Life cycle assessment of the most representative virgin olive oil production systems in Tunisia

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ABSTRACT

This study aims to analyze the environmental impacts of Tunisian olive oil production using a "cradle to gate" Life Cycle Assessment (LCA) in order to quantify, compare and establish the most environmentally sustainable practices. This is the first LCA study in Tunisia that covers together the agricultural and industrial activities of one of their most important product value chains. This analysis considers the main olive grove cultivation systems in Tunisia (extensive, intensive, and super intensive) as well as the main extraction systems (press, 3-phase and 2-3 phase combined system). Sixteen categories of environmental impact were assessed following the guidelines set down by the "Product Environmental Footprint Category Rules" for olive oil established by the European Commission. Through the results obtained, it is possible to identify which is the most impactful of the main types of cultivation and extraction systems considered for every impact category individually. As representative values, the impact in climate change category for the most representative value chain (extensive crops and 3 phase extraction) is 3.29 kg CO_2 eq. per kg of olive oil without considering biogenic C and 3.53 kg CO_2 eq. if biogenic C is considered. The study determines that agricultural activities represent the heaviest contribution in all impact categories for the most representative value chain (from 84.7% in photochemical ozone formation to 99.9% in land use). Therefore, efforts should be focused on reducing the impact of the agricultural stage and reaching a high olive oil yield to reduce the overall environmental impact. For that reason, the study proposes to improve efficiency in the agricultural field and continue the investments in the presence of the 2-3 phase combined system.

Keywords: Life Cycle Assessment; Life Cycle Inventory; Olive cultivation; Environmental Impacts; Tunisia.

List of abbreviations

AA	Acidification
CC	Climate change
DQR	Data quality rating
FET	Freshwater ecotoxicity
FE	Freshwater eutrophication
FU	Functional unit
HT	Human toxicity
IR	Ionizing radiation
LU	Land use
LCA	Life cycle assessment
LCI	Life cycle inventory
ME	Marine eutrophication
MFRD	Mineral, fossil & renewable resource depletion
OOM	Olive oil mill
OD	Ozone depletion
PM	Particulate matter
POF	Photochemical ozone formation
PPP	Plant protection products
PEFCR	Product environmental footprint category rules
TE	Terrestrial eutrophication
VOO	Virgin olive oil
WD	Water resource depletion

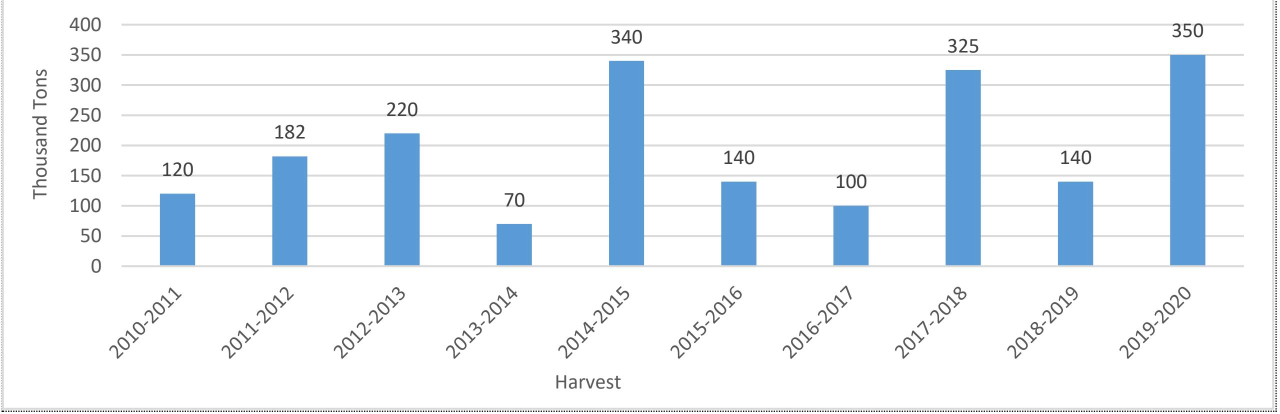
1. INTRODUCTION

Agriculture and climate change (CC) are strongly correlated, characterized by a complex cause-effect relationship (Agovino et al., 2019; McCarl, 2010). Therefore, food and agriculture are fundamental pillars of the 2030 Agenda for Sustainable Development, the successor to the Millennium Development Goals (MDGs), including the 17 Sustainable Development Goals (SDGs) containing 169 specific targets, adopted by the United Nations General Assembly in September 2015 (United Nations, 2015). The UN Food and Agriculture Organization (FAO) reports established that achieving the target of SDGs by 2030 to eradicate hunger is still going to be difficult (FAO, 2016). However, in order to move in the right direction, it is necessary to accept that agriculture has a mayor role to play in combating CC and it is actions and policies need to be implemented urgently to reduce the effects derived from climate variability (Arora, 2019; UNFCCC, 2021).

When analyzing the role of olive groves in global agricultural, it should be noted that, according to FAO statistics (FAO, 2021), the land area occupied by olive groves currently amounts to approximately 11 million hectares globally. Olive groves are present in fifty-eight countries, while the global annual production of olive oil is almost 20 million metric tons. Olive oil production is an important agricultural activity and the primary drive of the economy of many Mediterranean countries, prominent among which is Tunisia. Production of olives is an important part of the Tunisian agro-food sector; indeed, the olive oil sector contributes to Tunisian socio-economic development by providing 50 million working days per year (20% of agricultural employment) (International Olive Oil Council, 2012). Considering the last 30 years, Tunisia is the most relevant olive-growing country in the southern Mediterranean region, the fourth-ranked producer in the world (172,000 t/year) (after Spain, Italy, and Greece) and the third-ranked exporter (131,000 t/year) of olive oil in the world (after Spain and Italy) (International Olive Council, 2021). In Tunisia, over 35% of its cultivated land is dedicated to olive growing, having increased from 540,000 hectares in 1961 to 1.89 million hectares of olive groves today with nearly 105 million olive trees (AgriDATA, 2020; DGPA, 2020; FAO, 2021). One of its greatest handicaps is the scarce use of irrigation in its olive groves, due to the country's difficulties in terms of water resources, which results in a high level of alternate production (see Figure 1). In fact, 95% of the country’s olive grove (80% of the olive trees) is neither fertilized nor irrigated, depending entirely on rainwater (FAO, 2015). The world resources institutes predict that by 2040, Tunisia will become one of the thirty three most water-stressed countries in the world (Brown et al., 2017). The CC and weather variability effects must be considered as a serious threat for Tunisia’s agriculture (Zaied and Zouabi, 2016). In fact, there is evidence that with the current forecasts of population growth and global warming, unless there are improvements in irrigation technology, the Mediterranean area, including Tunisia, will not have enough water for satisfying irrigation requirements in 2080–2090 (Radhouane, 2018). In that context, the evaluation and communication of the environmental footprint of olive groves based on Life Cycle Assessment (LCA) provisions is crucial to move to sustainable olive grove management systems.

Olive trees are cultivated in widely varied climatic conditions in Tunisia, as follows: 15.7% in the north, 39.4% in the south, 16% in the Sahel-coastal region and 28.9% in central Tunisia (DGPA, 2020). Tunisia's climate is highly diversified with extremes ranging from the Saharan climate in the south to the European climate in the north. The average annual temperatures range from 35 °C in the south to 20°C in the north (Zaied and Zouabi, 2016). As shown in Figure 1, Tunisian olive production fluctuates considerably from one year to the next; this is due to the phenomenon of the alternate bearing of olive trees and extremely unpredictable weather conditions (80% of the olive trees are not irrigated and depend entirely on rainwater). The 2014/2015 harvest recorded the first record crop of 340,000 tonnes (an increase of 386% compared with the previous crop) and Tunisia was, excluding Spain, the world's leading olive oil producer. These results were surpassed according to the data from the last harvest for which figure are available (the 2019/2020 harvest), reaching a new record crop of 350,000 tonnes, which made it the world's third largest oil producer after Spain and Italy (International Olive Council, 2021).

Figure 1. Evolution of olive oil production in Tunisia from 2010-2011 to 2019-2020 (IOC, 2021)**.**



Olive oil exports are at the top of Tunisian's agricultural exports, accounting for about 75% of total production in the country and 5.5% of its total exports (ranked fifth on the list of sources of foreign exchange). The cultivation of olive trees in Tunisia contributes to job creation, food security and preservation and valorization of natural resources that are increasingly vulnerable (Bakari, 2020; Karray, 2012; Weber et al., 2020). The cultivation of olive trees in Tunisia accounts for 80% of the total area devoted to tree crop plantations, 35% of arable land, and 65% of all agricultural employment in Tunisia (Weber et al., 2020). Specifically, the region with the largest surface area of olive oil groves is Sfax with 363,386 ha, mainly traditional and rainfed with a low tree density (17-20 trees per ha) (AgriDATA, 2020; DGPA, 2020).

2. LITERATURE REVIEW

LCA is a very useful tool to analyze the impact and sustainability of the supply chain of products in the agrifood industry, including olive oil (Cellura et al., 2012b, 2012a; Espadas-Aldana et al., 2019). Several scientific studies related to the environmental performance of the olive oil sector, based on the LCA methodology, follow a "cradle to grave" or, more often, a "cradle to farm gate" approach. This is because the agricultural phase is generally identified in the scientific literature as the most impactful, particularly because of chemical fertilization, pesticides, and water management, while waste management represents a further crucial hotspot (Espadas-Aldana et al., 2019; Lombardo et al., 2021). According to this, it is important to highlight that organic waste generated could be re-introduced to the land as soil amendment (naturally or processed) to increase long-term carbon sequestration in the soil and refrain from further processes linked to additional environmental impacts (Nardino et al., 2013; Nieto et al., 2010; Sofo et al., 2005).

Most of the LCA studies of olive oil were conducted in Italy (Guarino et al., 2019; Proietti et al., 2017; Rinaldi et al., 2014). There are also interesting LCA studies on olive oil production in other major olive oil producing countries (mainly in the Mediterranean region), such as Spain (Fernández-Lobato et al., 2021b; Parascanu et al., 2018), Greece (Tsarouhas et al., 2015) or Turkey (Duman et al., 2020).

Very few studies focus on analyzing the environmental impact of olive oil production in Tunisia. Hjaila et al. (2013) investigated the environmental impact associated with activated carbon preparation from olive-waste cake via LCA. However, the first LCA publication for the olives production in Tunisia was elaborated by Ben Abdallah et al. (2021). This was the first publication that measures the environmental impact of the olives generation for the different agricultural systems in Tunisia (nine types), from the plantation to the production stage (up to six different stages), for a 50 years, considering two different functional units (FU). Six traditional growing types, two intensive types and one super-intensive were analyzed. The differences in type of cultivation methods between them (conventional or organic), the existence of irrigation management (irrigated or rainfed) and fertilization conditions (with or without it) were assessed. Their life cycle were studied separately in six productive stages depending on olive productivity (planting, young, growing, increasing production 1, increasing production 2 and full production). In this research, their results stated that the most modern olive cultivation methods (intensive and super-intensive) generated lower environmental impact per kg of olive oil for all categories compared with the other systems analyzed in a productive approach, but they produced higher environmental impact per area. Fertilization and soil management were the activities which presented the highest impacts in most of the categories analyzed (Ben Abdallah et al., 2021).

