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Research article

Life cycle assessment of olive oil: A case study in southern Italy

Francesco Guarino[a,*], Giacomo Falcone[b], Teodora Stillitano[b], Anna Irene De Luca[b], Giovanni Gulisano[b], Marina Mistretta[c], Alfio Strano[b]

[a] Department of Engineering, University of Palermo, Viale delle Scienze, Building 9 - 90128, Palermo, Italy
[b] Department of Agriculture "AGRARIA". Mediterranean University of Reggio Calabria. Feo di Vito, 89122, Reggio Calabria, Italy
[c] Department of Heritage, Architecture, Urbanism Department. Mediterranean University of Reggio Calabria. Salita Melissari, 89124, Reggio Calabria, Italy

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ABSTRACT

The paper describes the results of a specific LCA based analysis of the production of olive oil in the region of Calabria, in southern Italy.

The goal of the study is to assess the energy and environmental impacts of different scenarios involving conventional and organic cultivations, plains and hills cultivations and involving different operating techniques. The study also aims at assessing the share of each life cycle step on the total of energy and environmental impacts.

The functional unit chosen for the comparative analysis is a glass bottle of 0.75 L of extra virgin olive oil. A "from cradle to gate" perspective was chosen. The analysis was developed according to the LCA standards of the ISO 14040 series.

The analysis is based on a field analysis developed in the last years in the province of Reggio Calabria between more than 50 enterprises and stakeholders of the field, representative of the whole Calabria region and of most southern Italy. The data used for the development of mass and energy balances are related to the years 2013–2015.

The results clarify that for all indicators that the first part of the life cycle – from the production, including the growth of the olive plant to the full production stage – is the most relevant, variable between 80.6% share in the case of the particulate matter indicator to the 99.64% in the case of land use (Hill – Biological agriculture scenario).

Relevant differences can be also traced for each specific indicator among all scenarios; high impacts are traced for the agricultural stages among all scenarios (70% −90% in all indicators) with high impacts caused by fertilizers. Among the transformation stages the bottle production is one of the most relevant sources of life cycle energy uses and environmental impacts (80–90%).

1. Introduction

Olive oil production is a relevant agri-industrial sector in terms of both production and consumption in Europe. According to the International Olive oil Council (International Olive Oil Council, n.d.), olive oil production has been growing in the last decades with alternate variability from around one million tonnes in 1990–1991 up to more than 2.3 in 2015–16. The largest contributor has always been Spain, reaching more than 1.4 million tonnes in 2015–16 followed by Italy with 474.6 thousand tonnes.

The export market in the EU is also significant, since the total export flows amounted to more than 600 thousand tonnes in 2015–16, the highest contributor being Spain with 289.7 thousand tonnes and Italy with 233.3. The import market in the EU is significantly smaller than the export one and has remained fluctuating over similar values over the years, with a reversely similar pattern if compared to the variations in the production. The last recorded value for 2015-16 amounted to 116.5 thousand tonnes.

The numbers reported highlight the relevance of Italy in the market. In particular today Italian olive production covers approximately 1 700 000 ha, 80% of which are located in the southern zone of Italy, where in particular Puglia is responsible for around 370 000 ha followed by Calabria and Sicily. These three regions account for more than 60% of Italian olive oil production.

However, although being so widespread and having a relevant impact on economy and the market (Stillitano et al., 2016), olive oil

* Corresponding author.
E-mail address: francesco.guarino@unipa.it (F. Guarino).

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production is associated with several adverse effects on the environment that cause resource depletion, land degradation, air emissions and waste generation (Strano et al., 2014). The impacts may vary significantly as a result of the practices and techniques employed (Iofrida et al., 2018) in olive cultivation and olive oil production as well as with the analysis techniques adopted in the study and its assumptions (De Luca et al., 2018).

Several approaches are available concerning economic aspects as in (Stillitano et al., 2017) as well as about the long term feasibility of such systems (Stillitano et al., 2018) and/or social aspects, to account the complexity on such a relevant and cross-cutting market aspect. A well-recognised and solid approach towards the environmental sustainability of the olive oil sector is widely recognised in the Life Cycle Assessment (LCA) methodology (De Luca et al., 2018b), that can be applied within the framework of a more integrated sustainability performance evaluation (Büyüközkan and Karabulut, 2018), or in combination of the aforementioned methods (Kyriakopoulos, 2008).

Based on mass and energy balances developed in steady state, LCA aims at computing all flows in the life cycle of a product or of a service, through its “cradle” to its “grave”, and at translating them into impacts, being either human hazards for safety and health, environmental impacts, primary energy use, etc. (Kyriakopoulos, 2007).

LCA applications to the olive oil sector in the Mediterranean area has seen several previous applications in literature that will be briefly discussed in the following paragraphs.

The widest variety of studies are traced for Italy and are briefly summarized in the present paragraph.

(Rinaldi et al., 2014) analysed the cradle to grave carbon footprint and energy footprint of extra virgin olive oil produced in central Italy (Perugia – Umbria, Italy). System boundaries include olive orchard cultivation, oil extraction, bottling, packaging, storage at $-18\,^{\circ}C$ and distribution. The aim of the study was to establish the most environmentally intensive stages of the life cycle of the product. The functional unit chosen was 1 L of extra virgin olive oil, ready for distribution.

Environmental hotspots are mainly identified in the distribution stage, due to the preference in air-transport. Secondary hotspots can be found in the olive orchard fertilization, storage in the pre-distribution stage and lastly the manufacture of glass bottles. Authors suggest modifications in the transportation policies of the product as well as the use of lighter glass bottles.

(Proietti et al., 2014) analysed the life cycle of a “Leccino” cultivar in Central Italy. The environmental impacts associated with the management processes were evaluated with the LCA methodology within the use of standards UNI EN ISO 14040 and 14,044. A comparison between sequestrated CO_2 and emissions is also developed in the paper. Results identify the highest GWP100 value traceable in the first year of cultivation, as well as the highest weight of fertilizers in the overall cultivation environmental impacts. The breakeven point between sequestration and emission is between 4 and 5 years, after which sequestrated CO_2 reaches 5 to 6 times the value of emissions after year 10.

In (Salomone and Ioppolo, 2012), authors performed a LCA analysis of olive oil production in the province of Messina, in Italy, in the southern island of Sicily. The study focused on the whole province with the aim of giving an insight toward the development of eco-design actions within the olive oil production sector, including different combinations of cultivation practices, olive oil extraction methods and olive oil mill waste treatments. The analysis shows higher environmental impacts for conventional scenarios (except for impact categories associated with land use), and important environmental loads associated with some sub-processes (such as fertilization, the use of pesticides and the combustion of exhausted pomace), as well as significant positive contributions associated with the use of by products as fuels or fertilizers.

In order to have further positive local impacts on the whole supply chain, authors also suggest to enhance the particular qualities of local products, e.g. by exploiting the appropriate promotion and marketing strategies as well as developing circular economy and industrial symbiosis synergies between different actors and quality, traceability and environmental management systems with strong product orientation. The study also highlights some issues, most of all the poor availability of site-specific data.

(De Gennaro et al., 2012) reports an analysis of olive growing models and their environmental sustainability assessment: the two models analysed are “high density” (HDO) and “Super high density” (SHDO) orchards. Life cycle assessment and life cycle costing were applied to the two systems. The results highlighted that the HDO configuration performed consistently better for all impact categories, due to lower use of energy and chemicals as well as higher production yield. Results for several environmental categories are shown only for the orchard stage and they report variable highest contributions among fuel and lubricant, fertilizers and pesticides.

