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Sustainability Assessment of Different Extra Virgin Olive Oil Extraction Methods through a Life Cycle Thinking Approach: Challenges and Opportunities in the Elaio-Technical Sector

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Abstract: Owing to its important nutritional features, extra virgin olive oil (EVOO) is one of the world’s highest-value products, mostly manufactured in Mediterranean countries. However, its production exerts several negative environmental effects, mainly related to the agricultural phase (and the use of fertilizers, pesticides, etc.) and waste management. Olive oil can be extracted from the olive paste using different extraction systems, including pressure, centrifugation, and percolation. In particular, EVOO by-product composition strictly depends on the extraction technologies, and two- or three-phase centrifugal extraction methods are usually employed. Therefore, due to olive oil’s economic value, it might be useful to investigate its environmental impacts, to advise sustainable supply chain models. In this context, a valuable tool for assessing the product’s environmental compatibility is the Life Cycle Assessment, which is part of a broader Life Cycle Thinking philosophy. This research focused on evaluating the EVOO environmental impact by comparing two- and three-phases extraction processes. Additionally, two scenarios, (i.e., composting and bio-gasification), were proposed to assess the best valorisation strategy for the produced pomace. The results showed that the two-step extraction process was more sustainable than the three-step one in nine out of nine considered impact categories. By milling 1000 kg of olives, the first technology approximately produces 212 kg CO₂ eq, the latter 396 kg CO₂ eq. Finally, pomace valorisation by bio-gasification was found as the best recovery process, able to confer greater environmental benefit than composting.

Keywords: extra virgin olive oil; two-phase and three-phase centrifugal extraction processes; life cycle assessment; biogas; composting

1. Introduction

Globally, the olive oil sector experienced a positive consumption growth (+2.9%) over the last three crop years and should reach about 3,215,000 tons this year [1]. This trend is related to several established and emerging aspects. Among others, they include the Mediterranean diet acceptance, the recognition of extra virgin olive oil’s health-promoting effects, the consumers’ attitude after the pandemic to choose better quality products, and the widespread application of olive oil as an ingredient in cosmetic, pharmaceutical, and food formulations, as well as the support to single-origin premium olive oil and sustainable production practices [2,3]. At the temporary level, the annual olive oil production is further boosted by the scarcity on the market of sunflower oil, mainly produced and exported by Ukraine. As soon as the war will go on, production will suffer thus increasing the demand for other vegetable oils to be used in replacement. These issues fueled olive oil consumption, which rose faster than production, the latter expected to reach in the current year 3,100,000 tons [1]. In 2020/2021 the IOC members held 93% of the global olive oil production. Among producers, Spain dominated with about 47%, followed by Greece (9%) and Italy (9%) [1]. However, it should be underlined that, although Greece is expected to
increase olive production in 2023, threats were raised for Spain and Italy. Both countries suffered one of the most severe droughts of all time, leading to a decrease in production but also a lower quality of olive crops. Moreover, the high costs of energy, the rising demand, and the productive framework of both countries, further endanger the financial sustainability of the production process for many Spanish and Italian companies. Imports and exports are going to exceed 1 million tons (1,211,000 and 1,189,000 tons, respectively), with USA and Europe as the leading importers, followed by Brazil, Japan, Canada, and Russia. According to IOI outlooks, the European market will remain the more important producer, exporter, and consumer of olive oils with the Mediterranean countries (i.e., Spain, Italy, Greece, and Portugal) accounting for the largest shares worldwide. The same four countries in 2021 exported about 75% of the globally produced olive oil, led by Spain and Italy with about 46% and 20% export shares, respectively [1].

With 1.1 million hectares devoted to olive trees cultivation, 315,000 tons of olive oil produced in 2022, almost 50 Protected Designations of Origins (PDO) and protected geographical indication (PGI) certifications, and about 5000 olive oil mills spread all over the country, Italy is one of the key players in the olive oil market, as witnessed by the income produced by this sector that is proved to be one of the pillars of the Italian economy [4]. Nevertheless, in recent years, the Italian olive oil sector underwent a loss of competitiveness, due to the recent phytosanitary problems as well as to the scarce technological improvement and unproper process management in the mill plants [5]. Whereas the agronomic issues are going to be solved, the lack of technological innovation still needs to be addressed, being the high costs of machinery, the lack of infrastructures, the problems in waste disposal, and the small/medium industrial capacity are the most severe limiting factors [6].

