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LCA OF WASTE MANAGEMENT SYSTEMS

Circular economy paths in the olive oil industry: a Life Cycle Assessment look into environmental performance and benefits

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Abstract

Purpose The olive oil sector in Italy has a significant socio-economic, environmental, and cultural relevance. However, the environmental impacts of production and consumption models are considerable, mainly due to the demand for large quantities of resources (fuels, chemicals) and to the environmental impacts of residues' disposal. Due to the scarcity of resources and climate change concerns, circular economy principles based on industrial ecology concepts are emerging. In this paper, the principles of circular economy were specifically applied to the olive oil supply chain, to improve the environmental sustainability of the sector.

Methods The production chain of extra virgin olive oil was analyzed using the Life Cycle Assessment method, based on primary data from an oil farm and mill in Southern Italy. The environmental impacts were evaluated through the SimaPro software and the ReCiPe 2016 Mid-point (H) Impact Assessment Method, with reference to the functional unit of 1-L bottle of extra virgin olive oil. Some circular improvement options were investigated, comparing the impacts generated by (i) extra virgin olive oil linear production without valorization of by-products, (ii) extra virgin olive oil linear production with allocation of total impacts to co-products, and (iii) two circular production systems, incorporating improvements such as replacement of diesel with biodiesel and of electricity from the national grid with energy recovered from residues.

Results and discussion The environmental impacts of the business-as-usual production pattern were identified for possible improvements. In all phases of the production chain of organic extra virgin olive oil, the most affected impact categories were human carcinogenic toxicity, marine ecotoxicity, and terrestrial ecotoxicity. As expected, the major contributions to almost all the analyzed impact categories were determined by the agricultural phase (92.65%), followed by the bottling phase (7.13%) and the oil extraction phase (0.22%). The valorization of by-products was considered by widening the system boundaries to ensure the environmental sustainability by developing circular patterns that feedback waste materials to upstream steps of the same process. The environmental impacts resulted lower in almost all the impact categories, with the major benefits gained in the global warming and fossil depletion impact categories.

Conclusions The analysis proved that the reuse of pomace, prunings, and exhausted cooking oil initially considered as waste can bring benefits from an environmental point of view to the larger scale of the economy, by replacing fossil fuels, as well as to the olive oil chain itself, by providing the needed energy for production.

Keywords Life Cycle Assessment · Olive oil · Valorization of organic residues · Biorefinery · Linear production · Circular economy

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1 Introduction

The agri-food sector has been identified as one of the sectors with the highest environmental impact and it is important to improve the sustainability of this sector for the greater good of the entire planet. Due to the scarcity of resources and climate change concerns, many governments are now considering applying the principles of the circular economy in all sectors of the economy (European Commission 2018), including agri-food.

Focusing on the Mediterranean countries, a central component of their diet consists of olive oil (Karanikolas et al. 2018). An estimated 67% of the world's olive oil is produced by four major countries in the European Union, namely Spain, Italy, Greece, and Portugal (Eurostat 2017). The figures highlight the relevance of Italy in the market. Approximately, 80% of Italian olive production takes place in the southern regions and covers about 1,070,000 ha (International Olive Council 2018). The economic importance of this food product is much appreciated in these regions; however, it is associated with several adverse effects on the environment (Strano et al. 2014). The environmental impacts related to land degradation, resource depletion, air emissions, and waste pollution vary from farm to farm because of the different practices and techniques employed during cultivation and olive oil production. Considering the present literature in the sector, a number of environmental concerns linked to the linear production of olive oil have been raised and extensively assessed. Many previous studies have focused on the identification of hotspots within a linear life cycle perspective and on the comparison of different alternative systems relating to cultivation and processing of olives, without offering the much-needed improvements and explorations through circular economy approaches. Life cycle thinking perspectives and circular initiatives should increasingly be applied within the olive sector to inform future environmentally sustainable behaviors and attitudes (Iofrida et al. 2018). The application of the circular economy principles would provide significant benefits within the Italian economy, in terms of contribution to the national GDP (Gross Domestic Product), employment, optimization of natural resources' use, and reduced pressure on the environment (Salomone et al. 2015; Eurostat 2017; Ghisellini and Ulgiati 2020). According to Eurostat data (Eurostat 2017), the circular economy in Italy proves to have a greater weight than in other European countries. More than five hundred thousand Italians have a job linked to the circular economy approach. It is therefore important to investigate individual case studies of particular economic and environmental interest, such as the olive oil one, to increase productivity and decrease the impact of the product on the environment and the whole supply chain.

Circularity in the food supply chain means minimizing waste and reusing by-products (Ncube et al. 2021a; Santagata et al. 2019). To decrease the impacts associated with the production of extra virgin olive oil, the by-products of the main process can be used as new feedstock material for other production processes (Guarino et al. 2019). This is the basic principle of industrial ecology that, in summary, aims at designing industries as natural ecosystems, where available sources of material or energy are never wasted but rather exchanged among different actors of the system, throughout practices of industrial symbiosis, paving the way to the circular economy approach. The valorization of by-products and their upgrading to co-products allow a fairer distribution of the environmental impacts among the outputs of the olive oil production chain. However, many obstacles persist to the valorization of the oil by-products, such as bureaucratic and authorization challenges, bottlenecks in planning the supply of a raw material significantly dispersed throughout the territory, and the seasonal availability of the feedstock (European Commission 2012). This may require that industrial eco-parks and biorefinery-oriented industrial projects take into account the exploitation/conversion/upgrade of different typologies of by-products (including winery, dairy, cellulosic, tomatoes residues, among others), in order to optimize machinery and processes beyond seasonal availability constraints.

In the olive oil production chain, the olive pomace is the main solid by-product, representing about 64% by mass allocation of the product and by-products during the extraction process of olive oil from olives (Espadas-Aldana et al. 2019). Different valorization patterns can be followed and olive pomace has the potential to provide a sustainable and alternative cheap source for fertilizers, pharmaceutical industries, cosmetics, and other industries (Wedyan et al. 2017). Traditionally, after the pomace oil extracting phase, de-oiled pomace (exhausted olive pomace) is used to recover energy, whereas the additional recovered pomace oil, in spite of its low quality, is used in tuna fish canning and for cooking purposes (Caponio et al. 2010). Nowadays, the most common way to deal with olive pomace consists of extraction units, where additional oil is obtained from olive pomace by treatment with solvents (Clodoveo et al. 2015). However, due to the growing concerns from the public about the use of organic solvents in food processing, the need for the application of clean technologies such as pressurized liquid extraction (PLE) has also been proposed (Pavez et al. 2019). Through extraction, the remaining oil can be recovered from the waste of olive oil mills. The remaining solid residue, sometimes called olive press-cake, is an important source to produce olive stone oil that, once dry, represents a fuel capable of producing 14,653.8 kJ per kg (Vlyssides et al. 2004). According to Christoforou and Fokaides (2016), the most attractive and practical methods for energy recovery from the pomace biomass are, at present, pyrolysis, gasification, and combustion. The pomace from olive oil mills can be burnt in a biomass boiler and the produced heat can be used by the olive oil mills for satisfying their energy needs or it can be used to produce steam and then electricity. Another way to valorize the olive mill waste (OMW) is through the recovery of bio-based chemicals, such as antioxidants and other platform chemicals, due to its high polyphenolic content, by means of organic solvents or ultrasound-assisted extraction methods (Niaounakis and Halvadakis 2006; Chatzisymeon et al. 2013; Čepo et al. 2018). These olive pomace-based polyphenol-rich extracts can primarily be used in various chemical, food, and biological model systems. Extraction of chemicals goes much beyond the simplest and most conventional method of spreading pomace over agricultural fields after short-term storage, although the advantage of this solution is the fact that the chemical composition of olive pomace provides nutrients (especially carbon and potassium) to the soil (Kalderis and Diamadopoulos 2010). Another traditional way to valorize pomace is composting. The process includes transforming olive pomace into compost that can be later reused as fertilizer during the olive tree cultivation phase (Fernández-Hernández et al. 2014). Applying composted wastes from olive oil mills as fertilizers can have a positive influence on soils by increasing soil organic content (Cucci et al. 2008). Other minor by-products, such as olive seeds and wastewater, can be also upgraded into useful co-products. Beyond the state of art, the European Union's Horizon 2020 project TANNOW (TANNOW 2016) proposed to reuse OMW as raw material for producing innovative antioxidant tanning chemicals, and chromium-free leather articles, thus absorbing 9–18% of OMW available in the EU. In fact, in 2014, the EU published a regulatory ban on the use of chromium VI in leather articles with concentrations of 3 mg/kg or more and, as a result of this ban, several fashion groups were involved in finding alternative ways for tanning leather without chrome salts.

Another by-product to consider is the waste cooking oil that is not a by-product of oil production, but rather a by-product of its use for cooking. Waste cooking oil is considered a dangerous pollutant whose recycling/reuse is essential for the protection of our planet. According to the National Consortium for the Collection and Treatment of Used Oils and Fats (CONOE 2018), in 2017 in Italy, 260,000 tons of exhausted vegetable oils was produced, of which 64% deriving from domestic activities and 36% from the industrial sectors (food catering and hotels). Valorizing such a waste is a way to address the end-of-the-chain waste of oil production and use.

The recovery and transformation of by-products of the olive oil production chain can create a series of circular paths to avoid new impacts for their disposal or to obtain new products. Since changing the model of the current economy is a crucial goal for the next few years, according to the United Nations Development Programme (UNDP 2019), it is important to propose solutions that may facilitate the transition from both the environmental and economic point of view. Likewise, it is essential to thoroughly assess and quantify the potential environmental impacts of the proposed circular solutions to avoid miscalculations in pursuing the target of sustainability. Nevertheless, despite all the circular opportunities provided by the by-products of the olive oil production, there has not been enough effort from researchers to evaluate the sustainability of the potential side production processes and compare the linear and business-as-usual paradigms with circular patterns (Harris et al. 2021).

In order to bridge this gap, this paper proposes a comprehensive environmental assessment of the production of olive oil, based on data gathered from a representative company in Southern Italy. A comparison of the environmental performance, in a life cycle perspective, is made among different scenarios, namely the business-as-usual (BAU) scenario that represents the current linear production system of the investigated company, and other innovative circular scenarios, inspired to the biorefinery concept, to ascertain the enhanced degree of environmental sustainability. In the following, Sect. 2 provides detailed information regarding the investigated case study and the methodology selected to carry out the study, while Sect. 3 shows empirical evidence of the environmental performance of different scenarios for the production of olive oil and the valorization of by-products. In particular, Subsection 3.1 is referred to the assessment of the BAU scenario, whereas Subsection 3.2 explores the environmental loads and benefits of circular improvements. According to the results described in Sect. 3, Sect. 4 outlines an in-depth discussion on opportunities, limitations, and policy perspectives in the olive oil supply chain. Finally, Sect. 5 provides some broader conclusions of the study.

