Chapter 2
Life Cycle Assessment in the Olive Oil Sector

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Abstract The olive oil industry is a significant productive sector in the European Union and the related production process is characterised by a variety of different practices and techniques for the agricultural production of olives and for their processing into olive oil. Depending on these different procedures, olive oil production is associated with several adverse effects on the environment, both in the agricultural and in the olive oil production phase. As a consequence, tools such as LCA are becoming increasingly important for this type of industry. Following an overview of the characteristics of the olive oil supply chain and its main environmental problems, the authors of this chapter provide a description of the international state of the art of LCA implementation in this specific sector, as well as briefly describing other life cycle thinking methodologies and tools (such as simplified LCA, footprint labels and Environmental Product Declarations). Then, the methodological problems connected with the application of LCA in the olive oil production sector are analysed in depth, starting from a critical comparative analysis of the applicative LCA case studies in the olive oil production supply chain. Finally, guidelines for the application of LCA in the olive oil production sector are proposed.

Keywords Olive oil · Life cycle assessment · Life cycle costing · Environmental product declaration · Footprint labels

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2.1 Introduction

Olive oil production is an important agri-industrial sector (in terms of both production and consumption) in many Mediterranean regions (IOC 2013; Vossen 2007). Furthermore, the olive groves and olive production are increasing yearly (FAOSTAT 2013) and, recently, the importance of olive oil has also been growing in new producing countries located in America, Africa and Australia (IOC 2013). On a global scale, most olive cultivation areas[1] can be found in Mediterranean countries, such as Spain (2,503,675 ha), Italy (1,144,422 ha), Tunisia (1,779,947 ha), Greece (850,000 ha), etc. (FAOSTAT 2013). The leader of the international market is the EU, which produces over 70 % of the world's olive oil. As concerns importing countries, the most important are the USA, Japan, etc. With regard to exports, the most relevant are the main EU countries, exporting over 440,000 t of olive oil, followed by Tunisia, Syria and others (Table 2.1).

Despite the economic importance of this food product in many countries, olive oil production is associated with several adverse effects on the environment that cause resource depletion, land degradation, air emissions and waste generation. The impacts may vary significantly as a result of the practices and techniques employed in olive cultivation and olive oil production (Salomone and Ioppolo 2012) and life cycle thinking approaches and assessment methods have increasingly been applied in order to gain a better understanding of their role from a life cycle perspective.

In the following sections, these different practices and techniques, along with the relative environmental consequences, are briefly described (Sect. 2.2). Then, a description of the international state of the art of life cycle thinking methodologies and tools, suitable for the environmental assessment of products and implemented in this specific sector, is presented (Sect. 2.3), with a specific focus on life cycle

[1] Data for the year 2011.

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Table 2.1 The olive oil market on the international scale (the average values of the 2007/2008–2012/2013 olive crop six-year period). (Source: Data (IOC 2013))

Country	Production (1000 t)	Imports (1000 t)	Exports (1000 t)	Consumption (1000 t)
EU[a]	2057.6	111.9	447.1	1819.3
Spain	1215.1	24.0	184.3	543.4
Italy	455.8	79.1	204.2	658.5
Greece	317.6	0.0	12.1	224.8
Portugal	58.4	1.4	41.0	80.9
France	5.3	5.4	1.6	108.7
Cyprus	4.9	0.0	0.0	5.5
Slovenia	0.5	0.1	0.1	1.9
Other EU countries	–	1.9	3.8	195.6
Tunisia	167.0	0.0	130.3	34.3
Syria	159.3	0.8	21.0	118.7
Turkey	149.2	0.0	22.9	124.0
Morocco	110.0	4.0	13.1	96.0
Algeria	47.4	0.2	0.0	47.0
Argentina	22.7	0.0	16.5	5.8
Jordan	20.8	3.6	1.5	20.7
Chile	15.4	0.8	6.2	10.7
Palestine	14.9	0.1	2.4	13.0
Lebanon	14.8	2.0	2.8	15.8
Libya	14.7	0.0	0.0	14.7
Australia	14.6	30.4	5.7	39.3
Israel	9.2	8.3	0.3	16.5
Albania	7.3	1.1	1.2	7.2
Egypt	5.8	1.9	1.4	6.5
Croatia	4.8	1.9	0.1	6.3
Iran	4.8	3.7	0.0	8.3
USA	4.3	270.2	3.7	271.3
Saudi Arabia	3.0	9.4	0.5	11.3
Montenegro	0.5	0.0	0.0	0.5
Other producing countries	15.0	3.0	5.5	13.1
Non-producing countries	–	250.8	–	250.8

