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Role of Life Cycle Assessment in Promoting Olive Oil Sustainability: A State-of-the-Art Review

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Abstract

Olive oil production is a major economic driver in Mediterranean countries. In this production, olives are grown, and olive oil is extracted using various methods and techniques. There are a variety of adverse environmental effects linked with olive oil production, both in the agricultural stage and the olive oil extraction stage. One of the most valuable tools for assessing the value of agricultural and food products is the life cycle assessment (LCA). There has been a rise in recent years in the number of reports detailing studies of the environmental effects of the olive oil production industry. This analysis describes the leading olive oil production practices and technology and the primary environmental concerns of olive oil production. The current state of LCA studies in the olive oil sector and the methodological challenges connected with utilizing the LCA technique are described, after which a critical comparative analysis of existing LCA case studies in the olive oil supply chain is presented. Suggestions are made for using LCA in the olive oil industry.

Keywords: life cycle assessment, oil extraction, supply chain, sustainability, environmental impact

1. Introduction

Olive production, primarily for obtaining olive oil, is predominantly concentrated in Mediterranean countries (Donner et al., 2021). The societal and economic significance of the olive industry is undeniable, with approximately 2 million olive-growing enterprises in the Mediterranean region alone. This sector accounts for 80 percent of global olive oil production and sustains around 750,000 full-time jobs (Romani et al., 2019). (Abdallah et al., 2021) conducted a comprehensive literature review on the LCA of olive oil production spanning from 2008 to 2018. Their findings shed light on the environmental impacts associated with this vital industry.

The proximity of olive mills to production areas is crucial, as it is where the oil extraction process takes place. Table 1 outlines the top olive-growing countries and the corresponding number of olive mills in each.

Table 1: The number of olive mills and average production of olive oil in the main producing countries (according to International Olive Oil Council (IOOC))

Countries	Number of mills	Average production (ton/year)
Spain	10,920	650,000
Italy	7,500	462,000
Greece	2,800	281,000
Tunisia	1,209	168,750
Turkey	1,141	75,000

Similar to other food products, olive oil and its characteristics are regulated by stringent standards and legislation. The International Olive Oil Council (IOOC) has established standards categorizing various products within the olive oil sector. These standards distinguish several types of olive oil based on extraction processes, which significantly influence physicochemical properties and taste. Following oil extraction, olive pomace, the solid residue remaining, contains a residual amount of oil (between 2% and 5% by mass) that can be further extracted using organic solvents such as hexane, resulting in what is known as olive pomace oil.

In response to growing environmental awareness, research efforts in the agro-food industry are intensifying. Numerous LCA studies analyzing food items and extraction techniques have been published in the last decade (El jomri et al., 2023; Rapa et al., 2022).

The olive oil supply chain involves various processes, including planting, harvesting, pressing, bottling, and managing leftover olive residue. These processes can have significant environmental consequences, necessitating differentiation between mechanical and hand harvesting methods (Garino et al., 2019), as well as the disposal or reuse of residues.

Despite its economic significance, olive oil extraction is associated with various environmental challenges such as resource depletion, land degradation, air pollutants, and waste generation (dammak et al., 2016). The severity of these issues varies depending on cultivation practices and extraction techniques (Salomone et al., 2012) . To address these challenges and strive for sustainability, the adoption of LCA has become indispensable. LCA serves as a valuable tool for assessing the environmental impacts of olive oil production and identifying sustainable alternatives.

In this paper, the methodology is described in section 2. The olive oil life cycle is explored in section 3, providing a comprehensive understanding of its environmental footprint. Following this, Section 4 examines how LCA methodology can be utilized to enhance sustainability in olive oil production. Published LCA case studies are critically examined to explore methodological issues and challenges associated with the application of LCA in this industry. Finally, in the concluding section, the findings are synthesized and future perspectives for sustainable olive oil production are discussed

2. Methodology

LCA has been increasingly applied to understand the olive life cycle better and as a tool for better decision-making in favor of sustainable development. The aim of this paper is shown in figure 1.

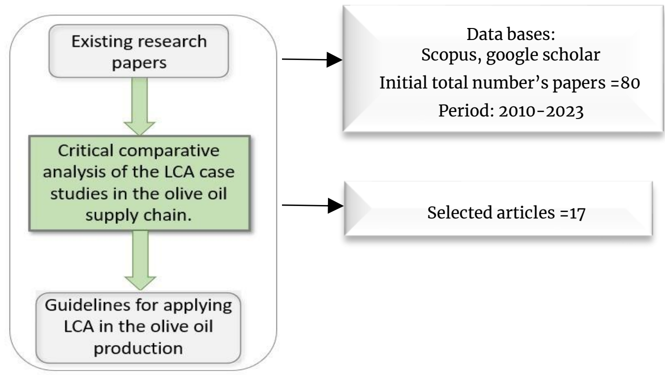

Figure 1. Reviewing Life Cycle Assessments of the Olive Oil Industry: A Methodological Overview

A literature review was conducted using Scopus and Google Scholar databases. This review identified 178 articles related to the LCA of olive oil, 17 articles were selected for comparative analysis. This selection process was based on the PRISMA methodology and to answer the following research questions:

RQ1: What is the importance of LCA technics in determining the best sustainable scenario for olive oil production?
RQ2: What's the primary gaps to be addressed by future research works?

The selection criteria for the studies included in this analysis were clearly defined to ensure relevance and quality. Inclusion criteria encompassed studies focusing olive oil production using LCA methodology, published in journals. Exclusion criteria filtered out studies not directly addressing olive oil production, lacking empirical data, or published in non-peer-reviewed sources. Articles not available in English or with significant methodological flaws were also excluded.