2 Materials and methods

The methodological framework used to assess the environmental performance of both linear and circular olive oil production patterns is the Life Cycle Assessment (LCA), as defined by ISO standards (ISO 2006a, b) and ILCD Handbook guidelines (EC 2010). To perform the analysis, primary data were collected from an oil farm and mill in the Campania Region (Southern Italy). For privacy reasons, it was deemed appropriate, in agreement with the owner of the company, not to disclose its name.

2.1 The investigated system

The company investigated as a case study is in the municipality of Carinola, in the province of Caserta, Italy. It covers an area of about 13 ha of cultivated land and has a three-phase continuous cycle oil mill inside. Five types of olive plants are grown: the Santa Caterina, the Leccino, the Frantoio, the Coratina and the Itrana. The cultivation is intensive and it is a monoculture breeding system. The entire cultivated area falls within the territory placed to protect the DOP (Protected Designation of Origin) Terre Aurunche which, in April 2011, obtained definitive recognition by the European Union. Since the 2011/2012 campaign, the company, having completed its conversion period in organic agriculture, was certified as organic oil producer. All stages of organic farming production are certified by the ICEA inspection body. The mill produces extra virgin olive oil with a continuous system equipped with a three-phase decanter. Three types of oil are produced: Sant'Ilario, Monte Greci, and Terra Felix. Since 2001, the packaging operations have also been incorporated into the company's production cycle.

2.2 The LCA approach

LCA is widely recognized as a suitable tool to measure and monitor the resource use, the release of emissions and waste into the environment, and the associated impacts, thus assessing environmental costs and benefits, in a consumer side perspective (Santagata et al. 2020). According to the LCA approach, stemming from resource extraction up to final disposal in a "from cradle to grave" perspective, the potential environmental impacts of the production, consumption, and disposal stages of a product or service need to be accurately analyzed for improvement or for strategic planning (Ulgiati et al. 2018). In the present study, we focus on shifting from a traditional linear production to a circular production system that recovers materials and energy from the organic residues. In order to understand the environmental implications of a circular paradigm versus the current olive oil production system, an inventory consisting of a quantified list of all the entering and outgoing flows involved in the production processes of olive oil was collected and analyzed.

2.2.1 Goal and scope

Targeting three main groups of actors, namely the olive oil mill owners, academia, and policy makers, the goal of this study is to perform a comparative evaluation of the environmental impacts associated with the linear production of organic extra virgin olive oil, obtained from an intensive cultivation system, versus some proposed circular pathways. The investigated circular pathways are designed to improve the production system hotspots, as identified in the assessment of the linear production process. An attributional LCI modelling framework is selected and the functional unit adopted is the production of 1-L bottle of extra virgin olive oil (corresponding to 0.92 kg of extra virgin olive oil). Concerning the definition of system boundaries, a cradle-to-gate approach is applied to the linear production process, not including the distribution and use phases (namely the transportation of bottles to the market and the disposal of the product at the end of use). When considering the circular options, the end-of-life phase of some by-products is included in a reuse/recycling/recovery perspective.

Figure 1 depicts the investigated system boundaries, including the biorefinery-oriented process to produce extra virgin olive oil with the feedback of some by-products to the upstream phases.

The investigated system is divided into two sub-systems, namely olive oil linear production (BAU scenario) and by-product valorization (to be added in the circular scenario), described hereafter:

A. *Olive oil production sub-system* (BAU scenario). It consists of the following phases:

   i. *Agricultural and harvesting phase*: This phase includes the preparation of the agricultural land (hoeing), the cultivation of the olive grove (pruning, fertilizing, irrigation), and the olive harvest, which took place between October and December 2018. The transport of the olives to the mill is also included. All input and output flows are reported in Appendix Table A1.
   ii. *Oil extraction phase*: During the industrial phase, the olives are weighed and then milled. There is an initial washing phase, in which the olives are freed from pruning residues (branches, leaves), and then, there is the crushing process, in which the olives are ground and reduced to a paste. Subsequently, the olives are kneaded and then, by means of a centrifuge, the oil is separated from the water. All input and output flows to the extraction phase are shown in Appendix Table A2.
   iii. *Bottling phase*: The bottling phase takes place within the company, which is equipped with a bottling machine and a labeling machine. The oil is bottled exclusively in glass bottles. Then, the cap is placed and finally the bottle is labeled. The bottles are then placed in cartons of six and subsequently sold. Transportation of the bottles to the store is not included in the analysis. All input flows to the bottling phase (Appendix Table A3) contribute to the

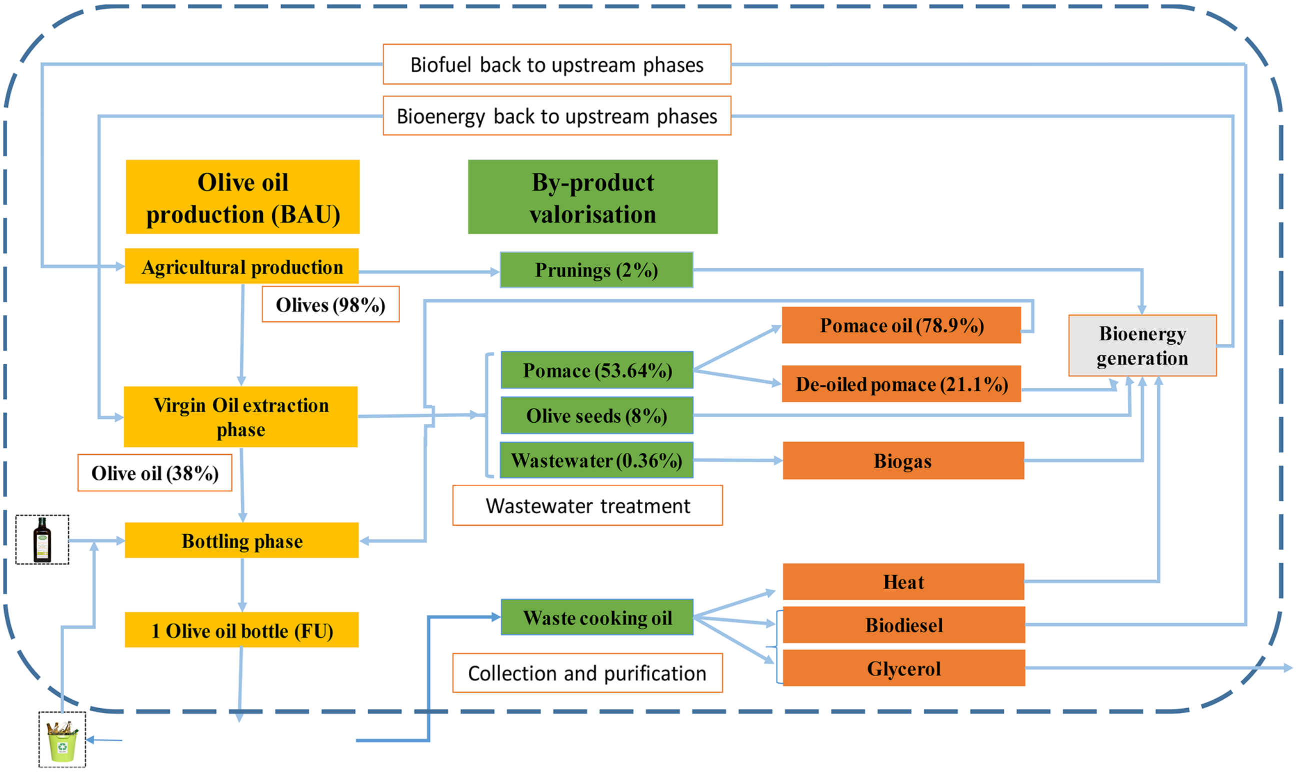


Fig. 1 Flow-chart of the biorefinery-oriented process to produce extra virgin olive oil, with valorization and feedback of some by-products to upstream phases. Percentage values refer to exergy of by-products in each considered step, according to Table 2. Exergy allocation is not applied to biodiesel and glycerol, since the exergy of glycerol is considered not significant in comparison with biodiesel (Fiorentino et al. 2014)

final evaluation of the bottled product ready to be distributed.

B. *By-product valorization sub-system* (as part of the circular scenario). The investigated micro-level farm is already putting in practice some circular approaches through the utilization of by-products. For example, the olive mill wastewater is currently treated in evaporation ponds and left to dry for later use through spreading on agricultural fields to improve soil fertility. Despite this form of traditional circularity, this practice can lead to groundwater problems due to the presence of organic matter and inorganic compounds which, when disposed of into water bodies, may cause severe environmental pollution, but if added to the soil can be beneficial to soil fertility and prevent erosion (Kapellakis et al. 2008). To increase value and reduce impacts from the current waste management practices, two additional circular patterns, as detailed below, are explored for the valorization of olive pomace and of exhausted cooking oil:

   iv. *Extra virgin olive oil and energy recovery from olive pomace*: A biorefinery-oriented process is assessed in order to enhance the value of olive pomace by recovering additional oil and energy rather than disposing of it as a waste. Data are modelled based on a previous study by Intini and Rospi (2012) on the Life Cycle Assessment of an energy recovery plant in the olive oil industries. All input and output flows of the pomace treatment (including the amount of pomace deriving from the previous phase) are reported in Appendix Table A4, concerning the pomace olive oil extraction process, and in Table A5, concerning the recovery of energy using prunings as additional source of heat. The pomace oil follows a similar bottling process as the extra virgin olive oil, while the de-oiled pomace can either be submitted to further processing for extraction of chemicals or feedback upstream as fertilizer or energy source (the latter case is assessed in this study).

   v. *Valorization of waste cooking oil*: The exhausted cooking oil can be collected and valorized by widening the system boundaries in a biorefinery-oriented process, in order to enhance its value by producing biodiesel through a trans-methyl esterification process (Lois 2007; Yaakob et al. 2013). Input and output data for biodiesel production are reported in Appendix Table A6.

2.2.2 Life Cycle Inventory of olive oil production and by-product valorization processes

This study is mainly based on primary data, collected through tailored questionnaires thanks to the collaboration of the olive mill operator. Secondary data for background processes and designed scenarios are extrapolated from pertinent literature and from the EcoInvent 3.5 database (allocation at point of substitution, dataset of unit processes). Except from the buildings whose impact is negligible, the machinery and infrastructure serving the olive grove and the oil mill are also included within the analysis, accounting for their component materials, the processing of these materials, and the electricity requirements during the operative phase. Local diesel emissions are calculated using the emission factors taken from the Environmental Protection Agency document (EPA 2018). For the supply of electricity, the Italian medium-voltage electric mix is selected, as the examined processes are carried out in Italy. The collected data have a temporal coverage of 1 year and refer to the year 2018. Table 1 shows the amount of products and by-products for each phase of the investigated systems, referred to the selected FU (1-L bottle of extra virgin olive oil), whereas the complete inventory data are reported in Appendix Tables A1–A6.