[a] The import and export data of the EU countries are reported without intra-Community trade

assessment (LCA). The methodological problems connected with the application of LCA in the olive oil production sector are analysed in depth, starting from a critical comparative analysis of the applicative LCA case studies in the olive oil production supply chain (Sect. 2.4). Finally, guidelines for the implementation of LCA in this sector are proposed (Sect. 2.5), in order to deal with and manage best the methodological problems presented above.

2.2 The Olive Oil Supply Chain: Production Processes, Technologies, Product Characteristics and Main Environmental Problems

A supply chain is a network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services delivered to the ultimate consumer (Christopher 1992). According to this definition, the olive oil supply chain can be briefly described as follows (IOC 2013; Niaounakis and Halvadakis 2006; PROSODOL 2011), using the different life cycle phases of the olive oil product: cultivation, olive oil production, by-product management, product transportation and distribution, consumption and waste management.

The ***cultivation phase*** includes the cultivation of olives using different treatments, such as soil management, pruning, fertilisation, irrigation, pest treatment and harvesting. Each of these treatments[2] can be carried out in different ways depending on whether:

- the cultivation derives from centuries-old trees—traditional systems—or new intensive plants (in the latter option, the supply chain study must include plant breeding and tree planting);
- the irrigation system uses the dry farming or the drip irrigation method;
- the cultivation practices are conventional, organic or integrated, using different typologies of fertilisers and pest treatments;
- the soil management, pruning and harvesting are manual or mechanised.

Harvesting is a very important process, because changes in the acidity level of olives occur after harvesting and other changes occur depending on the harvest methods: hand harvesting is the best method, but very expensive, while mechanical harvesting, if properly conducted (avoiding the breaking of the fruit skin), can give good results. After harvesting, the olives are sent to olive oil mills and processed within 24 h, in order to avoid fermentation phenomena.

Because the cultivation of olives can be carried out by means of various treatments, the environmental impacts can be very different in the various olive farming areas. However, by simplifying, three types of plantation can be considered: low-input traditional plantations (randomly planted and/or terrace-planted ancient trees managed with few or no chemical inputs and high manual work input); intensified traditional plantations (they have the same characteristics as the first type together with an increase in the tree density and the weed control, soil management using artificial fertilisers and irrigation, the use of pesticides and mechanical harvesting); and intensive modern plantations (high small-tree density managed with extensive use of mechanised systems and irrigation). The low-input traditional plantations have the lowest environmental impact and, moreover, they play a role

[2] Some of these treatments and practices are managed similarly to other fruit cultivation (see Chap. 6).

in safeguarding the biodiversity and landscape value. Instead, the other two types of plantations can give rise to various environmental problems (i.e. soil erosion, run-off to water courses, degradation of habitats and landscapes and exploitation of scarce water resources) (Beaufoy 2000).

Much of the international olive production is transformed into olive oil. Different methods are used to extract oil from the olives and these processes create large volumes of liquid and solid waste. The waste stream is highly hazardous to the environment and presents a number of treatment challenges to olive oil producers.