Among the extra virgin olive oil (EVOO) production steps, the extraction phase shows a great deal of room for improvement to enhance yields, product quality, and the environmental load of the whole production cycle. For the abovementioned reasons, currently, in the Mediterranean countries, the three-phases centrifugal extraction system is still the most widespread, followed by the two-phases extraction method and by the traditional discontinuous pressing process, with strong differences depending on the zone [7]. Known since the 1970s, the three-phase decanter gained popularity as it reduced labor while increasing the processing capacity and the oil yield. However, the high-water demand during malaxation, the high energy consumption, and the large amounts of wastewater generated pushed towards the implementation of a two-phases decanter able to separate the liquid phase (oil) from a wet solid phase, without the addition of water. Typically, the two-phase obtained oil is richer in antioxidants and aroma compounds, also avoiding the generation of highly polluting liquid wastes. However, in the two-phase process, the energy requirements are generally higher, and a certain loss of oil is recorded as it remains absorbed into the pomace. This results in a wet solid by-product (55–60% water content), particularly difficult to handle from environmental and economic points of view. Moreover, optimal control of the waste characteristics (moisture and solids, in particular) cannot be achieved during the two-phase extraction, as the solid and liquid phases are delivered together. It follows that, depending on the method, different advantages or drawbacks can be underlined [5,8].

For this reason, at the industrial level, the proper management of the extraction process represents one of the parameters to take into consideration to improve the economic, qualitative, and environmental features of the whole process. In particular, the latter issue gained much attention during the last decades as olive oil production causes relevant environmental impacts, gathered in both space (Mediterranean basin) and time (September-December) [9]. Huge amounts of different wastes are generated during production, mostly pruning residues (leaves, woody fractions, and thin branches), stones, olive mill wastewaters, and pomace. Among them, leaves represent about 10% of the picked olives, the same value as the fruit stones. Olive mill wastewaters (OMWW) and olive pomace (OP) account for 35–45% of the processed drupes. The latter categories are the most problematic in terms
of quantities (30 million m$^3$ per year and 2 million tons per year, respectively) and polluting capacities (pH, chemical and biological oxygen demand, etc.).