There is no other relevant scientific literature applying LCA to olive groves in Tunisia and, to our knowledge, there is no research applying LCA analysis to both phases (agricultural and industrial) in Tunisia. Considering this, the current paper sets out to fill a gap in the body of literature with regard to LCA studies in Tunisia. The objective of the present study is to analyze the environmental impact in the agricultural and industrial stages of Virgin Olive Oil (VOO) production in this country. It is remarkable that this investigation presents the first LCA study that, as stated above, includes the farming and industrial stages and follows the guidelines set down by the "Product Environmental Footprint Category Rules (PEFCR) for olive oil established by the European Commission (Schau et al., 2016). The comparative analysis in this research, analyzing the 2019/2020 harvest, cover the main olive production systems in Tunisia (extensive rainfed, intensive, and super intensive) and, in relation to the industrial phase, evaluate the three dominant types of olive oil mill systems (press, 3 phase or 2-3 phase combined extraction).

3. METHODS

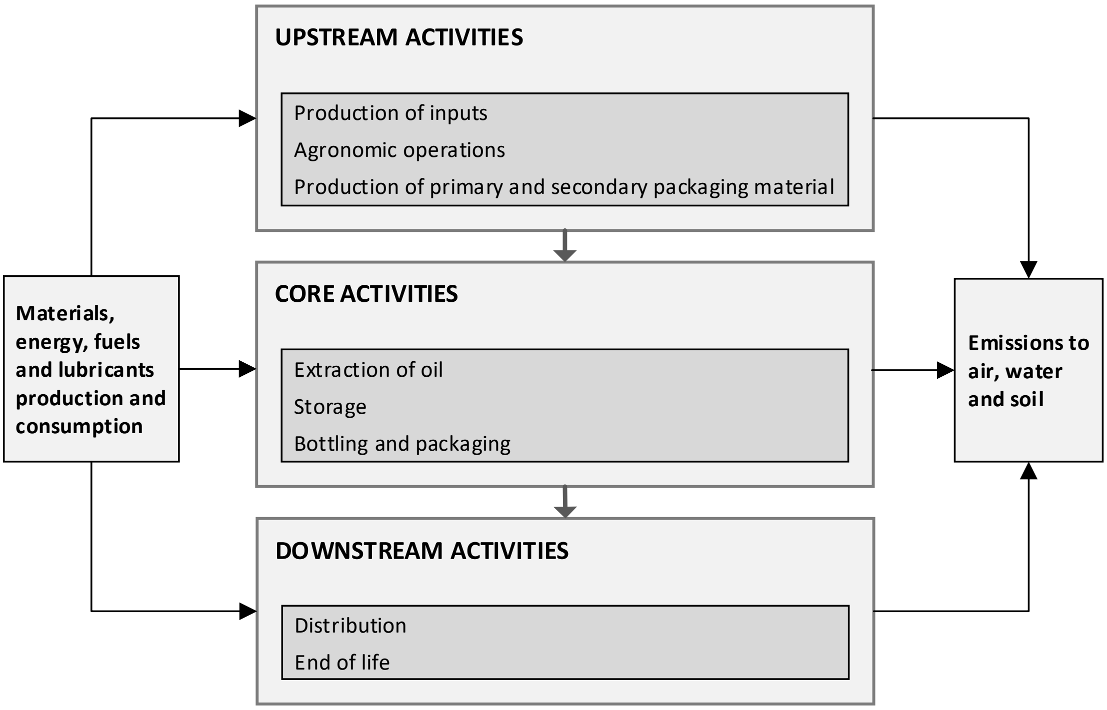
LCA is an analysis technique to evaluate environmental impact associated with all the stages of a product's life, which is from raw material extraction through materials processing, manufacture, distribution, and use (Muralikrishna and Manickam, 2017). The LCA of the olive oil production sector is based on ISO 14040 and ISO 14044 standards as a general framework (ISO, 2006a, 2006b) and, in general, the LCA framework includes four phases: Goal and scope definition, Inventory analysis, Impact assessment and Interpretation. Along with these international standards, an LCA study can deepen its analysis by following the rules described in PEFCR for olive oil – 3rd draft" (Schau et al., 2016). In April 2013, the European Commission (EC) published the Product and Organization Environmental Footprint (PEF/OEF) methodology -a life cycle-based multicriteria measure of the environmental performance of products, services, and organizations (European Commission, 2013; Lehmann et al., 2015). In June 2014, as a part of the implementation of the Environmental Footprint (EF) guidelines, the EC started 11 pilot projects for the development of PEFCR for food, feed and beverage products, and between them, olive oil is also considered (Benini et al., 2014; Russo et al., 2016). PEFCR are a necessary complement to the more general guidance for PEF studies and help direct the focus to the most important parameters of the PEF study, thus also reducing time, effort and costs. As stated by Russo et al. (2016: 2025), "LCA and environmental performance of products enters a new daring era with PEF" and this case study clearly moves in that direction applying the LCA in compliance with the Data Requirements Rules reported in the PEFCR for olive oil (Schau et al., 2016).

3.1. Goal and scope definition

The objective of this analysis is to know average values of the environmental impact in the agricultural and industrial stages, in different impact categories, for VOO production of the most representative systems in Tunisia. This research presents the first LCA study in Tunisia that includes the farming and industrial phases, analyzing the main olive production systems in Tunisia (extensive rainfed, intensive, and a representative case of super intensive) and the three dominant types of olive oil mill systems (press, 3-phase and 3 and 2 phase combined extraction).

The general system boundaries for olive oil production are described in Figure 2 (Maffia et al., 2020) for a whole LCA ("cradle to grave"). The system boundaries of this study include the processes from "cradle to gate" following the statements contained in the PEFCR for olive oil production (Schau et al., 2016). They include upstream and core processes for VOO production: production of inputs, olive production and extraction of oil, considering their respective waste management and emissions produced. "Upstream processes" include the resources, activities and emissions of the system in the farming stage (olives production). In relation to “Core processes”, they include the resources, activities and emissions in the olive oil extraction of the industrial stage, including the waste treatment and by-products generation up to this point. VOO storage, bottling and packaging are not part of this study because they are activities linked to marketing and distribution strategies that are not part of intrinsic VOO production processes, and therefore, should be considered as part of another study (Boesen et al., 2019; Giovenzana et al., 2019; Navarro et al., 2018). Downstream activities (distribution and end of life) are not included in a cradle-to-gate analysis (VOO production), so that, they are not part of this study.

Figure 2. System boundaries for life cycle assessment (LCA) (Maffia et al., 2020).



UPSTREAM ACTIVITIES

Production of inputs
Agronomic operations
Production of primary and secondary packaging material

CORE ACTIVITIES

Extraction of oil
Storage
Bottling and packaging

DOWNSTREAM ACTIVITIES

Distribution
End of life

Materials, energy, fuels and lubricants production and consumption

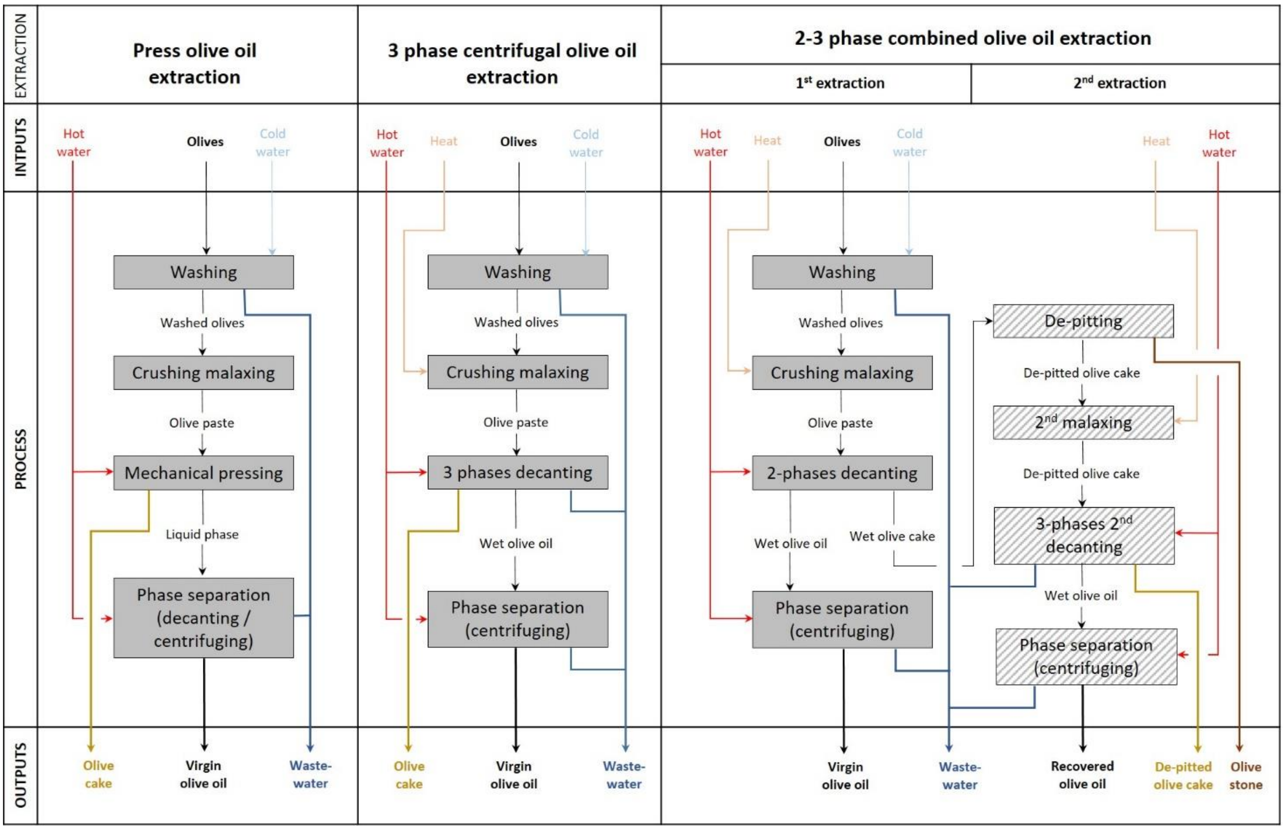
Emissions to air, water and soil

In order to ensure that the input and output data are normalized in a mathematically consistent way, the FU shall be clearly determined, measurable and reflect the marketable product (ISO, 2006b). The FU of the study is 1 kg of VOO at the OOM (not considering packaging or distribution). Previous studies of LCA of olive and olive oil production also used a volume or mass FU (Belaud and Clarens, 2012). Even though usually a liter is used as an FU in LCA studies (Proietti et al., 2017; Rinaldi et al., 2014; Tsarouhas et al., 2015), the FU of this research is expressed as a unit of mass, consistent with some other authors (Duman et al., 2020; El Hanandeh and Gharaibeh, 2016). It should be considered that when looking at olive oil at a production stage, mass units are more accurate, conversely to the final consumer product consideration, which is measured by volume.

