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Life Cycle Assessment of waste disposal from olive oil production: Anaerobic digestion and conventional disposal on soil

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ABSTRACT

Extra virgin olive-oil (EVO) production is an important economic activity for several countries, especially in the Mediterranean area such as Spain, Italy, Greece and Tunisia. The two major by-products from olive oil pro- duction, solid-liquid Olive Pomace (OP) and the Olive Mill Waste Waters (OMWW), are still mainly disposed on soil, in spite of the existence of legislation which already limits this practice. The present study compares the environmental impacts associated with two different scenarios for the management of waste from olive oil production through a comparative Life Cycle Assessment (LCA). The two alternative scenarios are: (I) Anaerobic Digestion and (II) Disposal on soil. The analysis was performed through SimaPro software and the assessment of the impact categories was based on International Life Cycle Data and Cumulative Energy Demand methods.

Both the scenarios are mostly related to the cultivation and harvesting phase and are highly dependent on the irrigation practice and related energy demand. Results from the present study clearly show that the waste disposal on soil causes the worst environmental performance of all the impact categories considered here. Important environmental benefits have been identified when anaerobic digestion is chosen as the final treat

ment. It was consequently demonstrated that anaerobic digestion should be a feasible alternative for olive mills, to produce biogas from common olive oil residues, reducing the environmental burden and adding value to the olive oil production chain.

1. Introduction

Global olive oil production reached almost 2854 million tons for the crop year 2017–2018 (from 1 October to 30 September), with a 12-percent increase over the previous year's output. According to data by FAOSTAT, in the years 1994–2013, Spain is the world's leading olive producer with an average production of 1,059,194 tons of olive oil while Italy is the second with 555,574 tons. More than 80% of Italy's olive oil production is concentrated in the Southern regions Puglia, Sicily, Basilicata, Sardinia, and Calabria (EUROSTAT, 2018). Other relevant producers are Greece (344,615 tons) and Tunisia (159,990 tons) (ISTAT, 2017; International Olive Council, 2018).

Olive oil extraction from drupes dates up to 5000 years ago (Boskou, 2006). The process consists in the recovery of olive oil, located in the mesocarp cells and stored in a particular type of vacuole called lipo-vacuole. Currently, olives are crushed to a fine paste by hammer, disc crusher, depitting machine or knife crusher. Separation of solids, water and oil is achieved either by physical techniques or by chemical sol-vents, generally hexane (Gunstone, 2011). The modern method of olive oil extraction uses an industrial decanter to separate the three phases: Olive Pomace (OP ∼ 30% w/w), Olive Mill Waste Waters (OMWW ∼ 50% w/w) and oil (∼20% w/w), according to their specific densities (OP > OMWW > Oil) (Vossen, 2007). Although the three-phase oil decanter is more effective, it produces larger quantities of OMWW than the two-phase oil decanter which is designed only for oil and wet pomace separation (Patumi et al., 1999).

According to a territorial survey conducted by Agri Regioni Europa, the amount of OP derived from olive mills in Italy is 2,264,483 t/y

(Chiodo and Nardella, 2011). Despite the economic relevance of this agricultural product, the olive oil industry causes diverse environmental impacts in terms of resource depletion, land degradation, air emissions and waste generation (Salomone and Ioppolo, 2012). OP and OMWW have low pH (5.6), a high organic content (COD > 250 g/L) and can include several chemical substances (such as nitrogenous (TN), ammonia (TAN) and phosphorous (TP) compounds). Consequently, an inadequate management of these waste-streams can result into significant environmental impacts in those regions characterized by an important oil production, as in the case of Southern Italy (Ruggeri et al., 2015). These impacts may vary significantly according to cultivation practice, oil production method and waste disposal (Ciancabilla et al., 2004).

Despite the existence of European regulation on waste (European Commission, 2008) there are no specific provisions for olive mill waste (Inglezakis et al., 2012). Hence, each country has developed its national legislation. The legislation on olive oil production applied in some of the most important producer countries has been collected and here reported. With respect to the Italian regulations, the maximum amount of olive waste allowed for the release on soil is 30 m^3 ha/year (Law n.574, 1996). The same value is prescribed in the 4/2011 Decree of the Regional Government of Andalusia, Spain (Decreto 4/2011). However, Portugal allows the practice of spreading vegetable water up to 80 m^3/ha per year (Law No. 626/2000). With regard to Greece, the law 1180/1981 regulates the production and processing of vegetable/animal fats and oils and establishes a monthly average limit of 5 kg of product for suspended solids as limit value. Finally, in Cyprus the Ordinance No. 254/2003 sets different limits depending on the process used for oil extraction (Inglezakis et al., 2012). Sierra and co-workers (Sierra et al., 2007) demonstrated that increasing the rate of OMWW on soil up to 360 m^3 ha/y can significantly enhance the fertility of the soil. However, the immobilization of nitrate, the increase of salinity and the