Table 1 List of the main products and by-products for each phase of the investigated systems, referred to the selected FU (1-L bottle of extra virgin olive oil)

Main product	Amount	By-products	Amount
Olive oil production (BAU)			
Agricultural and harvesting phase			
Olives	7.38 kg	Prunings	1.62 kg
Oil extraction phase			
Olive oil	0.92 kg	Olive pomace	3.25 kg
		Olive seeds	0.44 kg
		Wastewater	0.45 kg
Bottling phase			
1-L bottle	1 item (0.92 kg)		
By-product valorization			
Virgin pomace	3.25 kg	Pomace oil	0.28 kg
		De-oiled pomace	2.56 kg

2.2.3 Allocation procedure

In principle, in a multi-output system such as the olive oil production process, it is possible to produce oil and other co-products, such as pomace, and allocate 100% of environmental impacts to the main product, namely the extra virgin olive oil, considering the pomace as waste rather than as a co-product. Generally, the benefits that can derive from pomace valorization are measured only in monetary terms, so they keep bearing a relatively small importance in comparison to the main product. Moreover, small companies may find the conversion of pomace to usable co-products not sufficiently rewarding and therefore, most of the time, pomace is misused and its value not sufficiently appreciated. In this study, we characterize waste as a co-product, thus signaling its further reuse and recovery rather than its disposal fate. An appropriate allocation of the environmental burdens associated with the production of extra virgin olive oil and related by-products is therefore needed and cannot be based on monetary values (considering that some by-products do not have a market demand). Allocation should be rather based on a physical property that indicates very clearly the value that can be extracted from these by-products, namely their ability to drive and support further useful transformation. To this purpose, an appropriate metrics is the fraction of exergy content of each product compared to the total, i.e., the thermodynamic ability of products to support further transformations. Exergy is defined as the amount of work that a resource can provide when it is brought into thermodynamic equilibrium with its surrounding environment (Bejan 1989). Exergy analysis is a methodology that uses the exergy concept to determine the most effective way of improving the system under consideration (Rosen et al. 2008). Exergy losses and thus inefficiencies in energy processes and systems can be determined and fixed, to increase the exergetic efficiency and optimize the driving forces. The main objective of the exergy concept is to use energy and material resources in a more economical and physical efficient way (Wang and Feng 2000). Ultimately, a physical allocation based on exergy is preferred in this study, since a mass allocation would not fully estimate the value of by-products (for example, 1 kg of oil does not have the same value as 1 kg of pomace). An economic allocation is also not recommended, because it is too dependent on the country of production and the risk of price volatility (Goedkoop 2016). Besides the ability of using exergy to examine the magnitude and origin of inefficiencies, it can serve as a unifying numeraire across disciplines as, for example, the user-side quality of a resource can be expressed in joules (of benefit) instead of in monetary terms. In the interdisciplinary environment of circular economy, this opens the opportunity of “impartial” comparisons. Products can be compared without referring to their market value, but with reference to their environmental performance, in so preventing inaccurate evaluation due to lack of understanding. It also allows for a comparison over time, as exergy is a time-independent measure. To carry out such comparisons, established tools like LCA can be integrated using exergy allocations. Table 2 shows the calculated exergy allocation of each product and co-products in the production chain of olive oil. Environmental burdens and impacts can be allocated according to the actual ability of each output flow to provide a useful contribution to the economic and social system.

Of course, when environmental burdens and impacts are shared among different co-products, each of them carries a smaller impact and, therefore, can be considered less impacting on the global environment. The total impact of all the co-products remains the same, but, in a logic of boundary expansion, the co-products generated by appropriate conversion of "waste materials" will replace products from other processes, in so generating an "avoided burden." In so doing, the global impact at larger scale decreases, thanks to the valorization of waste and residues. Based on Table 2, it can be clearly observed that extra virgin olive oil and olive pomace are the two main co-products with the highest exergy values. The highest exergy value of pomace presents the 53.64% possibility of decreasing the impact of other processes that generate the same products that we can extract out of pomace. If pomace is used to generate alternative co-products, its 53.64% exergy and related impacts split to smaller fractions related to the different potential co-products.

Moreover, as mentioned, other impacts would be avoided from not producing these co-products in other processes powered by fossil sources. The advantage of valorizing by-products within a circular economy framework relies on the avoided impacts coming from feeding them back to replace some of the conventional production inflows (chemicals, energy, fertilizers). In the last step of this study, a system boundary expansion (or avoided burden approach), based on average data (i.e., market mix) for crediting energy recovery, is also applied to quantify the environmental benefits generated by the proposed circular patterns.

Table 3 LCA impact categories selected for the evaluation of extra virgin olive oil production patterns

Impact category	Unit	Abbreviation
Global warming	kg CO_2 eq	GWP
Freshwater eutrophication	kg P eq	FEP
Terrestrial ecotoxicity	kg 1,4-DCB	TETP
Freshwater ecotoxicity	kg 1,4-DCB	FETP
Marine ecotoxicity	kg 1,4-DCB	METP
Human carcinogenic toxicity	kg 1,4-DCB	HTP_{cn}
Human non carcinogenic toxicity	kg 1,4-DCB	HTP_{non_cn}
Land use	m^2a crop eq	LCP
Fossil resource scarcity	kg oil eq	FDP

2.2.4 Life Cycle Impact Assessment

Environmental impacts are evaluated by using the SimaPro v9.0.0.0 LCA software tool and the ReCiPe 2016 Mid-point (H) Impact Assessment method (Goedkoop et al. 2009). According to the LCA impact assessment procedure, all impacts are classified into the impact categories shown in Table 3, and then characterized and normalized according to characterization and normalization factors available within the ReCiPe Mid-point (H) method. The latter provides mid-point indicators for identifying the hotspots of a process and optimizing the energy and material recovery processes, thus supporting the overall circularity. The impact categories, listed in Table 3, were selected according to previous studies in the olive oil sector.

Table 2 Exergy content of co-products in the olive oil production chain (data adjusted to the yearly production in the 13-ha investigated farm), calculated from the standard chemical exergies of pure substances and main mixture components (Bejan 1989)

Product and co-products	Exergy values, kJ/kg	Quantity of product, kg	Exergy per product, kJ	% Exergy allocation
After harvest (percentages calculated with reference to total exergy of co-products of the agricultural step)				
Harvested olives	1.24E+04	36,400	**4.52E+08**	98.00%
Prunings	1.28E+04	728	9.32E+06	2.00%
After extraction (percentages calculated with reference to total exergy of co-products of the extraction step)				
Extra virgin olive oil	3.76E+04	4560	1.71E+08	38.00%
Wet olive pomace	1.51E+04	16,000	**2.42E+08**	53.64%
Olive seeds	1.67E+04	2180	3.65E+07	8.00%
Wastewater	9.00E+02	2230	2.01E+06	0.36%
Pomace treatment (percentages calculated with reference to total exergy of co-products of pomace processing step)				
Additional extracted olive oil	3.76E+04	1.36E+06	5.11E+07	21.10%
De-oiled pomace	1.51E+04	1.26E+04	**1.91E+08**	78.90%

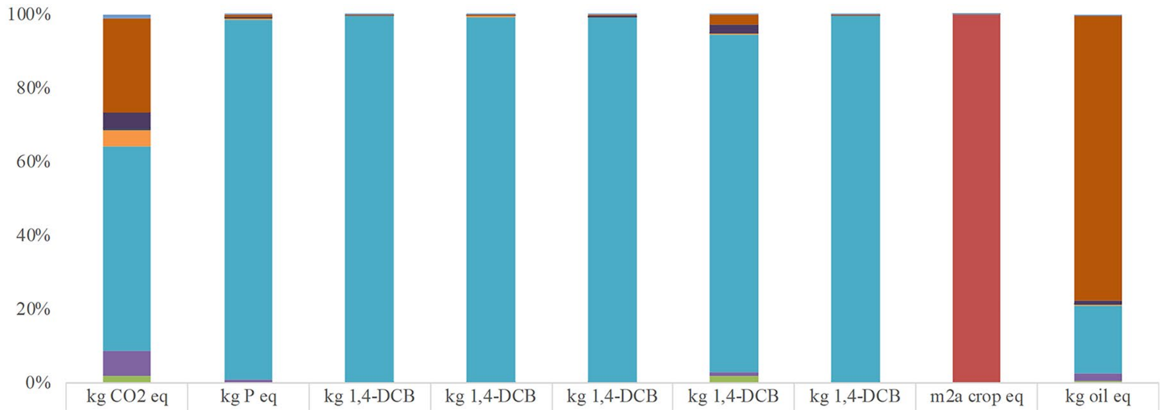
Furthermore, in order to verify the robustness of LCA results and their sensitivity to changes in the input flows included in the study, a sensitivity analysis is performed by assuming a change of the inputs correlated with relevant environmental loads (namely the amount and type of glass used for the packaging).

3 LCA results of the olive oil production

3.1 Linear sub-system (BAU scenario)

This section highlights the LCA characterized and normalized impacts for each of the different phases in the production of olive oil, after the exergy-based allocation of impacts to the main product and by-products of the production process was performed (Table 2). In so doing, only a fraction of total impacts is assigned to the main product, i.e., the extra virgin olive oil, while the rest is attributed to the pomace and other by-products. As mentioned in the above Sect. 2.2.3, without exergy allocation, the impacts associated to extra virgin olive oil would have been much higher (more than doubled), even if the total remains unchanged. Figure 2 shows the characterized impacts of the agricultural phase (namely to produce 7.38 kg of olives, required for the reference functional unit of 1-L bottle), detailing the contribution of each input flow to the impact generated in each impact category both as percentage and absolute values. The use of copper sulphate as fungicide contributes up to 55–99% to FEP, TETP, FETP, METP, HTP_{cn}, and HTP_{non_cn} impact categories, followed by diesel, generating 25% of total impacts on GWP and 77% on FDP. Diesel is used in all operations carried out at the olive farm with the tractor, i.e., for collection, spreading of fertilizers in the field, and harvesting. The actual operation of olive growing almost accounts for the totality of land use (99.83%), due to land occupation required for the plantation and cultivation of olives, while land demand associated to the production and transport of the other inputs is irrelevant.

