olive Growing Practices in Spain from a Life Cycle Assessment Perspective. *J. Clean. Prod.* **2017**, *149*, 25–37. [CrossRef]
23. Navarro, A.; Puig, R.; Martí, E.; Bala, A.; Fullana-i-Palmer, P. Tackling the Relevance of Packaging in Life Cycle Assessment of Virgin Olive Oil and the Environmental Consequences of Regulation. *Environ. Manag.* **2018**, *62*, 277–294. [CrossRef]
24. Parascanu, M.M.; Puig Gamero, M.; Sánchez, P.; Soreanu, G.; Valverde, J.L.; Sanchez-Silva, L. Life Cycle Assessment of Olive Pomace Valorisation through Pyrolysis. *Renew. Energy* **2018**, *122*, 589–601. [CrossRef]
25. Parascanu, M.M.; Sánchez, P.; Soreanu, G.; Valverde, J.L.; Sanchez-Silva, L.; Puig Gamero, M.; Sánchez, P.; Soreanu, G.; Valverde, J.L.; Sanchez-Silva, L. Environmental Assessment of Olive Pomace Valorization through Two Different Thermochemical Processes for Energy Production. *J. Clean. Prod.* **2018**, *186*, 771–781. [CrossRef]
26. Fernández-Lobato, L.; López-Sánchez, Y.; Blejman, G.; Jurado, F.; Moyano-Fuentes, J.; Vera, D. Life Cycle Assessment of the Spanish Virgin Olive Oil Production: A Case Study for Andalusian Region. *J. Clean. Prod.* **2021**, *290*, 125677. [CrossRef]
27. Fernández-Lobato, L.; López-Sánchez, Y.; Baccar, R.; Fendri, M.; Vera, D. Life Cycle Assessment of the Most Representative Virgin Olive Oil Production Systems in Tunisia. *Sustain. Prod. Consum.* **2022**, *32*, 908–923. [CrossRef]
28. Fotia, K.; Mehmeti, A.; Tsirogiannis, I.; Nanos, G.; Mamolos, A.P.; Malamos, N.; Barouchas, P.; Todorovic, M. Lca-Based Environmental Performance of Olive Cultivation in Northwestern Greece: From Rainfed to Irrigated through Conventional and Smart Crop Management Practices. *Water* **2021**, *13*, 1954. [CrossRef]
29. Tsarouhas, P.; Achillas, C.; Aidonis, D.; Folinas, D.; Maslis, V. Life Cycle Assessment of Olive Oil Production in Greece. *J. Clean. Prod.* **2015**, *93*, 75–83. [CrossRef]
30. Chatzisymeon, E.; Foteinis, S.; Mantzavinos, D.; Tsoutsos, T. Life Cycle Assessment of Advanced Oxidation Processes for Olive Mill Wastewater Treatment. *J. Clean. Prod.* **2013**, *54*, 229–234. [CrossRef]
31. Kalogerakis, N.; Politi, M.; Foteinis, S.; Chatzisymeon, E.; Mantzavinos, D. Recovery of Antioxidants from Olive Mill Wastewaters: A Viable Solution That Promotes Their Overall Sustainable Management. *J. Environ. Manag.* **2013**, *128*, 749–758. [CrossRef]
32. Ramos, J.S.; Ferreira, A.F. Techno-Economic Analysis and Life Cycle Assessment of Olive and Wine Industry Co-Products Valorisation. *Renew. Sustain. Energy Rev.* **2022**, *155*, 111929. [CrossRef]
33. Todde, G.; Murgia, L.; Deligios, P.A.; Hogan, R.; Carrelo, I.; Moreira, M.; Pazzona, A.; Ledda, L.; Narvarte, L. Energy and Environmental Performances of Hybrid Photovoltaic Irrigation Systems in Mediterranean Intensive and Super-Intensive Olive Orchards. *Sci. Total Environ.* **2019**, *651*, 2514–2523. [CrossRef]
34. Rahmani, A.; Gholami Parashkoohi, M.; Mohammad Zamani, D. Sustainability of Environmental Impacts and Life Cycle Energy and Economic Analysis for Different Methods of Grape and Olive Production. *Energy Rep.* **2022**, *8*, 2778–2792. [CrossRef]
35. Rajaeifar, M.A.; Akram, A.; Ghobadian, B.; Rafiee, S.; Heijungs, R.; Tabatabaei, M. Environmental Impact Assessment of Olive Pomace Oil Biodiesel Production and Consumption: A Comparative Lifecycle Assessment. *Energy* **2016**, *106*, 87–102. [CrossRef]