(Pattara et al., 2016) proposes five case studies in Abruzzo (central Italy) analysed through carbon footprint, in order to estimate greenhouse gas emissions due to the cultivation of olives and production of olive oil. Functional unit was chosen as 5 l of extra virgin olive oil with primary and secondary packaging. Results for the agricultural stage range from 3.34 to 7.74 kg CO_2 eq/FU (with a high share due to fertilizers and pesticides) while the packaging process in the industrial phase has a significant impact reaching 1.13 kg–3.20 kg of CO_2 eq.

(Proietti et al., 2017) describes a carbon footprint calculated through life cycle assessment of olive oil in Umbria (central Italy) starting from cultivation up to transformation and packaging, starting from data from different companies. The functional unit is 1 l of olive oil. Results are very variable from around 1 $kgCO_2$ eq/FU up to 4.5 $kgCO_2$ eq/FU but in all cases the olive grove phase represents the most significant contribution to the overall life cycle environmental impacts.

(Iraldo et al., 2014) proposes the results of an LCA based on the production of extra virgin oil in Val di Cornia (Tuscany, central Italy), using 1 kg of extra virgin olive oil as functional unit. Impact assessment was performed according to CML 2001 using several environmental impact categories as well as cumulative energy demand. Results mark a nearly complete predominance of the agricultural stage with percentages as high as nearly 94% in the case of the eutrophication that are instead in the lowest case equal to 60% for the case of photochemical oxidation.

It is worth mentioning that for acidification and eutrophication the most relevant contribution are fertilisers which cause more than 80% of the impacts highlighted by the indicator, while the other indicators mark mixed trends.

In (Accorsi et al., 2015), authors explore the operations of a global supply chain for extra-virgin olive oil (EVOO) in Italy according to a (LCA) methodology. The LCA assessment methodology is applied to determine the environmental impact categories associated with the bottled EVOO life cycle, focusing on packaging decisions. The study analyzes the most relevant hot-spots in the supply chain supporting decisions towards more efficient and environmentally-friendly operations. Results highlight the potential of bottles in reducing the environmental impact of EVOO supply chains and identify hotspots.

To a more limited extent, also in other countries the topic of LCA of olive oil has been tackled.

In Spain (Romero-Gámez et al., 2017), analyses the environmental impacts of olive fruit production systems in Andalusia (Southern Spain) aiming to the environmental sustainability assessment of different olive oil growing systems. The analysis considered only crop production up to the farm gate when the olive is harvested and transported to the oil mill, thus choosing 1 ton of olives as functional unit. Regional data from twelve different scenarios are described including studies from different sources. Climate change, acidification, eutrophication, eco-toxicity, land use and water resource depletion were chosen as impact categories. Results mark once more the high impact of fertilizers within most of the impact categories. Authors conclude that the manufacture and application of fertilizers contributed to the highest burdens in all impact categories and cropping systems, therefore, the reduction and optimization of fertilizers would be the most efficient way to improve the process environmentally. The most innovative systems (intensive and super-intensive) offered the worse environmental results caused by the high level of mechanization, the large volumes of water and energy used for irrigation and high doses of fertilizers and pesticides applied. The high productivity obtained in the intensive and super-intensive systems did not justify the largest environmental impact for most categories. These innovative systems should be optimally designed to minimize the impact of their mechanization. Lastly, authors suggest the use of renewable energy generation systems to improve the eco-profile of the olive oil and an optimization of the use of fertilizers and pesticides as top priority.

(Navarro et al., 2018) focus instead the role of packaging within the Life Cycle Assessment of Virgin Olive Oil, through a ISO 140444 study, performed with the CML impact assessment methodology, in different case studies in Spain. The stages included in the system boundaries are: Olive production, oil making, packaging, distribution and end of life, for three different types of bottles: glass, PET and Tin, using a wide range of environmental indicators and primary energy from cumulative energy demand. The functional unit is however different than most previous cases and considers instead 0.5 L of oil and its packaging. Glass and tin packaging are the ones adding more impact (average of 58% and 37% respectively) to most of the impact categories, while PET adds about 13% of impact.

In (Avraamides and Fatta, 2008), LCA was used to evaluate the use of raw materials and emissions of pollutants from olive oil production in Cyprus and to identify the processes causing the highest environmental impacts. The analysis is developed as "cradle to gate" and all results refer to a FU of 1 l of olive oil.

The results were organised in a classification of the individual processes in priority categories according to their potential optimization: fertilization and olive oil extraction processes should be considered as priority 1 processes, irrigation and pruning are classified in priority 2, pest control and olive oil management in priority 3 and tree planting, collection and transportation of olives to the processing unit (as their contribution to all the environmental flows considered was less than 0.5%) in priority 4. The production of the inorganic fertilisers used in the agricultural stage of olive oil production and the disposal of liquid effluent from olive mills to evaporation ponds were found to be "hot-spot" processes. However, the study does not fully develops environmental indicators, mainly focusing instead on "hot spots" processes, making fully fledged comparisons with previously described literature difficult and potentially non-relevant.

In (Busset et al., 2012) a LCA study of the French olive oil production sector is proposed, aimed at reducing the carbon footprint and optimising the waste management of the olive oil sector in the SUDOE area (Spain, Portugal and France). The results defined different scenarios for olive oil production in France based on the different olive production techniques (with or without irrigation, mechanical or not, organic or not), different extraction processes (pressing, centrifugation in two phases or centrifugation in three phases) and different waste management schemes (incineration or spreading). The expected result was a comparison of all the scenarios in order to identify the parameters that influence the environmental consequences of olive oil production.

A case study of olive oil production in Greece (Tsarouhas et al., 2015) is presented. LCA has been used to quantify the environmental performance of olive oil production in Gerakini, Chalkidiki region, Greece. The FU is 1 lt of olive oil using a plastic bottle. Fourteen subsystems of the overall olive oil production are investigated. All key parameters that are associated with the life cycle of olive oil production are studied and environmental "hotspots" are diagnosed. Cultivation of olive trees and production of olive oil are the sub-systems that are responsible for the majority of the environmental impacts and thus authors conclude that any effort to minimize the overall life cycle impact from olive oil production should include them. Concerning climate change emissions as example, in comparison to the 1.1 kg CO_2 eq representing the overall climate change impacts for the life cycle examined, the cultivation of olives itself has an impact of around 40%.

In (El Hanandeh and Gharaibeh, 2016), authors performed a comparison of different olive oil production practices in the Mediterranean region through a LCA study. Five environmental impact categories relevant in the context of Jordan were assessed: acidification (AP); particulate matter formation (PM10); human toxicity (HTP); climate change (GWP100) and agricultural land occupation (AGLO). Authors claimed that olive oil production in the northern region of Jordan is environmentally efficient when compared to large scale production practices common in other Mediterranean olive oil producing countries. In relation to the UF of 1 kg of olive oil, the life cycle includes all agricultural stages from the cultivation of the olive tree, harvesting, milling and oil extraction, as well as packaging and transportation. Life Cycle impacts are reported as average on a large number of small and micro-scale farmers in Jordan: Climate change is equal to 0.57 kg CO_2 eq, Acidification is equal to 11.83 g SO_2 eq, Particulate matter is 5.99 g PM_{10} eq Human toxicity is equal to 0.774 kg 1.4 dB eq.

Rajaeifar et al. (2014) analysed energy and economic flows and greenhouse gas (GHG) emissions of olive oil production in Iran through a LCA with considering four main stages of agricultural olive production, olive transportation, olive oil extraction and its olive oil transportation to the customer centres. Data were collected from 150 olive growers in the Guilan province of Iran. Energy and economic flows and greenhouse gas (GHG) emissions of olive oil production in Iran were investigated considering four main stages of agricultural olive production, olive transportation, olive oil extraction and transportation to the customer centres. The agricultural production stage ranked the first in GHG emissions among the four stages with the share of 93.81% of total GHG emissions.