Many attempts have been carried out to quantify the environmental loads of the olive oil supply chain, mostly by the application of the life cycle assessment (LCA) methodology [10–12] with or without carbon footprint (CF) and energy footprint (EF) estimates [7,13–16]. Sometimes also economic [17] and/or social evaluations [18] have been reported to further support the environmental assessment. Accordingly, it is generally recognized that farming practices exerted the most significant environmental burdens (chemicals, water, and energy consumption), although packaging/distribution (fuel consumption, emissions, and wastes) and transport (fuel consumption, air emissions) activities seemed to contribute as well [17]. As far as manufacturing operations are concerned, they were analysed for waste generation and to a lesser extent fuel and energy consumption. In this sense, the extraction method itself showed a limited impact (energy and water consumption, emissions), if compared to other supply chain phases [19,20]. Nevertheless, as the extraction method dramatically affects the characteristics of the by-products and wastes, its contribution should not be neglected, especially when a gate-to-gate approach is considered. In this regard, very few studies can be found in the literature, specifically focusing on the environmental assessment of the milling process [5,21,22]; more often this aspect is considered in a general approach concerning the whole supply chain where its effects are usually underrated in comparison to others, and/or it does not represent the main goal of the study. In a gate-to-gate approach, Cappelletti et al. evaluated different extraction methods (i.e., pressure, two-phase, three-phase, and de-stoning) finding similar performances for two- and three-phases methods (0.6 MJ L$^{-1}$ of produced oil), although cultivation was also considered [23]. Cini et al. studied how the reuse of olive stones could limit the environmental load during EVOO production [24]. In this sense, energy evaluations were accomplished, including the extraction methods, but once again not specifically related to this aspect. Perone et al. deeply evaluated only the extraction protocols (two- or three-phase) in terms of energy performances [6]. The authors found about double values of both energy use efficiency and overall equipment effectiveness for the continuous process (two-phase), in comparison with the batch production (three-phase). The authors concluded that new strategies are necessary to meet the small producers’ demands to improve energy management in batch processing, suggesting the rapid and non-destructive oil analysis during processing, the reduction of dead times, and pooling different batches to fit the malaxed capacity. Nevertheless, the research only focused on energy performances without a broader environmental analysis. It follows that a knowledge gap can be pointed out, as a deeper evaluation of the environmental loads of the olive oil extraction step could be of interest, mostly for producers, to optimize the overall environmental and economical performances of their mill plants. In this context, this work aims to evaluate the environmental compatibility of extra virgin olive oil production by comparing two extraction methods, one with two phases and another with three phases, through a Life Cycle Thinking approach, using LCA. Next, to verify the preferable disposal of the pomace produced by the two processes, a scenario analysis was carried out, integrating the evaluation of the two-phase and three-phases processes with two different valorisation routes, one for agricultural use, i.e., composting, and one for energy purpose, pomace bio-gasification. Both end-of-life options for spent pomace are considered sustainable solutions with high GHG-saving potential, playing a relevant role in the valorisation of agro-industrial by-products and contributing to the closing of organic matter cycles in a circular economy perspective, as also reported by literature studies. For example, Valenti et al. explore various management scenarios for spent pomace, showing how bio-gasification is the most sustainable solution [25]. Similarly, Batuecas et al. show how biogas production can be a feasible alternative to reduce the environmental burden of oil production, adding value to the supply chain [26]. Fernandez-Lobato et al. (2022) show how bio-gasification of olive pomace can be considered a key technology to reduce environmental impacts associated with the oil production process, generating 0.88 kWh of renewable electricity per kg of olive [27]. Panuccio et al. studied the application of
compost from OP as an agricultural soil conditioner showing how the chemical properties of soil treated with this by-product are positively affected [28]. Mamkagh et al. also used OP as a fertilizer, proving it to be of high quality, revealing how it could also be a viable alternative to synthetic pesticides for pest control [29]. Therefore, within this study, both pomace composting and its bio-gasification were compared from an environmental point of view. A farm in the province of Rome was chosen as the case study, and the evaluation was carried out using SimaPro 9.2.2. software.

2. Life Cycle Assessment

The Materials and Methods should be described with sufficient details to allow others. within this study, a Life Cycle Assessment was conducted by the following standards:

- ISO 14040:2006 [30]. Environmental management: Life Cycle Assessment—Principles and framework.
- ISO 14044:2006 [31]. Environmental management: Life Cycle Assessment—Requirements and guidelines.

The LCA is a valuable tool for comparing two or more options in terms of potential environmental impacts. It consists of four phases: (1) Goal and scope definition; (2) Life Cycle Inventory (LCI); (3) Life Cycle Impact Assessment (LCIA); (4) interpretation. The Simapro 9.2.2. software was used for the impact evaluation.

2.1. Goal and Scope Definition

The goal of the study was to analyse the environmental compatibility of the EVOO extraction process by centrifugation, comparing the two different extraction technologies, two-step and three-step decanters. As shown in Figure 1, the extraction phase follows several steps: washing (hulling carried out with mechanical equipment to remove stems and leaves and washing to clean dust and dirt on the drupe), crushing (breaking the cellular structure of the fruits to obtain the olive paste), and gramoling (mixing the olive paste).

Figure 1. Olive oil extraction by 2- and 3-phase centrifugation.

Then, the extraction can take place. This process can be carried out by a two- or three-stage horizontal decanter. The latter involves the addition of water (usually about 50%) to the gramulated olive paste, generating a product consisting of three phases (oil–water–pomace), subsequently separated by centrifugation. On the other hand, two-phase extraction does not involve adding water to the gram paste. Thus, only two final products are obtained: oil and pomace, mixed with OMWW, thus obtaining oil in greater quantities,
with higher polyphenol content and a decrease in the aqueous by-product [32]. An oil mill located in Moricone, in the province of Rome (Lazio, Italy), was chosen as a case study.