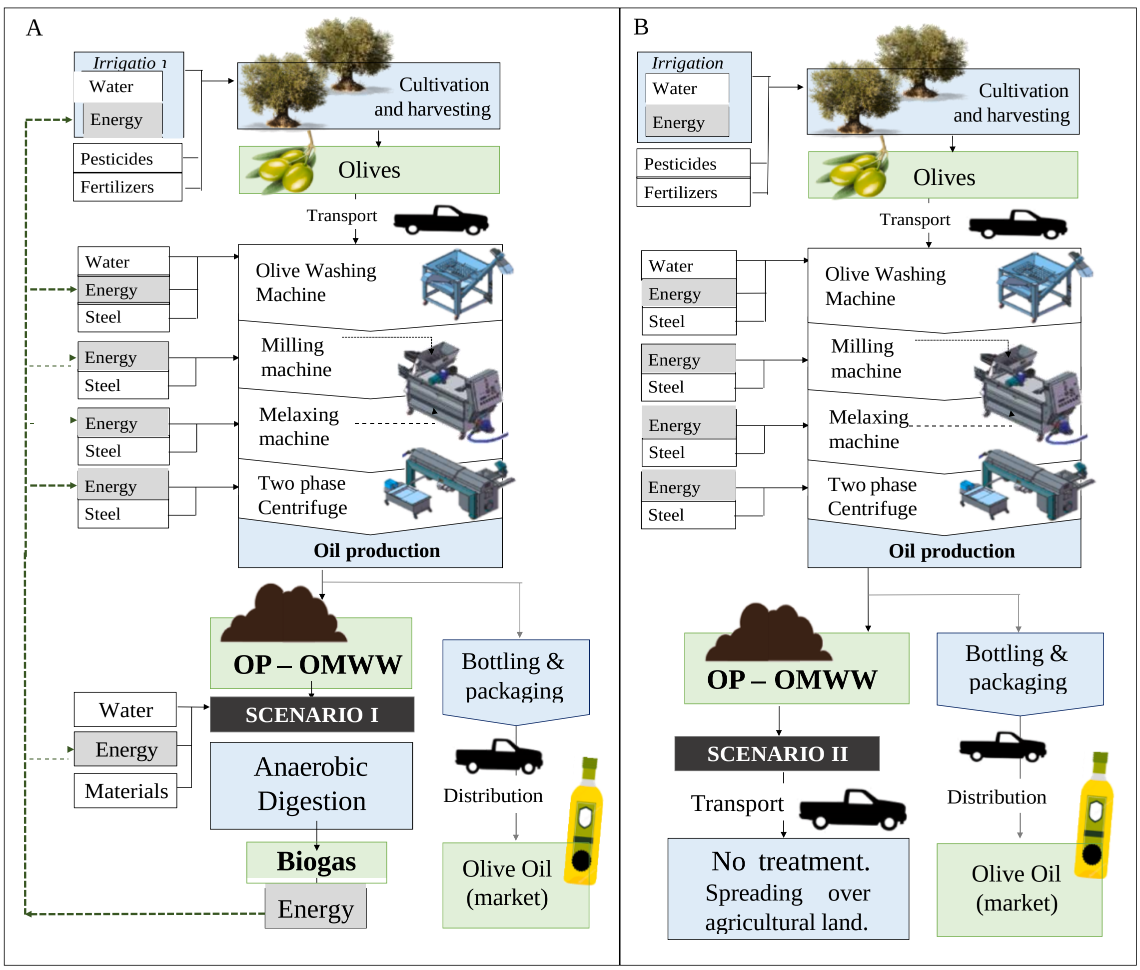

Fig. 1. Flowchart Diagram of the input and output in olive oil production system for 1 L of extra virgin olive-oil (EVO) and its waste treatment within the two examined scenarios. Part A and Part B represent scenario I and scenario II, respectively. Olive oil is only taken into account in terms of allocation.

accumulation of poly-phenolic compounds may negatively affect the ecosystem. In addition, a fraction of the carbon content is aerobically degraded through the contact with the atmosphere, generating Green House Gas (GHG) emissions while the disposal on soil increases the chance of aquifer pollution (Ciancabilla et al., 2004; European Commission, 2018).

The increase of GHG emissions and the simultaneous depletion of fossil fuels is attracting attention towards the use of clean and alternative energy sources. Considering the high organic loads, olive wastes (OP and OMWW) should be valorized through energy-recovery oriented technologies such as Anaerobic Digestion (AD) aimed at energy recovery, as indicated by the European resource and bio-economy strategy (De Besi and McCormick, 2015; Da Man and Friege, 2016; Chilosi et al., 2017) for other agro-food residual biomasses. AD is considered one of the most promising technology for treating the waste derived from olive oil processing (Battista et al., 2013) due to the numerous advantages it offers in terms of high abatement of organic substances, low nutrient supply for the degradation of the substrates, production of a stabilized sludge and production of biogas production with high methane content. Previous studies have demonstrated the high performance in biogas production from olive oil waste reaching 1.4 NL/L of biogas production with a methane content of 70% v/v in a 45 L fermenter in a continuous mode (Battista et al., 2013).

The use of OP and OMWW are used as feedstock for biogas production through AD can represent a useful alternative to the conventional olive waste disposal on soil. However, this option should be carefully assessed by evaluating their overall impacts and benefits. The present work aims to carry out this analysis through Life Cycle Assessment (LCA) applied to the two alternative scenarios.