3. Description of the Olive Oil Life Cycle

The life cycle of olive oil production is divided into seven main steps (**Figure 2**), the cultivation of olives, the oil extraction, the bottling, the consumption, the end life of the bottles, the olive pomace treatment, as well as the treatment of aqueous deposits (called olive mill waste water (OMW)) (Espadas-Aldana et al., 2019). The nuances of each step in this cycle are explored in the conversation that follows.

There are different cultivation practices for the production of olive fruits. The main trends are organic agriculture and conventional agriculture, with or without irrigation, manual or mechanized, marginal (in mountainous regions), traditional (between 90 and 100 trees per ha), intensive (between 300 and 650 trees per ha), or super-intensive (more than 1,000 trees per ha) (Mohammed et al., 2014). From the literature, it is possible to present a typical depiction of the cultivation itinerary of the olive tree that leads to the olive harvest. Many parameters, such as the physicochemical characteristics of the soil, the relief, the sunlight intensity, or the variety of the olive, play a significant role in the final olive oil yield.

Before the cultivation phase of perennially olive trees, the preliminary phase of the nursery is worth mentioning. It consists of cultivating olive shoots until planting in a production orchard (Rallo et al., 2018). This phase requires irrigation, fertilization, weeding, phytosanitary treatment, and soil maintenance processes (De Luca et al., 2018). After two years in the nursery, the olive trees are formerly transported to the orchard to be planted (Schuch et al., 2019).

In the agricultural phase, various processes are implemented to optimize the production of olive fruits, including irrigation, fertilization, weeding, phytosanitary treatment, soil maintenance, pruning, harvesting, and transportation to the olive mill. Each process occurs once or twice yearly, depending on the pedo-climatic zone conditions (Sales et al., 2022). The extraction of olive oil takes place in an olive mill. The olives are received before defoliation and washed with water (Dammak et al., 2015). Then, olives are crushed and mixed before the oil extraction process.

The refining process allows the processing of lampante, second centrifugation, and crude olive-pomace oils to be cut with virgin oils and consumed. It is based on physical-chemical processes that will eliminate the defects of the oils to be used for human consumption (Ruiz-Méndez et al., 2013) .

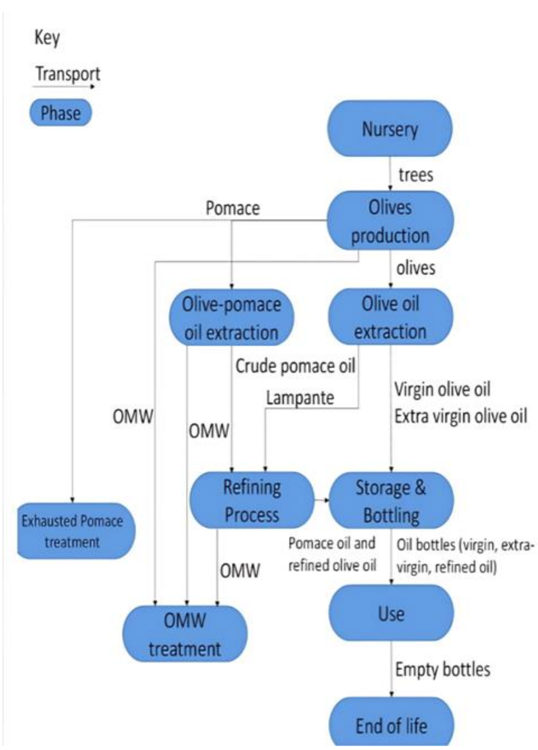

Figure 2. Olive oil life cycle (OMW).

Oils are stored in tanks or bottles. The storage tanks generally contain inert gas (CO_2 or N_2). They prevent oxidation reactions, suitable for a more extended storage period, allowing the bottling phase to spread over time. The oil is sold either in bulk or in bottles. The bottling process involves transferring the oil from the tanks to small-volume containers. Olive oil is mainly used for culinary purposes, either seasoning or frying. It can also be used in cosmetics. The consumption of olive oil differs according to the country and its culture. After the container opening, olive oil can be stored at room temperature. The olive oil end-of-life does not exist insofar as it is consumed as a food. On the other hand, empty packaging and containers are directed to different ends of life according to the consumer's behavior and the local waste treatment channels. These include reuse, recycling, landfill, or incineration. These treatment techniques may or not result in residue reuse (Sheldon et al., 2020).