Functional Unit (FU) and Systems Boundaries

The milling of 1000 kg of olives was chosen as the FU. Although among literature studies it is more common to use the liter as FU [14,33,34], in our case study the choice of FU was the milling of 1000 kg of olives, according to other literature data [10,35,36]. This choice well fits the analyses performed during olive oil production and is often referred to as the mass unit. Additionally, it should be considered that the oil yield is strictly related to the extraction process. Finally, performed LCA analysis is intended as a guidance to the company, to identify which of the two extraction processes can guarantee the best performance in terms of environmental impact. The two-phases decanter led to an 18.7% yield, and the three-phases one reached about 17.4% yield. So, considering these yields, approximately 187 kg (two phases) and 174 kg (three phases) of oil were obtained. “From gate to gate” (Figure 2) was chosen as the boundaries of the system, thus excluding the agricultural stage, and starting from the entrance of the olives to the mill not considering transportation, to focus only on the oil production process and pointing out the contribution of the different extraction systems.

Figure 2. System boundaries of extra virgin olive oil production considered in the study (dotted arrows refer to the process outputs).

As regards the oil processing by-products, this study considers the possibility of reusing OP, obtained from the two centrifugal extraction processes, as input for composting and bio-gasification scenarios. In the evaluation of the environmental impacts associated with the considering recycling scenarios, it was assumed that 100% of the OP was reused for the scenarios.

While, OMWW management was not included in the system boundaries, because the oil mill analysed in the study, uses oil wastewater as soil conditioners, without prior treatment. For the same reason, bottling and distribution were also excluded, because each producer has a different approach (oil can be bottled in 0.75 L, 1 L, or 5 L bottles) [37]. In our study, the production of the machinery was not considered, due to the unavailability of
the data and the reduced environmental contribution of this factor, considering the long useful life and depreciation of the capital goods [37,38].

2.2. Life-Cycle Inventory (LCI)

Primary data were collected through the administration of the questionnaires to employees in the oil mill, in the period of October 2020 and January 2021. The oil mill is located in Moricone (Rome, Italy) (Figure 3).

The farm covers an area of 9 hectares (ha) in hilly surroundings, of which 7 hectares (ha) are planted with olive trees of the Salviana mono cultivar from Sabina, (42°14′48″84 N; 12°41′34″80 E), in the Lazio region. On average, the company produces a total of 5 tons of olives per year, and about 750 L of olive oil has been produced in the considered period. In particular, the oil produced presented an acidity of 0.22% (% oleic acid), thus resulting in the commodity classification of extra virgin olive oil [39]. The inventory data (Table 1) consisted of primary data for the year 2021, representing a single extraction. The latter data were subsequently combined with secondary data referred to the background production flows (i.e., olives production) obtained from databases Agribalyse v3.0.1, Ecoinvent v3.8, and World Food LCA Database (WFLDB), provided in SimaPro 9.2.2.

EC Regulation 1513/2001 defines virgin olive oil as all those “oils obtained from the fruit of the olive tree only by mechanical or other physical processes, under conditions that do not cause alteration of the oil, and which have not undergone any treatment other than washing, decantation, centrifugation, and filtration, excluding oils obtained by solvent or with adjuvants having a chemical or biochemical action or by re-esterification processes and any mixture with oils of other kinds” [40]. The following specification is added to extra virgin olive oil, defined as an oil “whose free acidity, expressed as oleic acid, is a maximum of 0.8 g per 100 g and having the other characteristics conforming to those laid down for this category”. Therefore, the extra virgin olive oil production process, as stipulated in EC Regulation 1513/2001, involves the pressing of olives exclusively by mechanical means and methods and physical processes that do not cause alteration of the oil, not including inputs other than olives, water, and electricity. The outputs consist of EVOO, OP, OMWW, and pomace hazel (namely “nociolino di sansa”, basically the crushed olive kernel). In this study, the data refer to the milling of 1000 kg of olives and imply the use of 85 L of water for the two-phase process and 30 L for the three-phase, as well as ~55.4 kWh of electricity, were employed for both processes.