Some final and summarizing remarks can be formulated:

- The use of conventional technologies in the olive oil generation scenarios is usually tied with higher environmental impacts. Intensive production has usually higher environmental impacts, while extensive cultivation scenarios are characterized by lower productivity per area. It is also worth mentioning, that most LCA studies cannot take in consideration some aspects, such as the better organoleptic quality of organic materials, the higher level of antioxidants, longer shelf life than non-organic materials, and this should be kept in mind when comparing mere impact data tables (Longo et al., 2017).
- Different hot spots are also traced in the production and treatment phases throughout the different studies of the olive oil stage (Bernardi et al., 2018) The result trends are variable with the localization and the techniques used in the olive oil production stages as in (De Luca et al., 2018a).
- Similar trends and results can be traced within the three main producers in EU, Italy, Spain and Greece. Although a wide set of indicators were chosen for the LCAs as well as different functional units that make comparisons difficult, the following Fig. 1 includes the results achieved within the most used indicator (GWP) and functional unit (1 l of olive oil).

Fig. 1 reports the results as a comparison, including also all Environmental public declarations publicly available at (The International EPD system, 2019).

The differences are rather limited in the range 1–4 kg CO_2 eq with only one case being outside.

It is also worth mentioning that several papers related to these countries highlight as a relevant need the development of technological advancements in a supply chain that is often characterized by standard practices (Nayal et al., 2016) over the decades with limited mechanization.

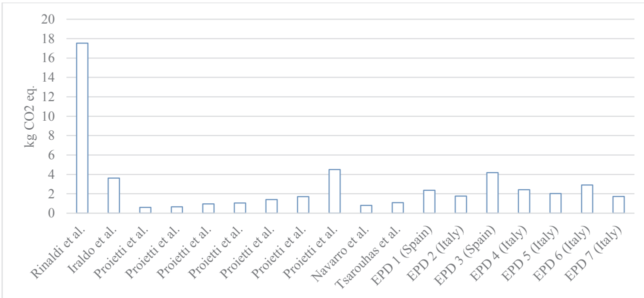

Fig. 1. State of the art on GWP with 1 l olive oil functional unit.

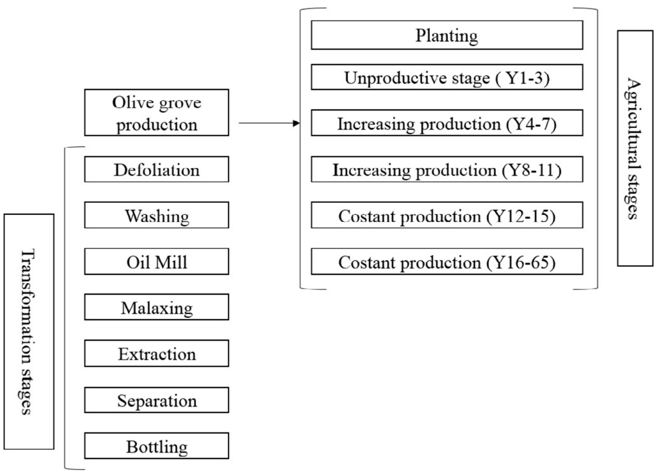

Fig. 2. System boundaries and life cycle stages included in the analysis.

Also the diffusion of renewable energy systems is also highlighted as a need to further aim towards the decarbonisation of the whole sector (Sklavos et al., 2015) and in general towards several fruit production systems (Cerutti et al., 2011).

In this context, the paper proposes an analysis of a case-study of olive oil production in Calabria - Italy. The study develops site-specific data useful to complement the state of the art in the context of a scenario analysis, based mostly on primary data. A set of different scenarios is proposed, ranging from different land use configurations or technical features. All scenarios analysed include plain and hill agriculture, conventional and organic, and standard milling techniques vs an innovative patented milling technique.

The contribution of the paper towards the available state of the art stands in the development of detailed site-specific data related to the region of Calabria in Italy with very different scenarios aiming to give a complete overview of the agricultural practices in Calabria.

Moreover, it aims at proposing energy efficiency technological solutions to improve the overall supply chain of olive oil, through the analysis of a specific patented innovative technology to be used in the milling stage. Its benefits on a life cycle stage and its life cycle performances in comparison to all other more mature technologies and cultivation methodologies are discussed in the paper.

The study is developed in the context of the Project PON "Oliopiù", aimed to introduce advanced technologies and integrated bio-technological systems targeted to the increase of value of products and the exploitation of by-products, the development of new sectors and the creation of eco-friendly productive systems. The project wanted to redesign the productive technological system of the olive growing and processing sector, by the achievement of a chain model utilizable by all the Mediterranean world and able to create both innovative processes and products in the field of excellence and environmental compatibility.

2. Methods

LCA is a useful tool to assess resource use, energy and environmental burdens related to the full life-cycle of products and services, widely used for analysis of the sustainability of the agro-food sector, ranging from single products applications (Cellura et al., 2012a) to more in depth analyses of the sustainability of a supply chain (Cellura et al., 2012b). In this paper, it was applied according to the international standards of series ISO 14040 ("ISO 14040, 2006 Environmental management – Life cycle assessment – Principles and framework," 2006), which refers more to the aims and general framework of the methodology and ("ISO 14044, 2006 Environmental management - Life cycle assessment," 2006), giving more detailed information on the structure of LCA, requirements and guidelines.

2.1. Goal and scope definition

The goal of the study is to assess the energy and environmental impacts of different scenarios involving conventional and organic techniques, plane and hills cultivations and involving different operating techniques. The aim of the study is to check which ensemble of techniques and practices selected in the Calabria region in Italy is the most sustainable from a life cycle perspective.

The production of a glass bottle of 0.75 l of extra virgin olive oil was chosen for the comparative analysis as functional unit. The selection of a mass-based functional unit has the goal of comparing different products (olive oil produced with different techniques).

The study is developed 'from cradle to gate', including all the life cycle steps from the production of the olive plants up to the bottling of the olive oil and not taking in consideration the distribution and use of the product.

The energy use was quantified through the Cumulative Energy Demand (CED) methodology (Frischknecht et al., 2007). The environmental impacts were calculated according to the ILCD Mid-point 2011 methodology (Van Oers, 2016).

2.2. Inventory analysis

The main input and output mass and energy flows of the whole life cycle of the olive oil bottle, as well as the main stages of the analysis and the relative modelling assumptions will be recapped in the following paragraphs.

The study is based on primary, secondary and tertiary data.

All mass and energy flows of the main processes are primary and are based on interviews with more than 50 enterprises working in the province of Reggio Calabria in the olive oil sector. Interviews took place in 2016, data are related to the period 2012–2015 and are averaged on all polls' results.

Data on energy use and the environmental impacts related to the main processes are mostly from Ecoinvent 3 (Frischknecht and Rebitzer, 2005) while fertilizers data are from Brentrup et al. (2000), and pesticides data are from Margni et al. (2002).

The following life cycle stages are included in the analysis for all scenarios, as in the summary of Fig. 2.

The life cycle of the product was divided in two sections: the agricultural stage, where the cultivation of the olives occurs, and the transformation stages, where the olive oil is extracted from the olives. In detail, the whole life cycle of the orchard is modelled, considering a useful life of the plants of 65 years.

The planting stage includes the cutting and planting of an olive branch on a substrate made up of inert materials and a nutrient one, to be later arranged in cell packs. The plants will then be placed on the desired area, after some preparation treatments for the ground and use of fertilizers.

In the unproductive stage the plant has not yet started the production of olives, but some technical operations on the shaping of the

Table 1
Assumptions used in all scenarios for the agricultural stages.