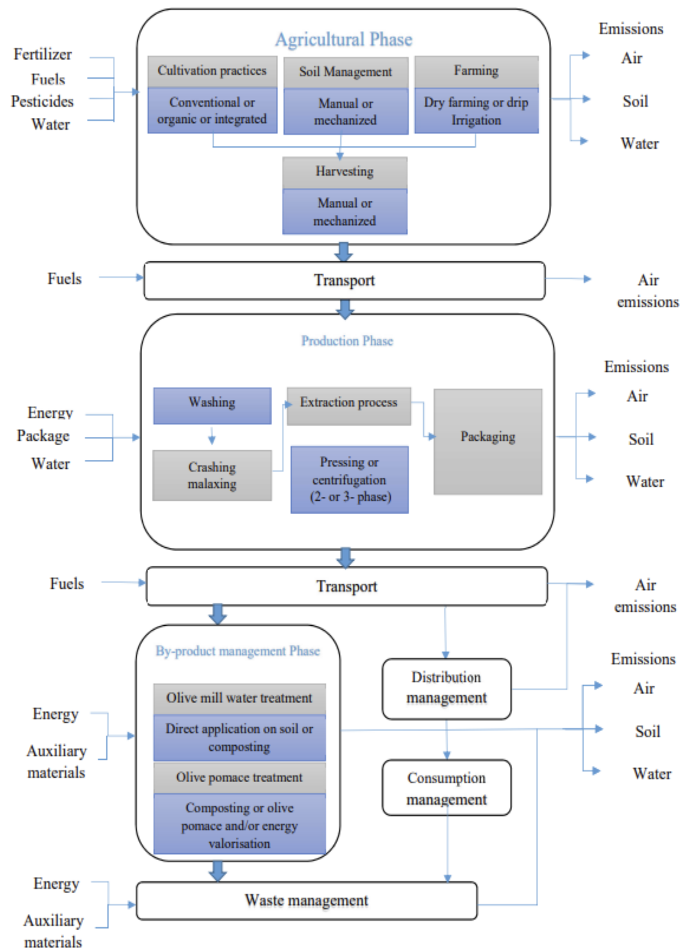

Figure 3. Olive oil production chain and subsequent environmental impacts.

The end-of-life cycle of olive oil extraction encompasses the generation of pomace and OMW, both significant waste streams due to their substantial quantities. While the oil itself accounts for only 20% of the mass of olive fruits, the remaining 80% comprises residues in the form of pomace and OMW. Various primary practices are employed for treating these residues, including spreading over land, composting, and gasification (Khdair et al., 2020). Among these options, incineration of the pomace emerges as the most viable due to the energy it generates. However, composting, while commonly practiced, presents challenges due to the environmental impact of regularly turning over organic material . Transportation plays a crucial role throughout the olive oil life cycle, appearing in almost every phase, from delivering plant protection products to the field to transporting empty bottles to the olive mill, and from transferring harvested olives from the orchard to the mill.

The olive oil supply chain and its associated environmental impacts are depicted in **Figure 3**. It's worthy to note that mass and energy balances reveal that the production of 1 kg of olive oil consumes 0.0264 kg of fertilizers (N_2, P_2O_5, K_2O), 0.019 kg of pesticides, 0.00855 kg of fuel, 0.243 kg of lubricating oil, and 0.359 kWh of electrical energy (Salomone et al. 2. , 2015).

4. Towards Olive Oil Production Sustainability Using LCA Methodology

The LCA methodology is increasingly applied in recently published studies to find the best sustainable scenarios by analyzing the product life cycle (El jomri et al., 2023). The first stage involves determining the study's goals, scope, system function, functional unit, and boundaries. Two main goals are typically considered: i) the environmental comparison of stages within a single life cycle to identify the most impactful stages or pollution transfers, and ii) the environmental comparison of multiple life cycle scenarios for a specific product or process to identify the most environmentally friendly systems (see Figure 2). The objectives of the study dictate the level of detail required in the subsequent inventory phase. Depending on the objective, certain life cycle stages may be excluded, or only a single environmental impact, such as global warming, may be evaluated. The quality of the LCA heavily depends on the rigor of this initial phase, which is often overlooked in practice. During this stage, data on inputs (renewable and nonrenewable raw materials, energy consumption) and outputs (air, water, soil emissions) of the system under study are compiled and quantified across the product life cycle. Although data collection for the inventory phase is extensive and tedious, it is possible and recommended to simplify it by considering only the most relevant flows based on their relative importance and environmental significance.

Various approaches described in the literature can be employed to compile a life cycle inventory (Venkatraj et al., 2021). The impact assessment stage involves collecting inputs and outputs to determine the relative contribution of various factors to environmental issues. These impacts can be categorized into local/regional impacts (toxic and ecotoxic consequences, nuisances, eutrophication, acid rain, photo-oxidative pollution) and global impacts (climate change, depletion of natural resources). Evaluating these impacts facilitates the production of an environmental report, which is complex and requires understanding impact mechanisms, using characterization methods, and selecting impact indicators for calculation. Several impact characterization methods, such as ILCD 2011, IMPACT 2002+, and ReCiPe 2008, have been developed. Characterizing the effects allows for impact quantification, for which impact indicators are crucial. These indicators reflect the potential environmental effects of substance emissions by a system and are obtained from databases with essential access and quality requirements for the final LCA.

In this step, the best sustainable scenario, life cycle hotspots, and improvement opportunities for the studied system can be identified. However, the conclusions and recommendations derived from the combination of inventory results (phase 2) and impact assessment (phase 3) must align with the study's objective and scope (phase 1) (see **Figure 3**). Additionally, they should be clear and usable by decision-makers. To ensure reliability, a sensitivity analysis is essential, measuring the variation associated with each calculated impact primarily using statistical tools.

4.1. Scope of the Study

The literature survey showed that most LCA studies in the olive oil sector present a comparative nature. Five authors have conducted both a life cycle environmental assessment and a life cycle cost assessment (Mohammed et al., 2014; De Lucaa et al., 2018; Maesano et al., 2021; De Gennaro et al., 2012; Vanella et al., 2023). The surveyed studies' objectives focused on identifying life cycle hotspots to understand the system better, comparing two production systems, the relationship between the environmental impacts and consumers, or combining these three objectives. Table 2 compiles the main characteristics of the selected LCA studies.

Table 2: General characteristics of selected LCA studies related to olive oil production.