The obtained EVOO is approximately 187 kg for the two-stage process and 175 kg for the three-stage process, with a larger amount of pomace for the two-stage (784 kg) compared to the three-stage one (376 kg). In contrast, less OMWW is obtained in the two-phase process (60 L) in comparison to the three-phase counterpart (535 L). Data were modeled on the databases in Simapro 9.2.2, especially, Electricity and Water from Ecoinvent 3.4 [41], while Olive was from World Food LCA Database [39]. The Ecoinvent 3.4 database contains LCI data for energy production, transportation, and chemical production, while World Food LCA Database is a comprehensive LCI database, returning data for agricultural
and agri-food products. In the case of electricity, the Italian mix was considered for the year 2021–2022, which is composed as follows: natural gas (43.2%), renewable sources (41.7%), coal (7.9%), nuclear (3.5%), oil sources (0.5%), other (3.1%) [42]. The Italian electricity mix, in accordance with the Ecoinvent consequential system, is based on projections of future electricity market compositions (Ecoinvent v3.8, 2022) by national and international authorities, such as the European Commission (2016) and the International Energy Agency (2016). Therefore, the data for electricity, olives, and water have also been adjusted for Italian conditions based on Simapro 9.2.2 and the database (i.e., Ecoinvent v3.9) updates. So, the data used are based on the average process from the international databases mentioned above (since they are the only ones available in the LCA software package used in this study) and adapted to be as consistent as possible with the objective and scope of this study.

Table 1. Life Cycle Inventory for the olive milling process (Referred to as 1000 kg olives).

| Input                  | 2-Phases | 3-Phases | Ref |
|------------------------|----------|----------|-----|
| Olives                 | 1000 kg  | 1000 kg  | [42]|
| Washing Electricity    | 5.5 kWh  | 5.5 kWh  | [43]|
| Water                  | 30 L     | 30 L     |     |
| Crushing Electricity   | 22 kWh   | 22 kWh   | [43]|
| Water                  | 9.4 kWh  | 22 kWh   | [43]|
| Gramoling Electricity  | 9.4 kWh  | 22 kWh   | [43]|
| Water                  | -        | 55 L     |     |
| Centrifugal extraction | 18.5 kWh | 28 kWh   | [43]|

| Output                 | 2-Phases | 3-Phases |
|------------------------|----------|----------|
| Industrial yield (%)   | 18.7%    | 17.4%    |
| Extra virgin Olive Oil | ~187 kg  | ~174 kg  |
| Pomace                 | ~783 kg  | ~376 kg  |
| Wastewater             | ~60 L    | ~535 L   |
| Emissions to air (kg CO₂ eq) | 189.4 | 353.9 |
| CO₂                    | 189.4    | 353.9    |
| CH₄                    | 17.4     | 32.5     |
| NOₓ                    | 4.1      | 7.5      |
| SF₆                    | 1.1      | 2.1      |
| Emissions to freshwater (kg P eq) | 0.016 | 0.016 |
| Phosphate              | 0.016    | 0.016    |
| Phosphorus             | 0.01     | 0.01     |
| Emissions to marine water (kg N eq) | 0.00730 | 0.00730 |
| Ammonium, ion          | 0.00730  | 0.00730  |
| Nitrate                | 0.10141  | 0.10141  |
| Nitrite                | 0.00002  | 0.00002  |
| Nitrogen               | 0.00427  | 0.00427  |

2.3. Life Cycle Impact Assessment (LCIA)

To have an assessment spectrum of the environmental performance of the two processes, the ReCiPe 2016 Midpoint (H) was used. This methodology was chosen and preferred over other calculation methods such as ILCD 2011, CML 2001, or TRACI, because having the availability of eighteen impact categories (compared to 16 of ILCD 2011 Midpoint, 15 of IMPACT 2002+, 11 of CML-IA Baseline, and 9 of TRACI) can provide more comprehensive, articulate, and specific results on the environmental impacts of olive milling than other methodologies with fewer impact categories. Therefore, Recipe 2016 Midpoint could give a broader picture with a greater degree of detail on the environmental impacts of production. It considers the following impact categories: Global Warming (GW); Stratospheric Ozone Depletion (SOD); Ionising Radiation (IR); Ozone Formation, Human Health (OFHH); Fine Particulate Matter Formation (FPMP); Ozone Formation, Terrestrial Ecosystems (OFTE); Terrestrial Acidification (TAP); Freshwater Eutrophication (FE); Marine Eutrophication (ME); Terrestrial Ecotoxicity (TEC); Freshwater Ecotoxicity (FEC); Marine
Ecotoxicity (MEC); Human Carcinogenic Toxicity (HCT); Human Non-Carcinogenic Toxicity (HNCT); Land Use (LU); Mineral Resource Scarcity (MRS); Fossil Resource Scarcity (FRS); Water Consumption (WC).