3.1.1. Data collection

The most representative type of olive grove in Tunisia is extensive (or traditional) rainfed and unfertilized. In fact, the Tunisian olive oil industry is a special case with a unique characteristic: it is not exposed to the intensification of inputs since over 95% of the 1.89 million hectares of olive trees are grown under rainfed conditions without any kind of intensification and almost no chemical fertilizers (Niklis et al., 2014). The structure of olive tree cultivation reveals a dominance of small and medium-sized farms. Currently, there are 1,672 Olive Oil Mills (OOM) in Tunisia (with 78% of the daily milling capacity using 3-phase system) (DGPA, 2020), 15 refineries, 10 olive pomace oil extraction units, and more than 40 modern bottling plants (Mariem et al., 2019). In terms of number, olive mills are distributed in Tunisia as follows: north 14% (Tunis, Manouba, Ariana, Ben Arous, Bizerte, Beja, Jendouba, Kef, Siliana, Zaghouan, Nabeul), coast-Sahel 29% (Sousse, Monastir, Mahdia), Sfax 22%, center and south-west 21% (Kairouan, Kasserine, Gafsa, Sidi Bouzid) and south-east 13% (Médne, Gabès, Tataouine). As stated by Bakari (2020), “Tunisia is currently making major efforts to restructure and modernize the sector in order to improve the quality of olive oil and increase the area allocated for the cultivation of olive trees”. The sector of olive oil is being restructured and its technologies are being improved in order to generate a better olive oil product, reducing costs and environmental impacts, while social well-being keeps in a good position. It can be noted in some data like the increment of extraction capacity from 8,000 tonnes per day in 1986 to more than 70,000 tonnes per day in 2020. Despite the important number of traditional oil mills (pressure system) still existing in Tunisia, accounting for about 28% of the total number of olive mills, this system has significantly decreased in terms of volume as it represents only 7.5% of the theoretical daily capacity of the olive mills in the country (DGPA, 2020).

Figure 3. Main virgin olive oil extraction processes in Tunisia.



Three methods are used in the olive oil extraction processes: the press system, 3 phase centrifugal extraction and the 2 phase decanter system mostly present in combination with a 3-phase recovery decanter (Figure 3). The use of only two phase decanting is very limited in Tunisia because of the lack of infrastructure for wet pomace handling. The most common olive processing method in the Mediterranean region, including Tunisia, is the continuous centrifugation system, i.e. the so-called three-phase system. In this process, the centrifugal decanter allows for the separation of three flows of matter: the olive oil, pomace (solid remains of the olives) and wastewater (Zbakh and El Abbassi, 2012). The 3 phase centrifugal extraction generates two by-products: a by-product composed by olive pulps and pits, called olive cake) and wastewater from washing and processing olives (Brunetti et al., 2005; Khdair and Abu-Rumman, 2020). As stated by Khdair and Abu-Rumman (2020), concerning the olive mass, the 3 phase system generally produces about 20% olive oil, 30% olive cake and 50% olive mill wastewater, so that the residues generated are up to 4 times higher than the olive oil”. The 2 phase extraction system was introduced in Tunisia by high-capacity olive mills (more than 100 tonnes/day) when a second extraction line is quite profitable. This second line uses a 3-phase decanter resulting in a dual extraction system (combining 2-3 phases). It should be noted that the implementation of the combined unit for oil recovery has been particularly developed during the last 10 years in Tunisia. They re-extract the oil from these residues by the establishment of a second decanter. The recovering process allows obtaining between 40% and 50% of the olive oil remaining in the 2-phase olive pomace, thus increasing profitability (Jmeii et al., 2019).

The primary data for this research were obtained through surveys of farmers and of OOM managers, which represent the characteristics of VOO production in Tunisia. The questionnaires were designed according to the PEFCR guidelines, thus including qualitative and quantitative questions on agricultural or industrial stages, including main activities, resources, processes, consumptions, emissions and residues treatments (Schau et al., 2016). Farming and industrial experts with experience in olive oil production and researchers with experience in the topic tested the data sheets to ensure the quality of the data collection. Accordingly, two types of questionnaires were carried out, one to assess the agricultural stage, and another to assess the industrial stage. The surveys were open to permit add sensible information that cannot be obtained by solely quantitative forms. They were conducted in person, visiting olive groves and facilities to verify the data provided, according to the publications of Rajaeifar et al. (2014) and Guarino et al. (2019).

Completed surveys were accepted for the study after an initial filter, whereby inconsistent surveys were discarded if their data (with particular attention to their olive or olive oil yield) were far from a suitable range. Next, a statistical processing was carried out to rule out false or non-representative values, based on the data quality requirements (DQR) expressed in the PEFCR (Schau et al., 2016) (see appendix 1). The inventory was designed with the weighted average according to the representativeness of the case studies (olive tree crops or OOMs) for the 2019/2020 harvest. The source of the items (input/output) considered is mainly the survey, although information contained in or adapted from the PEFCR was included as secondary data. Life Cycle Inventory (LCI) is defined as a phase of LCA involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle (Islam et al., 2016; ISO, 2006b). To complete the LCI, information related to the activities performed in the background system (i.e., agricultural products production, tools or transportation vehicles) were referenced from scientific publications and databases such as Ecoinvent and Agribalyse.

It should be noted that, with the exception of the olive yield, the data do not show relevant variations between different years (except pruning, which is made once every two years) due to the systems and processes, in farming and industrial stages, remain essentially without changes along years. Therefore, the average values of the considered data represent the main behavior in the LCA. Olive yields (agricultural stage) can be significantly different between years, mainly due to differences in weather circumstances and, in addition, to the biological essence of the olive grove, which results in an important factor in the environmental impact (Rajaeifar et al., 2014; Rinaldi et al., 2014; Russo et al., 2016).

In this research, the olive yields of the surveys collected for the 2019-2020 harvest for extensive rainfed unfertilized crop type are over 800 kg of olives/ha, with an average of 1,213 kg/ha. However, this was an exceptional year; in fact, this production range has only been repeated three times in the last ten years. According to official statistics (DGPA, 2020), the average production of rainfed olive groves in Tunisia (almost all of which are extensive and unfertilized) is about 500 kg/ha from 2013/2014 to 2019-2020. They were 400 kg/ha in Sfax, the region with the largest surface area in extensive rainfed and unfertilized olive groves. Therefore, for this type of crop (extensive rainfed unfertilized), this research takes the value of 500 kg/ha in order to give representativeness for a regular season, as the rest of the variables do not fluctuate significantly between seasons. For the rest of the crop types, the value of the surveys is taken because their productions are scarcely affected by climatic conditions as they have irrigation systems.

Table 1 shows the distribution of the main types of olive tree crops in the main olive-producing regions of Tunisia (Olive Tree Institute, 2017). The most representative type of agricultural practice is extensive (or traditional), mostly non irrigated, therefore, the research focus on extensive rainfed as the most representative type of olive grove in Tunisia. It should be noted that, as shown in the table below, the sample covers 45% of the production, 34% of the area and 27% of the number of trees.

Table 1. Representativeness of the main typologies of olive grove considered in this study by its location.

MOST REPRESENTATIVE TREE CROPS			REPRESENTATIVENESS OF THE SAMPLE		
Density (trees/ha)	**Tree area (m)**	**Region**	**Based in production**	**Based in territory**	**Based in quantity of trees**
TRADITIONAL (EXTENSIVE)					
17-20	24 x 24	Sfax	16.0%	18.7%	6.7%
35	17 x 17	Mahdia	9.6%	8.4%	5.3%
70	12 x 12	Sousse	6.8%	4.0%	4.3%
100	10 x 10	Teboursouk	3.5%	1.7%	3.1%
INTENSIVE					
204	7 x 7	Gafsa	3.6%	0.6%	2.8%
204	7 x 7	Bizerte	0.2%	0.0%	0.1%
208	8 x 6	Sfax	2.5%	0.5%	1.7%
555	6 x 3	Gabes	2.4%	0.6%	1.2%
SUPER-INTENSIVE					
1666	4 x 1.5	Zaghouan	1.4%	0.3%	2.4%
TOTAL REPRESENTATIVENESS			**45.9%**	**34.7%**	**27.5%**

As shown in Table 2, although the most representative OOM in Tunisia (3-phase olive oil extraction) is the most prevalent in the data collected (70% of the industrial-phase surveys), the press and the combined systems are also evaluated because their presence and data collection is sufficiently representative. The representativeness and surveys considered are shown in Table 3.

Table 2. Representativeness of the main typologies of the industrial phase by the number of OOM, their theoretical milling capacity, and estimated actual daily volumes (DGPA, 2020).

MOST REPRESENTATIVE EXTRACTION TECHNOLOGIES			REPRESENTATIVENESS OF THE SAMPLE		
System	**Main characteristics**	**Average effective hours per day (2019/2020)**	**Based in number of units**	**Based in daily theoretical milling capacity**	**Based in actual daily volume**
3-Phases	Small to large size/ continuous	12	59.3%	78.6%	77.8%
2/3-Phases combined[1]	Large size/ continuous	15	12.6%	13.9%	17.2%
Press	Small size/ continuous	8	28.1%	7.5%	5.0%
TOTAL REPRESENTATIVENESS			100%	100%	100%

Regarding sample size in Table 3, 12 farmers, with different types of crops, completed the surveys correctly, covering an area of 750 ha, divided into three categories: 121 ha (extensive), 109 ha (irrigated) and 520 ha (super-intensive). Therefore, the LCIs are elaborate for extensive (30 trees per ha on average), intensive (403 trees per ha on average) and super-intensive (1,666 trees per ha on average). In relation to the industrial phase, this research analyzes data including all extraction

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[1] Official statistics do not consider the OOM using only 2 phase system without a recovering 3 phase line due to the limited number of such kind of unit and/or their small size.

technologies present in Tunisia: press (5 OOM), 3-phase (21 OOM) and 2-3 phase combined system (4 OOM). Expressed in tonnes, the total volume of olive oil processed by the olive mills surveyed in this study is 35,587 tonnes, accounting for 10.17% of Tunisia's olive oil production during 2019/2020 harvest (350,000 tonnes).

Table 3. Sample size of the types analyzed for the farming and industrial phases in Tunisia.

FARMING PHASE			
TYPE	**EXTENSIVE**	**INTENSIVE**	**SUPER-INTENSIVE**
SUBTYPE	RAINFED	IRRIGATED	IRRIGATED
Overall Representativeness in Tunisia (by olive grove area)	94.3%	4.9%	0.8%
Farmers Surveyed	7	4	1
Area Covered (ha)	121	109	520
INDUSTRIAL PHASE			
TYPE	**3-PHASE**	**2/3-PHASE COMBINED**	**PRESS**
Overall Representativeness in Tunisia (by their theoretical daily milling capacity)	77.8%	17.2%	5.0%
Olive oil mills surveyed	21	4	5

The modelling software used was SimaPro 9.0 ("System for Integrated Environmental Assessment of Products"), that gives the processes environmental impact values in different categories according to different scientific databases (ecoinvent 3.5, Agri-footprint 4.0, ELCD, Industry data 2.0, Methods). SimaPro helps to create a model according to the data collected, analyzing the different activities through an assessment method, that gives values of EIs to them in a systematic way (Proietti et al., 2017, 2014). Results are given in form of contribution and absolute environmental impact values in different impact categories for all the activities, resources and emissions of the processes analyzed. The impact categories selected for the study are those determined by the assessment method "2011 ILCD Mid-point+" (CML - Department of Industrial Ecology, 2016), namely: Climate Change (CC) 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 molec. 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 & Renewable resource Depletion (MFRD) in kg Sb eq.

3.2. Life cycle inventory

LCI gathers the required data quantifying the relevant inputs and outputs of the production system drawing on a combination of different sources. LCA Inventories of this study show every input and output that refer to the FU. The particularities of the activities assessed in the farming stage in Tunisia are described below.