The ***olive oil production phase*** includes two main phases: the preparation of a homogeneous paste and the oil extraction from the olives. First, the olives are classified and separated by quality; then, they are washed in order to remove the pesticides, dirt and impurities collected during harvesting (stems, leaves, twigs, etc.). A few olive oil mills do not wash olives, which are processed 'as they are' to overcome the problems connected with water consumption and the treatment of the polluted washing water. This is often motivated by the fact that extra moisture can involve problems (extractability and lower polyphenol content). However, these advantages should be cautiously compared with the disadvantages, since the pollution load of washing water demonstrates that olives need to be cleaned, otherwise pesticide and impurities remain on the olives and in the olive oil. After washing, crushing (tearing of the flesh cells to facilitate the release of the oil from the vacuoles) and malaxing (mixing the paste, allowing small oil droplets to combine into bigger ones) are essential steps. The next step consists of separating the oil from the rest of the olive components: oil is extracted using a press or a decanter, by pressing (the traditional or classical system) or by centrifugal separator (a continuous system), which can further use a three-phase or a two-phase decanter.

Traditional pressing (a discontinuous process) is still in use in some small mills that use a hydraulic press, but it is a relatively obsolete technology that has mainly been replaced with centrifugation systems, allowing lower manufacturing costs, better oil quality and shorter storage time of olives before processing. This process generates a solid fraction (olive husk or olive pomace) and an emulsion containing the olive oil, which is separated by decantation from the remaining wastewater.

Continuous centrifugation with a three-phase system, even though offering a higher production capacity with respect to traditional pressing, has some disadvantages, such as greater water and energy consumption (due to the addition of warm water to dilute the olive paste). This process uses a three-phase decanter that generates solid waste (olive husk or olive pomace), olive oil and wastewater.

Continuous centrifugation with a two-phase system allows the separation of oil from olive paste without the addition of water and this leads to the elimination of the problem of vegetable water. In fact, the two-phase system generates only olive oil and a semi-solid waste called olive wet husk or wet pomace (or two-phase olive mill waste).

Continuous centrifugation with a two-and-a-half-phase system (also called a modified system or water-saving system) exists; between a three-phase system and a two-phase one, it brings together the advantages of the two different systems (it requires the addition of a small amount of water and generates a solid fraction (olive wet husk or olive wet pomace) that includes part of the vegetation water and a smaller quantity of olive mill wastewater.

Another innovative technology is *oil extraction from de-stoned olives*. In the de-stoning process, the pits are removed before the kneading; some authors state that this process improves the quality of the extra virgin olive oil (better sensory qualities and shelf life) (Del Caro et al. 2006; Pattara et al. 2010). However, other authors (Di Giovacchino 2010) believe that this technology produces lower yields with a similar chemical sensory quality. Oil extraction from de-stoned olives can be made with both the three-phase and the two-phase system.

On average, the above-described techniques can produce around 200 kg of olive oil from 1 t of processed olives (Arvanitoyanni and Kassaveti 2008).

Therefore, as the average annual world production of olive oil in the 2007/2008–2012/2013 olive crop six-year period was equal to 2,862,800 t (IOC 2013), on the basis of the data available in the literature, it is possible to estimate that, on average in a year, the olive oil industry needs 572,560,000–1,674,738,000 kWh of energy and 1,431,400–16,045,994 m^3 of water, generating 5,725,600–8,588,400 t of solid waste and 8,588,400–17,176,800 t of wastewater (estimation from Arvanitoyanni and Kassaveti 2008).

The designation of *virgin olive oil* is solely recognised as the olive oil obtained from the fruit of the olive tree by mechanical or other physical means under conditions, particularly thermal conditions, that do not lead to alterations in the oil, which has not undergone any treatment other than washing, decantation, centrifugation and filtration, excluding oil obtained using solvents or re-esterification processes and any mixture with oils of other kinds (EC 1991, 2007, 2008, 2013a). In particular, in accordance with the standards of the International Olive Council (IOC n. d.) and the EC regulations, *virgin olive oils* are classified into:

- *extra virgin olive oil*, which is a higher quality olive oil with no more than 0.8 g per 100 g of free acidity (expressed as oleic acid) and a superior taste (fruitiness and no sensory defect). It must be produced entirely by mechanical means without the use of any solvents, and under temperatures that will not degrade the oil (lower than 30 °C);
- *virgin olive oil*, which has no more than 2 g per 100 g of free acidity and a good taste;
- *lampante olive oil*, which is virgin olive oil with free acidity, in terms of oleic acid, of more than 2 g per 100 g, and/or the other characteristics of which comply with those laid down for this category use.