Authors	Place of case	Functional unit	System Bound.	Alloc.	Env. priority
Abdallah, Elfkih	Sfax and Sidi Bouzid (Tunisia)	1 ton of olives and 1 ha of cultivated olive growing area	from cradle to the farm gate	no	Comparison
De Gennaro, Notarnico-la	Apulia (Italy)	1-ton olives	from cradle to farm	no	Comparison
De Luca, Falcone	Gioia Tauro Plain (Italy)	1 ha of cultivated olive growing area	from cradle to the farm gate	no	Comparison

De Lucaa, Stillitanoa	Calabria (Italy)	1 bottle containing 0.75 L of extra virgin OLO	from cradle to the milling plant gate	Eco.	Effect of co-adjuvant addition during malaxation
El Hanandeh and Gharaibeh	Irbid, Ajloun and Jerash (Jordan)	1 kg of OLO	from cradle to grave	Eco	Identification of sensitive points + comparison
Espadas-Aldana, Vialle	Ribera Baja (Spain)	5.4 L OLO	from cradle to mill	Eco.	Identification of sensitive points + region assessment
Fernández-Lobato, LópezSánchez	Jaen (Spain)	1 kg of virgin OLO	from cradle to gate	no	Identification of sensitive points
Guarino, Falcone	Reggio Calabria (Italy)	0.75 L of extra virgin OLO	from cradle to gate	no	Comparison
Iraldo, Testa	Val di Cornia (Italy)	1 kg of extra-virgin OLO	from cradle to mill	Eco.	Identification of sensitive points + comparison
Maesano, Chinnici	Sicily (Italy)	1 kg of olive	from cradle to gate farm	no	Identification of sensitive points + comparison
Maffia, Pergola	Salerno (Italy)	1 L olive oil	from cradle to grave	no	Comparison
Mohamad, Verrastro	Apulia (Italy)	1 ha olive-growing area	from cradle to the farm gate	Eco.	Comparison
Proietti, Sdringola	Umbria Region (Italy)	1 L of OLO	from cradle to gate	no	Identification of sensitive points + comparison
Romero-Gámez, Castro Rodríguez	Andalusia (Spain)	1 ton of olives	from cradle to the farm gate	no	Comparison
Sales, Figueiredo	Alentejo (Portugal)	1 ha of cultivated olive growing area	from cradle-to farm gate	Price-based Alloc.	Comparison
Salomone and Ioppolo	Messina, Sicily (Italy)	1 L of virgin OLO	from cradle to gate	no	Identification of sensitive points + comparison
Tsarouhas, Achillas	Gerakini, Chalkidiki (Greece)	1 L of extra virgin OLO	from cradle to mill	no	Identification of sensitive points

note: Env.: environmental, Eco: economic, Alloc: allocation, Bound.: Boundaries, Olive oil: OLO

4.1.1. Functional Unit

In the case of studies dedicated to olive fruit production, the functional units correspond to the quantity of produced olives (1 ton or 1 kg) (Abdallah et al., 2021; Maesano et al., 2021; Romero-Gámez et al., 2017) or the area of cultivation (1 ha) (Abdallah et al., 2021; Mohammed et al., 2014). For olive oil extraction studies, the functional units correspond to the quantity of olive oil extracted (1 kg) (Fernández et al., 2021; El Hanandeh et al., 2016) or the volume of olive oil produced (0.75 L, 1 L, or 5.4 L) (Espadas-Aldana et al., 2019; Garino et al., 2019).

4.1.2. Allocation

LCA is fundamentally based on assumptions that must be made explicit (Guinée et al., 2022). These assumptions generally gave the specificity of the results obtained in a study. One of the principals applied assumptions is the choice of flow allocation between the different co-products, such as olive oil, pits, raw pomace, OMW, and pruning (branches and leaves). The clear choice of the selected allocation types is shown in **Table 2**. On the other hand, no allocation is used between the different oils, namely virgin oils (including extra virgin oils), olive-pomace oils, and olive oils (refined).

4.1.3. System Boundaries

System boundaries can be defined as "cradle to grave," "cradle to gate," or "gate to gate," depending on the chosen functional unit. To adapt these expressions to LCA studies of olive oil production, the system boundaries will be cradle-to-grave, mill-to-mill for studies focused on the oil extraction phase only, cradle-to-mill for studies focused on both agricultural and oil extraction phases, cradle-to-field for studies focused on the agricultural phase only. The use phase is excluded from the surveyed studies because of the diversity of uses. However, suppose a study has to include social aspects (i.e., the health benefits to the consumer).

4.2. Life-Cycle Inventory

The data collection for life cycle inventory is divided into two parts depending on whether the data is direct or indirect. The first part comes from professional associations or practical's in the field, while the second part is taken from the literature (Minunno et al., 2021). The direct data include energy and material inputs and qualitative information on the practices of professionals. They do not include calculated emissions. They are obtained through questionnaires, interviews, and measurements (Rapa et al., 2022). The indirect data are extracted from databases, i.e., Eco-Invent, ESU world food LCA, Environmental Footprint, Agribalyse 3.0, scientific literature, or technical reports. Some indirect data are derived from calculations based on methods available in guides or the scientific literature, Data Quality, Uncertainties, and Monte Carlo Analysis .Although data quality and uncertainty analysis have been considered in a few case studies (Table 2), Few studies (De Gennaro et al., 2012; El Hanandeh et al., 2016) present a Monte Carlo analysis to estimate uncertainty. The Monte Carlo technique employs a data-heavy approach by iteratively conducting thousands of simulations based on the possible input parameter values to estimate the uncertainty of the outcomes.