- Land soil Management. This activity includes the use of agricultural machinery (with their respective energy consumption) necessary to carry out the works on the land throughout different periods of the year: harrowing, ploughing and tillage by Canadian cultivator, chisel plow and/or disc harrow.
- Irrigating. Extensive systems only take rainwater in most cases, so, irrigation systems are only found in intensive and super-intensive crops. They include a pumping system with water distribution by pipes laid on the land. It includes water and electricity supply that normally comes from the Tunisian national power grid. In certain cases, the electric supply is provided by a fuel-powered feed (mainly diesel) or photovoltaic system, but their representativeness is very limited. Pipes are generally built using low or high-density polyethylene (PE) and polyvinylchloride (PVC), with an estimated lifespan of 30 years, a yearly replacement rate in the order of 3-4% with their respective final disposal in a landfill, where they are generally burned.
- Fertilizers. Tunisian olive groves have usually been and continue to be cultivated without irrigation systems and with no application of chemical fertilizers or quite a small amount of them (Lockwood, 2009; Mezghani et al., 2019). In extensive cultivation, chemical fertilizers are not generally used; the only fertilizer inputs used are organic, principally animal manure. Their biogenic CO2 emissions were not accounted for because they were considered in the short-term carbon natural cycle, and their positive effect in terms of long-term carbon sequestration is considered negligible, due to the hard soil management practices (Notarnicola et al., 2015; Schau et al., 2016; Sofo et al., 2005). Nevertheless, their transport, application and other effects on the soil such as acidification, or heavy metal contamination were considered in any case. For its part, intensification of olive grove management

(intensive and super-intensive) entails increased use of organic and chemical fertilizers, especially nitrogen, phosphorus, and potassium-based (Zipori et al., 2020). These fertilizers can be mixed into the irrigation water, introduced by foliar application or directly applied to the land by a fertilizer spreader once a year.

- Plant protection products (PPP) and herbicides. For intensive and super-intensive crops, the use of chemical products such as fungicides, pesticides and herbicides (commonly known as phytosanitary products) is habitual to prevent production problems in olive groves. Dimethoate is applied as insecticide for extensive rainfed olive tree crops, while deltamethrin is generally applied as an insecticide for intensive and super-intensive tree crops. The PPP and herbicides are usually applied by field sprayer or mixed in irrigation water.
- Harvesting. Hand picking is the most common method of harvesting olives in the extensive and intensive plantations. Nevertheless, the use of an olive harvester in the super-intensive system is prevalent. The transport of olives is generally carried out by tractor and trailer or truck from the field to the OOM. This study, following the PEFCR’s indications, includes the olive tree cutting and pruning processes as part of the harvesting. This task is carried out using manual saws and pruning shears. In a few cases, machinery such as chainsaws or similar equipment is used for lopping tree branches, with their respective consumption of oil lubricant and fuel. Irrigated systems generally carry out this process once a year, while rainfed crops do it every two years.
- Pruning waste management. In the traditional and intensive tree crops, pruning management is carried up manually. The super-intensive systems offer the possibility of using disc-pruning or semi-mechanized equipment. The left-overs of the pruning are divided into two categories: a) Heavy wood with a diameter larger than 10cm: for all kinds of olive crops in Tunisia, it is sold at the orchard at an average price of 170TND per metric tons mainly to be classified and used for traditional handicrafts (less than 10%) or charcoal; b) Leafy branches to be crushed with mulchers on the soil or burned at the orchard for super-intensive crops while in the traditional and intensive plantations they are mainly transported to the closest farms where they are used for sheep feed (leaves) and the rest is transformed into charcoal (branches

between 2cm and 10cm in diameter) or used as a fuel in traditional ovens (twigs smaller than 2cm in diameter).

In order to fill in the data not obtained through the survey, certain assumptions are made due to certain limitations: fertilizers, PPP and herbicides. This information was recorded as chemical elements or compounds to homogenize their composition, including their packaging and distribution.

- Land use change. The olive growing system is consolidated in most cases, so, the plantations are considered without changes of crop in the long term.
- Pruning waste treatment. Pruning wastes are usually supplied to local farmers within a radius of 1 km to be used for animal feed and dried to be used as a source of energy. In the three farming systems, the most widespread final destination of the wood is conversion into charcoal and use as fuel, so in this study this is the main consideration for the end of life of this item.
- Transport. The transport distance is an approximation from the most representative cultivation sites to the nearest seaports and industrial cities. The olive groves and related OOM are more concentrated according as they approach to the coastal regions of the country. Therefore, considering the North and East areas of the country to be the most representative ones, the average distance covered by the transport of agricultural and industrial products is estimated as 50 km. This transport is carried out by using diesel-fueled trucks with a capacity of up to 3.5 tonnes. Once in the most representative area, it is assumed that a similar kind of truck is used in the transportation between the agricultural areas, the supply depots and the OOM.
- Infrastructure. Small buildings or warehouses and their associated consumption of resources are negligible for the LCA of VOO production (Salomone et al., 2015).
- Emissions to air, water or soil. These emissions are factored in following the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (Amstel, 2006) to maintain the same relation with the resources and processes established by the PEFCR (Schau et al., 2016).

- Biogenic C. Trees absorb CO_2 from the atmosphere that keeps it fixed to permanent and non-permanent tree structures (roots, trunk, fruits and leaves) as biogenic C. Part of this C is gradually re-emitted to the atmosphere as a result of the natural C cycle, while another part could be stored by the soil under conservative soil cultivation management (Nieto et al., 2010; Schau et al., 2016; Sofo et al., 2005). This study does not consider the biogenic C balance in the farming stage, because the soil regime is normally high, so it can be assumed that most of the biogenic C is re-introduced to the atmosphere (The British Standards Institution, 2011).

The survey of the industrial phase yielded data on the main values of resources and processes in the OOM considered. From this information, the different inputs and outputs are categorized in different groups that represent the whole extraction process. The different processes of the main extraction system in Tunisia (3-phase) and their description can be read below:

- Washing. The OOM receive the olives generally free of branches and leaves because they are manually separated on the farm. However, a small part of the branches, twigs, leaves and dust is eliminated through washing. This produces wastewater that goes away with the liquid effluent of the mills. This process is often prevented by press systems.
- Milling and malaxing. After washing, the olives go through these processes to be converted into an olive paste that will then be ready for the oil extraction. It is helpful to increase the temperature of the paste to almost 30ºC to improve the extraction.
- Decanting and centrifugation. Decanting is the main process for obtaining the extractable olive oil from olive paste. The 3-phase decanter produces the separation of the olive cake, a residual paste separated from the olive oil which is composed by the rest of the organic matter. Vertical centrifugation is also applied to the oil obtained from the tri-canter to eliminate resides such as wastewater and traces of plant material from it. A second vertical centrifuge is generally used to recover the residual oil existing from the wastewater obtained from the decanter. These processes require a large quantity of electricity, water and heat. In contrast with the 2-phase system, the 3-phase centrifugation system generates a large quantity of olive mill wastewater, because it uses large volumes of water, which is one of the most critical

hotspots of olive oil extraction (Jellali et al., 2021). This olive mill wastewater is usually transported to big open-air drafts where it evaporates naturally.

- Olive cake production and management. The olive cake generated in the 3-phase extraction process is an organic material with olive pulp, stones and a moisture content of about 50-55% that contains about 3.5-4% oil according to the surveyed sample. In Tunisia, it is generally sold as a by-product to pomace oil extractor plants. In seasons with a high production, other systems such as de-pitting followed by compost processes are used due to the large quantity of this by-product. In the 2-phase decanter of the combined system, OOM usually separate the olive stone with a de-pitting machine before recovering the oil in the second extraction line.
- Drying of the olive cake and pomace extraction. The olive cake resulting from the OOM is mainly sent to pomace oil extractor plants with the purpose of obtaining valuable by-products. Firstly, the olive cake is dried to get an exhausted pomace with a moisture about 4-5%. Secondly, crude pomace olive oil, a by-product with economic value in the olive pomace oil industry, is extracted through a chemical extraction with the use of organic solvents such as hexane. The inputs consumed throughout these processes are electricity, water, organic solvent and heat (the latter, generated in the combustion of part of the exhausted pomace obtained).

Some assumptions were also made in the development of the inventory based on PEFCRs and data availability:

- Infrastructure. The area and buildings of the OOM are accounted for considering the part of OOM resulting from the division by the annual VOO production FU and 50 years of useful life.
- Emissions to air, water or land. As in the farming stage, the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (Amstel, 2006) were followed to maintain the PEFCR relations between processes or products and emissions.

- Biogenic C. Approximately 50% of the biogenic C absorbed by the trees in a productive year is contained in their fruits, and is transferred to the industrial stage. From the olive fruit, about 20% of the C content becomes part of the VOO, while the other 80% becomes part of the resulting organic material (primarily olive stones and olive cake) (Fernández-Lobato et al., 2021a). At the industrial stage, CC results are given without considering biogenic C (as in the farming stage), and additionally, considering the biogenic C emissions produced by the energy conversion processes of biomass. In this way, it is possible to know the environmental impact of the industrial stage considering fossil fuel emissions and biomass fuel emissions involved in the processes.
- Olive stones. They are generally not separated from olive cake in the most representative value chain, and therefore, so the LCA is developed on this basis. Only in certain cases, can a proportion of them be used to generate heat instead of the consumption of other fuels (normally fossil fuels). Consequently, in these minority cases, the main effect of their combustion would be to have biogenic emissions instead of fossil emissions to the atmosphere, but due to their low significance, it is considered negligible in this study.
- Olive cake treatment. The olive cake treatment belongs to the most representative value chain. Thus, the quantity of olive cake generated is counted according to the data obtained in the questionnaires, while its treatment is carried out considering the process proposed in the PEFCR. This process was adapted appropriately to the moisture of the olive cake considering appropriate quantities of different inputs and outputs.
- Olive mill wastewater treatment. Emissions from this waste management were obtained from Amstel (2006), using the worst-case scenario of lagoon evaporation, along the same lines as other authors such as Figueiredo et al. (2014). This study considers the treatment of olive mill wastewater with average values of 82.5% for chemical oxygen demand, 90% for phenols and 61% for biochemical oxygen demand (Paraskeva and Diamadopoulos, 2006). Methane (CH_4) emissions, one of the most impactful in CC, is considered due to prolonged ambient temperatures above 15ºC. They are set with a methane production capacity of 0.25 kg per kg of chemical oxygen demand removed with a correction factor of 0.3. As another important

emission considered in the study, nitrous oxide (N_2O) was obtained with the basis of an average content of nitrogen in wastewater of 0.88% (Paredes et al., 1999), and an emission factor of 0.25, the worst scenario considered in Amstel (2006).

The data contained in the LCI was classified into different types of agricultural and industrial systems or types of plantations and extraction processes. Average quantities of activities and products of the farming phase are defined in Table 4. In general, the quantities of inputs increase at the same rate as intensification in the cultivation method and their olive yields are higher. This fact and the different olive yields strongly influence the EI. The industrial phase LCI is shown in Table 5. It is more homogenous than the farming phase, despite the different extraction processes, because they demand similar inputs in more equivalent quantities per VOO production than the farming phase, in order to be economically efficient.

Table 4. Farming phase LCI summary in Tunisia (inventory data per ha) (*C.V: coefficient of variation).