Other classifications are related to the definition of *olive oil*, distinguishing:

- *refined olive oil*, obtained by the refining of virgin olive oil using methods that do not lead to alterations in the initial glyceridic structure; it has no more than 0.3 g per 100 g of free acidity;
- *olive oil*, which is a blend of refined oil and virgin oil (excluding the lampante virgin oil), fit for consumption as it is and having no more than 1 g per 100 g of free acidity;

- *olive pomace oil*, obtained by treating olive pomace with solvents or other physical treatments. This oil can be sold as *crude olive pomace oil*, which is intended for refining (then designated for human consumption) or for technical use, and *refined olive pomace oil*, which is obtained from crude olive pomace oil by refining methods, producing an oil with no more than 0.3 g per 100 g of free acidity.

In the olive oil production phase, the ***packaging process*** is also included, even though the olive oil is often sold unbottled (to final consumers or to national or multinational bottling companies) and only a few mills directly bottle olive oil with their own label. Olive oil is generally bottled in stainless steel containers or, better, in glass bottles (in order to preserve better the stability of virgin olive oil), although there are cases of the use of innovative packaging, e.g. bottles made of polyethylene terephthalate (PET), which are 100 % recyclable (Salomone et al. 2013a).

In the ***by-product management phase***, two methods are used to extract pomace oil. Olive pomace oil obtained from two-phase processing, with a moisture content close to 70 %, is physically extracted by centrifugation. The process also produces a residual water solution containing mineral salts, sugars and polyphenols (EC 2010). To extract pomace oil from the traditional and three-phase production methods, solvents are used. The olive pomace is mixed with the solvent hexane, which dissolves any residual oil. The exhausted pomace is then separated from the oil and hexane solution (called miscella) by filtration. Any hexane residues in the solid pomace are removed by means of a desolventiser, which evaporates the solvent (then captured for reuse). The oil and hexane solution is distilled, allowing the hexane to be recovered and reused, whilst the solvent-free oil undergoes further processing, such as refining. The solid waste from olive oil mills is also referred to as 'olive cake' and the liquid waste streams are termed olive mill wastewater. In recent years, the by-product management has been considered a strategic phase in the olive oil supply chain, because each of the different olive oil production methods creates different amounts and types of by-products, all of which are potentially hazardous to the environment. Therefore, the above-mentioned environmental problems have given rise to a series of studies for the development of methods for the treatment and valorisation of olive mill wastewater (Demerche et al. 2013; Kapellakis et al. 2008; Stamatelatou et al. 2012) and olive stones from de-pitted virgin olive oil (Pattara et al. 2010). In particular, the olive oil mill wastes have a great impact on land and water environments due to their high phytotoxicity (Roig et al. 2006) and their management is one of the main problems of the olive oil industry. Many options have been proposed for their treatment, disposal or valorisation (Niaounakis and Halvadakis 2006; Roig et al. 2006; Vlyssides et al. 2004):