2. Methodology

The environmental analysis of management alternatives for waste disposal from olive oil production was carried out by means of the LCA methodology. In this context, LCA is a useful tool for analyzing potential impacts during the whole olive oil production process and product life; from the extraction of resources, production of materials, equipment, use of the product and its end of life, which is the focus of the work (Finnveden et al., 2009). LCA ISO standards (ISO, 2006a; 2006b) have been considered to define the principles, framework, requirements and guidelines of handling the present LCA study. The approach can be synthesized in the following closely intertwined stages: i) Goal and scope, ii) Life Cycle Inventory (LCI), iii) Life Cycle Impact Assessment and, iv) Interpretation.

2.1. Goal and scope definition

The first LCA phase aims to define the goal and scope, the system boundary and the functional unit. Fig. 1 shows the flowchart of the two considered scenarios, where it is possible to distinguish the system boundaries. Both scenarios consider the whole system required to produce olive oil (and consequently OP and OMWW as co-products), including cultivation and harvesting, olives transport from fields to the mill, all stages of olive oil production and, finally, the end-of-life of the olive oil production waste. The main goal is quantitatively assessing how much the analyzed end-of-life disposal solutions affect the overall environmental impacts, highlighting the potential for future improvements in the production chain.

Scenario I, according to Circular Economy principles, consider the anaerobic digestion as the final step where the significant organic load of OP and OMWW is converted into biogas and therefore its energy content effectively recovered. In addition, this scenario considers that the recovered energy is utilized within the same life cycle closing the loop and adding value to the olive oil productive chain. Finally, the organic matter content of the digestate from AD process is expected to be exploited as fertilizer (Tekin and Dalgıç, 2000) according to the standards provided by regulations.

On the contrary, Scenario II involves the "traditional" disposal of the wastes on the soil with no preliminary treatment as the OP-OMWW blend is just transported to the field and discharged on the agricultural land. Although the high environmental impact of the practice, this scenario still represents the typical waste management for many regions in the world (Alfano et al., 2003).

The analysis here presented includes inputs and outputs from the olive cultivation and harvesting to the 1 L of olive oil production, till the final solution for the waste management. The functional unit is used as a basis for comparison and then all inputs and outputs in the inventory phase are referred to it. The functional unit in both scenarios is the amount of waste (the OP-OMWW blend) from the production of one litre of EVO. It is assumed that 3.5 kg of OP and 1.5 kg of OMWW are produced per litre of oil (ISTAT, 2017), to which the environmental impacts are related in both the two different management scenarios. Although the whole olive oil production is considered in the analysis, the impacts are allocated (as described below) in order to focus on those specifically related to the waste production and management.

When a process originates two or more products at the same time (co-products) the inputs and outputs for the process need to be allocated, to indicate the exact flows corresponding to the specific product. Allocation is defined as "partitioning the input or output flows of a process or a product system between the product system under study" (ISO, 2006a). Hence, the inputs and outputs of the system should be partitioned between its different products in a way that reflects the physical (i.e. quantities in kg) or economical (i.e. their market costs) relationships (Ardente and Cellura, 2012; ISO, 2000). Physical allocation is considered unfair when the coproduct is characterized by a lower value with respect to the main product, like in the present case. To prevent this unfairness, Economic allocation was chosen in this analysis. With regard to the foregoing and being the waste (OP-OMWW) a coproduct from olive oil, in the present study allocation of environ- mental impacts between the olive oil and its waste were performed from an economic point of view. By considering the market price of 1 kg of olive oil, the economic allocation was conducted with an allocation factor for the olive oil of 97.2% (Parascanu et al., 2018) which includes the olive oil productive chain from the field to the market, while an allocation factor of 2.8% was considered for the OP-OMWW blend.

2.2. Life Cycle Inventory (LCI)

Life Cycle Inventory (LCI) gathers the required data quantifying the relevant inputs and outputs of the production system. Table 1 shows the LCA Inventory of this work with every input and output referred to the functional unit (FU). As explained below, this stage was accomplished through a collection of foreground data from scientific literature.

Regarding water consumption in the cultivation and harvesting phase, it was found that irrigation plays an important role in the olive oil production. There are several irrigation approaches from full irrigation up to rainfall fed dry systems. In this regard, a sustained deficit irrigation (SDI) approach is a suitable alternative in Mediterranean climate where full irrigation is not always a viable strategy. Moriana et al. (2003) estimated that the SDI consumes a yearly average of 166 L/m which entails nearby 225 L of water for the considered FU. Similar values were also reported for water consumption in other studies (Perea et al., 2018).

The energy input of the FU was gained from a study by Cappelleti et al. (2014) where the authors reported data on the energy demand required to irrigate 100 kg of olives.

Fertilizers and pesticides were estimated taking into account the soil nature and the production ratio (Moriana et al., 2003) as reported in Foteinis and Chatzisymeon (2016), and other research works (Moriana et al., 2003).

In accordance with technical and scientific literature (Moriana et al., 2003; Parascanu et al., 2018), the production of 1 L of EVO

Table 1
LCA Inventory. Inputs and outputs are referred to the Functional Unit.