36. Christoforou, E.A.; Fokaides, P.A. Life Cycle Assessment (LCA) of Olive Husk Torrefaction. *Renew. Energy* **2016**, *90*, 257–266. [CrossRef]
37. Avraamides, M.; Fatta, D. Resource Consumption and Emissions from Olive Oil Production: A Life Cycle Inventory Case Study in Cyprus. *J. Clean. Prod.* **2008**, *16*, 809–821. [CrossRef]
38. Hjaila, K.; Baccar, R.; Sarrà, M.; Gasol, C.M.; Blánquez, P. Environmental Impact Associated with Activated Carbon Preparation from Olive-Waste Cake via Life Cycle Assessment. *J. Environ. Manag.* **2013**, *130*, 242–247. [CrossRef] [PubMed]
39. Ben Abdallah, S.; Elfkih, S.; Suárez-Rey, E.M.; Parra-López, C.; Romero-Gámez, M. Evaluation of the Environmental Sustainability in the Olive Growing Systems in Tunisia. *J. Clean. Prod.* **2021**, *282*, 124526. [CrossRef]

40. Ben Abdallah, S.; Parra-López, C.; Elfkih, S.; Suárez-Rey, E.M.; Romero-Gámez, M. Sustainability Assessment of Traditional, Intensive and Highly-Intensive Olive Growing Systems in Tunisia by Integrating Life Cycle and Multicriteria Decision Analyses. *Sustain. Prod. Consum.* **2022**, *33*, 73–87. [CrossRef]
41. Özilgen, M.; Sorgüven, E. Energy and Exergy Utilization, and Carbon Dioxide Emission in Vegetable Oil Production. *Energy* **2011**, *36*, 5954–5967. [CrossRef]
42. Duman, A.K.; Özgen, G.Ö.; Üçtuğ, F.G. Environmental Life Cycle Assessment of Olive Pomace Utilization in Turkey. *Sustain. Prod. Consum.* **2020**, *22*, 126–137. [CrossRef]
43. Kara, F.; Bas, T.; TIrmandioğlu Talu, N.H.; Alola, A.A. Investigating the Carbon Emission Aspects of Agricultural Land Utilization in Turkey. *Integr. Environ. Assess. Manag.* **2022**, *18*, 988–996. [CrossRef]
44. Muralikrishna, I.V.; Manickam, V. *Environmental Management: Science and Engineering for Industry*; Butterworth-Heinemann: Oxford, UK, 2017; ISBN 9780128119907.
45. *ISO 14040*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
46. *ISO 14044*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
47. Schau, E.M.; Palomino, J.A.P.; Michalopoulos, G.; Russo, C. *Product Environmental Footprint Category Rules for Olive Oil. Draft for 3rd Public Consultation Phase*; European Commission: Brussels, Belgium, 2016.
48. Benini, L.; Mancini, L.; Sala, S.; Schau, E.; Manfredi, S.; Pant, R. *Normalisation Method and Data for Environmental Footprints*; European Union: Luxembourg, 2014; ISBN 9789279408472.
49. European Commission Recommendation 2013/179/EU on the Use of Common Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations. *Off. J. Eur. Union* **2013**, *210*, 1–214. [CrossRef]
50. Lehmann, A.; Bach, V.; Finkbeiner, M. Product Environmental Footprint in Policy and Market Decisions: Applicability and Impact Assessment. *Integr. Environ. Assess. Manag.* **2015**, *11*, 417–424. [CrossRef] [PubMed]
51. Russo, C.; Cappelletti, G.M.; Nicoletti, G.M.; Michalopoulos, G.; Pattara, C.; Palomino, J.A.P.; Tuomisto, H.L. Product Environmental Footprint in the Olive Oil Sector: State of the Art. *Environ. Eng. Manag. J.* **2016**, *15*, 2019–2027. [CrossRef]
52. Olive Oil—International Olive Council. Designations and Definitions of Olive Oil. Available online: https://www.internationaloliveoil.org/olive-world/olive-oil/ (accessed on 20 May 2023).