- Olive mill wastewater (OMW), deriving from traditional pressing and from the three-phase system, is the main polluting mill waste. This is constituted by vegetable water from the olives and the water used in the oil extraction and its chemical composition is variable depending on the olive varieties, growing practices, harvesting period and oil extraction technology. In any case, it is highly polluting due to the presence of organic compounds (organic acids, lipids, alcohols and polyphenols), even though it also contains valuable substances such as nutrients (especially potassium). Untreated olive mill wastewater is a major ecological issue for olive oil producing countries due to its highly toxic organic loads. Olive mill wastewater can lead to serious environmental damage, ranging from colouring natural waters, altering soil quality, phytotoxicity and odour nuisance. Traditional olive oil processing methods are estimated to produce between 400 and 600 litres of *alpechin* (OMW—olive mill wastewater) for each ton of processed olives (Di Giovacchino 2010; EC 2010). The olive mill wastewater levels from three-phase processes are much higher, producing between 800 and 1000 L of OMW for each ton of processed olives. Virtually no wastewater is produced by the two-phase process, although its *wet pomace* waste streams tend to have high liquid contents that remain costly to treat. The olive mill wastewater is composed essentially of water (80–83 %), organic compounds (mainly phenols, polyphenols and tannins) that account for a further 15–18 % of the wastewater content and inorganic elements (such as potassium salts and phosphates) that make up the remaining 2 %. These proportions can vary depending on factors related to the climatic and soil conditions, farm management, harvesting methods and oil extraction processes. The presence of proteins, minerals and polysaccharides in OMW means that it has potential for use as a fertiliser and in irrigation. However, the reuse opportunities are restricted by the abundance of phenolic compounds, which are both antimicrobial and phytotoxic. These phenols are difficult to purify and do not respond well to conventional degradation using bacteria-based techniques. The olive oil mill polluting loads are therefore significant, revealing levels of both BOD_5 (biological oxygen demand in 5 days) and COD (chemical oxygen demand) between 20,000 and 35,000 mg per litre. This represents a notably large organic matter load compared with standard municipal wastewater, which exhibits levels between 400 and 800 mg per litre. Anaerobic digestion of *alpechin* results in only 80–90 % COD removal and this treatment remains insufficient to permit olive mill wastewater effluent to be discharged back into the environment. Discharging unsafe olive mill wastewater back into natural water systems can result in a rapid rise in the number of microorganisms. These microorganisms consume large amounts of dissolved oxygen in the water and so reduce the share available for other living organisms. This could quickly offset the equilibrium of an entire ecosystem. Further concerns are caused by the high concentrations of phosphorus in olive mill wastewater, since if released into water courses this can encourage and accelerate the growth of algae. The knock-on impacts include eutrophication, which can destroy the ecological balance in both ground and surface water systems. Phosphorous remains difficult to degrade and tends to be dispersed only in small amounts via deposits through food chains (plants–invertebrates–fish–birds, etc.). The presence of large quantities of phosphorous nutrients in olive mill wastewater provides a medium for pathogens to multiply and infect waters. This can have severe consequences for local aquatic life, as well as the humans and animals coming into contact with the water. Several other environmental problems can be caused by olive mill wastewater. These include lipids in the olive mill wastewater producing an impenetrable film on the surface of rivers, their banks and surrounding farmland.

At a glance, the most common treatment methods of OMW are:

a. evaporation in storage ponds in the open—this method produces sludge that may be disposed of in landfill sites or used as a fertiliser in agriculture (after a composting process with other agricultural by-products);
b. direct application to soil—this is a positive valorisation method of OMW considering its high nutrient content and its high antimicrobial capacity, but it also causes negative effects on soil associated with its high mineral salt content, low pH and presence of polyphenols. Land spreading of waste arising from olive processing is specifically regulated by law (e.g. in Italy by the Ministerial Decree—MIPAF 2005);
c. co-composting—this method refers to the co-composting of OMW with olive pomace or olive wet pomace; it allows the return of nutrients to cropland and avoids the negative effects previously cited when OMW is directly applied to soil (Cappelletti and Nicoletti 2006; Salomone and Ioppolo 2012);
d. the extraction of valuable organic compounds—the recovery of high-value compounds (phenolic compounds, squalene and tocopherols, triterpenes, pectins and oligosaccharides, mannitol, polymerin) or the utilisation of OMW as raw matter for new products is a particularly attractive way to reuse it, as the recovery process is of economic and practical interest (Fernández-Bolaños et al. 2006).