Process	Subprocess	Input	Amount	Unit
Cultivation and harvesting	Irrigation	Water	225	L
		Energy	2.78	kWh
	Fertilizers	Manure	36	kg
		Calcium nitrate	1.20E-03	kg
	Pesticides	Kocide Opty (30% CuOH)	1.20E-04	kg
		Aliette (80% Fosetyl-Al)	1.20E-06	kg
		Ridomi gold (64% Mancozebe 4% MetoXyo-M)	1.50E-06	kg
		Output	**Amount**	**Unit**
		Olives	6	kg
Transport of olives to milling sites		**Input**	**Amount**	**Unit**
		Diesel	0.01125	L
Olive Oil production	**Subprocess**	**Input**	**Amount**	**Unit**
	Olive washing machine	Water	0.35	L
		Energy	0.0200	kWh
		Steel	3.66E-05	kg
	Milling machine	Energy	0.029	kWh
		Steel	5.20E-05	kg
	Malaxing	Energy	0.006	kWh
		Steel	2.85E-05	kg
	Centrifuge	Energy	0.00375	kWh
		Steel	7.938E-05	kg
		Output	**Amount**	**Unit**
	Olive Oil	1	L	
	Waste	**Olive Pomace**	3.5	kg
		Olive Mill Waste Water	1.5	kg
Scenario I: Anaerobic Digestion	**Subprocess**	**Input**	**Amount**	**Unit**
	Waste	Olive Pomace	3.5	kg
		Olive Mill Waste Water	1.5	kg
		Water	10	L
	Output	**Amount**	**Unit**	
	Biogas	**10.5**	L	
Scenario II: No treatment	**Subprocess**	**Input**	**Amount**	**Unit**
	Waste	Olive Pomace	3.5	kg
		Olive Mill Waste Water	1.5	kg
	Transport	Diesel	9.375E-03	L
	Output		**Amount**	**Unit**
	Waste spreading over agricultural land		**5**	**kg**

requires about 6 kg of olives, obtained as the output of the cultivation and harvesting process (Table 1 and Fig. 1). This amount of olives is considered being transported to olive mills in a pick-up van assuming 20 km of distance on average, 7.5 L/100 km of diesel consumption and 800 kg of total load transported.

The olive oil production phase includes a sequential process of washing, milling, malaxing and centrifugation with an assumed machinery lifetime of 10 years. The study considers a standard 6.67 kW olive washing machine (Alfa Laval, 2018) made of 1070 kg of stainless steel, with an hourly productive capacity of 2000 kg/h of olives and a water consumption of 2800 L/day (technical data). Milling is done in a 22 kW machine, with a productive capacity of 4500 kg/h (Industrias de la Rosa, 2018). Subsequently, malaxing is conducted in a 3 kW power steel-made machine, weighing 1250 kg and with a 900–2000 L of processing capacity (Pieralisi, 2018). The final treatment stage for the olive oil extraction uses a 7.5 kW power centrifugation (Haus, 2018) with the simultaneous separation of the waste-streams.

Taking into account the amount of olives for 1 L olive oil production (FU), the life time, materials, energy and water consumption were stated from the technical data sheets machinery as reported in Table 1. To simplify the analysis all materials not stainless steel-made were considered out of the scope of this work. This simplification was considered acceptable as the remaining materials, mainly made of plastic, were irrelevant in mass and so negligible in terms of contribute to the environmental impacts (less of 0.1% to any of the investigated impact categories).

With regard to Scenario I, the water required in the fermentative broth to carry out the AD of olive pomace and olive mill waste water, the biogas production rate and the energy produced were estimated on the basis of the following assumptions:

- Battista et al. (2013) estimated the biogas production from olive oil waste products in the Puglia region (Italy); the authors established the total solids (TS) content in the olive waste was nearly 30% w/w;
- An extensive study of biogas production from olive pomace (Tekin and Dalgıç, 2000) yielded results of 0.70 L of biogas per L of digester volume, corresponding to a 10% TS with a methane content of the biogas in the range of 75–80%;
- Ruggeri et al. (2013) studied biogas energy from AD and demonstrated a 50% drop in the amount of net energy vs. the useful energy principally due to the materials and the energy required to run the plant; this is the so-called energy amortization. This drop of over half a percentage point is not showed in Table 1 but it has been included in the modelled scenario;
- It was considered a 78% of CH_4 volume content in biogas (Tekin and Dalgıç, 2000) with an available energy content of 36 $MJ/m^3\ CH_4$ (Angelidaki et al., 2018). It results in 0.041 kWh recovered for the considered Functional Unit.
- On one hand, digesters can be made of different materials depending on the application (Garfí et al., 2016; Tekin and Dalgıç, 2000). On the other hand, it is known that environmental impacts related to materials are significantly reduced when lifetime of the plant (at least 10 years) is assumed (Battista et al., 2013). This research work aims to determine the environmental benefits of introducing AD in the olive mills to valorize their waste. This technology is a new approach and there are few olive mills applying this practice, that is why there is a lack of available technical data. Moreover, among the few available data, the operative phase of these plants has not been fully reported yet. The level of detail and transparency provided in the present article must allow reproducibility of this study. Hence, it was decided to disregard the materials from the digester. In this study it is intended to know the applicability of this approach from an environmental point of view. Authors consider this research work as the starting point for future investigations.