In Fig. 3, the characterized impacts generated by the extra virgin olive oil extraction phase are shown as well as the percentage contribution of the inflows to each impact category. It should be noted that olives are not included as an input in the assessment of the extraction phase, because our focus here is only on the additional environmental burdens



	kg CO2 eq GWP	kg P eq FEP	kg 1,4-DCB TETP	kg 1,4-DCB FETP	kg 1,4-DCB METP	kg 1,4-DCB HTPcn	kg 1,4-DCB HTP non cn	m2a crop eq LCP	kg oil eq FDP
■ Electricity	3.87E-03	1.33E-06	3.97E-03	9.34E-05	1.24E-04	1.03E-04	1.76E-03	1.60E-04	1.13E-03
■ Diesel	9.40E-02	9.36E-06	9.37E-02	8.50E-04	1.54E-03	1.95E-03	2.77E-02	1.30E-03	2.71E-01
■ Steel	5.84E-07	5.15E-10	3.96E-06	7.58E-08	1.07E-07	4.31E-07	2.23E-06	1.08E-08	1.17E-07
■ Agricultural machinery	1.60E-02	7.63E-06	6.99E-02	5.56E-04	7.94E-04	1.87E-03	1.66E-02	3.22E-04	3.40E-03
■ Cast iron	4.01E-06	1.30E-09	1.86E-05	1.56E-07	2.28E-07	3.87E-06	2.94E-06	5.03E-08	7.99E-07
■ Polyethylene	2.66E-04	4.66E-09	1.16E-04	7.27E-07	1.05E-06	5.66E-06	1.94E-05	5.06E-07	1.96E-04
■ Lime	1.37E-03	3.84E-07	2.64E-03	2.08E-05	2.96E-05	4.43E-05	5.82E-04	2.64E-05	3.66E-04
■ Manure	1.61E-02	2.16E-06	3.67E-02	2.01E-04	2.52E-04	2.31E-04	2.26E-03	1.08E-02	1.41E-03
■ Copper sulfate	2.04E-01	1.57E-03	3.91E+01	2.96E-01	4.26E-01	6.98E-02	1.04E+01	1.67E-02	6.44E-02
■ Kaolin	2.47E-02	1.11E-05	3.74E-02	5.31E-04	7.43E-04	8.27E-04	1.42E-02	5.27E-04	6.89E-03
■ Tap water	6.37E-03	3.36E-06	1.24E-02	1.95E-04	2.71E-04	1.40E-03	4.33E-03	1.17E-04	1.57E-03
■ Land occupation	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.81E+01	0.00E+00

Fig. 2 Characterized impacts of the agricultural phase, per functional unit of 1-L bottle of olive oil

of olive processing to extra virgin olive oil. In the extraction phase, electricity used to power the extracting machinery is responsible for the heaviest environmental load in all the investigated impact categories (with contributions of 75% and above) compared to all other inputs. Environmental loads also derive (indirectly) from the machinery manufacturing processes, such as cast iron, contributing to HTP_{cn} and TETP with 28% and 5% of total impacts, respectively. Venting of nitrogen is another input used as a disinfectant, with its highest contribution of about 5% to FEP.

Figure 4 shows the characterized impacts generated by the bottling phase and the percentage contribution of the inputs to each impact category. Once again, as for Fig. 3, extra virgin olive oil is not included in the assessment of the bottling phase, in order to focus only on the additional environmental burdens linked to this phase. Coated flat glass has the largest environmental load in all impact categories (72% and above), followed by corrugated board box (21% of total impact in LCP category) and polyvinyl chloride (9% in HTP_{non_cn}), used as part of packaging materials.

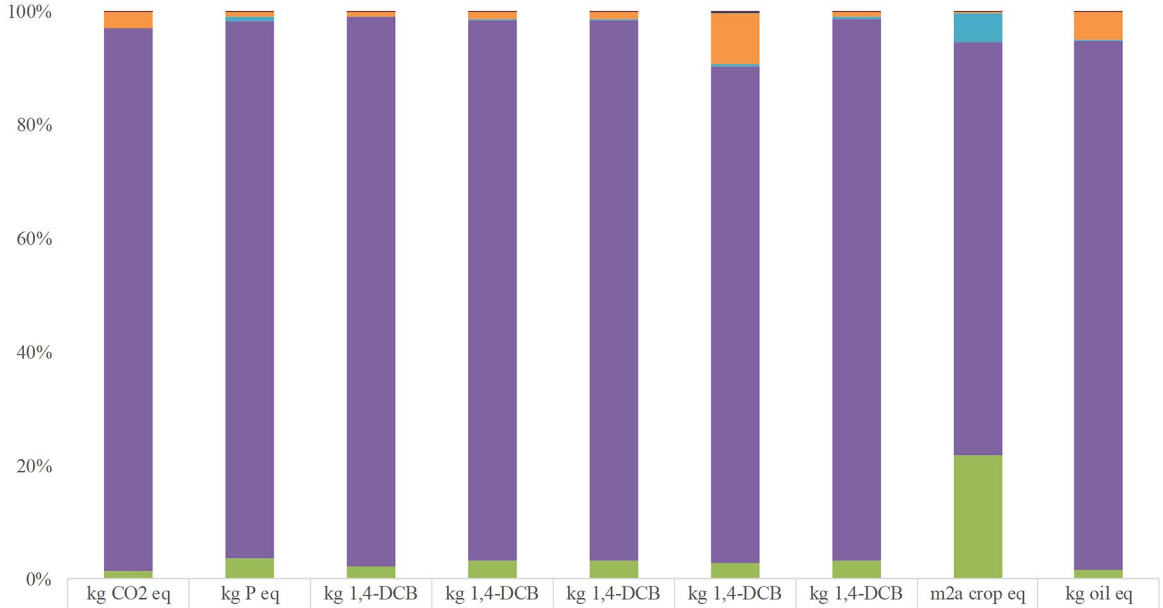
Finally, Fig. 5 shows the characterized impacts of the different steps of extra virgin olive oil production, both in absolute and % values.

If we focus on the individual production steps, we can achieve a deeper and quantitative understanding of the contribution of each phase of extra virgin olive oil production to the total environmental burden, in order to identify the most appropriate choices to decrease impacts. By splitting the characterized results into the three main phases of the process (namely the agricultural phase, the oil extraction phase, and the bottling phase), it is possible to observe that the agricultural phase, although organic, shows the heaviest impacts on all the investigated impact categories, except for GWP, FDP, and HTP_{cn}, in which the bottling phase is more impactful. The oil extraction (industrial) phase has the lowest impact, as it consists of oil extraction from the harvested olives. This process is based on mechanical and physical mechanisms, which do not require the addition of particularly polluting substances, thus generating minimal environmental impacts compared to the agricultural and bottling phases.

To identify the impact categories that are mostly affected, we need to normalize the characterized values of Fig. 5, referring to the entire process, to generate a diagram where impacted categories are shown as dimensionless units, in so being comparable among each other (Fig. 6). Considering

	kg CO2 eq GWP	kg P eq FEP	kg 1,4-DCB TETP	kg 1,4-DCB FETP	kg 1,4-DCB METP	kg 1,4-DCB HTPcn	kg 1,4-DCB HTP non cn	m2a crop eq LCP	kg oil eq FDP
🟧 Electricity	2.42E-02	8.28E-06	2.48E-02	5.83E-04	7.77E-04	6.42E-04	1.10E-02	1.00E-03	7.04E-03
🟦 Cast iron	4.05E-04	1.31E-07	1.88E-03	1.57E-05	2.30E-05	3.91E-04	2.97E-04	5.09E-06	8.08E-05
🟪 Tap water	1.02E-04	5.37E-08	1.97E-04	3.10E-06	4.32E-06	2.23E-05	6.91E-05	1.87E-06	2.51E-05
🟩 Venting of nitrogen	9.71E-04	5.35E-07	8.36E-04	2.17E-05	2.96E-05	3.86E-05	4.95E-04	1.28E-05	2.44E-04

Fig. 3 Characterized impacts of the oil extraction phase, per functional unit of 1-L bottle of olive oil (the processed amount of olives, namely 7.38 kg per bottle, is not included as an input)

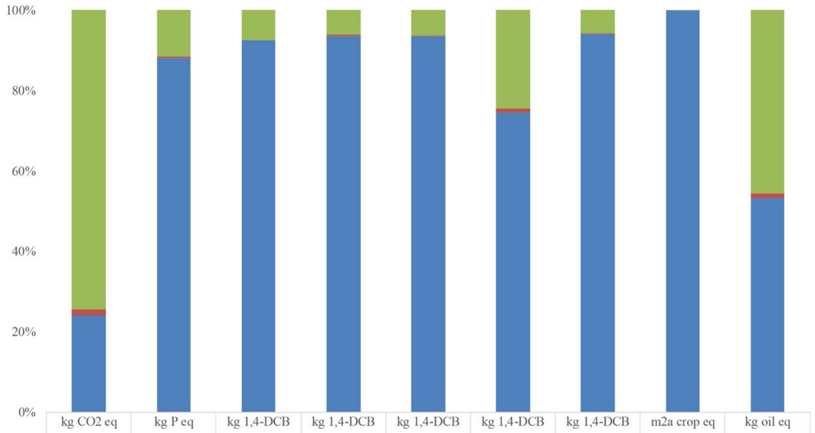


	kg CO2 eq GWP	kg P eq FEP	kg 1,4-DCB TETP	kg 1,4-DCB FETP	kg 1,4-DCB METP	kg 1,4-DCB HTPcn	kg 1,4-DCB HTP non cn	m2a crop eq LCP	kg oil eq FDP
■ Electricity	1.23E-03	4.21E-07	1.26E-03	2.97E-05	3.95E-05	3.26E-05	5.60E-04	5.09E-05	3.58E-04
■ Cast iron	5.09E-05	1.88E-08	2.47E-04	2.19E-06	3.19E-06	5.44E-05	4.11E-05	7.59E-07	9.89E-06
■ Polyvinylchloride	3.17E-02	1.46E-06	2.62E-02	2.30E-04	3.27E-04	2.29E-03	6.11E-03	5.35E-05	1.47E-02
■ Paper, woodcontaining	1.98E-03	1.63E-06	4.97E-03	6.53E-05	9.14E-05	9.87E-05	2.42E-03	1.78E-03	5.54E-04
■ Glass	1.09E+00	1.99E-04	3.06E+00	1.90E-02	2.77E-02	2.21E-02	6.18E-01	2.51E-02	2.81E-01
■ Corrugated board box	1.64E-02	7.85E-06	6.70E-02	6.61E-04	9.32E-04	7.03E-04	2.10E-02	7.55E-03	4.68E-03

Fig. 4 Characterized impacts of the bottling phase, per functional unit of 1-L bottle of extra virgin olive oil (oil is not included as an input)

the normalized impacts, the most affected impact categories (among those listed in Table 3) are METP, FETP, and $HTP_{non\ cn}$.

The toxicity categories are the most impacted, as a result of the very large number of chemical products that can percolate in the soil and end up in the aquifers and marine waters, such as copper sulphate and kaolin which are heavily used during the cultivation stages. However, the uncertainty is high due to the lack of a standardized procedure coupled with the lack of consensus in the scientific community about how to measure toxicity (Roos et al. 2018; Ncube et al. 2021b). Therefore, although the highest impacts are recorded for the toxicity categories, the other impacts on global warming, fossil resource scarcity, land use, and freshwater eutrophication should not be disregarded.