4.2.1. Machinery, infrastructure, and real estate

The machinery, infrastructure, and real estate owned and used by the olive oil sector's professionals vary drastically from one to another, mainly depending on the size of the farm or the olive mill. Moreover, their consideration in LCA remains a challenge, as it is complex to estimate the impacts of these elements. For this reason, only six studies have considered them in their analysis (Abdallah et al., 2021; Venkatraj et al., 2021; De Luca et al., 2018; Sales et al., 2022; Halloran et al., 2016; Proietti et al., 2017). The product category rules (PCR) document advises not to include in the LCA of food products properties with a life span exceeding three years (Del Borghi et al., 2020). The other authors make two prominent opinions for excluding machinery, infrastructure, and real estate from their studies: (i) the lack of reliable inventory data regarding this type of asset (Del Borghi et al., 2020) and (ii) the lack of relevance of this type of asset from the life cycle analysis perspective (Salomone et al.,2012). However, no sensitivity analysis has been conducted to corroborate such a conclusion in the olive sector. iv) Carbon Storage in olive tree.

Olive trees are known to live for several decades or even centuries. Therefore, they likely play a role in carbon storage by immobilizing it for a long time in their permanent parts (i.e., roots, trunk, and main branches). In order to quantify carbon storage in the olive tree, (Sales et al., 2022)set up a scientific protocol over five years to provide an initial answer to this crucial question. This protocol was applied in three LCA studies (Fernández et al., 2021; Proietti et al., 2017; De Luca et al., 2018). In addition, the soil can also act as a carbon sink if organic fertilizers such as pomace or pruning are returned to the soil.

4.2.2. Impacts of fertilizer

Farmers use fertilizers to boost olive tree growth and production, providing vital nutrients like nitrogen, phosphorus, and potassium. However, improper fertilizer application can lead to nitrogen and phosphate runoff into air, water, and soil, causing eutrophication, soil degradation, and air pollution. Five LCA studies address this issue (Abdallah et al., 2021; Garino et al., 2019; De Gennaro et al., 2012; Sales et al., 2022; Proietti et al., 2017). The application of mineral fertilizers is responsible for emissions of nitrous oxide (N_2O), ammonia (NH_3), and nitrogen oxides (NO_x) to the air, nitrates (NO_{3-}), and phosphates (PO_4^{3-}) to water and soil. The molecules NH^3, NO_x, and PO_4^{3-} are mainly emitted during the pulverization of mineral fertilizers. The calculation of emitted molecule quantities relies on various methodologies. Widely utilized methods include those developed by (Houghton,1996; Bouwman ,1998; Hordijk and Kroeze,1997), as well as (Audsley et al., 1997) . Additionally, studies assessing fertilizer emissions typically employ the (Hauschild,2000) method to quantify pesticide emissions.

4.2.3. Soil erosion

The intensive cultivation of olive trees leads to soil erosion, a phenomenon that is damaging to soil ecosystems, nutrient regulation, and water storage. One of the solutions could be spreading pomace and OMW over the land to restore part of the consumed organic matter to the soil. However, the composition of solid (pomace) and liquid (OMW) residues raises other environmental problems. Indeed, due to their composition, olive residues present a potential phytotoxic effect on the soils, aquatic ecosystems, and even the air (Ladhari et al, 2021). Also, the spreading of pomace and OMW bring a large quantity of organic matter that will necessarily degrade and produce, among other things, methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2).

4.2.4. Transportation

Worker transportation is specifically addressed in one study (Tsarouhas et al., 2015), while distribution, which varies greatly between farms and years, is considered in only three LCAs (Abdallah et al., 2021; Espadas-Aldana et al., 2019; El Hanandeh et al., 2016). To provide guidance on assessing transportation impacts, the PCR guide suggests calculating the average distance traveled by different modes of transport, including maritime transport, airfreight sea, airfreight, rail, and trucking (Proietti et al., 2017).

4.3. Impacts Assessment

4.3.1. Software Tools

The impact assessment was performed using dedicated LCA tools in 12 of the 17 studies. SimaPro software is the most used tool for analyzing life cycle (used by 16 studies), the other two being GEMIS (version 4.5) and Gabi (version 4.4).

4.3.2. Impacts Categories

Planning is essential for a successful LCA to complete the study within its intended parameters. The ISO14044 standard defines the LCA's required and optional components: category selection, classification, characterization, Normalization, grouping, weighting, and sensitivity analysis (Stillitano et al., 2019). The assessment of impacts could be carried out using a wide range of evaluation methods. The methods applied in the case of the surveyed studies correspond to the most recognized in the LCA community, namely Eco-indicator 99 and CML 2000. Indeed, the more recent methods, 2002+ and ReCiPe, are based on the two previously cited methods. The most evaluated impact category is global warming potential (GWP), whose results are expressed in kg CO_{2eq}. All the surveyed studies evaluate this impact using the same calculation method, Eco-indicator 99. Ozone depletion potential (ODP) is an impact category expressed in kg $CFC\text{-}11_{eq}$. The other impact categories differ from one study to another or rely on different evaluation methods. Of the four studies that conduct life cost analysis, only one conducts a complete life cycle cost analysis (Mohammed et al., 2014). The other analyses that investigate costs only consider labor costs and direct material and energy inputs (Maesano et al., 2021; De Gennaro et al., 2012; De Luca et al., 2018). Finally, standardization and weighting steps are carried out in a few studies to reduce the number of environmental indicators (Salomone et al.,2012; De Luca et al.,2018).