Waste from olive oil production constitutes a hazardous stream which represents one of the main problems of the olive oil industry (Roig et al., 2006). Since the AD from olive oil waste and its energy conversion still lack of a widespread full-scale application, it becomes difficult the access to primary data that is the main reason for the use of secondary data. Therefore, more research and data verification are needed since the recovery of biogas from olive oil waste is at an early stage compared with other energy-recovery system. The use of secondary data is also justified because there are several studies in the field of LCA in olive oil production (Iraldo et al., 2014; Rajaeifar et al., 2014; Avraamides and Fatta, 2008), but none of them are jointly related with LCA, anaerobic digestion (Mata-Alvarez et al., 2000; Khalid et al., 2011) and olive oil waste valorization.

One of the most representative studies in this field (Salomone et al., 2015) stated that the waste from olive oil "should be considered as a new raw material necessary to make a new product and it should be valorized in LCA studies". Following this statement, it was assessed the feasibility of generating electricity in the plant and how it could reduce the environmental impacts in view of the life cycle thinking and the circular economy principles. On this basis, Scenario I inventory was created.

The energy recovered in the Scenario I, can be used as a feedstock of a new life cycle. Hence, in order to minimize the waste and pollution and to maximize the use of renewable resources this energy is provided back in the process, closing the loop.

Scenario II was modelled according to the assumption that OP and OMWW is transported to the agricultural field and just released on the soil. Transport assumption is similar to those utilized in the transportation of olives: a pick-up van, 20 km of distance average, 7.5 L/100 km of diesel consumption and 800 kg of total load transported.

Table 2 shows the biomass characterization for OP and OMWW. It can be observed as the organic load and the other parameters of OP and OMWW exceed the limits imposed by the Italian national law (Law n. 574, 1996) or the 4/2011 Decree of the Regional Government of Andalusia, Spain (Decreto 4/2011): as a consequence, it is expected that the aerobic degradation of these substrates and the adsorption of chemical compounds by the soil are responsible for air, ground and aquifers pollutions.

2.3. Life Cycle Impact Assessment

During the third phase of LCA, the evaluation of the potential environmental impacts, using the data from the inventory phase, is carried out.

Regarding the methods, last decade the European Commission (2011) analyzed numerous Life Cycle Impact Assessment (LCIA) methodologies and worked on it. These efforts were collected in a method called International Life Cycle Data system (ILCD) recommendations for LCIA in the European context. In the present study, for the sake of consistency and quality assurance, the ILCD was applied. Among all ILCD impacts categories only four of them, i.e. CC, AC, TE, WRD, were considered as discussed in the following. Finally, energy is involved in all life cycles and it represents a critical issue in the economic systems, then Cumulative Energy Demand method (Frischknecht et al., 2007), was also included among the selected impact categories assessing the CED indicator.

Tillman (2000) stated the possibility of conducting different methodological choices depending on the purpose of LCA and its different applications. For the sake of simplicity and to focus on the main aims, many authors focus their works on few environmental categories. For instance, Palacios-Munoz et al. (2018) carried out a study considering CC and CED. Impact category choice in other study (Botas et al., 2017) was to evaluate CC, CED, AC, Human Toxicity and Ecotoxicity. Encinas-Sánchez et al. (2018) assessed CC, WD and CED and Hennequin et al. (2018) assessed just 7 of the 12 impact categories that CML methodology considers.

In this study we have chosen the impact categories on the basis of the following motivations: Greenhouse reduction gases (40% by 2030 relative to 1990 levels) and optimization of energy consumption (improving energy efficiency and 27% sharing of renewable energy) are targeted by European Union framework for climate and energy policies in the 2020–2030 (European Commission, 2014). Hence, it was considered highly appropriated to provide our results in terms of Climate Change (CC) and Cumulative Energy Demand (CED) categories. On the other hand, worldwide water crisis was defined as the crisis of 21st century (Rajindar, 2008) and that is why it was evaluated this critical issue by means of the Water Resource Depletion indicator. Additionally, Scenario II assessed the OMWW land spreading practice. For this reason, authors have considered interesting assessing those environmental impacts more specifically related with the soil by calculating Terrestrial Eutrophication (TE) and acidification (AC) impact categories.

The assessment procedure was carried out using Simapro 8.5.2, in accordance with the principle of ISO standards (ISO, 2006a; ISO, 2006b). The data were provided by the Ecoinvent database V3.4 (Frischknecht and Gerald, 2005; Ecoinvent, 2018). The geographical scope was set in Southern Italy. Consequently, that is, the inventory data for biomass composition, technologies and the legislation context in terms of efficiency and emissions were referred to Italian conditions in the medium term.

The fourth and last LCA phase is focused on the interpretation of the results, which is performed in the following section.

3. Results and discussion

3.1. Scenario I: olive-oil waste as feedstock in anaerobic digestion

The results from LCA application to Scenario I are shown in Table 3. Instead, Fig. 2 shows a thorough depiction of the main contributions to the total environmental impact.