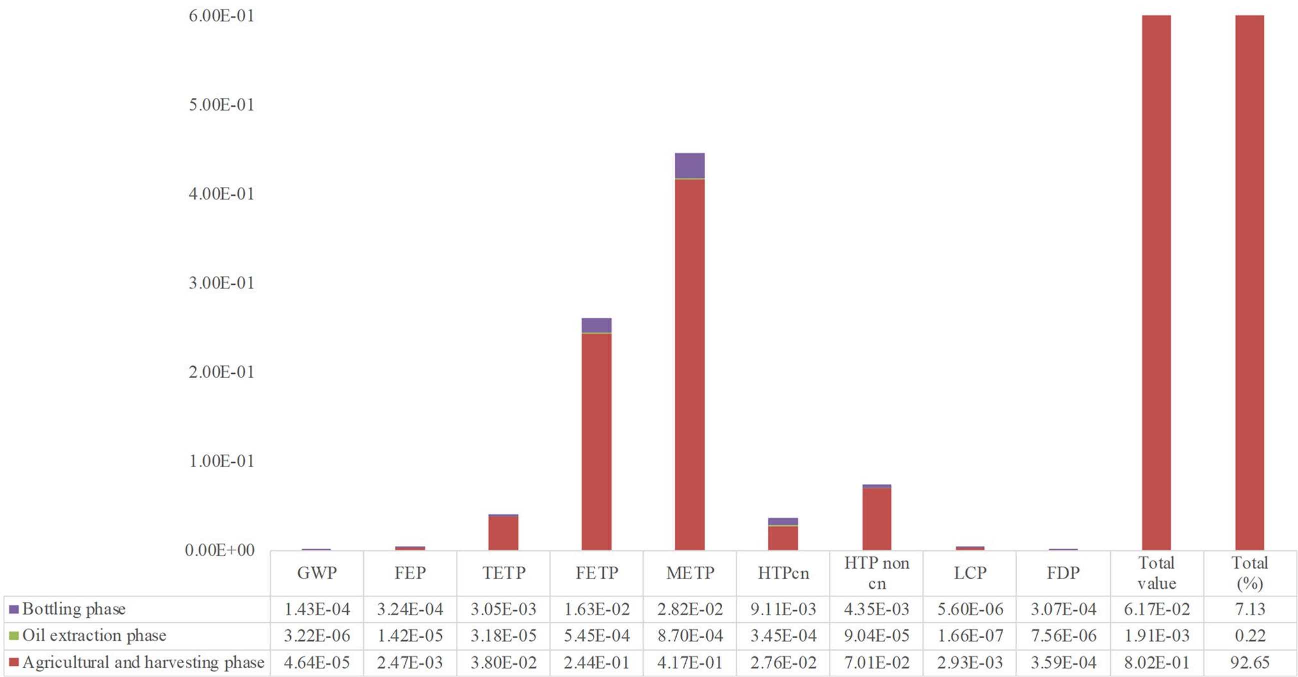


	kg CO2 eq GWP	kg P eq FEP	kg 1,4-DCB TETP	kg 1,4-DCB FETP	kg 1,4-DCB METP	kg 1,4-DCB HTPcn	kg 1,4-DCB HTP non cn	m2a crop eq LCP	kg oil eq FDP
■ Bottling phase	1.14E+00	2.10E-04	3.16E+00	2.00E-02	2.91E-02	2.52E-02	6.49E-01	3.46E-02	3.01E-01
■ Oil extraction phase	2.57E-02	9.24E-06	3.30E-02	6.69E-04	8.98E-04	9.55E-04	1.35E-02	1.03E-03	7.41E-03
■ Agricultural and harvesting phase	3.67E-01	1.61E-03	3.94E+01	2.99E-01	4.30E-01	7.66E-02	1.04E+01	1.81E+01	3.52E-01

Fig. 5 Relative distribution of impacts (absolute and % values) among different production phases within each impact category

3.1.1 Design for reduction of impacts

Figure 6, seen in parallel to Figs. 2, 3, and 4, where the % contributions of each inflow to each category in each phase are clearly quantified, helps suggest improvements to all categories. The greatest contribution to almost all the investigated impact categories is given by the agricultural phase (92.65%), which is responsible for impacts in the range between 25 and 70% in the different categories (Fig. 5). Several previous studies have also identified the agricultural phase as the hotspot phase, since agricultural practices such as fertilization, irrigation, and treatment carry the most significant portion of the environmental burden (Salomone et al. 2015; Pattara et al. 2016; Banias et al. 2017; Espadas-Aldana et al. 2019). As highlighted in Fig. 2, the most impactful input flow of the agricultural phase in most impact categories results to be copper sulfate, which, mixed with water, forms the verdigris. Verdigris is one of the few compounds allowed in organic farming and is used to prevent fungal infections. Reducing its use could result in serious damage to the olive grove, which calls for urgent and deeper research about new and less impacting ways to fight crop infections. The diesel used is also very impactful on the agricultural phase. For this reason, in the following section the possibility of using biodiesel produced from exhausted cooking oil is analyzed, to lower the impacts of the production chain by reducing the use of fossil fuels. In accordance with extant literature, the extraction phase shows a minimal contribution compared to the agricultural phase, of about 0.22%, since the procedure for extracting oil from olives is based on a mechanical and non-chemical process. Apart from the electricity used to operate the machinery, there are no particularly significant inputs at this stage. Environmental impact reduction can only be determined by choosing a system that produces less waste that is easier to treat, such as the 2-phase or 2.5-phase modified systems that have better performance when compared to the 3-phase system (Salomone and Ioppolo 2012). Another hotspot of the investigated value chain is the packaging phase. Although a number of LCA studies have excluded bottle production and transportation to bottling facilities (Accorsi et al. 2015), it has been demonstrated that packaging gives a significant contribution to the environmental impact of the finished product, taking into consideration the extraction of raw materials, subsequent production of the container, and its transportation (Espadas-Aldana et al. 2019). Guiso et al. (2016) have highlighted that packaging impact increases depending on the mass of the material used. Analogously, Espadas-Aldana et al. (2019) stated that reducing the weight of the glass bottle could help in reducing environmental impacts. Navarro et al. (2018) also studied the contribution of different packaging materials by comparing glass, polyethylene terephthalate (PET), and tin packages, PET resulting the material with the greatest environmental load. In this study, the bottling phase contributes to the total impacts at an extent of 7.13%. It is noteworthy that the bottles used by the investigated company consist of a very heavy type of glass, which



	GWP	FEP	TETP	FETP	METP	HTPcn	HTP non cn	LCP	FDP	Total value	Total (%)
🟪 Bottling phase	1.43E-04	3.24E-04	3.05E-03	1.63E-02	2.82E-02	9.11E-03	4.35E-03	5.60E-06	3.07E-04	6.17E-02	7.13
🟩 Oil extraction phase	3.22E-06	1.42E-05	3.18E-05	5.45E-04	8.70E-04	3.45E-04	9.04E-05	1.66E-07	7.56E-06	1.91E-03	0.22
🟥 Agricultural and harvesting phase	4.64E-05	2.47E-03	3.80E-02	2.44E-01	4.17E-01	2.76E-02	7.01E-02	2.93E-03	3.59E-04	8.02E-01	92.65

Fig. 6 Normalized impacts of extra virgin olive oil production (considering the allocation procedure to extra virgin olive oil, pomace, and other by-products as from Table 2)

is also very impactful. The reason why the company uses these bottles is to increase the prestige of the oil and improve its preservation. The packaging, in fact, has an important role in preserving the quality of the oil. The material used for packaging must have characteristics of impermeability to oil, impermeability to gases, and protection from light. In addition, the containers must be chemically inactive and not change the composition of food products or deteriorate their organoleptic characteristics. However, there are no regulations prohibiting the use of a lighter bottle (i.e., the same bottle that is used in non-organic oil bottling). Therefore, an option to improve the production process can be to use lighter glass bottles or to use recycled glass bottles. In this regard, a sensitivity analysis is carried out, based on different kinds of bottles and, consequently, different amounts and types of glass.

3.1.2 Sensitivity analysis in the bottling phase

A sensitivity analysis is carried out by changing the input of glass in the bottling phase, comparing the use of 0.92 kg glass bottles with 0.46 kg glass bottles, both in virgin and recycled glass, although there are some claims that a different kind of bottle could affect the quality of the oil and decrease its commercial value. Some companies start using plastic bottles in order to decrease transport and manufacturing costs, but this option opens the issue of the quality of the oil conservation (Kanavouras 2019) and is not considered in the present study. In Fig. 7, the impacts of the different bottling processes are compared. As far as the change of weight is concerned, by using 0.46 kg glass bottles, the contribution to most impact categories decreases by 50%, as expected. The use of a lighter bottle also entails a decrease of transport costs from producer to retailer.

The replacement of virgin glass with recycled glass in the bottling phase has the potential of decreasing environmental burdens associated with the packaging of the final olive oil product at a significant extent (Espadas-Aldana et al. 2019; Lonca et al. 2020). In fact, except for the LCP impact category, where the impacts of recycled glass bottles are higher than of virgin glass bottles (due to the land requirements for recycling infrastructure), the use of recycled glass decreases the generated impacts in a range varying from 79% (in FDP) to 92% (in TEPT), depending on the impact categories, in so adding potential to the circularity of the whole process.