	Description	Input/Output	PC
Planting	Plant Propagation Box	Cuttings	700 nursery cutting/m^2
		Substrate	25 cm/m^2 perlite
			5 cm/m^2 sand
	Cell pack	Cell pack	250
		Fertilizers	300 gr/plants
			0.5 gr/pumice seedling
		Substrate	3 l/cell pack peat
Unproductive stage (Y 0)		Number of plants	250 plant/ha
			250 m^3 digging holes
		Plants Transport by van	30 km
		Organic fertilization	60 t/ha
		Irrigation	500 m^3 water
Increasing production (Y 1–3)	Manufacturing	Diesel olive oil	80 l/ha
	Irrigation	Water	500 m^3/ha
	Fertilization	Fertilizers	750 kg/ha
		Diesel olive oil	6 l/ha
	Phytosanitary treatments	Pesticides	3 kg/ha Glyphosate
		Diesel olive oil	6 l/ha
Increasing production (Y 4–7)	Manufacturing	Diesel olive oil	80 l/ha
	Irrigation	Water	500 m^3 water
	Fertilization	Fertilizers	875 kg/ha
		Diesel olive oil	6 l/ha
	Phytosanitary treatments	Pesticides	3 kg/ha Glyphosate
			0.75 kg/ha Rogor
			3 kg/ha oxychloride
			0.75 kg/ha Metomil
		Diesel olive oil	6 l/ha
	Harvesting	Diesel olive oil	23.3 l/ha
Increasing production (Y 8–11)	Manufacturing	Diesel olive oil	80 l/ha
	Irrigation	Water	500 m^3 water
	Fertilization	Fertilizers	1000 kg/ha
		Diesel olive oil	6 l/ha
	Phytosanitary treatments	Pesticides	3 kg/ha Glyphosate
			1.2 kg/ha Rogor
			4.8 kg/ha oxychloride
			1.2 kg/ha metomil
		Diesel olive oil	6 l/ha
	Harvesting	Diesel olive oil	70 l/ha
Increasing production (Y 12–15)	Manufacturing	Diesel olive oil	80 l/ha
	Irrigation	Water	500 m^3 water
	Fertilization	Fertilizers	1250 kg/h
		Diesel olive oil	6 l/ha
	Phytosanitary treatments	Pesticides	3 kg/ha Glyphosate
			1.5 kg/ha Rogor
			6 kg/ha oxychloride
			1.5 kg/ha metomil
		Diesel olive oil	6 l/ha
	Harvesting	Diesel olive oil	120 l/ha
High costant production (Y 16–65)	Manufacturing	Diesel olive oil	80 l/ha
	Irrigation	Water	500 m^3 water
	Fertilization	Fertilizers	1250 kg/ha
		Diesel olive oil	6 l/ha
	Phytosanitary treatments	Pesticides	3 kg/ha Glyphosate
			1.5 kg/ha Rogor
			6 kg/ha oxychloride
			1.5 kg/ha metomil
		Diesel olive oil	6 l/ha
	Harvesting	Diesel olive oil	140 l/ha
Low costant production (Y 16–65)	Manufacturing	Milling + shredding	80 l/ha
	Irrigation	Water	500 m^3 water
	Fertilization	Fertilizers	100 kg/ha
		Diesel olive oil	6 l/ha
	Phytosanitary treatments	Pesticides	3 kg/ha Glyphosate
			1.5 kg/ha Rogor
			6 kg/ha oxychloride
			1.5 kg/ha metomil
		Diesel olive oil	6 l/ha
	Pruning	Diesel olive oil	80 l/ha
		Gasoline	20 l/ha
		Wood	3 t/ha

Table 2
Differences among all the life cycle stages.

Planting	Description	Input/Output	PC	PB	CC	CB
	Cell pack	Cell pack	250	250	150	150
Unproductive stage (Y 0)		Number of plants	250 plant/ha	250 plant/ha	150 plant/ha	150 plant/ha
			250 m^3 digging holes	250 m^3 digging holes	150 m^3 digging holes	150 m^3 digging holes
		Organic fertilization	60 t/ha	60 t/ha	50 t/ha	50 t/ha
Increasing production (Y 1–3)	Fertilization	Fertilizers	750 kg/ha	6 t/ha organic	450 kg/ha	5 t/ha organic
Increasing production (Y 4–7)	Fertilization	Fertilizers	875 kg/ha	7.5 t/ha organic	450 kg/ha	5.5 t/ha organic
	Phytosanitary treatments		0.75 kg/ha Rogor	-	0.75 kg/ha Rogor	-
			3 kg/ha oxychloride	-	-	-
			0.75 kg/ha metomil	-	-	-
Increasing production (Y 8–11)	Fertilization	Fertilizers	1000 kg/ha	12 t/ha organic	720 kg/ha	9 t/ha organic
	Phytosanitary treatments	Pesticides	3 kg/ha Glyphosate	4.8 kg/ha oxychloride	2.4 kg/ha glyphosate	4.8 kg/ha oxychloride
			1.2 kg/ha Rogor	-	1,2 kg/ha rogor	-
			4.8 kg/ha oxychloride	-	-	-
			1.2 kg/ha metomil	-	-	-
Increasing production (Y 12–15)	Fertilization	Fertilizers	1250 kg/ha	15 t/ha organic	900 kg/ha	11 t/ha organic
	Phytosanitary treatments	Pesticides	3 kg/ha Glyphosate	6 kg/ha oxychloride	3 kg/ha glyphosate	6 kg/ha oxychloride
			1.5 kg/ha Rogor	-	1.5 kg/ha rogor	
			6 kg/ha oxychloride	-	-	
			1.5 kg/ha metomil	-	-	
High costant production (Y 16–65)	Fertilization	Fertilizers	1250 kg/ha	15 t/ha organic	900 kg/ha	11 t/ha organic
	Phytosanitary treatments	Pesticides	3 kg/ha Glyphosate	6 kg/ha oxychloride	3 kg/ha glyphosate	6 kg/ha oxychloride
			1.5 kg/ha Rogor	-	1.5 kg/ha rogor	-
			6 kg/ha oxychloride	-	-	-
			1.5 kg/ha metomil	-	-	-
Low costant production (Y 16–65)	Fertilization	Fertilizers	1 Q/ha	15 t/ha organic	900 kg/ha	11 t/ha organic
	Phytosanitary treatments	Pesticides	3 kg/ha Glyphosate	6 kg/ha oxychloride	3 kg/ha glyphosate	6 kg/ha oxychloride
			1.5 kg/ha Rogor	-	1.5 kg/ha rogor	-
			6 kg/ha oxychloride	-	-	-
			1.5 kg/ha metomil	-	-	-

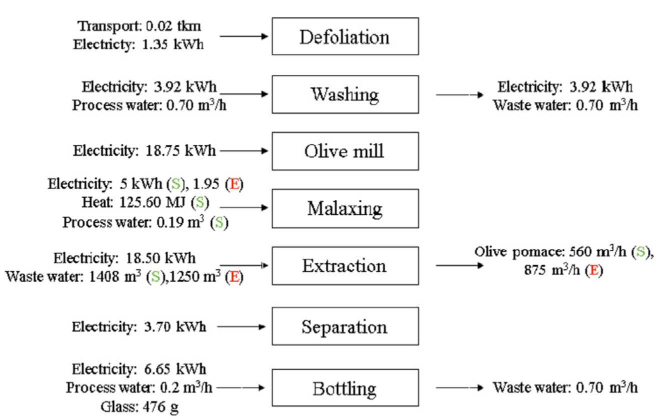

Fig. 3. Modelling assumptions in the transformation stages.

foliage are needed. No relevant treatments are expected in this stage as well as only limited use of fertilizers.