Fig. 2 shows as the cultivation and harvesting phase (consisting of irrigation water, fertilizers, pesticides and energy contributions) causes the highest impact being close to 90% of the total impact for four of the all investigated categories. This result is mainly attributed to the energy required in the irrigation phase which contributes to 84%, 81%, 74% and 83% of the total impact in case of CC, AC, TE and CE respectively. Data obtained from previous studies (Salomone and Ioppolo, 2012) using direct application on fields of olive mill waste, indicated environmental impacts (CC, ET, AC) ranging from 88.7 to 100%. Water Resource Depletion (WRD) is not so heavily impacted by the cultivation and harvesting phase because the main contributor to this impact is not the energy from irrigation but the fertilizers. Environmental impacts are scarcely affected by pesticides, transport of olives and the olive oil production itself in all the assessed categories (1.9% highest value in WRD impact category).

With regard to the impacts deriving from the use of water, results reveal lower impacts from water used in irrigation than those from the water added to carry out the AD in all the assessed categories with the exception of WRD.

All of the impact categories show negative values for the energy produced. Negative values reveal benefits for the environment, while positive values represent environmental impacts. In the Scenario I, waste is considered as a feedstock of a new life cycle. Hence, these negative values (environmental benefits) are a consequence of the energy recovery by closing the loop and using the energy produced from biogas in the same life cycle. The recovered energy influences the WDR impact with a 47% (negative values) and is never lower than 39% in the other impact categories assessed. In the circular economy vision, it is interesting to highlight that also the digestate, could be recovered for the production of fertilizer, allowing a further reduction of the CC impact.

3.2. Scenario II: disposal on soil without olive-oil waste treatment

Analogous to Scenario I, the Scenario II was analyzed to determine the main contributions of the different inputs/outputs considered in the total environmental impact.

The total environmental impact associated to Scenario II is presented in Table 3 for the different environmental indicators considered in this work. Fig. 3 shows the main results related to each stage considered in the investigation. Besides the parameters assessed in Scenario I, related to the cultivation and harvesting phase, olives transport and the oil production the transport of the OP-OMWW blend from the olive

Table 2
Biomass characterization.

	OP	OMWW
Density (kg m^{-3})	960.70 ± 39.65	934.96 ± 7.14
pH	5.12 ± 0.08	4.89 ± 0.04
TS content (% *w/w*)	32.16 ± 2.06	0.91 ± 0.03
VS content (% w/w)	30.21 ± 2.02	0.08 ± 0.11
TAN (g/L)	1.78 ± 0.53	0.01 ± 0.00
TN (g/L)	1.78 ± 0.53	0.27 ± 0.02
TP (g/L)	0.62 ± 0.11	0.11 ± 0.01
Polyphenols concentration (mg gallic acid/L)	24.78 ± 2.38	254.45 ± 12.38

Table 3
LCA Results according to the impact categories.

Impact Category	Abbreviation	Unit	Scenario I	Scenario II
Climate change	CC	kg $CO_{2\ eq}$	3.096E-02	5.674E-02
Acidification	AC	mol H^+_{eq}	1.609E-04	2.937E-04
Terrestrial eutrophication	TE	mol N_{eq}	2.826E-04	4.841E-04
Water resource depletion	WRD	$m^3\ _{H2O\ eq}$	1.021E-01	1.825E-01
Cumulative Energy Demand	CED	MJ	5.004E-01	1.282E+00

mills to the agricultural lands is encompassed in the evaluation. As reported in Fig. 3 this contribution to the final impacts was measured in 7.8%, 11.0%, 10.9%, 0.7%, and 34.4% for CC, AC, TE, WRD and CED, respectively.

As in the case of Scenario I, also in Scenario II the olive oil production did barely contribute to the assessed impact categories while the cultivation and harvesting stage was the most impactful step of the whole process as mainly affected by the energy required in irrigation.

Finally, the contribution of oil production phase (in both scenarios) is negligible in comparison to other phases such as cultivation and harvesting. From the inventory reported in Table 1 it is possible to distinguish as this stage is mainly composed by materials (steel) and energy. Hence, this result reinforces the assumption of disregarding the contribution, to the overall impacts, of the other materials in the construction phase of the bio-digester.

3.3. *Comparative LCA*

The comparative environmental assessment of the olive oil waste management practices in the two analyzed scenarios is reported in Table 3 and Fig. 4. A significant reduction is exhibited by all the indicators when Scenario I is considered which highlights the environmental advantages in the adoption of anaerobic digestion technology for all the considered LCA impact categories. It is confirmed that the high organic load of OP and OMWW, composed by polyphenols and short and long chain fatty acids, represents a serious risk for groundwater and surface water pollution (Alfano et al., 2003) as its release on soil cause a negative environmental effect in all the different impact categories and particularly in acidification category as the low pH of OP and OMWW (Table 2), due to humic and fulvic acids, produces the modification of the pH of soil, altering the equilibrium of the microorganisms typically present in the eco-system. In comparison the AD scenario, shows a 45% impact reduction for the acidification impact category. A considerable reduction is also evident for the eutrophication category, which is $4.84 \cdot 10^{-4}$ mol N_{eq} in the case of waste released on the soil (Scenario II) and only $2.83 \cdot 10^{-4}$ mol N in the case of the waste managed through AD (Scenario I). Furthermore, nitrogen and phosphorous compounds found in OP and OMWW (Table 2), together with some micro-nutrients, such as magnesium and potassium, are here considered responsible for the uncontrolled proliferation of herbs which lead the farmers to an additional use of herbicides (Goldsmith et al., 2010).