3.2 By-product valorization sub-system

3.2.1 Circular design for new products: additional olive oil extraction and energy recovery from olive pomace

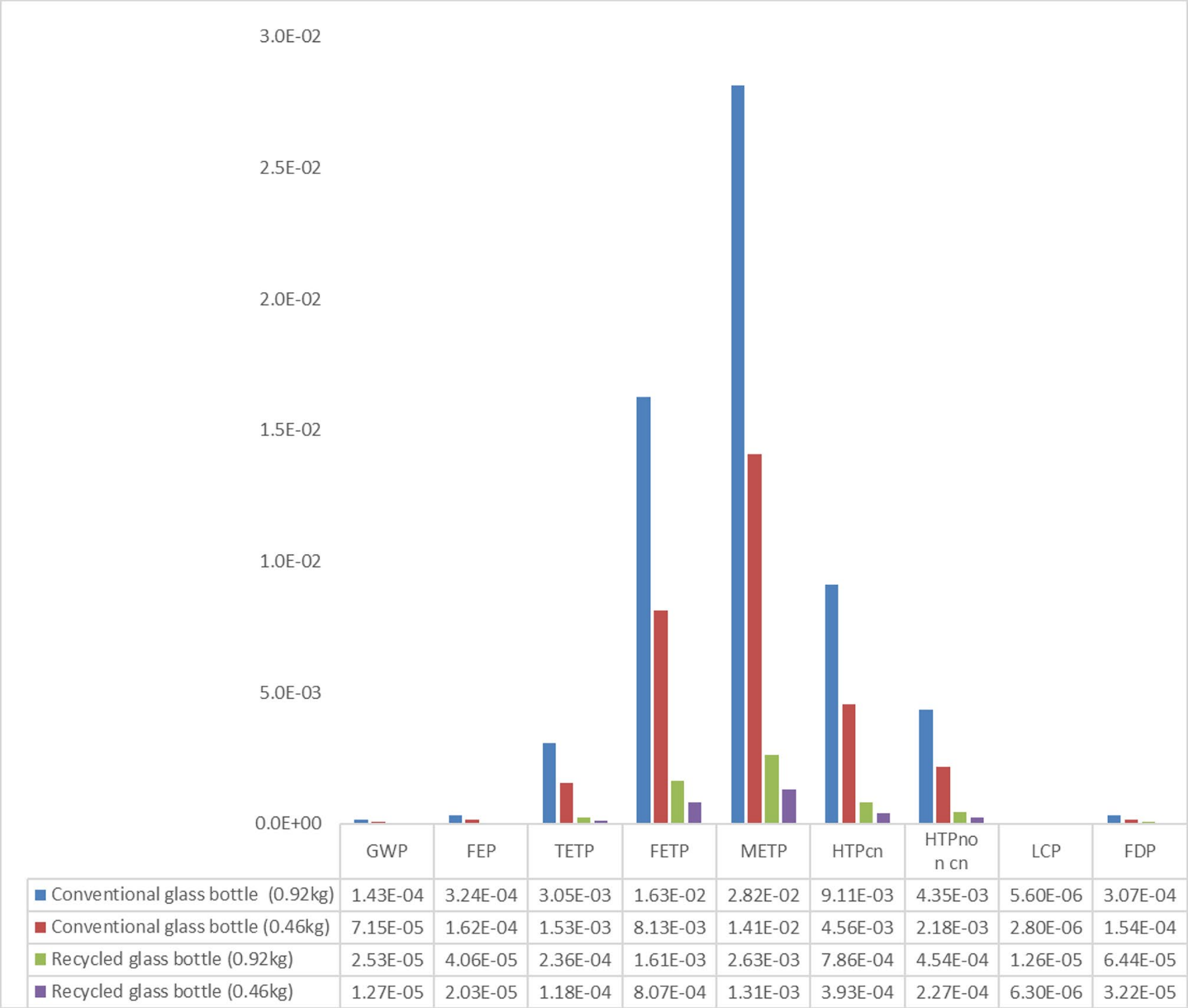
Considering that olive pomace accounts for a higher value as a co-product of the olive oil production system compared with other co-products, such as seeds and olive mill waste, it is possible to apply a biorefinery-oriented approach in order to enhance its value and reduce impacts. Table 4 lists the characterized overall environmental impacts of extracting residual oil from wet olive pomace, calculated considering the exergy allocation between oil and residual pomace (as described in Table 2). As expected, the dry pomace inflow plays a dominant role, with a share of 91–100% of the total impacts in all the investigated impact categories. This is because olive pomace carries a relevant portion of the production process impacts, originally allocated to it based on its exergy, namely 53.64% of the total. The fact that pomace exergy is so high suggests pomace to be a valuable resource and calls for its valorization (additional oil extraction, chemicals, fertilizer, energy), in parallel to the already recognized high value of the extracted extra virgin olive oil. Concerning the other input flows, only heat from steam, used in the distillation process, gives a contribution of 8% in the GWP impact category, while electricity required for pomace drying and hexane used for the extraction of the residual oil contained in dry pomace do not contribute to the generated impacts at any significant extent.

As mentioned above, the circular process of extracting oil from dry pomace generates a residue (i.e., de-oiled pomace) which can be further utilized to recover energy. In recovering energy from de-oiled pomace, woodchips can be added (Intini and Rospi 2012). However, in our case, woodchips are replaced with prunings available at the plant, thus avoiding the procurement and transportation of woodchips. The biomass of prunings (branches and leaves), available to be added to de-oiled pomace for energy purposes, corresponds to 7.28E+02 kg (in the specific assessment, 1.62 kg/FU). The characterized impacts of recovering energy from the exhausted pomace, including prunings, are shown in Table 5, referred to the functional unit of 1-L bottle of extra virgin olive oil.

Once again, de-oiled pomace is entered as an input, carrying a relevant fraction of the environmental burdens and impacts of the whole production process, proportionally to its exergy content. Its contribution to the impacts generated from energy recovery ranges from 65% in FETP to 83% in FDP, whereas the impact share from prunings varies from 16% in FDP to 35% in LCP.

3.2.2 Circular design for new products: biodiesel from exhausted cooking oil

If the exhausted cooking oil is disposed of in drainage and landfills, the environmental and economic cost of disposal must be considered an additional cost for the food industry. Instead, it can be converted to energy purposes, thus providing some advantages. In our study, due to the nature of the feedstock used, a zero-burden approach was adopted, considering the exhausted cooking oil neither as



	GWP	FEP	TETP	FETP	METP	HTPcn	HTPno n cn	LCP	FDP
🟦 Conventional glass bottle (0.92kg)	1.43E-04	3.24E-04	3.05E-03	1.63E-02	2.82E-02	9.11E-03	4.35E-03	5.60E-06	3.07E-04
🟥 Conventional glass bottle (0.46kg)	7.15E-05	1.62E-04	1.53E-03	8.13E-03	1.41E-02	4.56E-03	2.18E-03	2.80E-06	1.54E-04
🟩 Recycled glass bottle (0.92kg)	2.53E-05	4.06E-05	2.36E-04	1.61E-03	2.63E-03	7.86E-04	4.54E-04	1.26E-05	6.44E-05
🟪 Recycled glass bottle (0.46kg)	1.27E-05	2.03E-05	1.18E-04	8.07E-04	1.31E-03	3.93E-04	2.27E-04	6.30E-06	3.22E-05

Fig. 7 Sensitivity analysis showing the normalized impacts of glass bottles with different weights, both in virgin and recycled glass

a by-product nor a co-product, but instead as a waste not carrying any previous impact (Nakatani 2014). Table 6 highlights the relative contribution to the environmental impacts deriving from the different phases of the biodiesel production, based on the inventory listed in Appendix Table A6.

Table 4 Characterized impacts of the pomace oil extraction process, per functional unit of 1-L bottle of extra virgin olive oil (0.276 kg of pomace oil, as detailed in Table 1)

Impact category	Unit	Total	Dry pomace	Heat	Electricity, medium voltage	Hexane
GWP	kg CO_2 eq	9.08E−02	8.26E−02	7.61E−03	4.95E−04	1.08E−04
FEP	kg P eq	1.91E−04	1.90E−04	9.83E−07	1.69E−07	2.87E−08
TETP	kg 1,4-DCB	4.55E+00	4.52E+00	2.55E−02	5.08E−04	3.73E−04
FETP	kg 1,4-DCB	3.46E−02	3.46E−02	4.69E−05	1.19E−05	2.96E−06
METP	kg 1,4-DCB	4.98E−02	4.97E−02	7.65E−05	1.59E−05	4.45E−06
HTP_{cn}	kg 1,4-DCB	9.79E−03	9.70E−03	8.10E−05	1.31E−05	3.56E−06
HTP_{non_cn}	kg 1,4-DCB	1.20E+00	1.20E+00	1.47E−03	2.25E−04	9.95E−05
LCP	m^2a crop eq	2.06E+00	2.06E+00	2.79E−05	2.05E−05	2.83E−06
FDP	kg oil eq	1.10E−01	1.07E−01	2.22E−03	1.44E−04	1.54E−04

Table 5 Characterized impacts of the production of energy from de-oiled pomace and prunings, per functional unit of 1-L bottle of extra virgin olive oil (4.74 kWh from 2.56 kg of de-oiled pomace and 1.62 kg of prunings, as detailed in Table 1)

Impact category	Unit	Total	De-oiled pomace	Prunings	Urea	Tap water
GWP	kg CO$_2$ eq	4.38E−01	3.39E−01	8.30E−02	1.61E−02	2.71E−07
FEP	kg P eq	1.08E−03	7.14E−04	3.60E−04	2.85E−06	1.43E−10
TETP	kg 1,4-DCB	2.59E+01	1.70E+01	8.82E+00	8.47E−02	5.27E−07
FETP	kg 1,4-DCB	1.97E−01	1.29E−01	6.70E−02	3.33E−04	8.29E−09
METP	kg 1,4-DCB	2.83E−01	1.86E−01	9.63E−02	5.15E−04	1.15E−08
HTP$_{cn}$	kg 1,4-DCB	5.40E−02	3.66E−02	1.71E−02	3.40E−04	5.96E−08
HTP$_{non\_cn}$	kg 1,4-DCB	6.84E+00	4.49E+00	2.34E+00	1.13E−02	1.85E−07
LCP	m^{2}a crop eq	1.17E+01	7.68E+00	4.06E+00	1.63E−04	4.99E−09
FDP	kg oil eq	4.94E−01	4.09E−01	7.88E−02	6.29E−03	6.70E−08

Each phase in the production of biodiesel from waste cooking oil is analyzed to identify the hotspots for improved management and higher environmental sustainability. Thanks to the zero-burden approach, focus is placed only on the environmental impacts of refining and upgrading the waste oil (1.11 kg of refined oil is needed for producing 1 kg of biodiesel). In the oil collection phase (referred to 1.34 kg of waste cooking oil), diesel is the input that contributes to the highest environmental load, producing about 2.39E − 01 kg CO$_2$ eq in GWP and 5.98E − 02 kg oil eq in FDP. In the oil pre-treatment phase, electricity used to power the machinery is the most impactful flow in all the impact categories with a contribution of over 95% of impacts, except for the HTP$_{cn}$ category, where it has a share of 70% versus 30% due to the cast iron, which is a component of machinery, mainly consisting of steel. The refined oil is then mixed with methanol, phosphoric acid, and potassium hydroxide in the trans-methyl esterification phase to produce biodiesel (detailed impacts generated by the trans-methyl esterification phase are shown in Appendix Table A7). Again, at this stage the refined oil is not included as an input to the trans-methyl esterification process, because the focus is to understand the additional environmental burdens related to the upgrade itself. Methanol has the highest environmental load compared to all the other inputs, contributing to 76% in FDP, 73% in FETP, 68% in METP, and 47% in GWP and HTP$_{non\_cn}$. Phosphoric acid is the main contributor to HTP$_{cn}$ (with 77% share), whereas potassium hydroxide mainly contributes to FET (32%). 78% of impacts on TETP derive from transport and LCP is affected at 38% by electricity requirements. Overall, the contribution of the trans-methyl esterification phase ranges from 58% in GWP and 67% in FDP to values higher than 83% in all the remaining impact categories, raising concerns on toxicity and requiring optimized strategies aimed at reducing the fossil fuels and energy demand in the production of biodiesel.

Consequently, although the biodiesel option is preferable to generating diesel from crude oil (Ripa et al. 2014), an alternative option is to purify waste cooking oil to a sufficient extent so that it can be burned for heat and power production, instead of converting it to biodiesel. In so doing, the energy-related improvements can be achieved without having to face additional toxicity increase (Hussain et al. 2011; RECOIL 2012). If the option to proceed with the trans-methyl esterification process is selected, it is appropriate to mention any possible improvement that can be examined in the future. In addition to biodiesel, quite pure glycerol is also produced and it can be used in the pharmaceutical industry, to produce syrups or inside creams. It can also be used in the food industry, as an additive, or to produce triacetin, which constitutes cigarettes, or even in the

Table 6 Characterized impacts of the biodiesel production process from exhausted waste cooking oil (referred to 1 kg of produced biodiesel)

Impact category	Unit	Total	Oil collection phase	Pre-treatment phase	Trans-methyl esterification phase*
GWP	kg CO$_2$ eq	1.17E+00	2.39E−01	2.53E−01	6.75E−01
FEP	kg P eq	6.43E−05	2.59E−06	6.35E−06	5.54E−05
TETP	kg 1,4-DCB	7.66E−01	3.53E−02	4.73E−02	6.84E−01
FETP	kg 1,4-DCB	5.57E−03	2.37E−04	5.04E−04	4.83E−03
METP	kg 1,4-DCB	8.34E−03	3.93E−04	7.51E−04	7.20E−03
HTP$_{cn}$	kg 1,4-DCB	1.35E−02	9.16E−04	1.34E−03	1.12E−02
HTP$_{non\_cn}$	kg 1,4-DCB	1.59E−01	7.03E−03	1.21E−02	1.40E−01
LCP	m^{2}a crop eq	7.33E−03	2.68E−04	7.19E−04	6.34E−03
FDP	kg oil eq	3.70E−01	5.98E−02	6.35E−02	2.47E−01

*The impacts of the trans-methyl esterification phase are detailed in Appendix Table A7 production of nitro-glycerine. From the energy point of view, it can be used both as a carbon source in anaerobic digestion processes and as an energy vector in catalytic processes for hydrogen production (Tabatabaei et al. 2019; Andreeva et al. 2022; Khademi and Lotfi-Varnoosfaderani 2022).