TYPE	**EXTENSIVE**		**INTENSIVE**		**SUPER-INTENSIVE (particular case)**	**DATA SOURCE**
SUBTYPE	**Rainfed**		**Irrigated**		**Irrigated**	
	Mean	**C. V.***	**Mean**	**C. V.***		
Olive yield (kg olives)	500 (2013/2020) 1,213 (2019/2020)	- 0.14	6,009.20	0.16	8,653.80	
ACTIVITY / PRODUCT:						
HARVESTING						
Petrol, two-stroke blend (kg)	-	-	4.4	1.44	0.4	Survey
Transport, tractor and trailer (tkm)	8.2	1.27	29.3	0.36	245.8	Survey
Polyethylene, linear low density (kg)	0.7	1.23	2.5	0.16	3.5	Survey
CUTTING						
Petrol, two-stroke blend (kg)	-	-	0.5	1.56	0.1	Survey
IRRIGATING						
Electricity, low voltage (kwh)	-	-	2,373.90	0.24	1,788.50	Survey
Water (m^3)	-	-	2,334.90	0.36	2,500.00	Survey
Polyethylene, linear low density (kg)			15.97	0.64	65.6	Survey
Polyethylene, high density (kg)			7.29	0.72	30.2	Survey
Polyvinyl chloride (kg)			11.72	0.43	48.5	Survey
PPP & HERBICIDES						
Application of PPP (ha)	0.4	3.23	3.4	4.37	6	Survey / PEFCR
Water (m^3)	0	-	0.1	0.88	0.2	Survey / PEFCR
Insecticide (kg)	0	-	3.1	0.64	4.5	Survey
Fungicide (kg)	-	-	-	-	16.2	Survey
Herbicide (kg)	-	-	8.4	1.03	15	Survey
SOIL MANAGEMENT						
Harrowing (ha)	0.8	0.6	3.6	0.55	-	Survey
Tillage (ha)	3.2	0.35	4	0.26	-	Survey
Transport, lorry 3.5 t (tkm)	0.1	0.44	0.1	0.36	0.1	PEFCR
PRUNING MANAGEMENT						
Transport, tractor and trailer (tkm)	18.2	1.27	65	0.36	545.9	Survey
FERTILIZING						
Fertilizing, by broadcaster (ha)	0	-	0.1	1.42	0.5	Survey
Organic fertilizer (kg)	1,655.60	1.42	4,954.10	0.80	15	Survey
Nitrogen fertilizer (kg)	-	-	65.2	0.29	80	Survey
Potassium fertilizer (kg)	-	-	38.2	0.59	50	Survey
Phosphate fertilizer (kg)	-	-	119.2	1.13	37.2	Survey
Borax (kg)	0	-	0.7	0.51	0.7	Survey

Table 5. Industrial phase LCI summary in Tunisia (inventory data per 1 ton of VOO) (*C.V: coefficient of variation).

TYPE	3-PHASE		2/3-PHASE COMBINED		PRESS		DATA SOURCE
	Mean	**C. V.**	**Mean**	**C. V.**	**Mean**	**C. V.**	
Olives (kg)	4,973.47	0,03	4,572.91	0,06	5,944.27	0,05	Survey
Electricity, low voltage (kWh)	110.00	1,11	100.00	2,43	110.00	3,27	Survey
Gas (kg)	0.22	4,94	-	-	0.90	2,11	Survey
Water (m^3)	3.06	0,48	2.85	0,95	5.67	0,68	Survey
Olive stones consumption (kg)	-	-	31.06	1,14	-	-	Survey
Exhausted pomace consumption (kg)	91.34	4,56	-	-	-	-	Survey
Transport, tractor and trailer (tkm)	25.16	1,94	32.06	1,48	-	-	Survey
Lubricating oil (kg)	0.03	0,56	0.01	0,83	0.62	1,43	Survey
Soap (kg)	0.32	1,50	0.24	0,53	1.84	0,67	Survey
Sodium perborate, powder (kg)	0.01	6,62	-	-	0.03	1,93	Survey
area of OOM dedicated with an expected lifetime of 50 years (m^2)	0.02	2,64	0.01	1,58	0.01	3,46	Survey
Olive cake treated (kg)	2,317.86	0,29	-	-	1,965.94	0,38	Survey
Exhausted olive cake treated (kg)	-	-	2,010.35	0,43	-	-	Survey
BY-PRODUCTS GENERATION							
Olive stones (kg)	-	-	449.56	0,34	-	-	Survey
Exhausted pomace (kg)	1,097.93	0,26	634.85	0,37	1,034.71	0,74	Survey
Crude pomace olive oil (kg)	81.13	0,62	44.44	0,48	72.43	0,71	Survey / PEFCR
RESIDUES GENERATION							
Olive mill wastewater (kg)	4,770.12	0,16	4,365.83	0,34	3,219.81	0,18	Survey

In these cases, the consumption of olives is particularly significant, since the environmental impact of the cultivation phase depends directly on this data. Therefore, considering only the olives needed per kg of VOO, the most efficient process is the 2/3 combined phase process (with 4.57 kg of olives per kg of VOO) followed by the 3 phase system (the most common in Tunisia) which uses 4.97 kg of olives per kg of VOO. Finally, the least efficient system is the press system with 5.94 kg of olives per kg of VOO. The quantification of the most important inputs, such as electricity and water, as well as by-products and residues and waste generation, is in line with the values accepted in the scientific literature (Vera, 2013). Generally, 2-3 phase combined systems have lower consumption of water and electricity than 3-phase or press systems per VOO production. In addition, 2-3 phase combined system do not produce the quantity and concentrated oil mill wastewater that other systems produces. The olive cake treated input refers to organic material with different moisture contents, depending on the system. These items are disaggregated into exhausted pomace (dry organic matter with about 4-5% moisture), crude pomace oil and its water content, which is evaporated in the process.

3.3. Economic allocation to main product and by-products

The VOO is the main product of the value chain, while the by-products related to its production are in this case: olive wood, olive stones, exhausted pomace and crude pomace olive oil. Olive wood burning is considered as part of the activities of the olive farming stage, as it is associated in most cases with energy uses related to farming activities or directly burned in the olive grove. The calorific energy released by this combustion for traditional, intensive and super intensive systems based on the quantity of wood generated is in the order of 6,900, 15,700 and 22,000 MJ per ha respectively (IDAE, 2020). The rest of the by-products are generated at the end of the industrial stage, after the extraction activities in the OOM and in the pomace extraction plant for the cases of exhausted pomace and crude pomace olive oil. They have a quantified mass per kg of VOO and a prize, which determines their total economic value. This total economic value is useful to allocate the environmental impact in the same proportion, according to the statements of Notarnicola et al., (2015). The generation of olive cake in the three-phase extraction process includes olive stones and a low degree of moisture, so it is usually easy to sell as an intermediate by-product to obtain crude pomace olive oil and exhausted pomace as final by-products. The average sale prices of three-phase olive cake between 2018/2019 to 2021/2022 was 0.050 TND. However, its economic profitability can fluctuate depending on the year, with the lowest prices after good harvests of 0.010 TND and the highest price after low harvests of 0.150 TND. With the advent of de-pitting machines, fluctuations in the sale of olive cake were observed, especially in years of high production, and it can even be treated with on-site composting systems when it is usually sold at a lower price of 0.020 TND.

The environmental impact of the processes are allocated to the main product and by-products proportionally to their total economic value in accordance whit the formula (Notarnicola et al., 2015):

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

Where *EA* is the economic allocation (%); *EV* indicates the economic value in Tunisian Dinar (TND) per kg; *M* refers to the mass of every element produced (kg). The results can be calculated for “*n*” elements (the main product and by-products with economic value.

4. RESULTS AND DISCUSSION

Tables 6 to 9 show the LCA results for the total environmental impact of VOO production considering 16 different impact categories (17 when considering CC with and without biogenic carbon). Rows shaded in light gray in the following tables indicate the environmental impact categories that are most significant to olive oil production as proposed in PEFCR (Schau et al., 2016).

Firstly, the environmental impact of the different activities in the farming phase in Tunisia are analyzed in Table 6. The trend of most of the environmental impact per FU is correlated with the intensification of the different types of tree crops analyzed. Extensive tree crop has a very low density of trees per hectare, with an average olive yield of 500 kg/ha for the period 2013/2014 to 2019/2020. On the other hand, the 2019/2020 harvest obtained 1,213 kg/ha, which is 143% higher (the selection of the average is justified in "data collection section"). According to the inputs, the intensive irrigated type rose the most, while the olive yield increased (6,009 kg/ha) and its olive production impacts more negatively on the environment than extensive rainfed. The super-intensive case is based on the data of a single survey that accounts for 520 ha (Table 3), and follows similar principles to intensive, with an olive yield of 8,653 kg/ha and a larger consumption of inputs, but resulting in lower environmental impact per FU. The environmental impact of the most representative crop type in the agricultural phase (extensive rainfed) is shown in Table 6 for an average olive yield of 500 kg/ha and for an exceptional olive yield of 1,213 kg/ha for the 2019/2020 harvest. Since environmental impact per FU is inversely proportional to the olive yield, results of the extensive rainfed type considering the olive yield of the season 2019/2020 would be 68.88% lower than the average considered. For example, while Table 6 shows a value of 3.14 kg CO_2 eq. in CC category for this type of tree crop considering the average olive yield of 500 kg/ha in a period of six harvests, this environmental impact would result in 1.29 kg CO_2 eq. for the olive yield of 1,213 kg/ha recorded for the 2019/2020 harvest. It is assumed that the value most appropriate to characterize the most representative VOO value chain is the one obtained by the using the average of six harvests. In this regard, results show that intensive crops have a 9% higher impact per FU in CC. Finally, in the particular case of super-intensive production analyzed in this study, the value drops to 2.55 kg CO_2 eq per FU. In a previous LCA study of Tunisian olive groves, the results demonstrate that, in general, the irrigation systems generate higher environmental impact in most categories per ha, but lower values in relation to their production (Ben Abdallah et al., 2021). In this respect, it is important to highlight that we obtained small differences of environmental impact per FU between the different systems. They represent unitary values, while the global EIs depend on the surface and yield of every system, and are much more impactful per ha than intensive and super-intensive systems. Other data that emerge from the tables are the use of land in the extensive crops, which is more than ten times higher than with the intensive types. On the other hand, according to the WD impact category, it is negative in the case of extensive cultivation (-0.02 m^3 water eq.) (it does not represent a negative impact for the environment) while irrigated cases represent substantial EIs in this category. Comparing the main results with those of Ben Abdallah et al. (2021), it is worth noting that, in the mentioned research, soil management was the highest contributor in most impact categories of the traditional rainfed non fertilized system, which is confirmed in this study. The WD impact category is very significant in the Tunisian context where water resources are extremely limited compared with other olive producing countries (Bchir et al., 2021). As shown in Table 6, the irrigated area represents 5.7% of the total olive growing areas both in intensive and super-intensive cropping systems. The implementation of irrigated olive plantations in Tunisia is mainly explained by the need to stabilize production fluctuation from year to year. As an example, the total olive oil country’s production oscillated between 220 thousand metric tons in 2012/2013, and 70 thousand metric tons in 2013/2014 harvest, and then 340 thousand metric tons in 2014/2015 (International Olive Council, 2021). Such a fluctuation, mainly due to the effect of climatic conditions on the rainfed traditional plantations, causes major disturbance in the olive oil market, even threatening the sustainability of the overall value chain at the local level (Larbi et al., 2021). The increase in irrigated areas in Tunisia raises questions on water productivity concept regardless the adopted irrigated cropping system. Table 6 shows WD values of -0.02 m^3 water eq. in extensive rainfed olive tree crops, 0.31 m^3 water eq. in intensive irrigated plantations and 0.22 m^3 water eq. in super-intensive irrigated plantations. The low significant negative value in the extensive rainfed type is caused by the use of different metals such as aluminum and iron, because they produce water in their production chain. The difference of impact between the irrigated systems is explained by the higher production per kg of olives in super-intensive groves.