The production stages are similar but differ only by the quantity of inputs and outputs. The first three sub-stages (Years 4–7, Years 8–11, Years 12–15) are characterized by a steadily growing production of olives as well as an increase in treatments and fertilizers.

The constant production stage is characterized by two sub-stages, with alternative changes in olive production rates, to be modelled on a year by year basis. All production scenarios include olive collection by means of mechanical vibrators harvesting machines.

The harvested olives undergo a treatment of defoliation and washing, before being sent to the mill, where the continuous process of milling takes place. The output mixture, made up of olive oil, water, olive stones fragment and other residues, is then sent to the malaxing stage, where the fluid is mixed steadily at a temperature of around 35 °C. In the extraction stage, the olive oil mixture goes through a centrifuge machine that separates the different phases. Further centrifugal treatments are performed in the separation stages before the olive oil is finally ready to be bottled in the last stages in 0.75 l glass bottles.

The analysis is developed as a comparison of different technologies and scenarios, defined as:

i. Conventional agriculture developed on plain areas (PC),
ii. Conventional agriculture on hill areas (HC),
iii. Organic agriculture on plain areas (PO),
iv. Organic agriculture on hill areas (HO).

The agriculture scenarios on plain areas, if compared to the hill scenarios, are characterized by higher plant densities (respectively 250 plants*ha^{-1} vs. 150–250 plants*ha^{-1}) and higher production rates (on average about +35%), while the main difference between conventional and organic scenarios is the lack of use in the latter of synthesis products.

A further set of scenarios is also analysed including an innovative and patented technology in the milling process, called ‘Evoline’ (Veneziani et al., 2015). This leads to further four scenarios that are labelled as:

i. Conventional agriculture developed on plain areas - Evoline (PCE),
ii. Conventional agriculture on hill areas - Evoline (HCE),
iii. Organic agriculture on plain areas - Evoline (POE),
iv. Organic agriculture on hill areas - Evoline (HOE).

The Evoline scenarios are characterized by a more efficient malaxing process: after the milling stage, the olive oil mixture is pumped into a pressurized heat exchanger thus achieving a slight increase in temperature of the fluid. Internal fins serve the purpose of increase the mixing rate. After this process the mixture reaches a standard malaxing

Table 3
Overall Life Cycle Impacts for the main scenarios.

	Unit	PC	PO	HC	HO
Climate change	kg CO_2 eq	8.16E+00	−1.13E+00	6.26E+00	−2.50E-01
Ozone depletion	kg CFC-11 eq	7.44E-07	6.60E-07	6.56E-07	6.46E-07
Human toxicity, non-cancer effects	CTUh	2.51E-06	2.85E-06	2.82E-06	2.87E-06
Human toxicity, cancer effects	CTUh	3.50E-07	5.26E-07	4.10E-07	4.97E-07
Particulate matter	kg PM2.5 eq	7.98E-03	3.88E-03	7.06E-03	4.00E-03
Ionizing radiation HH	kBq U235 eq	6.25E-01	1.74E+00	7.08E-01	1.42E+00
Ionizing radiation E (interim)	CTUe	2.32E-06	5.39E-06	2.34E-06	4.45E-06
Photochemical ozone formation	kg NMVOC eq	2.48E-02	2.65E-02	2.26E-02	2.65E-02
Acidification	molc H+ eq	5.79E-02	4.60E-02	5.14E-02	4.52E-02
Terrestrial eutrophication	molc N eq	1.27E-01	1.31E-01	9.50E-02	1.23E-01
Freshwater eutrophication	kg P eq	2.33E-03	1.41E-03	3.08E-03	1.41E-03
Marine eutrophication	kg N eq	9.01E-03	2.11E-02	7.82E-03	1.94E-02
Freshwater ecotoxicity	CTU eq	6.63E+01	4.51E+01	7.21E+01	4.68E+01
Land use	kg C deficit	1.80E+02	4.16E+02	1.60E+02	3.82E+02
Water resource depletion	m^3 water eq	1.03E-01	1.40E-01	1.06E-01	1.55E-01
Mineral, fossil & ren resource depletion	kg Sb eq	1.06E-03	2.48E-04	1.50E-03	2.68E-04
Primary Energy	MJ	9.68E+01	1.97E+02	9.28E+01	1.81E+02

Table 4
Variation of the 'Evoline' life cycle impacts in comparison to the standard processes.

	PCE [%]	POE [%]	HCE [%]	HOE [%]
Climate change	−0.46	−3.29	−0.59	−14.86
Ozone depletion	−0.56	−0.63	−0.63	−0.64
Human toxicity, non-cancer effects	−0.16	−0.14	−0.14	−0.14
Human toxicity, cancer effects	−0.31	−0.21	−0.26	−0.22
Particulate matter	−0.18	−0.36	−0.20	−0.35
Ionizing radiation HH	−0.83	−0.30	−0.74	−0.37
Ionizing radiation E (interim)	−0.61	−0.26	−0.61	−0.32
Photochemical ozone formation	−0.31	−0.29	−0.34	−0.29
Acidification	−0.32	−0.40	−0.36	−0.41
Terrestrial eutrophication	−0.20	−0.19	−0.26	−0.2
Freshwater eutrophication	−0.40	−0.67	−0.30	−0.66
Marine eutrophication	−0.32	−0.14	−0.37	−0.15
Freshwater ecotoxicity	−0.21	−0.30	−0.1	−0.29
Land use	−0.02	−0.01	−0.03	−0.01
Water resource depletion	−1.83	−1.34	−1.76	−1.21
Mineral, fossil & ren resource depletion	−0.20	−0.85	−0.14	−0.79
Primary Energy	−1.14	−0.56	−1.19	−0.61

Table 5
Breakdown of the bottling stage impacts.

Bottle production (476 g)	Washing	Bottling	Incapsulation	Labelling
8.07E+00	1.25E-02	1.84E-02	3.07E-03	1.47E-02

process. The whole stage lasts for around 7 min and allows higher hourly rates of mixture treatment, allowing more 'continuous' operation of the decanter in the extraction stage. This allows a variation in the olives mass flow that is handled per hour (from 1200 to 1875 kg/hour).

The detailed assumptions and quantitative references to the modelling adopted in the LCA are listed in Tables 1 and 2. Table 1 reports the assumptions that are common to all scenarios during the agricultural stage, while Table 2 indicates all the differences in the agricultural life cycle of all the scenarios.

Fig. 3 reports all the main assumptions performed in the modelling of the two different transformation processes: standard (S) and Evoline (E). It is worth mentioning that the Standard approach refers to the first four scenarios (PC, HC, PO, HO), while the Evoline data refer to the PCE, HCE, POE and HOE scenarios.

Further assumptions of the study are:

- The agricultural stage was modelled by considering the whole life cycle of the arboretum in order to take in consideration all impacts tied to the fostering stage, including planting, fostering, growing production and constant production, including the differences in production between charging and discharging production from year to year;
- The transformation stage is based on the analysis of a continuous hammer milling plant with three steps handling around 1200 kg/h of olives.

3. Results

In the following paragraphs all results achieved in the analysis will be presented in terms of aggregated data and more in-depth dominance analysis.

3.1. Aggregated scenarios results

Table 3 shows the results for the first four scenarios of the study, including the standard plains agricultural scenarios, as well as the hill agriculture scenarios in the first two variants (conventional and organic).

The picture of the whole life cycle describes different results that do not identify a clear better scenario among all the four cases in all indicators.

The highest differences among the various scenarios are traced in the comparison between organic and conventional scenarios, although it follows a symmetric trend between the two conventional and the two organic scenarios.