With respect to WRD impact, results revealed an 80 L of water reduction into the impact by applying Scenario I instead of Scenario II for the considered Functional Unit.

The best improvement is revealed in CED category. Apart from all the other AD advantages, the fact of producing and consuming the electricity, within the same production chain, causes clear benefits for the environment by reducing to 0.78 MJ (more than 60% reduction) the Cumulative Energy Demand in the Scenario I in comparison to Scenario II.

With regards to Climate Change impact category, it is possible to notice (Table 3) that the waste release on soil (Scenario II) leads to the emission of about 57 g of equivalent carbon dioxide. On the other hand, anaerobic digestion (Scenario I) although involving the production of a gaseous mixture composed by methane and carbon dioxide, with methane having a GWP impact 25 times higher than carbon dioxide, does not involve direct emissions to the atmosphere as the methane is used for the production of electricity. Table 3 shows that the total CO_2 emissions deriving from Scenario I are 31 g but the expected production of electricity and its later use in the productive chain adds value reduces the $CO_{2\ eq}$ impact of almost 50%.

Fig. 5 shows the network of the Climate Change Impact category for the Scenario I. This network is a graphical representation of the model and its contribution according to the chosen impact category. It is possible to distinguish the amount of inputs used and how the end-of-life treatment is represented by a flow in opposite sense to the flows of energy and materials used. This network shows how energy data is looped and highlights as the recovered energy causes a significant reduction of the environmental impact. It is possible to note two different senses of the flow: the red one represents the energy expenditures from olive cultivation and harvesting to the final biogas production. The

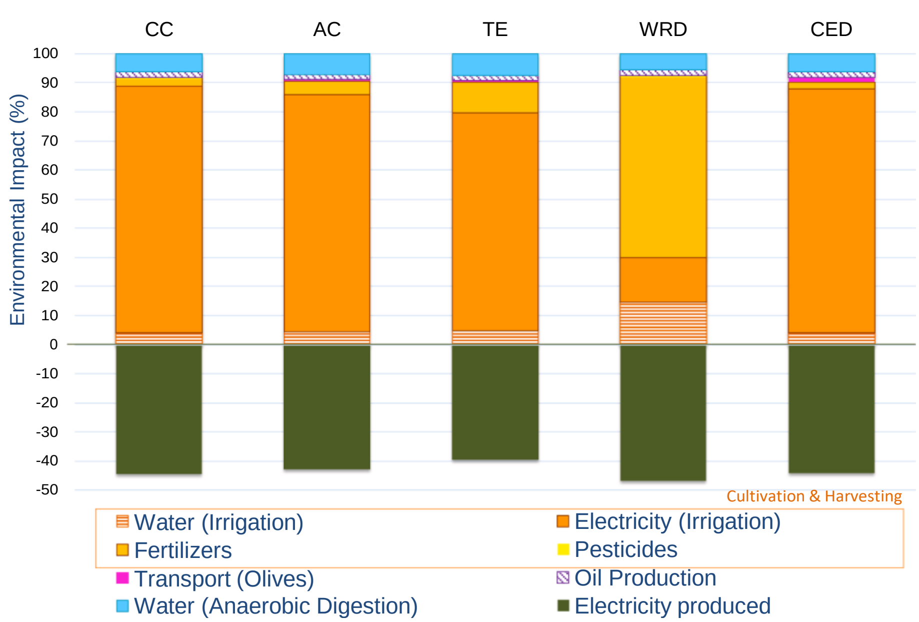

Fig. 2. LCA Results for Scenario I: olive-oil waste as feedstock in Anaerobic Digestion.

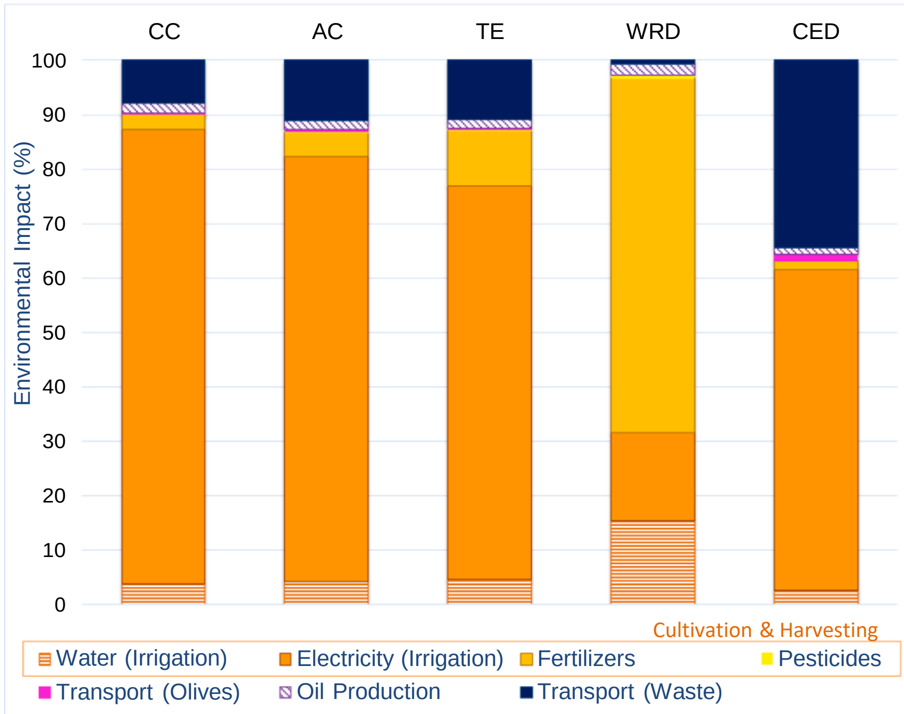

Fig. 3. LCA Results for Scenario II: disposal on soil without olive-oil waste treatment.