4.3.3. Interpretation

The analysis follows a structured approach in line with international standards (ISO 14044), encompassing key identification, evaluation considering completeness, sensitivity, and consistency checks, and subsequent conclusions, limitations, and recommendations (Stillitano et al., 2019).

While all analyzed papers offer some level of detail on the interpretive process, a significant portion lacks comprehensive discussions on findings, limitations, and suggestions. The interpretations often lack specificity, hindering the return of critical insights. Transparency is compromised due to varying selections of functional units and system boundaries.

Despite these challenges, findings indicate that farming emerges as the most impactful aspect of olive oil production in half of the studies. Particularly, fertilizer and pesticide use are identified as the most environmentally damaging agricultural practices, contributing to eutrophication, acidification, and ecotoxicity. However, sensitivity analysis, a crucial tool for validating interpretation outcomes, is employed in only 16% of the trials

4.4. Best Practices and Methodological Recommendations for the Applications of LCA

The review of agricultural practices and extraction techniques applied in the olive oil production sector; also, the critical analysis of the surveyed LCA studies presented in the previous section allowed us to highlight the problems and limits faced during the application of LCA methodology in the olive oil production sector, and many points for reflection and improvement emerged.

A thorough understanding of the investigated supply chain and all applicable standards and guidelines (such as ISO 14040, ISO 14044, the International Reference Life Cycle Data System (ILC), the carbon footprint of products ISO 14067, and Product Category Rules (PCR)) is necessary before beginning an LCA study. The rules stress the significance of taking a life cycle perspective, which considers the entire process from raw material extraction to final disposal (Vidergar et al., 2021).

Below is a quick summary of the challenges arising from current practices and the need for further research to improve the implementation of LCA in this agrifood sector, as determined by the literature review results and critical comparative analysis. Experts performing LCA studies in olive oil are encouraged to consider the following recommendations for methodological concerns and potential hotspots.

4.4.1. The Goal and Scope

An LCA in the olive oil industry necessitates well-defined objectives and a clear rationale for its undertaking. Defining the study's purpose and scope is pivotal as it influences the selection of the functional unit, determination of system boundaries, study time horizon, depth, and direction. Specific attention should be given to:

- Explicitly stating the rationale for selecting a particular scope, such as hotspot detection.
- Identifying the target audience and intended use of the LCA information to ensure its utility.

4.4.2. The Functional Unit

The selection of a functional unit (FU) is paramount in LCA studies as it forms the foundation of the analysis. The FU, a standardized measurement unit, is instrumental in measuring production system performance. Several considerations, including intended outcomes, influence FU selection (Stillitano et al., 2019):

- Weight or volume is recommended as the most appropriate FU by the European food sustainable consumption and production round table.
- Product quality should also be considered in the FU, particularly due to variations in olive oil quality.
- Sensitivity analysis using multiple FUs is encouraged to evaluate result dispersion.
- Careful consideration is essential when selecting an appropriate approach for LCA in the olive oil industry, especially considering the complexity of the product lifecycle and variability in quality.

4.4.3. The System Boundaries

The study's purpose and scope will determine which processes will be included or omitted from the analysis. It relies on the reliability of the examined processes and readily available information. The lack of data on specific stages of the olive supply chain led researchers to exclude those stages from the analysis, which necessitated redefining and recalibrating the study's purpose and scope, as revealed by the studies surveyed. There is a paucity of information about the burning of olive pomace, the physicochemical features of pomace compost, and the various pomace qualities, as well as about the emissions of gases during the composting process, the combustion of spent pomace, and the application of OMW to the soil. The purpose of future research, according to this statement, should be to provide reliable findings.

4.4.4. Quality of Data

Research on the olive oil production industry has highlighted a lack of comprehensive and reliable information across various stages of the industry's life cycle, with the agricultural stage being particularly affected. This dearth of data results in moderate evaluations of this stage, characterized by several factors:

- Specific Types of Agrochemicals: The use of certain fertilizers, herbicides, or pesticides poses challenges due to limited data availability. Utilizing generic products available in databases and proportionally incorporating quantitative consumption data can address this issue.
- Farm Machinery Emissions: Emissions from farm machinery are influenced by factors such as operation type and soil type. However, emissions from gasoline consumption are often the only ones considered due to data scarcity or unreliability.
- Utilization of Tree Pruning Residues: The destination of tree pruning residues, often used as fertilizers or for home heating, is significant but often overlooked. Incorporating this information is crucial as it brings about significant benefits and effects.
- Mislabeling and Count Duplication: Primary data collected from olive farms may contain reliable information on fertilization methods. To prevent double counting and misclassification, it is vital to provide all data acquired for functional unit selection, especially if the farm produces multiple agricultural commodities.
- Insufficient Focus on Transport and Distribution: The transport and distribution phase, particularly concerning the final packaged product's journey to markets or consumers, receives inadequate attention. Increasingly incorporating this phase in LCA assessments is essential, especially considering major importers like the United States, Brazil, and Japan and the Mediterranean's role as the primary supplier.
- Expansion of Impact Indicators: According to (Guinée et al., 2022), it is crucial to consider additional indicators related to climate change, resource consumption, and the potential impact on water consumption and land use.

4.4.5. Impacts Assessment

LCA study of the olive oil supply chain should report water consumption, energy, and other resources and consider greenhouse gasses, ozone-depleting gasses, acidifying gasses, ground-level ozone-contributing gasses, oxygen depletion gasses, and the emissions associated with toxicity to humans and animals. In addition, the assessment of water consumption impact must be improved in future research. Indeed, water is considered necessary since climate change is intensified, and improved inventory data and agreement on which LCA should be used to assess relevant aspects are needed.