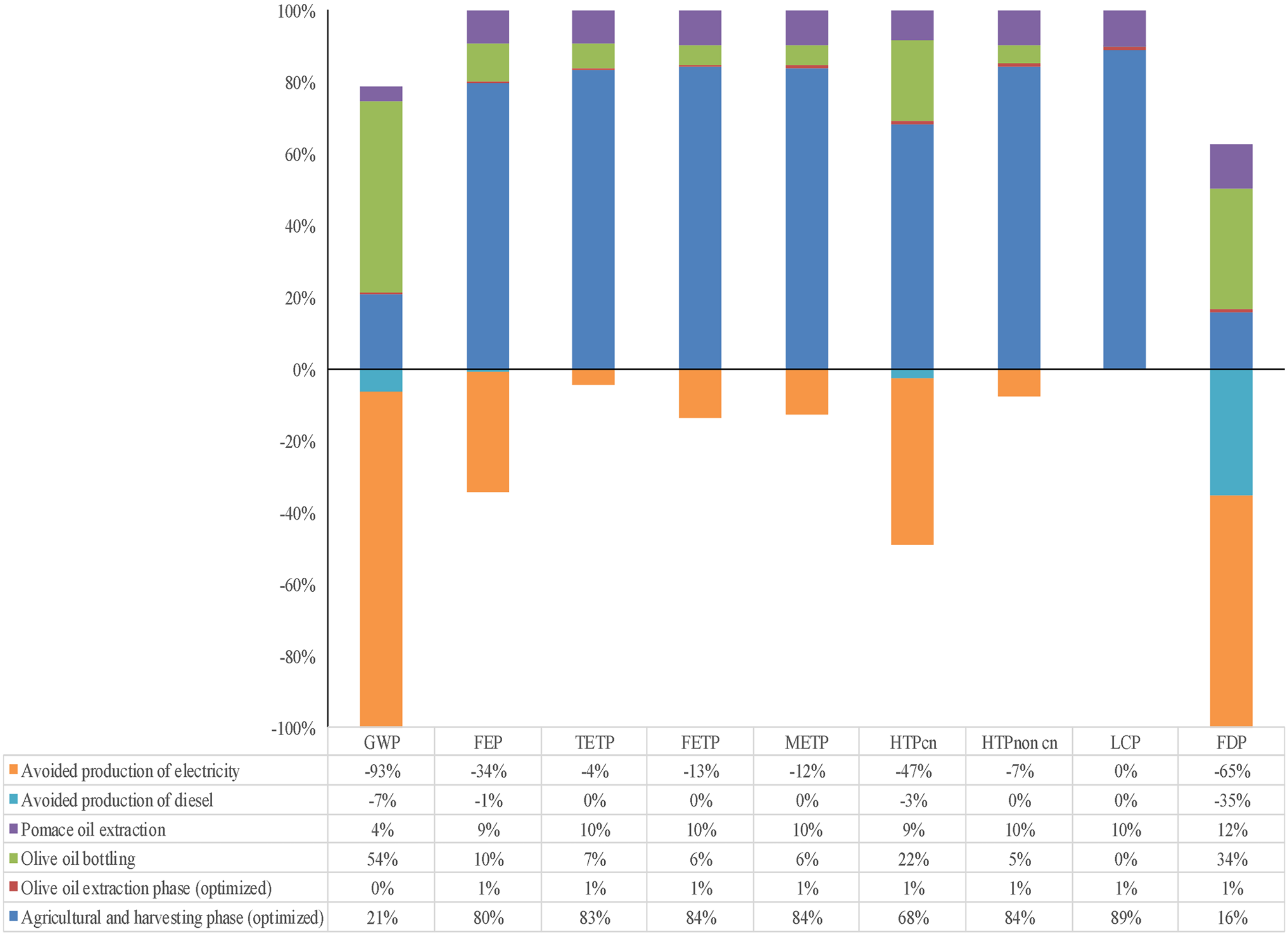
3.2.3 Circular design for new products: reuse in earlier steps of the process

As last step of the present study, an expanded system is implemented including improvements in the olive oil production system, through the substitution of fossil-derived fuels and energy with bioenergy and biofuels recovered from by-products which act as feedback to the upstream processes. Biodiesel produced from exhausted cooking oil is assumed to be reused back in the previously analyzed process of production of organic extra virgin olive oil (namely as a fuel in the agricultural step). As an alternative (not tested in this study), refined oil can be used to provide heat for in-farm electricity production. The two choices are not equivalent. In fact, using biodiesel entails the additional toxicity impacts of the trans-methyl esterification process, while using the exhausted cooking oil to generate heat carries much lower impacts. In the present assessment, it is assumed that biodiesel is produced nearby the oil mill, thus neglecting its transportation from the manufacturer to the oil mill. Moreover, the energy recovered from residual biomass (prunings and de-oiled pomace) is assumed to replace the electricity from the grid. Therefore, the new improved olive oil production system is assessed considering the above feedback inflows to the production of extra virgin olive oil and the extracted pomace oil. Figure 8 shows the environmental impacts of the new production process of olive oil with a circular outlook and perspective, by using renewable fuel and energy.

By replacing electricity from the grid with the energy recovered from prunings and de-oiled pomace, we can clearly see decreased impacts on GWP (− 93%), FDP (− 65%), and HTP_{cn} (− 47%). The replacement of diesel with the biodiesel obtained from waste cooking oil gives rise to environmental benefits in terms of FDP (− 35%) and GWP (− 7%). Negative values represent the benefits of burdens that are avoided not producing fossil-derived diesel and electricity.

In order to get a clearer view of the environmental benefits of the investigated circular improvement options, we compared the relative environmental impacts generated by (i) extra virgin olive oil linear production without valorization of by-products (business-as-usual (BAU), without allocation), (ii) extra virgin olive oil linear production with allocation of total impacts to produced oil and pomace (business-as-usual (BAU), with allocation), and finally (iii) two circular production systems, incorporating improvements, such as the replacement of electricity from the national grid with the energy recovered from biomass residues (de-oiled pomace and prunings) (Scenario A) and the replacement of electricity plus the replacement of fossil diesel with biodiesel from exhausted cooking oil (Scenario B). Table 7 shows the comparison of the investigated production options.

The linear system with a 100% allocation to the main product (extra virgin olive oil) has a much higher environmental load than the business-as-usual (BAU) and circular scenarios (A and B). In the BAU scenario, the environmental burdens and impacts are distributed among co-products based on their exergy content and, as a result, if we refer to the selected functional unit, all the impact categories have an overall lower environmental load (about 2.4 times, which translates into a 41.6% impact reduction according to the normalized values) compared to the linear system with no allocation. Moreover, the reuse and recycling of waste cooking oil, pomace, and prunings for biofuel and energy recovery gives a noteworthy contribution to the environmental performance, especially in the GWP and FDP impact categories, where the negative values of the impacts indicate that the gained benefits are higher than the produced loads. In Scenario A, although only electricity is recovered from biomass residues (de-oiled pomace and prunings) and biodiesel production is avoided to address toxicity concerns without providing any alternative for fossil diesel, the overall decrease in generating impacts compared to the linear system remains significant. For example, a reduction of about 2.20 kg CO_2 eq in GWP and 0.7 kg oil eq in FDP per 1-L bottle will result in avoiding 10,850 kg CO_2 eq and 4930 kg oil eq respectively, if we consider 4930 bottles produced per 13 ha per year. Likewise, regarding Scenario B, the use of both biodiesel and bioelectricity will result in a GWP potential reduction of about 2.3 kg CO_2 eq per 1-L bottle of olive oil produced and an overall reduction of 11,403 kg CO_2 eq per 13 ha per year, with an added reduction in fossil fuel demand (1.1 kg oil eq per bottle of olive oil). The slight characterized differences in Scenarios A and B are expected, due to the reuse options of biodiesel. By using biodiesel and bioenergy (Scenario B), the impacts on GWP and FDP categories are significantly reduced, but the challenge of toxicity will persist. Based on Table 7, it is therefore logical to produce biodiesel from the waste cooking oil, despite the toxicity threat due to the trans-methyl esterification process. Therefore, when considering circular designs to reduce impacts and optimize the reuse of co-products, some choices have to be made. This represents one of the challenges of a bioeconomy/circular economy: while environmental benefits may be obvious, in some cases, increased circularity may lead to a worse performance in terms of environmental



	GWP	FEP	TETP	FETP	METP	HTPcn	HTPnon cn	LCP	FDP
🟧 Avoided production of electricity	-93%	-34%	-4%	-13%	-12%	-47%	-7%	0%	-65%
🟦 Avoided production of diesel	-7%	-1%	0%	0%	0%	-3%	0%	0%	-35%
🟪 Pomace oil extraction	4%	9%	10%	10%	10%	9%	10%	10%	12%
🟩 Olive oil bottling	54%	10%	7%	6%	6%	22%	5%	0%	34%
🟥 Olive oil extraction phase (optimized)	0%	1%	1%	1%	1%	1%	1%	1%	1%
🟦 Agricultural and harvesting phase (optimized)	21%	80%	83%	84%	84%	68%	84%	89%	16%

Fig. 8 Characterized impacts (expressed in % values) of the expanded production process of extra virgin olive oil including additional circular patterns, per functional unit of 1-L bottle of extra virgin olive oil

sustainability (raising, for example, toxicity concerns) (Blum et al. 2020; Fiorentino et al. 2017). Focus on incremental improvements toward circular activities can do more harm than good considering the issue of toxicity in the case of the production of biodiesel, despite all the good intentions of CE practices. For circular economy to be effective, there is

Table 7 Comparison of characterized impacts among the linear extra virgin olive oil production system, the current business-as-usual scenario, and the suggested circular scenarios (A and B), per functional unit of 1-L bottle of extra virgin olive oil