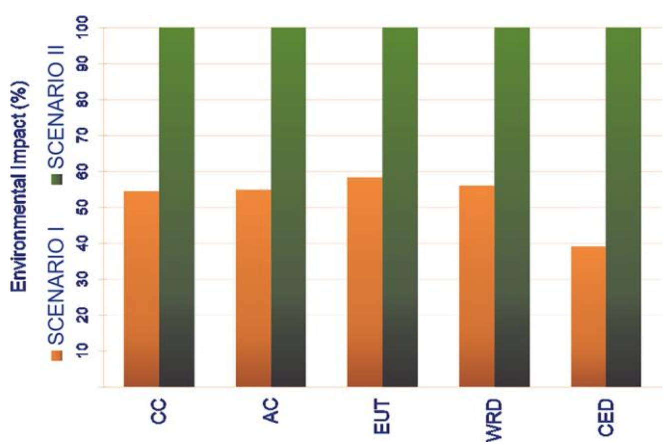

Fig. 4. Comparative LCA Results, taking into account different impact categories: Climate change (CC), acidification (AC), terrestrial eutrophication (TE), water resource depletion and Cumulative Energy Demand (CED).

green one (in the opposite sense) represents the energy recovery due to the use of the biogas. These network flows represent the lower energy requirement in Scenario I reducing the final $CO_{2\ eq}$ more than 40% withrespect to Scenario II.

In Scenario II, the major fraction of equivalent CO_2 emission is caused by the aerobic degradation of the spreading of the OP-OMWW on land.

4. Conclusions

The present study has compared the environmental impacts of two different scenarios for the residues of EVO production: Scenario 1 - anaerobic digestion of olive oil production waste with production of energy from biogas and Scenario 2 – direct release of OP-OMWW on soil without any treatment. The study considers the whole life-cycle required, from olives cultivation and harvesting, to olive oil production and the two end-of-life alternatives of produced waste in order to

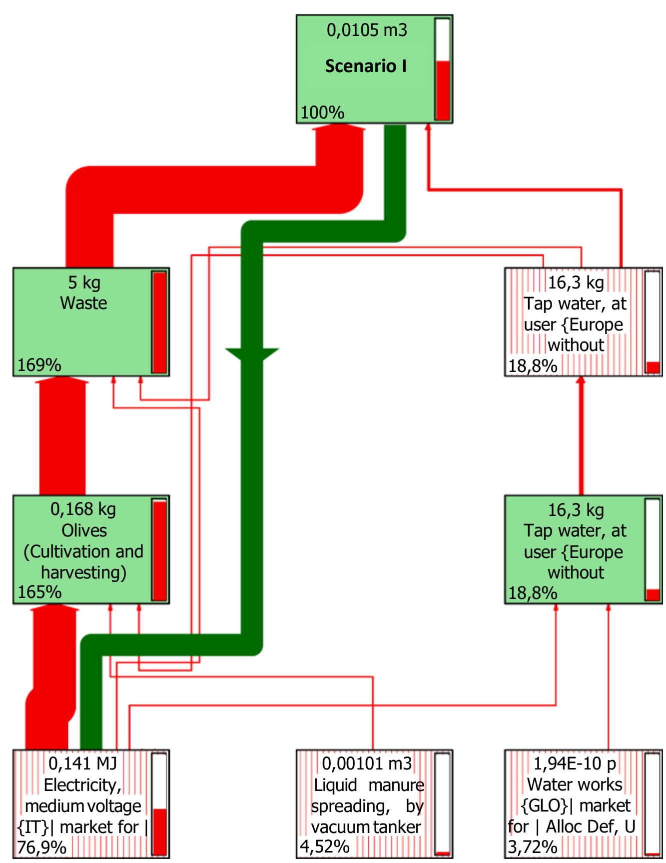

Fig. 5. Climate Change Network representation of Scenario I. Cut-off 3.8%. Contributions with impacts lower than cut off are not showed in the network.

compare the difference in terms of overall impact.

Results revealed that the highest impact are produced in the cultivation and harvesting phase for both analyzed scenarios, and clear environmental benefits should be obtained by reducing the energy request in the irrigation phase in all the impact categories. Scenario I, i.e. when olive-oil waste acts as feedstock in AD for biogas production, shows a significant reduction in the environmental impacts with respect to Scenario II in all the assessed categories. It was found that the common practice of releasing the olive waste (OP and OMWW) on soil represents an environmental hazard due to the alteration of the chemical properties of the soil and the contamination of the aquifers, causing more severe impacts in climate change, acidification, terrestrial eutrophication, water resource depletion and cumulative energy demand. In this respect, the work provides a preliminary overview of the need to introduce AD in the production process of olive oil.

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