53. Maffia, A.; Pergola, M.; Palese, A.M.; Celano, G. Environmental Impact Assessment of Organic vs. Integrated Olive-Oil Systems in Mediterranean Context. *Agronomy* **2020**, *10*, 416. [CrossRef]
54. Proietti, S.; Sdringola, P.; Regni, L.; Evangelisti, N.; Brunori, A.; Ilarioni, L.; Nasini, L.; Proietti, P. Extra Virgin Olive Oil as Carbon Negative Product: Experimental Analysis and Validation of Results. *J. Clean. Prod.* **2017**, *166*, 550–562. [CrossRef]
55. Rinaldi, S.; Barbanera, M.; Lascaro, E. Assessment of Carbon Footprint and Energy Performance of the Extra Virgin Olive Oil Chain in Umbria, Italy. *Sci. Total Environ.* **2014**, *482–483*, 71–79. [CrossRef]
56. El Hanandeh, A.; Gharaibeh, M.A. Environmental Efficiency of Olive Oil Production by Small and Micro-Scale Farmers in Northern Jordan: Life Cycle Assessment. *Agric. Syst.* **2016**, *148*, 169–177. [CrossRef]
57. Rajaeifar, M.A.; Akram, A.; Ghobadian, B.; Rafiee, S.; Heidari, M.D. Energy-Economic Life Cycle Assessment (LCA) and Greenhouse Gas Emissions Analysis of Olive Oil Production in Iran. *Energy* **2014**, *66*, 139–149. [CrossRef]
58. Olive Research Institute. *Olive Research Institute 2020 Report*; Olive Research Institute: Izmir, Turkey, 2020.
59. Proietti, S.; Sdringola, P.; Desideri, U.; Zepparelli, F.; Brunori, A.; Ilarioni, L.; Nasini, L.; Regni, L.; Proietti, P. Carbon Footprint of an Olive Tree Grove. *Appl. Energy* **2014**, *127*, 115–124. [CrossRef]
60. CML—Department of Industrial Ecology CML-IA Characterisation Factors. Available online: https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors#downloads (accessed on 23 January 2020).
61. Islam, S.; Ponnambalam, S.G.; Lam, H.L. Review on Life Cycle Inventory: Methods, Examples and Applications. *J. Clean. Prod.* **2016**, *136*, 266–278. [CrossRef]
62. Salomone, R.; Cappelletti, G.M.; Malandrino, O.; Mistretta, M.; Neri, E.; Nicoletti, G.M.; Notarnicola, B.; Pattara, C.; Russo, C.; Saija, G. *Life Cycle Assessment in the Olive Oil Sector*; Springer: Cham, Switzerland, 2015; ISBN 9783319119403.
63. Salomone, R.; Ioppolo, G. Environmental Impacts of Olive Oil Production: A Life Cycle Assessment Case Study in the Province of Messina (Sicily). *J. Clean. Prod.* **2012**, *28*, 88–100. [CrossRef]
64. The British Standards Institution. *Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services*; The British Standards Institution: London, UK, 2011.
65. Jellali, A.; Hachicha, W.; Aljuaid, A.M. Sustainable Configuration of the Tunisian Olive Oil Supply Chain Using a Fuzzy TOPSIS-based Approach. *Sustainability* **2021**, *13*, 722. [CrossRef]
66. (CAR/PL). *Prevención de La Contaminación En La Producción de Aceite de Oliva*; Regional Activity Centre for Sustainable Consumption and Production: Barcelona, Spain, 1998.
67. Vera, D. *Generación Eléctrica Distribuida y Aprovechamiento de Los Residuos de La Industria Del Olivar*; University of Jaen: Jaen, Spain, 2013.
68. Notarnicola, B.; Salomone, R.; Petti, L.; Renzulli, P.A.; Roma, R.; Cerutti, A.K. *Life Cycle Assessment in the Agri-Food Sector*; Springer: Cham, Switzerland, 2015; ISBN 9788578110796.
69. Environdec. *The EPD | EPD International*; Environdec: Stockholm, Sweden, 2023.
70. Environdec. *Environmental Product Declaration for Sellás Olive Oil*; Environdec: Stockholm, Sweden, 2013.
71. Environdec. *Environmental Product Declaration for Borges Olive Oil*; Environdec: Stockholm, Sweden, 2021.

72. Environdec. *Environmental Product Declaration for Monini Olive Oil*; Environdec: Stockholm, Sweden, 2023.
73. Environdec. *Environmental Product Declaration for De Cecco Olive Oil*; Environdec: Stockholm, Sweden, 2017.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.