The biggest difference is traced in the climate change indicator, where the two organic scenarios report similar negative results, nearly one order of magnitude lower than the conventional ones. Other indicators report also relevant lower results if compared to the conventional ones: the plain and hills organic scenarios are generally lower than their conventional counterpart in the case of particulate matter (by roughly 50%), acidification (around 20% if compared to the plain conventional scenario, around 10% in the case of the hill conventional scenario), freshwater eutrophication (more than 40% lower), mineral, fossil and renewable resource depletion, where the two organic scenarios would be four times lower than the best performing conventional scenario (PC).

On the other hand, some indicators report a very different trend, including primary energy (HO and PO higher by nearly twice the results of the conventional scenarios), water resource depletion (with the organic scenarios higher by roughly 30%), land use, marine eutrophication, ionizing radiation (all with results higher by two times if compared to the conventional scenarios), and human toxicity cancer effects

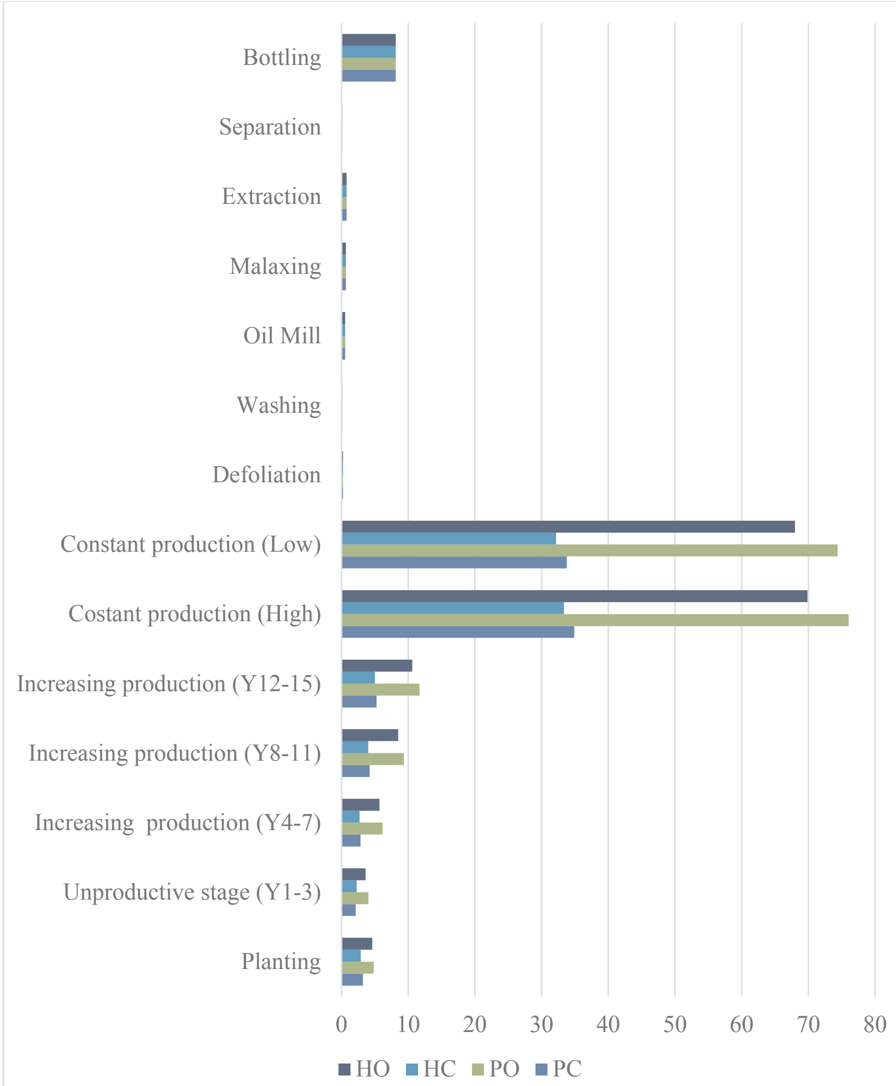

Fig. 4. Dominance analysis on life cycle energy.

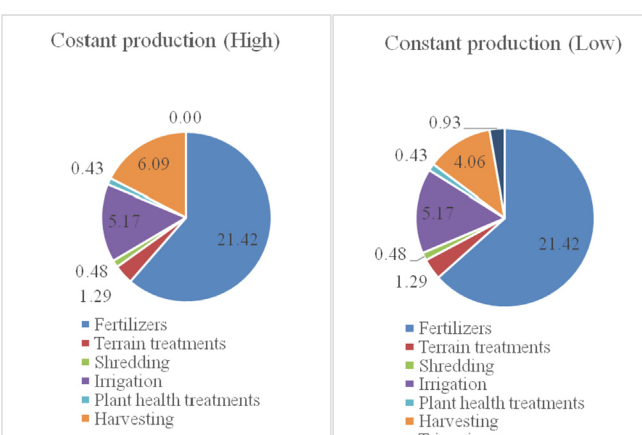

Fig. 5. Dominance analysis on life cycle energy, scenario PC.

(+50% for the organic scenarios).

If the plain scenarios are instead compared to the hill ones, more limited variations are traced. In the case of the organic scenarios, the hill scenario has higher impacts in the range of +20% only in the case of the two ionizing radiations indicators. In all the other cases the difference among the two plain organic scenarios is contained within +10% and −10% almost evenly among the various indicators used.

Regarding the Evoline scenarios, the results for the whole life cycle are reported in Table 4 as percentage variations compared to the correspondent conventional scenario.

All results mark a reduction in the impacts in the case of the Evoline scenarios if compared to the existing ones. Although some exceptions can be found in the case of climate change (−3.29 and −14.86%), all reductions found are very limited and largely below 2% in all scenarios and in all indicators.

3.2. Dominance analysis results: energy

The results can be further clarified by performing a break-down of the overall impacts described in Table 5. Fig. 4 shows the dominance analysis related to the whole life cycle studied in terms of Primary Energy use for all main scenarios. As it is clear from the analysis, the stages of the life cycle that are mostly energy-intensive are the two parallel stages of constant production, that together reach more than 70% of the total life cycle energy. It is also worth mentioning that the agricultural macro-stage is cause of more than 90% of the total impacts with only 9.80% impacts related to the final transformation stages. All differences among the scenarios investigated are due to the agricultural

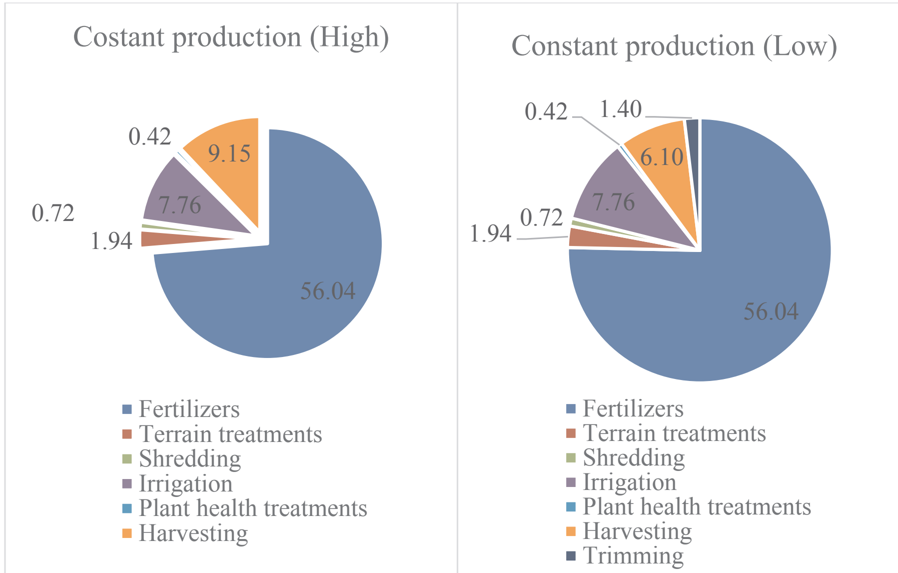

Fig. 6. Dominance analysis on life cycle energy, scenario PO.