Table 6. LCA-Farming stage (by type and subtype of agricultural system in Tunisia).

TYPE		**EXTENSIVE**		**INTENSIVE**	**SUPER-INTENSIVE**
SUBTYPE		***Rainfed***		***Irrigated***	***Irrigated***
OVERALL REPRESENTATIVENESS IN TUNISIA		94.3%		4.9%	0.8%
CATEGORY	**UNIT**	*2013/2020*	*2019/2020*		
Climate change	kg CO_2 eq	3.14	1.29	3.44	2.55
Ozone depletion	kg CFC-11 eq	$4.39\cdot10^{-7}$	$1.81\cdot10^{-7}$	$2.31\cdot10^{-7}$	$1.59\cdot10^{-7}$
Human toxicity, non-cancer effects	CTUh	$2.57\cdot10^{-6}$	$1.06\cdot10^{-6}$	$1.16\cdot10^{-6}$	$9.90\cdot10^{-7}$
Human toxicity, cancer effects	CTUh	$2.50\cdot10^{-7}$	$1.03\cdot10^{-7}$	$1.44\cdot10^{-7}$	$9.45\cdot10^{-8}$
Particulate matter	kg PM2.5 eq	$4.37\cdot10^{-3}$	$1.80\cdot10^{-3}$	$2.38\cdot10^{-3}$	$1.86\cdot10^{-3}$
Ionizing radiation HH	kBq U235 eq	0.22	$9.07\cdot10^{-2}$	0.22	0.17
Ionizing radiation E (interim)	CTUe	$1.21\cdot10^{-6}$	$4.99\cdot10^{-7}$	$1.34\ 10^{-6}$	$1.39\cdot10^{-6}$
Photochemical ozone formation	kg NMVOC eq	$3.01\cdot10^{-2}$	$1.24\cdot10^{-2}$	$1.21\cdot10^{-2}$	$7.97\cdot10^{-3}$
Acidification	molc H+ eq	$2.70\cdot10^{-2}$	$1.11\cdot10^{-2}$	$1.88\cdot10^{-2}$	$1.33\cdot10^{-2}$
Terrestrial eutrophication	molc N eq	0.12	$4.95\cdot10^{-2}$	0.06	0.04
Freshwater eutrophication	kg P eq	$6.65\cdot10^{-4}$	$2.74\cdot10^{-4}$	$8.71\cdot10^{-4}$	$5.17\cdot10^{-4}$
Marine eutrophication	kg N eq	$9.91\cdot10^{-3}$	$4.08\cdot10^{-3}$	$5.11\cdot10^{-3}$	$3.47\cdot10^{-3}$
Freshwater Eco toxicity	CTUe	21.7	8.94	81.3	73.0
Land use	kg C deficit	411	169	40.3	27.9
Water resource depletion	m^3 water eq	-0.02	$-8.20\cdot10^{-3}$	0.31	0.22
Mineral, fossil & renewable resource depletion	kg Sb eq	$3.70\cdot10^{-4}$	$1.52\cdot10^{-4}$	$3.70\cdot10^{-4}$	$2.20\cdot10^{-4}$

Figure 4 shows the detailed results for the extensive rainfed olive crop, the most representative of the Tunisian olive oil value chain. The characteristics of this representative type of crop are linked to a low density of trees (17-100 trees/ha according to the survey), low yields, low consumption of inputs and standard soil management. It should be noted that in most of the impact categories Soil Management is the most responsible of the EI, representing around 80-90% of the impact produced in all the categories analyzed (with the exception of the WD category), while the rest of the activities have a minor effect. The contribution of the different activities in CC is also represented in Figure 4. It shows how soil management is responsible for most of the environmental impact (accounting for 89.20% of CC), followed by fertilizers (organic) (6.38% of CC).

Figure 4. Contribution of farming stage activities (extensive rainfed).

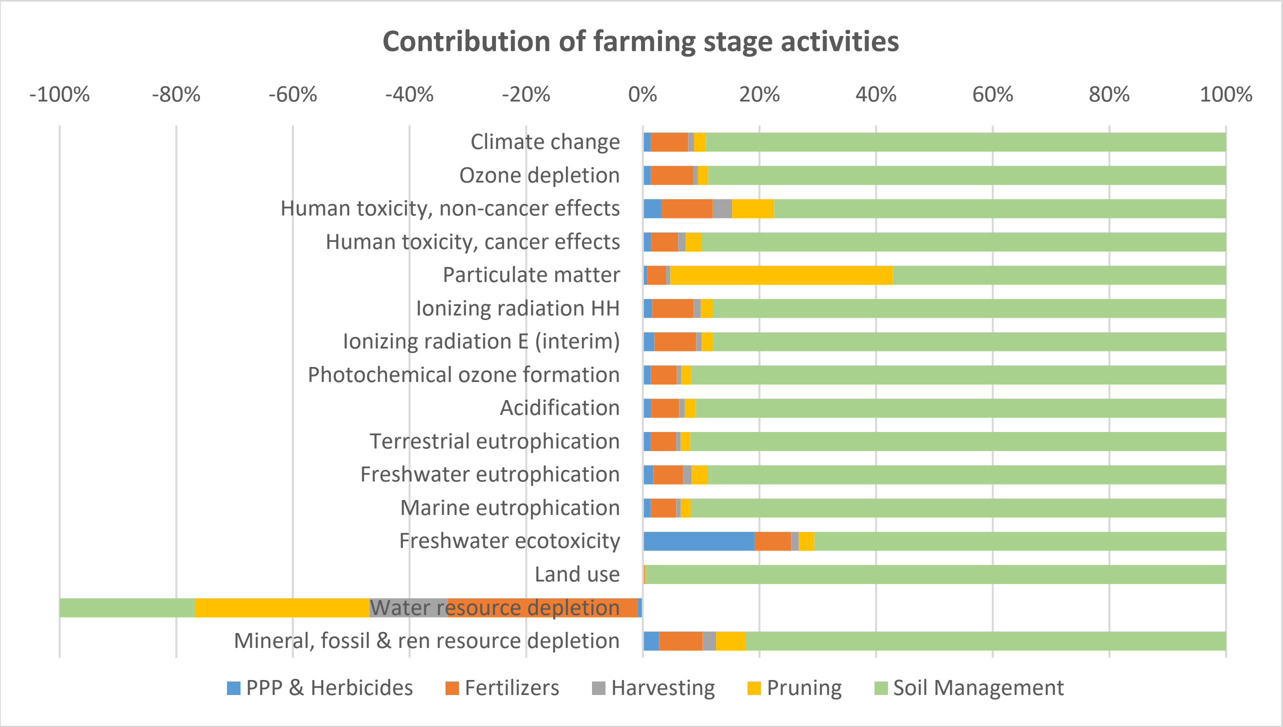


Table 7 shows the total values (sum of all activities) of the LCA in the industrial phase for Tunisia, comparing the three olive oil extraction systems present in the country (3-phase, 2-3 phase combined and press). It can be appreciated that only the category WD has a negative balance, therefore, the environmental impact of the industrial stage in this category is beneficial to the environment due to the use of metals in the transports and facilities. It should be noted that this research presents the first LCA study of the industrial phase carried out for Tunisia. The 3-phase system (78% representativeness in the Tunisian OOM) is the one that produces the greatest environmental impact in most of the categories (including CC, the most important impact category). However, the EIs of the different cases in CC (without considering biogenic C) are not very representative with respect to the agricultural phase (they account for only around 4% of the global EI). Therefore, in this category among others, the industrial yield of olive oil extraction is a very important point to consider, due to the huge representativeness of the environmental impact of the input olives. In this regard, the press system proves to be very inefficient, as compared to the 3-phase system, increasing the impacts of the agricultural phase by 16.3%, because it requires 0.97 kg more olives per FU. For its part, the combined system reduces the impacts of the agricultural phase by 8.8%, as it extracts the same amount of oil with 0.4 kg fewer olives. Considering the extensive cultivation system, the difference in yields means that the agricultural phase impacts +0.51 kg CO_2 eq. in CC if extraction by press is used and -0.27 kg CO_2 eq. in CC if extraction by the combined system is used instead.

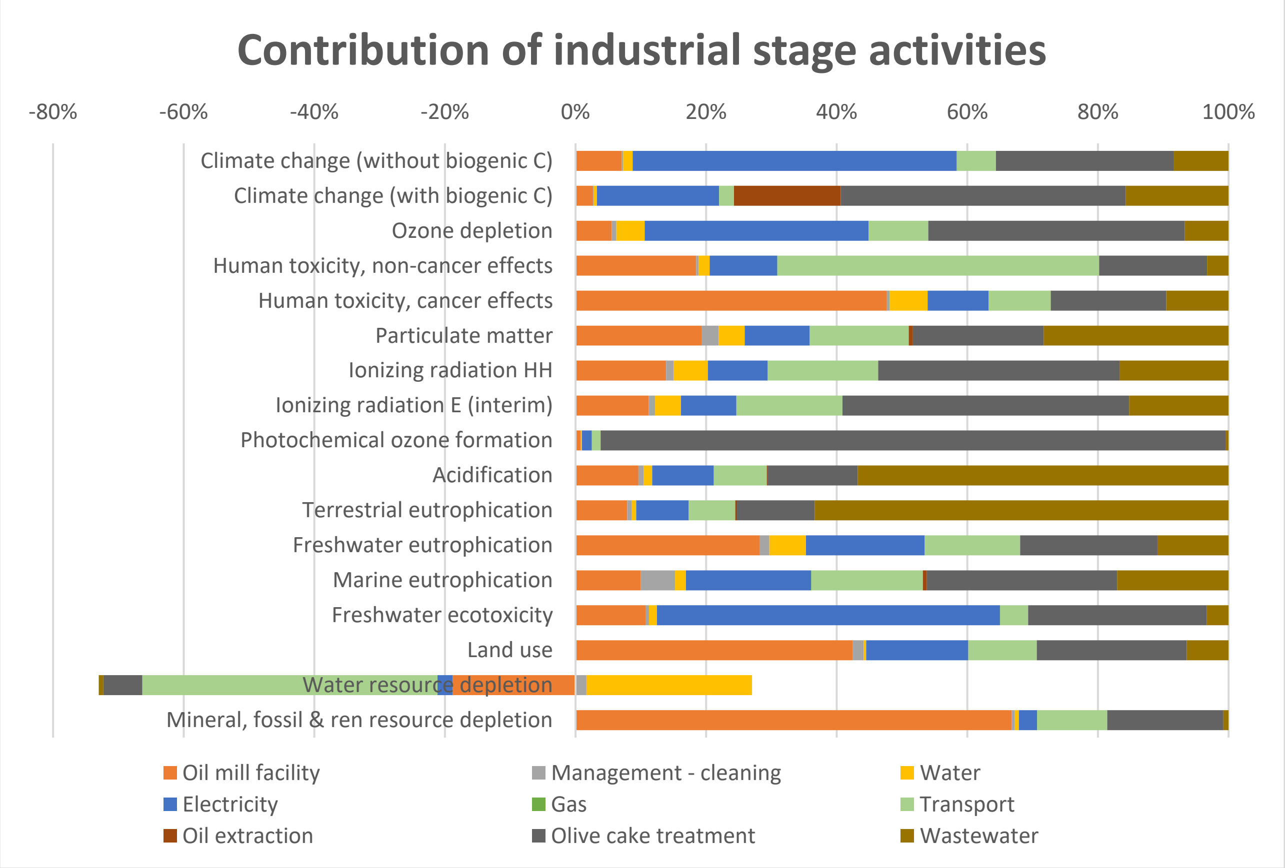
Table 7. LCA-Industrial stage (by type and subtype of industrial system in Tunisia).