3. Results

The results of the LCA comparison between the two extraction systems are reported in Table 2.

| Impact Categories                                     | Unit   | Two-Phases | Three-Phases |
|-------------------------------------------------------|--------|------------|--------------|
| Global warming                                        | kg CO₂ eq | 212        | 396          |
| Stratospheric ozone depletion                         | kg CFC₁₁ eq | 0.000613  | 0.000646     |
| Ionizing radiation                                    | kBq Co-60 eq | 0.362     | 0.362        |
| Ozone formation, Human health                         | kg NOₓ eq | 0.294      | 0.373        |
| Fine particulate matter formation                     | kg PM₂.₅ eq | 0.218     | 0.275        |
| Ozone formation, Terrestrial ecosystems                | kg NOₓ eq | 0.299      | 0.379        |
| Terrestrial acidification                             | kg SO₂ eq | 1.07       | 1.27         |
| Freshwater Eutrophication                             | kg P eq  | 0.0173     | 0.0173       |
| Marine Eutrophication                                 | kg N eq  | 0.113      | 0.113        |
| Terrestrial ecotoxicity                               | kg 1.4-DCB | 114       | 114          |
| Freshwater ecotoxicity                                | kg 1.4-DCB | 0.724     | 0.724        |
| Marine ecotoxicity                                    | kg 1.4-DCB | 0.438     | 0.438        |
| Human carcinogenic toxicity                           | kg 1.4-DCB | 1.05     | 1.05         |
| Human non-carcinogenic toxicity                       | kg 1.4-DCB | 140       | 140          |
| Land use                                              | m² a crop eq | 183       | 183          |
| Mineral resource scarcity                             | kg Cu eq  | 0.348      | 0.416        |
| Fossil resource scarcity                              | kg oil eq | 22.4       | 30.4         |
| Water consumption                                     | m³      | 5.65       | 5.71         |

A remarkable difference was recorded in nine categories: Global Warming, Stratospheric Ozone Depletion, Ozone Formation—Human Health, Fine Particulate Matter Formation, Ozone Formation—Terrestrial Ecosystems, Terrestrial Acidification, Mineral Resource Scarcity, Fossil Resource Scarcity, and Water Consumption. Regarding the other impact categories, although the three-step process is more impactful than the two-step process, the differences are minimal. For example, regarding the Freshwater Eutrophication category, the two-phase, with 0.0173 kg P eq, has an impact of −0.01% compared to the three-phases process and a Marine Eutrophication of −0.0003%. Therefore, even evaluating the very low values of the other impact categories, and the considered perspective (Hierarchist, contemplating a 100-year time frame), the remaining categories were neglected. Then, the results concerning the impact categories with significant differences were expressed as relative impact (Figure 4).

In this case, through the software, the results of the study expressed in various units (kg CO₂ eq, kg SO₂, kg PM₂.₅, etc.) are multiplied by the characterisation factors and expressed in terms of relative impact. In other words, the sum of the emissions of the various phases is set equal to 100%, and the various individual results are calculated accordingly as relative impact. This type of visualisation makes LCIA results more usable, especially when applying calculation methods, such as the ReCiPe 2016 Midpoint, which considers impact categories with different units of measurement. This permits to analyse the categories as reported to the same scale and underlining specific trends, simplifying the comparisons between the two processes. The recorded results clearly showed the three-step extraction process is more impactful than the two-step one in all the categories, making the latter more sustainable. GWP is the impact category where the difference between the two methods is more evident, with the three-phase extraction generating about 212 kg CO₂ eq, −46% compared to the other process (396 kg CO₂ eq). The second category showing a valuable difference is then FRS, where the three-stage system generated a depletion of 30.4 oil eq, +26% compared to the two-stage system, which returned FRS.
value of 22.4 oil eq. In the range of 20–21% is the difference related to FPMP (0.275 kg PM$_{2.5}$ for the three-stage vs. 0.218 kg PM$_{2.5}$ for the two-stage, −20%), to OFHH (0.373 kg NOx eq vs. 0.294 kg NOx eq, −21.2%) and OFTE (0.379 kg NOx eq vs. 0.299 kg NOx eq, −21.1%), in favor of the two-stage extraction process. Slightly, smaller differences were recorded for the MRS, where the three-phase generated 0.416 kg Cu eq, −16% compared to the two-phases process (0.348 kg Cu eq) and TAP (1.27 kg SO$_2$ eq vs. 1.07 kg SO$_2$) −15% impacts for the two-phases process. Finally, in the case of SOD, the two-phases process produced $6.13 \times 10^{-4}$ kg CFC11 eq, a difference of −5% compared to the three-phases process ($6.46 \times 10^{-4}$ kg CFC$_{11}$ eq). Therefore, the LCA results showed that the two-step oil extraction process is generally more sustainable than the three-step process.