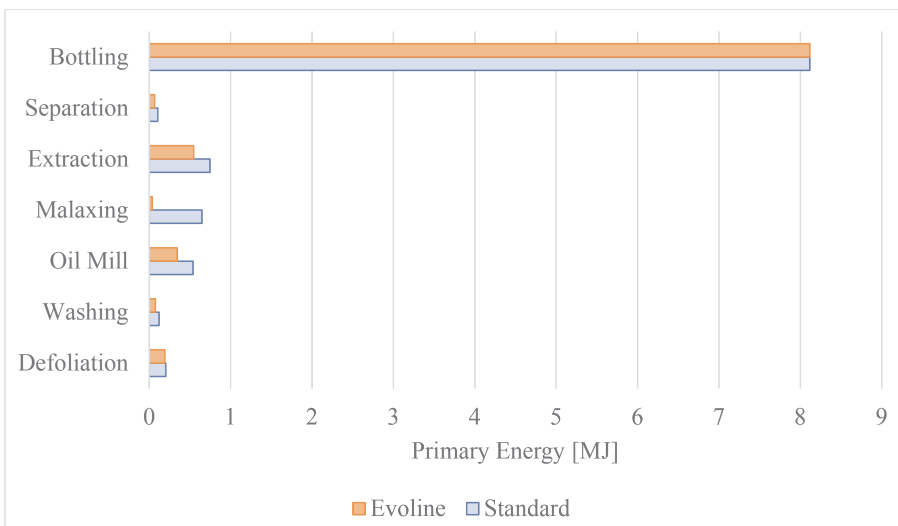

Fig. 7. Dominance analysis on life cycle energy for the transformation stage between the “Evoline” and standard approach.

stages, since the bottom part of the life cycle is the same in all four scenarios.

The distribution of energy uses throughout the life cycle stages is similar between the four main scenarios, with organic scenarios marking a life cycle energy use slightly higher than the conventional correspondent scenario by around 8% for the hill scenarios and 4% for the plains scenarios.

Further insight can be gained in the analysis of the most impactful stages of the life cycle, by exploring the single components of the energy uses. Fig. 5 represents the single contributions related to both the constant high and low production from year 15–65 of the life cycle, in the agricultural stage.

The main difference in the two cases, considered as alternating from one year to the other, is a further trimming stage in the low production years, paired with a lower harvesting energy need, due to a lower olives production. In both cases, the most relevant contribution to the whole energy uses is due to the fertilizers that cause more than 60% of the total impacts. A similar trend is reported also in Fig. 6 where instead the organic plain scenario is described. Although reaching energy uses as high as twice the values reported in the conventional scenario, the fertilizers impacts on the total energy uses cause more than 75% of the overall energy uses.

The most impacting step of the transformation stage is instead the bottling process with around 9% of the overall life cycle energy uses. Table 5 shows a breakdown of the main impacts of this stage. Bottle production is thus larger by two order of magnitude than all other contributions life cycle energy use.

Fig. 7 explores instead the dominance analysis on life cycle energy in the ‘Evoline’ scenarios. As the agricultural stages are the same in all four ‘Evoline’ scenarios, only the transformation life cycle stages will be shown below.

Although, the ‘Evoline’ methodology has only moderate impacts on the total life cycle energy, Fig. 7 shows some relevant reductions in some stages: the defoliation stage energy uses are reduced by around 7%, washing and milling by roughly 35%, malaxing by more than 95%, extraction by 26% and separation by 36%. The bottling stage remains exactly the same, as no modifications are expected in the process. The overall reduction in the primary energy uses for the transformation stages are around 10.5%, due to the heavy share of the total that is caused by the bottle manufacturing.

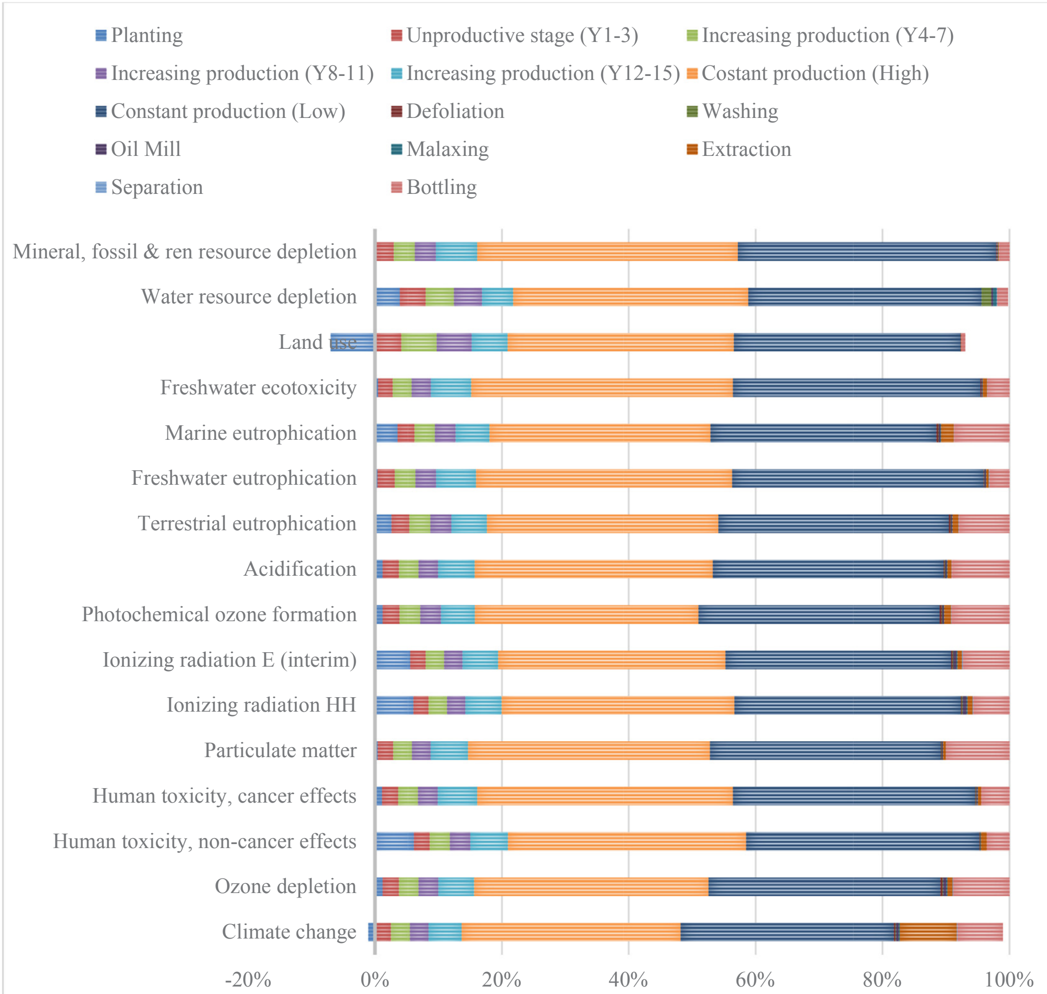

Fig. 8. Dominance analysis for the HC scenario.