- Olive husk (OH), deriving from traditional pressing and from the three-phase system, is usually sent to oil factories (oil husk extraction mills) that, after a drying process, extract oil with specific solvents (traditionally hexane). This treatment process produces oil and a solid waste called *exhausted olive husk*, which is used as fuel since the dried OH presents high calorific power.
- Olive wet husk (OWH) derives from the two-phase system. In this case, olive vegetation waters are included in the OWH. Compared with the OH, the higher moisture level in the OWH creates more difficulties for its treatment in oil factories (mainly the higher energy demand for the drying process causing higher costs). For this reason, there are other methods for the treatment of the OWH and the most common are:

    1. Direct application to soil—due to its high potassium concentration and its low economic value, it can be directly applied to soil on land near the production site, but this practice could cause a negative effect on the soil even if it is less phytotoxic than wastewater (Cichelli and Cappelletti 2007);
    2. Composting (with or without the de-stoning process to obtain biomass for heat or electricity)—this method consists of the co-composting of OWH with other agricultural wastes (straw, leaves, etc.) or with manure used as a bulking agent. The compost obtained has a good degree of humification, no phytotoxic effect and a good amount of mineral nutrients (Cappelletti and Nicoletti 2006; Russo et al. 2008).

The ***packaging phase*** includes bottling olive oil in glass, tin or PET containers. As the average annual world consumption of olive oil in the 2007/2008–2012/2013 olive crop six-year period was equal to 2,862,800 t (IOC 2013), assuming that only containers capable of holding 1 kg of olive oil are used, the packages in circulation could amount to more than 2,860,000,000 per year.

The ***transportation and distribution phase*** includes the transport activities (related to raw materials, by-products and wastes) and the distribution of the product in local, regional, national or international markets. Transport activities can also occur elsewhere in the life cycle (other than those instances already mentioned), either between any two subsequent life cycle stages or within a given stage, depending on the site-specific means of processing and the level of supply chain integration.

The ***consumer phase***, in the case of olive oil, is certainly not significant from a life cycle perspective, considering that the product consumption does not need further preparation or treatments. Table 2.1 shows that the consumption of olive oil is quite widespread on the international scale in countries such as Italy, Spain, the USA, Greece, Turkey, Syria, etc.

Finally, the ***waste management phase*** (end of life) includes the treatment of bottles and packaging waste (cardboard boxes, etc.). This phase can also have great impacts on the environment depending on the method of waste management chosen (for example, reuse, recycling, landfilling, etc.).

The phases of the olive oil supply chain with the related main environmental consequences are synthetically represented in Fig. 2.1.

As far as the materials and energy balance related to the oil production are concerned, it is possible to highlight that the production (agricultural and industrial phases) of 1 kg of olive oil (double pressed) involves the consumption of 0.0264 kg of fertilisers (N_2, P_2O_5, K_2O), 0.019 kg of pesticides, 0.00855 kg of fuel, 0.243 kg of lube oil and 0.359 kWh of electrical energy (Nicoletti and Notarnicola 2000).

2.3 Life Cycle Thinking Approaches in the Olive Oil Production Sector: The State of the Art of the International Practices

As exhaustively reported in Chap. 1, the growing awareness of food sustainability is driving an increase in research activities in the agri-food sector and, among these studies, over the last 15 years or more, numerous life cycle thinking (LCT) approaches have been followed (mainly life cycle assessment studies), evaluating food products and processes in order to identify and pursue sustainable food production and consumption systems.

The specific sector of olive and the olive oil supply chain has been investigated by several LCT studies since 2000. A critical analysis and state of the art of LCA studies applied in the olive oil sector was, firstly, conducted in 2008 (Salomone 2008) and then updated in 2010 (Salomone et al. 2010a), but contained only

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