Impact category	Unit	Business-as-usual (BAU) scenario (without allocation)	Business-as-usual (BAU) scenario (with allocation of environmental impacts to all co-products)	Circular Scenario A (only electricity recovery within the process)	Circular Scenario B (biofuel use and electricity recovery within the process)
GWP	kg CO_2 eq	1.73E+00	1.53E+00	−6.11E−01	−7.23E−01
FEP	kg P eq	2.64E−03	1.83E−03	3.44E−04	3.29E−04
TETP	kg 1,4-DCB	1.16E+02	4.26E+01	2.09E+01	2.08E+01
FETP	kg 1,4-DCB	2.12E+00	3.20E−01	1.23E−01	1.22E−01
METP	kg 1,4-DCB	2.68E+00	4.60E−01	1.82E−01	1.80E−01
HTPcn	kg 1,4-DCB	1.40E−01	1.03E−01	1.22E−02	9.65E−03
HTPnon_cn	kg 1,4-DCB	2.60E+01	1.11E+01	5.00E+00	4.96E+00
LCP	m^2a crop eq	3.98E+01	1.81E+01	9.03E+00	9.03E+00
FDP	kg oil eq	9.57E−01	6.60E−01	−2.94E−02	−4.23E−01

a need to evaluate and assess the sustainability aspects and its performance before full implementation, especially in the absence of coherent policies at local, country, and global level (Blum et al. 2020; Harris et al. 2021). For example, a possible solution to ensure the environmentally sustainable production of biodiesel is to minimize the use of chemicals to reduce toxicity. Instead of methanol, the adoption of ultrasonics has been proposed by some researchers to improve the trans-methyl esterification process (Chand et al. 2010; Gude and Grant 2013). Regarding biofuels, Ulgiati (2001) cautioned that on a large scale, the biofuel route may not be a viable alternative based on economic, energy, and emergy evaluations. This study has validated this claim and confirms that, at an appropriate scale, the biofuel option contributes to optimizing the bioenergy and resource balance of small-scale industrial production systems.

4 Discussion: opportunities, limitations, and policy trends in the olive oil supply chain

In the attempt to scale up the results achieved at company level, it should be considered that the potential residue available for olive pomace in the Campania Region is about 53,000 tons per year, based on the data concerning the harvesting of olives in the region, thus representing a promising material stream with a huge potential towards circularity. The evaluated system mainly considered pomace which carried a 53.64% environmental burden. Under linear production systems of take, make, and dispose, the pomace is not fully valorized. To avoid the burden of an improper disposal of the pomace, we considered an exergy allocation through the recovery of clean energy and biofuel. After replacing the required energy (45 kWh in the agricultural phase and 728 kWh in the oil extraction phase; Appendix Tables A1 and A2) with the energy recovered from biomass residues, the remaining surplus of energy, amounting to about 22,627 kWh, can be fed back to the Italian national grid, thus representing a further step towards supporting renewable energy policies in Europe. The consumption of bioenergy will contribute to the current 20% renewable energy 2020 target by the European Union, and will also contribute in meeting the long-term 2030 and 2050 energy security targets using biomass (EEA 2013). Recently, Eni S.p.A., an Italian multinational oil and gas company headquartered in Rome, and CONOE, the National Consortium for the Collection and Treatment of Used Oils and Fats, signed a Memorandum of Understanding to promote and increase the collection of vegetable oils that will supply the Eni's Venice biorefinery. Representing the final stage of the virtuous cycle of the circular economy in the olive oil sector, the Venice plant is expected to transform organic waste residues into high-quality biofuels. However, there are very few, if not any, biorefineries in the Campania Region, coupled with the absence of regulations that favor the recycling of waste. It is therefore difficult, for an average olive oil producer, to consider this option for waste management because it is not economically rewarding, especially without incentives from government.

Furthermore, the pomace from Southern Italy is transported for long distances (more than 500 km) to reach the Northern regions, where established biorefineries exist. Faced with this challenge, many local farmers prefer the lower cost and no value addition option of spreading olive mill waste in ponds and leave it to dry for application on fields to improve soil fertility for the next farming season. Yet, from this study, it is evident that the exploitation of by-products has an added advantage especially on the potential for energy and biofuel recovery at local scales. The results in Table 7 have highlighted the best circular scenarios, assuming that the pomace is processed internally within the farm disregarding transportation impacts. By exploring a micro-level case study and its environmental performance, we were able to point out its relation to circular economy resulting in decreased resource use and environmental impacts. However, from an environmental perspective, the results of a company-tailored LCA do not allow to carefully plan and design more sustainable solutions, particularly addressing challenges due to transportation of residual materials to biorefinery centers. In fact, in the circular economy framework, the transportation aspect deserves special attention and each scenario proposed should be contextualized and assessed. Micro-scale case studies do not provide a clear and full picture of the entire circular economy debate, nor can they ensure that circular economy is always a solution instead of becoming a new problem (rebound effect, or the risk for greenwashing strategies, of developing new technologies without sufficient knowledge of their consequences). For sensitivity purposes, the transportation of olive pomace to certain distances was considered in order to decide on the best possible locations for biorefinery centers and to identify the best option generating reduced environmental burden from transportation activities. We conservatively considered 50 km, 100 km, 200 km, and 500 km as distances to be covered. Table 8 evidences the resulting environmental burden when transportation is included in the analysis. The environmental impacts tend to increase the more we move away from the olive farm. For example, when distance was increased from 50 to 100 km, the environmental load in almost all impact categories was doubled. In other words, this means that the further the eco-industrial park/biorefinery is from the agri-food farms, the more the environmental burden of transporting any residual biowaste material. Others may argue that beyond a reasonable distance it is better to continue with business-as-usual practice as there are no

Table 8 Sensitivity analysis considering distance and transportation systems

Impact category	Unit	Transport by lorry (50 km)	Transport by lorry (100 km)	Transport by lorry (200 km)	Transport by lorry (500 km)	Transport by freight train (50 km)	Transport by freight sea (50 km)
GWP	kg CO_2 eq	4.68E + 00	9.98E + 00	2.06E + 01	5.24E + 01	8.05E − 01	4.54E + 00
FEP	kg 1,4-DCB	9.85E − 04	1.01E − 03	1.07E − 03	1.23E − 03	6.67E − 05	2.88E − 05
FETP	kg P eq	1.17E + 00	1.20E + 00	1.24E + 00	1.37E + 00	1.17E + 00	1.15E + 00
TETP	kg 1,4-DCB	1.87E + 02	3.11E + 02	5.58E + 02	1.30E + 03	6.48E + 01	1.22E − 01
METP	kg 1,4-DCB	1.54E + 00	1.64E + 00	1.82E + 00	2.38E + 00	1.47E + 00	1.46E + 00
HTP_{cn}	kg 1,4-DCB	5.72E − 02	6.48E − 02	8.01E − 02	1.26E − 01	7.96E − 02	6.92E − 02
HTP_{non_cn}	kg 1,4-DCB	1.54E + 01	1.73E + 01	2.11E + 01	3.25E + 01	1.42E + 01	1.37E + 01
LCP	m^2a crop eq	2.14E + 01	2.14E + 01	2.14E + 01	2.16E + 01	2.14E + 01	2.14E + 01
FDP	kg oil eq	1.33E + 00	3.08E + 00	6.57E + 00	1.70E + 01	1.45E − 02	1.13E + 00

environmental benefits (refer to Table 7 for comparison). For example, at 500 km the GWP (5.24E + 01 kg CO_2 eq) and FDP (1.70E + 01 kg oil eq) are significant discouraging transportation. Moreover, the longer the distance, the more local farmers will need to pay for transportation costs. When there are no subsidies and incentives from government, it is expected that business-as-usual practices will persist. As an extended discussion, we also explored the sensitivity of using different transportation systems, namely road (freight, lorry), water (freight, sea), and rail (freight train). Table 8 further pinpoints the favorable transportation system in terms of overall environmental impacts. For example, freight rail and sea show lower environmental burdens (8.05E − 01 and 4.54E + 00 kg CO_2 eq in GWP, respectively) than the road transportation system (4.68E + 00 kg CO_2 eq).

Future studies should further explore the transportation parameters in detail, covering economic and environmental costs and benefits. This study has only explored the valorization of by-products mainly towards the recovery of bioenergy, but there is an urgent need for additional studies exploring the recovery of useful platform bio-based chemicals and further extended in-depth analyses. The full exploitation of the by-products from the olive oil sector can only be realized through extended innovative material recovery and extraction techniques. The challenge, however, is that most of these side production processes are not yet fully established and most are still at the experimental phase, thus making it extremely difficult to obtain reliable inventory data needed for LCA evaluation. Overall, the implications of moving towards a circular economy in the olive oil production sector has proven to be beneficial in this study. However, there are some constraints that also emerged. For example, the recovery of biodiesel from waste cooking oil highlighted some potential hotspots related to toxicity impacts, despite the need for renewable fuels nowadays. Transportation is also considered a major bottleneck, calling for increased collaboration for the development of recycling and biorefinery centers within a region to minimize transportation costs and environmental externalities. We also did not manage to evaluate economic and social organizational factors, which may influence decision-making, as it was beyond the scope of this LCA study which focused on environmental implications of circularity. Overall, this study has shown the environmental performance of some technical aspects related to the implementation of CE strategies from the cultivation, oil extraction up to bottling, and the valorization of by-products for reuse in upstream processes. Surely, some policy perspectives can be drawn from this study especially regarding the need for building more infrastructures towards biorefineries or recycling centers through local collaboration among farmers with the possibility of creating synergic and diffuse exchange systems of converting agri-food by-products into new co–products to minimize resource use and environmental impacts.

5 Conclusions

This study was intended to suggest and assess options for reducing the impacts of the olive oil supply chain by applying the principles of the circular economy, thus shifting from linear to circular production, in which by-products are used as raw materials in extended production processes. By assessing the environmental impacts and possible improvements that can be implemented in the production process by the involved company, this study has demonstrated the environmental benefits that the transition from a linear to a circular supply chain would entail, that is, by the valorization of what is generally considered "production waste." It should be emphasized that the improvements, in addition to affecting companies, must also affect international policies, so that they can encourage the development of increasingly "green" sources. In this study, it was possible to analyze the production of olive oil and identify potential hotspots to reduce impact through the design for new products and valorization of by-products (pomace, prunings, and wasted vegetable oil).

The recovery of energy and biofuel and the implications of such extended production processes were also evaluated from an environmental point of view using LCA. In exploring potential pathways towards a circular economy in the olive oil sector, some decisions must be made in choosing to increase environmental benefit and reduce negative impacts. The recovery of biodiesel highlighted some potential hotspots related to toxicity impacts, despite the need for renewable fuels nowadays. Therefore, circular economy pathways need to be carefully understood and evaluated, as not all material and energy recovery processes from waste are environmentally sound. In the Campania Region, due to the lack of centers for by-product reuse, the cost of recycling, coupled with a lack of information on opportunities offered by a circular economy, leaves many mills to adopt cheaper reuse practices as only a regulatory obligation. The obstacles for starting a more incisive phase in closing the loop in the olive oil production sector seem to be economical and organizational, but, if overcome, paths that are economically advantageous and, at the same time, targeted at greater environmental sustainability can be followed.

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Data availability All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Declarations

Competing interests The authors declare no competing interests.

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