		3-PHASE	**2/3-PHASE COMBINED**	**PRESS**
Industrial yield (kg VOO/kg olives, in %)		20.11%	21.87%	16.82%
CATEGORY	**UNIT**			
Climate change (without biogenic C)	kg CO_2 eq	0.15	0.13	0,13
Climate change (with biogenic C)	kg CO_2 eq	0.39	0.36	0.23
Ozone depletion	kg CFC-11 eq	$1.16\cdot10^{-8}$	$1.00\cdot10^{-8}$	$9.83\cdot10^{-9}$
Human toxicity, non-cancer effects	CTUh	$5.21\cdot10^{-8}$	$4,96\cdot10^{-8}$	$1.72\cdot10^{-8}$
Human toxicity, cancer effects	CTUh	$9.96\cdot10^{-9}$	$6.22\cdot10^{-9}$	$4.65\cdot10^{-9}$
Particulate matter	kg PM2.5 eq	$5.34\cdot10^{-5}$	$4.39\cdot10^{-5}$	$3.70\cdot10^{-5}$
Ionizing radiation HH	kBq U235 eq	$3.78\cdot10^{-3}$	$3.16\cdot10^{-3}$	$2.60\cdot10^{-3}$
Ionizing radiation E (interim)	CTUe	$1.88\cdot10^{-8}$	$1.58\cdot10^{-8}$	$1.32\cdot10^{-8}$
Photochemical ozone formation	kg NMVOC eq	$5.43\cdot10^{-3}$	$3.74\cdot10^{-3}$	$5.02\cdot10^{-3}$
Acidification	molc H+ eq	$8.81\cdot10^{-4}$	$7.65\cdot10^{-4}$	$5.78\cdot10^{-4}$
Terrestrial eutrophication	molc N eq	$3.44\cdot10^{-3}$	$3.03\cdot10^{-3}$	$2.24\cdot10^{-3}$
Freshwater eutrophication	kg P eq	$1.75\cdot10^{-5}$	$1.33\cdot10^{-5}$	$1.11\cdot10^{-5}$
Marine eutrophication	kg N eq	$1.33\cdot10^{-4}$	$1.17\cdot10^{-4}$	$1.20\cdot10^{-4}$
Freshwater ecotoxicity	CTUe	1.86	1.56	1.56
Land use	kg C deficit	0.57	0.37	0.3
Water resource depletion	m^3 water eq	$-8.81\cdot10^{-4}$	$-8.70\cdot10^{-4}$	$9,13\cdot10^{-4}$
Mineral, fossil & renewable resource depletion	kg Sb eq	$2.39\cdot10^{-5}$	$1.20\cdot10^{-5}$	$6,17\cdot10^{-6}$

Despite the better efficiency and lower environmental impact of the combined system, its use is only present in large OOM in the country, where it is economically profitable, as it requires larger infrastructures and additional processes. However, due to the currently small number of this kind of OOM, the distances to them could be longer in many cases, resulting in higher transport EI. As essential parts of the industrial phase, this study considers biogenic carbon emissions produced by olive stones and exhausted pomace burned in the extraction processes and the olive cake treatment processes. The CC (with biogenic C) category does not consider the origin of the carbon emissions to arrive at the EI, including them in the sum. Conversely, the impact category without biogenic C only considers fossil sources of carbon emitted to air, not counting biogenic carbon for that category. This differentiation is useful because this kind of carbon emission belongs to a natural cycle in which it is captured equally from the atmosphere in the growing phase of a plant or a tree.

Figure 5 shows detailed results for the EIs for a 3-phase system, including the values of all activities in each category.

Figure 5. Contribution of industrial stage activities (3-phase extraction).



In the 3-phase system, the environmental impact in CC category without considering biogenic C was 0.15 kg CO_2 eq. and 0.39 kg CO_2 eq. considering biogenic C. The olive cake treated in this process has a lower environmental impact in CC category due to the lower heat consumption in the drying process if biogenic C emitted is considered (Fernández-Lobato et al., 2021b). Factoring in biogenic C, the influence of olive cake treatment on the total value is 43.59%, while other processes such as electricity and wastewater treatment are next in importance. Figure 5 shows how, without considering the biogenic C in CC, the weight of the most impactful activities is inverted in these activities, with the consumption of electricity (49.12%) in first place and the olive cake treatment (27.33%) in second place.

Table 8 shows the main parameters for the calculation of the economic allocation, considering the main by-products of the value chain and representing its influence on the LCA. It depends on the prices of VOO in the country analyzed and the price and quantity of the rest of by-products that can be sold from the industrial phase. In Spain, for example, olive oil extraction produces olive stones and 2-phase pomace, which has a high moisture content (up to 70%) and it is not profitable by itself.

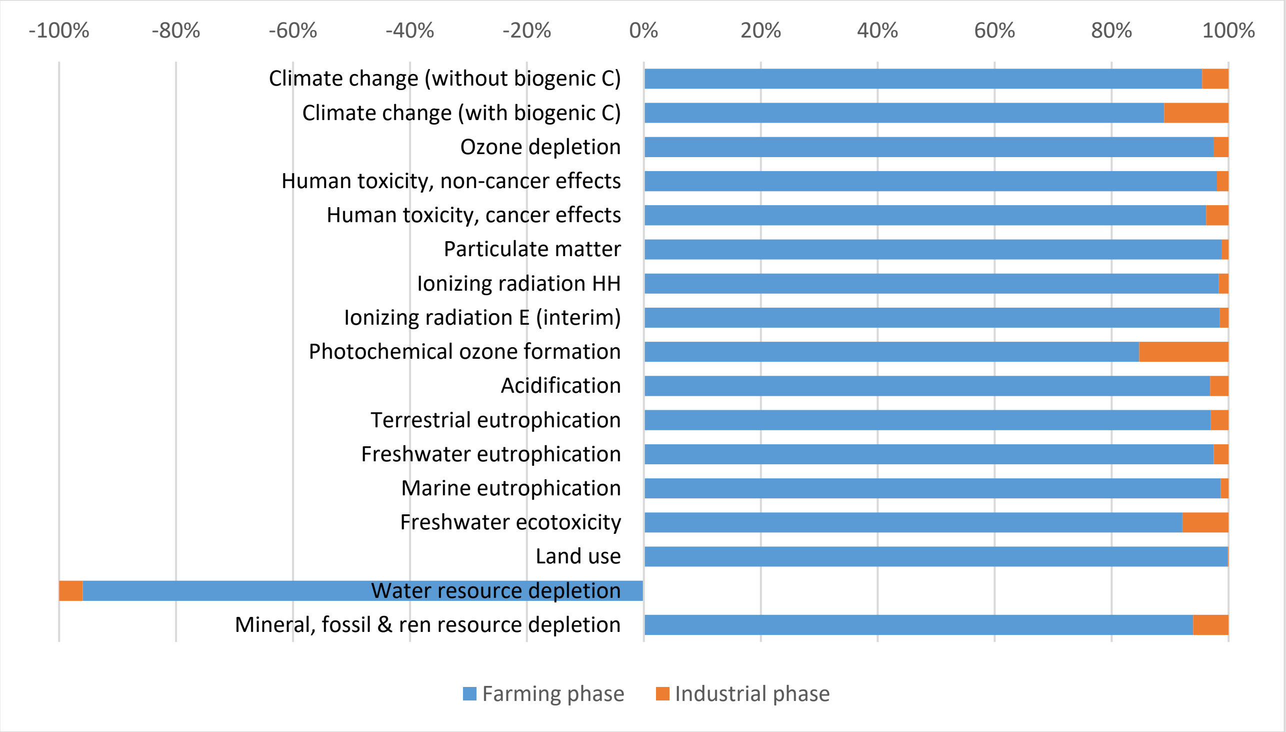
Therefore, pomace treatment evaporates most of the water content (leaving exhausted pomace with a moisture content of 10-15%) and a small quantity of valuable crude pomace olive oil is extracted, while the rest is sold as fuel (exhausted pomace) (Fernández-Lobato et al., 2021b). In Tunisia, for the 3-phase extraction, stones are not usually obtained in the OOM; they are part of the organic matter content in olive cake. This olive cake follows the same process as pomace but with lower moisture, and for this reason it is more profitable. The differences in allocation indicate the different percentages of the total environmental impact assigned to these different products. According to Fernández-Lobato et al. (2021), it is possible to see how in Spain, the by-products are more valuable as a characteristic of the value chain. Meanwhile, in Tunisia, the main by-products produce lower benefits in relation to VOO, which obtains most of the economic allocation. All these factors make the Spanish value chain more competitive and complex. Due to that economic allocation, the environmental impact of the FU in the farming and industrial phases can be assumed by 92.36% in Spain and 96.09% in Tunisia.

Table 8. Economic allocation of different by-products (Traditional cultivation and 3-phase extraction).

OUTPUT	Economic value 2015-20 (TND)	Mass (kg)	Economic Allocation
VIRGIN OLIVE OILS	8.91	1.00	96.09%
EXHAUSTED POMACE	0.08	1.10	0.41%
CRUDE POMACE OLIVE OIL	3.67	0.08	3.50%

The participation of every phase, for all categories, in global environmental impact can be observed in Figure 6. The farming phase is responsible for most of the differences among total values. Farmers who did not add chemical fertilizers to the soil and use animals for tillage would have a minimal impact in most categories because they do not use these inputs. For its part, the industrial phase is strongly influenced by electricity consumption and olive cake treatment.

Figure 6. Contribution to the environmental impact of the farming and industrial phases (VOO production, Tunisia).



Finally, the main results of this research could be compared with other LCA studies of different countries with a similar scope, assumptions and boundary conditions. Espadas-Aldana et al. (2019) offered different results of LCA studies up to the present time. From them, the studies that best fit with the methodology of the present study are those carried out by Pattara et al. (2016) and Proietti et al. (2017). In addition, a recent study of the most representative VOO production value chain in Spain is included to contextualize the comparison (Fernández-Lobato et al., 2021b) focusing on the chosen territorial framework, the only previous LCA study on olive production in Tunisia is the one conducted by Ben Abdallah et al. (2021). Table 9 summarizes the information collected among them, offering general contextualization data and their main results.

In terms of production Spain accounts for 45.07% of world olive oil production, followed by Italy (10.33%) in the period 2015-2020. (International Olive Council, 2021). (International Olive Council, 2021). Considering these data, comparisons are made with Italy and Spain on the one hand because of their representativeness of the olive oil sector at world level and, on the other hand, because the selected studies use the same methodology and scope.