5. Conclusions and Future Perspectives

The analysis of relevant literature illuminates critical considerations for the implementation of LCA in the olive oil-producing industry. Extra virgin olive oil emerges as the most environmentally friendly option, though concerns persist regarding land use. The agricultural stage exerts significant environmental impacts, with conventional practices contributing to eutrophication, acidification, and land consumption. In contrast, organic agriculture shows promise in mitigating environmental harm. The unique challenge of olive mill water disposal underscores the need for sustainable solutions to minimize groundwater pollution during extraction. Efficiency gains in the two-phase extraction method highlight opportunities for improving environmental performance over traditional techniques. While further investigation is needed to enhance the reliability of LCA results, the technique remains indispensable for identifying optimal environmental practices in olive oil production. Moreover, integrating environmental disposal and waste management into the supply chain is crucial for sustainability. Looking ahead, advancements in technology, data collection methods, and agricultural practices offer promising avenues for refining LCA implementation. Remote sensing, precision agriculture, and artificial intelligence present opportunities for more accurate and comprehensive assessments of environmental impacts. Collaborative efforts between researchers, industry stakeholders, and policymakers will be instrumental in driving innovation and implementing evidence-based strategies to minimize the industry's environmental footprint. A holistic assessment of the entire supply chain, from farming to consumer, will be essential for identifying areas for improvement and driving environmental reform efforts forward. By embracing these future perspectives and leveraging emerging technologies, the olive oil industry can pave the way for a more sustainable and environmentally responsible future, ensuring the continued enjoyment of this valuable commodity for generations to come.

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References

Abdallah, S. B., Elfkih, S., Suárez-Rey, E. M., Parra-López, C., & Romero-Gámez, M. (2021). Evaluation of the environmental sustainability in the olive growing systems in Tunisia. Journal of cleaner production, 282, 124526.

Audsley, E., Alber, S., Clift, R., Cowell, S., Crettaz, P., Gaillard, G., ... & van Zeijts, H. (1997). Harmonisation of environmental life cycle assessment for agriculture. Final Report, Concerted Action AIR3-CT94-2028. European Commission, DG VI Agriculture, 139(1).

Bouwman, A. F. (1998). Nitrogen oxides and tropical agriculture. Nature, 392(6679), 866-867.

Dammak, I., Neves, M., Isoda, H., Sayadi, S., & Nakajima, M. (2016). Recovery of polyphenols from olive mill wastewater using drowning-out crystallization-based separation process. Innovative food science & emerging technologies.

Dammak, I., Neves, M., Souilem, S., Isoda, H., Sayadi, S., & Nakajima, M. (2015). Material balance of olive components in virgin olive oil extraction processing. Food Science and Technology Research, 21(2), 193-205.

De Gennaro, B., Notarnicola, B., Roselli, L., & Tassielli, G. (2012). Innovative olive-growing models: an environmental and economic assessment. Journal of cleaner production.

De Luca, A. I., Falcone, G., Stillitano, T., Iofrida, N., Strano, A., & Gulisano, G. (2018). Evaluation of sustainable innovations in olive growing systems: A Life Cycle Sustainability Assessment case study in southern Italy. Journal of Cleaner Production, 171, 1187-1202.

De Lucaa, A. I., Stillitanoa, T., Falcone, G., Squeob, G., Caponiob, F., Stranoa, A., & Gulisanoa, G. (2018). Economic and environmental assessment of extra virgin olive oil processing innovations. CHEMICAL ENGINEERING, 67.

Del Borghi, A., Moreschi, L., & Gallo, M. (2020). Life cycle assessment in the food industry. In The interaction of food industry and environment (pp. 63-118). Academic Press.

Donner, M., & Radić, I. (2021). Innovative circular business models in the olive oil sector for sustainable mediterranean agrifood systems. Sustainability, 13(5), 2588.

El Hanandeh, A., & Gharaibeh, M. A. (2016). Environmental efficiency of olive oil production by small and micro-scale farmers in northern Jordan: Life cycle assessment. Agricultural Systems, 148, 169-177.

El Joumri, L., Labjar, N., Dalimi, M., Harti, S., Dhiba, D., El Messaoudi, N., ... & El Hajjaji, S. (2023). Life cycle assessment (LCA) in the olive oil value chain: a descriptive review. Environmental Development, 45, 100800.

Espadas-Aldana, G., Vialle, C., Belaud, J. P., Vaca-Garcia, C., & Sablayrolles, C. (2019). Analysis and trends for Life Cycle Assessment of olive oil production. Sustainable Production and Consumption, 19, 216-230.

Fernández-Lobato, L., López-Sánchez, Y., Blejman, G., Jurado, F., Moyano-Fuentes, J., & Vera, D. (2021). Life cycle assessment of the Spanish virgin olive oil production: A case study for Andalusian region. Journal of cleaner production, 290, 125677.

Guarino, F., Falcone, G., Stillitano, T., De Luca, A. I., Gulisano, G., Mistretta, M., & Strano, A. (2019). Life cycle assessment of olive oil: A case study in southern Italy. Journal of environmental management, 238, 396-407.

Guinée, J. B., de Koning, A., & Heijungs, R. (2022). Life cycle assessment-based Absolute Environmental Sustainability Assessment is also relative. Journal of Industrial Ecology.

Halloran, A., Roos, N., Eilenberg, J., Cerutti, A., & Bruun, S. (2016). Life cycle assessment of edible insects for food protein: a review. Agronomy for Sustainable Development, 36, 1-13.