3.3. Dominance analysis results: environmental impacts

Trends similar to those described for primary energy can be traced also for the environmental impacts. A more in-depth investigation is reported in Fig. 8 and 9, reporting the dominance analysis for the hills based agriculture scenarios chosen as further example, respectively HC and HO.

In both scenarios and in all the indicators the constant production sub-scenarios (high and low) report the highest results throughout the whole life cycle. In particular, the high production stage accounts for around 35–41% of the total impacts, while the low constant production has a variation range that is in average 1–2% lower. Differences between the conventional and the organic agriculture scenario have a variation rate of maximum 4%. Together, the whole constant production stage accounts for a general 70–85% of the total impacts, according to the indicator selected.

If also the other production stages are computed in the total (thus considering all the agricultural stages as in Fig. 1), in the case of scenario HC they would be responsible for 82.5% (climate change) to 97.93% of the overall life cycle impacts.

4. Discussion

The results highlight some specific considerations that can effectively sum up the main findings of the study.

First, although some specific differences can be traced due to the nature of the indicators used, there is a substantial common trend among all indicators, having comparable relative importance among the life cycle stages. The most relevant stages are always tied to the agricultural stages in large amounts and as such they are accounted for the largest potential for energy and environmental potential eco-design actions.

The results highlight also that among all the scenarios described in the paper there is not a clear best one, from all the angles of the analysis. For several indicators the organic scenarios reach better results than the conventional ones (e.g. Particulate matter, Acidification, Freshwater eutrophication, climate change) and vice versa in others it is the conventional scenarios having better performances (e.g. Human toxicity, Marine eutrophication, Land Use, Primary Energy). Also in the plain/hills agriculture scenarios mixed results are found, although differences are more relevant between the two conventional scenarios, while for the organic scenarios, differences between hills and plain scenarios are mostly below ± 20%.

As per the 'Evoline' transformation scenario, it was found that it has only a modest positive impact on the overall life cycle impacts and energy uses, although it could have significant impacts in the reduction of most post-agricultural stages. However if the whole life cycle is considered, the overall impact of the technology is marginal, instead in order to achieve significant reductions in the life cycle impacts, the most significant hot-spot of the life cycle to be focused by eco-design actions should be the agricultural stage and in particular the use of more environmental-friendly fertilizers.

Another hot-spot in the life cycle is furthermore marked by the production of the bottle that covers the 80% of all energy uses in the

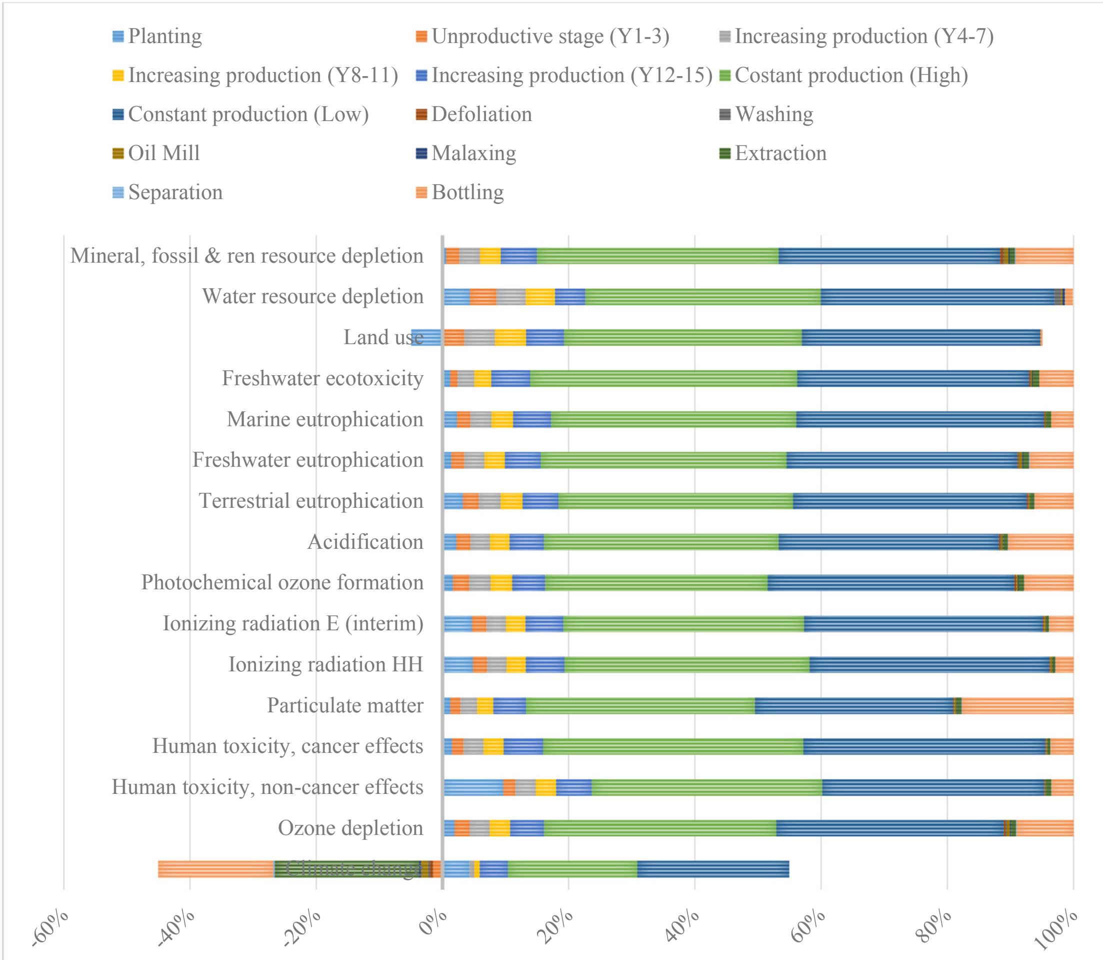

Fig. 9. Dominance analysis for the HO scenario.

transformation stage and similar percentages for all the environmental impacts. Thus, planning a careful selection of 'greener' materials to be used in this stage could be paramount to improve the eco-profile of the olive oil bottle.

5. Conclusions

The paper has examined the life cycle of the production of a 0.75 l extra virgin olive oil glass bottle based on the results of field analysis in 50 different enterprises in the area of Reggio Calabria, in the southern part of Italy. The LCA study is developed as comparative analysis between alternatives, including in the paper different scenarios concerning assumptions, techniques to be adopted in both the agricultural stages and the olive oil production stages: four different scenarios for the agricultural stage – plain and hills agriculture, using conventional and organic techniques – and two for the olives treatment - comparing standard techniques and a more efficient scenario, called 'Evoline'.

The research has verified that pushing energy efficiency and innovative technologies in the post-agricultural stages, although having tangible and solid benefits in these specific stages as well as potential long-term economic benefits, has only limited effects in the whole life cycle from and energy and environmental point of view.

The Evoline technique proves actually to be particularly efficient in largely reducing the energy use and environmental impacts within the transformation stages, having potential relevant impacts from the economical and technical side and from the point of view of the stakeholders operating in this segment of the life cycle.

However, if a more appropriate holistic point of view is adopted extending the point of view to the whole life cycle, its potential is bound by the limited impact these stages have on the total of the life cycle energy uses and environmental impacts.

Specific benefits can for sure be attained by operating in the transformation stages, but the bulk of the life cycle impacts are spread across the years of cultivation, especially due to the use of fertilizers in these stages that need to be chosen with care to limit energy use and environmental impacts: this for sure needs to be a core focus of further research within the eco-design of the olive oil supply chain.

Lastly, the data shown and discussed in the paper have been investigated and extrapolated from a wide range of local primary data and thus can for sure serve as basis for specific comparisons in further studies as a starting point for further developments and studies on similar geographical context.

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