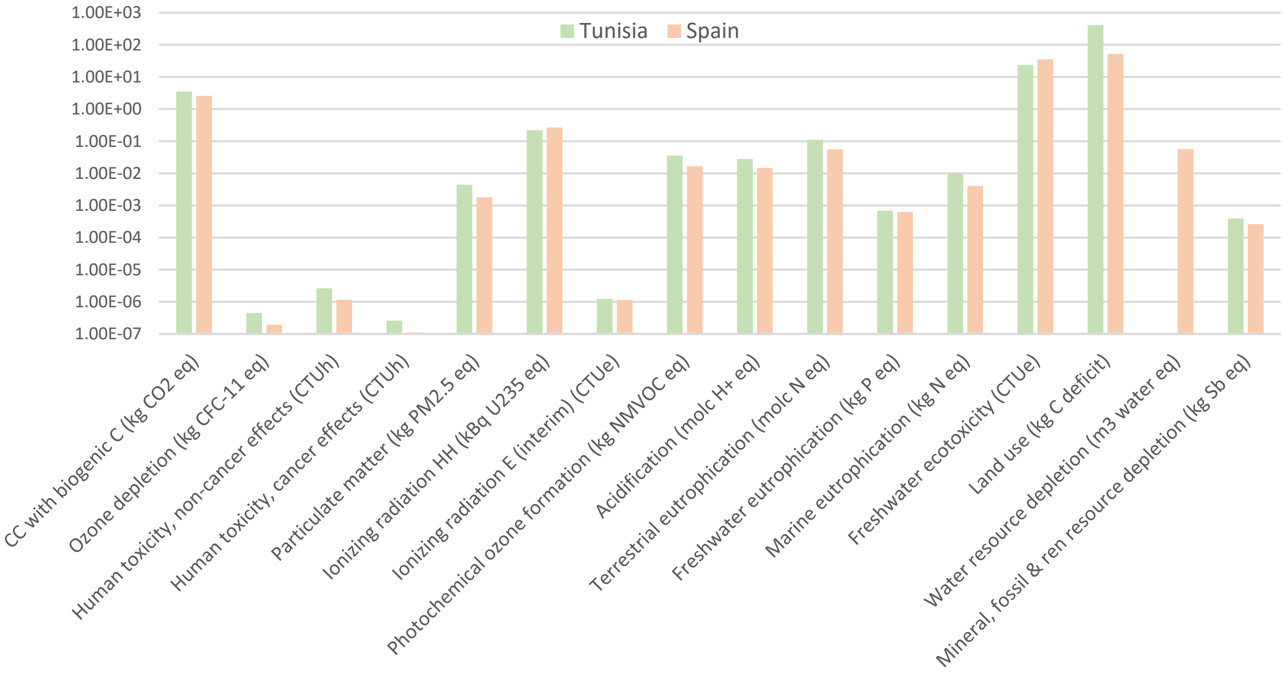
It is important to point out that the choice of the FU as VOO does not consider the different qualities of this product, which is a limitation of this study and a constraint on comparison with other studies that use extra virgin olive oil (Extra VOO) as FU (Pattara et al., 2016; Proietti et al., 2017).

Table 9. Representative data and results comparison between the present work and other related studies.

	Present work	Fernández-Lobato et al., (2021)	Ben Abdallah et al., (2021)	Pattara et al., (2016)		Proietti et al., (2017)	
Territory	Tunisia	Andalusia (Spain)	Tunisia	Abruzzo (Italy)		Umbria (Italy)	
Seasons (years)	1 (2019-2020)	5 (2015-2020)	Historical record	1 (2014-15)		1 (2014-15)	
Scope	Cradle-to-gate	Cradle-to-gate	Cradle-to-cradle	Cradle-to-gate		Cradle-to-gate	
FU	1 kg VOO	1 kg VOO	1 t olives (for 48 years)	5 L Extra VOO		1 L Extra VOO	
Representative case	Traditional conventional rainfed	Traditional representative	Traditional conventional rainfed	Case 2 (lowest impact)	Case 5 (highest impact)	Case A (lowest impact)	Case G (highest impact)
Density (trees/ha)	17-100	100-150	17-34	± 200	± 200	390	478
Olive oil yield (L/ha)	109	950	-	1,345	1,025	1,172	467
CC (Global impact)	3.53	2.39	-	4.48	10.10	0.67	4.48
CC (Farming phase)	3.14	1.84	$2.34 \cdot 10^4$	3.34	7.74	0.30	3.33
CC (Industry phase)	0.39	0.55	-	1.14	3.20	0.37	1.14

Continuing toward the discussion, Figure 7 shows a comparative analysis between the most representative value chain of the present study and a recent LCA in the Spanish one, showing the environmental impact values of the same categories and with similar methodological considerations (same scope and system boundaries).

Figure 7. Total environmental impact of Spain and Tunisia for VOO production (all impact categories).



As Figure 7 shows, the environmental impact of the most representative value chain in Tunisia are higher than those of Spain in most categories (13 out of 16 categories), with 1.14 kg CO_2 eq. more in Tunisia than in Spain for CC impact category (Fernández-Lobato et al., 2021b).

On the other hand, comparing the main results with Ben Abdallah et al. (2021), it is worth noting that while the results of that research show that greater intensification correlate with a lower impact, the same correlation is observed in the present study, although not in the CC category for the intensive type. This is mainly due to the data considered in the LCI because this study is based on recent data of a productive phase (2019-2020 harvest), while the data of Ben Abdallah et al. (2021) come from records covering a longer period and a life cycle of 48 years with different cropping phases (see literature review). Table 10 provides the main data that led to the difference in the results obtained (the text in bold highlights the types studied in this research and non-bold data are those of Ben Abdallah et al. (2021) results). In the present study, the densities considered are slightly different than those in the data found by Ben Abdallah et al.(2021). In addition, the agricultural yields are significantly lower, while for the intensive and super-intensive cases, the electricity consumption per ha is much higher, especially in the intensive case, which is about twice that provided by Ben Abdallah et al. (2021) and higher than that of the super-intensive case studied. This parameter is very decisive in the impact on CC, and can account for 30-40% of the impact, which is why the intensive crop sample is very impactful, and the super-intensive case produces a lower impact than these. It can be concluded that, for each case, agricultural yield and irrigation electricity consumption are very important factors in intensive and super-intensive crops and need to be specially considered to establish whether their impact is greater or less than that of the traditional rainfed sample. The comparison between Tunisia and Spain is particularly interesting for a better understanding of the olive sector in the world from an environmental point of view. It confirms the specificity of the olive sector in each country revealing the interest of performing more specific LCAs at a local level in other producing countries. Such a comparative LCA also informs about the existing opportunities throughout the overall value chain. In the production phase, Tunisia is mainly characterized by the predominance of extensive rainfed groves, which do not use many inputs but produce lower yields contributing to the increase of their environmental impact per kilogram of olive oil. Tunisia also has a lot of land engaged in olive production. In contrast, the Spanish olive sector adopts a more intensive production system and is better organized and efficient per unit of land, which contributes to the decrease in the environmental impact per kilogram of olive oil. The same applies to the industrial phase which differs between a Tunisian transformation infrastructure characterized by a large number of small olive mills that are geographically dispersed while the Spanish infrastructure is characterized by large capacity cooperatives which are much more efficient and organized, thus contributing to the lower impact per kilogram of olive oil. It could be of a great interest for Tunisia at both the economic and environmental levels to better organize the olive oil value chain, improve the efficiency in both the agronomic and industrial phases, introduce innovative solutions like the use of renewable energy, water and soil conservation works (WSCW) (Jouini et al., 2019) and valorize co-products using new emerging technologies.

Table 10. Comparative analysis of the main results of farming phase EI.

	Work	Density (trees/ha)	Yield (kg/ha)	Electricity (kWh/ha)	CC (kg CO_2 eq. per 4.97 kg olives)	CC (kg CO_2 eq. per 1t olives for 48 years)
TRADITIONAL RAINFED UNFERTILIZED	**Present work**	**17-100**	**500**	**-**	**3.14**	**$3.03 \cdot 10^4$**
	Ben Abdallah	17-34	622	-	-	$2.34 \cdot 10^4$
INTENSIVE IRRIGATED FERTILIZED	**Present work**	**204-555**	**6009**	**2374**	**3.44**	**$3.32 \cdot 10^4$**
	Ben Abdallah	204-278	7000	878	-	$1.73 \cdot 10^4$
		416-555	9500	1210	-	$1.23 \cdot 10^4$
S-INTENSIVE IRRIGATED FERTILIZED	**Present work**	**1666**	**8654**	**1789**	**2.55**	**$2.46 \cdot 10^4$**
	Ben Abdallah	1250-1666	10600	1345	-	$1.24 \cdot 10^4$

5. CONCLUSIONS

The Tunisian olive oil value chain strongly influences the country's environment, people and economy, this paper has carried out an LCA to know its EIs in order to take strategic decisions to improve its VOO production. The main LCA values obtained in the study determine the environmental impact of different production systems at the farming and industrial stages, providing the opportunity to compare them for every impact category of the sixteen considered.

Regarding the main impact category, CC, the environmental impact of the most representative crop type (extensive rainfed) has a value of 3.14 kg CO_2 eq. per kg of VOO, while the intensive crops have a 9.6% higher impact, and the super-intensive case has 18.8% less impact. The contribution of the industrial phase to the total environmental impact is between 0.1% (LU) and 15.3% (POF), or 4.5% in CC without considering biogenic carbon and 11.0% if it is considered. The CC values of the industrial phase (3-phase system) are 0.15kg CO_2 eq. (without considering biogenic C) and 0.39 kg CO_2 eq. (considering biogenic C) per kg of VOO. This means that most of the CC impact of the industrial phase is attributable to the biomass combustion in oil extraction and pomace treatment processes. Regarding total CC impact, VOO production in the most representative value chain of Tunisia results in an emission of 3.29 kg CO_2 eq. per kg considering only fossil fuel emissions, and 3.53 kg CO_2 eq. per kg considering also biogenic C emissions. Another important fact that is very significant for Tunisian development is that its most representative olive oil value chain does not have a negative impact on the depletion of water resources. It is hoped that this will continue to be the case in order to maintain the sustainability of the sector. Notwithstanding the above, this aspect is currently changing in Tunisia with the implementation of intensive and super-intensive irrigation systems in recent years. This development may not be compatible with the ongoing effects of CC for the coming seasons, with particular emphasis on the availability of fresh water.

The results of this study present the EIs that cover the agricultural and industrial stage of olive oil production systems in Tunisia for the first time and they may help decision-makers to find more sustainable options for olive oil supply chain in different impact categories. Research proposals concerning sustainability in the olive oil sector include the research into additional aspects, such as long-term carbon sequestration in soils, other LCAs of different phases of the life cycle, alternative systems such as biological approaches and technological improvements. The adoption of agricultural best practices to increase yields while under rain fed conditions is a key solution to ensure the sustainability of the traditional Tunisian olive groves. This may be achievable by innovative soil and water conservation practices including but not restricted to: a) Decreasing tillage while using short cycle cover crops, b) Supporting water and soil conservation works (WSCWs) in the traditional groves, c) Organic amendments from animal origin, by composting and/or by the incorporation of pruning wood into the soil, d) Increasing planting density per hectare while using adapted cultivars. However, it is also crucial to optimize water and energy in the new expanding irrigated plantations in Tunisia so as ensure a rationalized production by unit of input. This means making greater efforts in terms of energy efficiency and water productivity in the irrigated orchards in order to maximize production while using the minimum areas of cultivation in a sustainable way. In the industrial phase, the most challenging issues are the use of energy and the management of co-products. Some of the most promising solutions could be: a) Supporting renewable sources of energy in olive mills, such as photovoltaic systems; b) Promoting the introduction of two-phase extraction systems on a large scale; c) Optimizing transport through all the steps of the value chain d) Introducing innovative technologies that can improve energy efficiency, and valorization of co-products like pyrolysis or gasification technologies (one of the best available technologies for bioenergy production that also generates biochar, a valuable product for soil enhancement). It is thus recommended to perform future LCAs in the Tunisian olive sector considering each technology/best practice individually and assessing its EI.

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