Hauschild, M. (2000). 22. Estimating pesticide emissions for LCA of agricultural products. Agricultural data for life cycle assessments, 70.

Hordijk, L., & Kroeze, C. (1997). Integrated assessment models for acid rain. European Journal of Operational Research.

Houghton, R. A. (1996). Converting terrestrial ecosystems from sources to sinks of carbon. Ambio, 267-272.

Iraldo, F., Testa, F., & Bartolozzi, I. (2014). An application of Life Cycle Assessment (LCA) as a green marketing tool for agricultural products: the case of extra-virgin olive oil in Val di Cornia, Italy. Journal of Environmental Planning and Management, 57(1), 78-103.

Khdair, A., & Abu-Rumman, G. (2020). Sustainable environmental management and valorization options for olive mill byproducts in the Middle East and North Africa (MENA) region. Processes, 8(6), 671.

Ladhari, A., Zarrelli, A., Ghannem, M., & Ben Mimoun, M. (2021). Olive wastes as a high-potential by-product: Variability of their phenolic profiles, antioxidant and phytotoxic properties. Waste and Biomass Valorization, 12, 3657-3669.

Maesano, G., Chinnici, G., Falcone, G., Bellia, C., Raimondo, M., & D'Amico, M. (2021). Economic and environmental sustainability of olive production: A case study. Agronomy, 11(9), 1753.

Maffia, A., Pergola, M., Palese, A. M., & Celano, G. (2020). Environmental impact assessment of organic vs. integrated olive-oil systems in Mediterranean context. Agronomy.

Minunno, R., O'Grady, T., Morrison, G. M., & Gruner, R. L. (2021). Investigating the embodied energy and carbon of buildings: A systematic literature review and meta-analysis of life cycle assessments. Renewable and Sustainable Energy Reviews.

Mohamad, R. S., Verrastro, V., Cardone, G., Bteich, M. R., Favia, M., Moretti, M., & Roma, R. (2014). Optimization of organic and conventional olive agricultural practices from a Life Cycle Assessment and Life Cycle Costing perspectives. Journal of Cleaner Production, 70, 78-89.

Proietti, S., Sdringola, P., Regni, L., Evangelisti, N., Brunori, A., Ilarioni, L., ... & Proietti, P. (2017). Extra Virgin Olive oil as carbon negative product: Experimental analysis and validation of results. Journal of cleaner production, 166, 550-562.

Rallo, L., Barranco, D., Díez, C. M., Rallo, P., Suárez, M. P., Trapero, C., & Pliego-Alfaro, F. (2018). Strategies for olive (Olea europaea L.) breeding: cultivated genetic resources and crossbreeding. Advances in Plant Breeding Strategies: Fruits: Volume 3, 535-600.

Rapa, M., & Ciano, S. (2022). A review on life cycle assessment of the olive oil production. Sustainability, 14(2), 654.

Romani, A., Ieri, F., Urciuoli, S., Noce, A., Marrone, G., Nediani, C., & Bernini, R. (2019). Health effects of phenolic compounds found in extra-virgin olive oil, by-products, and leaf of Olea europaea L. Nutrients, 11(8), 1776.

Romero-Gámez, M., Castro-Rodríguez, J., & Suárez-Rey, E. M. (2017). Optimization of olive growing practices in Spain from a life cycle assessment perspective. Journal of Cleaner Production, 149, 25-37.

Ruiz-Méndez, M. V., Aguirre-González, M. R., & Marmesat, S. (2013). Olive oil refining process. In Handbook of olive oil: analysis and properties (pp. 715-738). Boston, MA: Springer US.

Sales, H., Figueiredo, F., Patto, M. C. V., & Nunes, J. (2022). Assessing the environmental sustainability of Portuguese olive growing practices from a life cycle assessment perspective. Journal of Cleaner Production, 355, 131692.

Salomone, R., & Ioppolo, G. (2012). Environmental impacts of olive oil production: a Life Cycle Assessment case study in the province of Messina (Sicily). Journal of cleaner production.

Schuch, M. W., Tomaz, Z. F. P., Casarin, J. V., Moreira, R. M., & Silva, J. B. D. (2019). Avanços na propagação vegetativa de Oliveira. Revista Brasileira de Fruticultura, 41, e-003.

Sheldon, R. A., & Norton, M. (2020). Green chemistry and the plastic pollution challenge: towards a circular economy. Green Chemistry, 22(19), 6310-6322.

Stillitano, T., Falcone, G., De Luca, A. I., Piga, A., Conte, P., Strano, A., & Gulisano, G. (2019). A life cycle perspective to assess the environmental and economic impacts of innovative technologies in extra virgin olive oil extraction. Foods.

Tsarouhas, P., Achillas, C., Aidonis, D., Folinas, D., & Maslis, V. (2015). Life Cycle Assessment of olive oil production in Greece. Journal of cleaner production, 93, 75-83.

Vanella, D., Consoli, S., Continella, A., Chinnici, G., Milani, M., Cirelli, G. L., ... & Barbagallo, S. (2023). Environmental and Agro-Economic Sustainability of Olive Orchards Irrigated with Reclaimed Water under Deficit Irrigation. Sustainability, 15(20), 15101.

Venkatraj, V., & Dixit, M. K. (2021). Life cycle embodied energy analysis of higher education buildings: A comparison between different LCI methodologies. Renewable and Sustainable Energy Reviews, 144, 110957.

Vidergar, P., Perc, M., & Lukman, R. K. (2021). A survey of the life cycle assessment of food supply chains. Journal of cleaner production, 286, 125506.