![Figure 4. LCIA of the two extraction methodologies compared: three phases vs. two phases (Results characterized). GWP: Global Warming Potential; SOD: Stratospheric Ozone Depletion; OFHH: Ozone Formation—Human Health; FPMF: Fine Particulate Matter Formation; TAP: Terrestrial Acidification Potential; MRS: Mineral Resource Scarcity; FRM: Fossil Resource Scarcity; WC: Water Consumption.](image)

4. Discussions

The LCA results showed that between the two oil extraction processes, the two-stage decanter process displayed the greatest environmental compatibility. These results can be mainly explained by considering the highest water volumes used in the three-step process. In this regard, over-exploitation of freshwater bodies, including groundwater used for water for agricultural/industrial use, can create a water crisis for future generations. Water scarcity is a global problem particularly concerning the countries of the Mediterranean area, affected by the highest level of water stress, with a score of 4.5 out of 5.00, as well as inequitable distribution of water resources. In this context, Italy ranks first in Europe for water withdrawals for drinking (9 billion m$^3$ per year) [43] and it is placed among European countries with medium to high water stress (with a score of 3.51 out of 5.00) [44]. In many Mediterranean regions, groundwater replenishment depends mainly on rainfall, although in recent decades the reduction in rainfall events hinders the renewal of sufficient water levels. An important aspect related to the use of groundwater is its extraction, which is mainly done through the use of electricity [45], which in turn requires additional water consumption [46]. Water extraction processes are therefore highly energy-intensive and have a high environmental impact due to the significant electricity production [42]. This one is mainly based on the use of fossil fuels and is responsible for the direct emission of
greenhouse gases, such as CO$_2$ and N$_2$O, which inevitably affect GWP, as well as FPMP [47]. Table 2 and Figure 3 highlighted that major differences were recorded in the impact categories mainly related to the atmospheric effects (GWP, SOD, OFHH, OFTE, FPME, and TAP), as well as depletion of abiotic resources (MRS, FRS, and WC). Thus, the production of electricity for water extraction can be considered as the main reason causing the increase in the environmental impact of the process. For example, in the case of GWP, the different electricity mixes produce the major impact on GHG emissions from electricity generation growing to 33.1 GT CO$_2$ eq in 2018 [48]. Therefore, power plants and electricity generation burning fossil fuels (coal, oil, or gas) are the main sources of GHGs, especially carbon dioxide and nitrous oxide. For example, one Million British Thermal Units of energy is produced by burning anthracite coal resulting in the release of 102 kg CO$_2$ eq [49]. Therefore, the excessive burning of coal and other fossil resources for electricity generation and power plant operation leads to consequent excessive production of CO$_2$, but also particulate matter, NO$_X$ (these also greatly influenced by energy intensity) [50] and SO$_2$, thus affecting GWP, ozone formation, terrestrial acidification, and particulate matter formation. In the LCA perspective of the extra virgin olive oil, the electricity generation required in the gramoling stage for the additional 55 L of water pumping, could lead to an increase in GWP, as well as in FPME, ozone formation, and TAP. In addition, a high potential for TAP could also result from desulphurisation processes during the processing and production of fossil fuels [51]. On the other hand, in the case of abiotic resources, particularly fossil and mineral resources, their depletion is likely to be related precisely to the reduction in coal and other fossil resources, as well as mineral resources for their extraction. Finally, in the case of water consumption, the difference in impact between the two extraction techniques can be related to a mere difference in quantity, but also the water supply for power plant cooling towers [50]. Additionally, the Ukraine war generated the current energy crisis and the related price raising, emphasizing the importance of energy source management and the transition to eco-friendly resources. Water saving, as well as lower greenhouse gas generation, could be useful strategies for Italy to achieve the goals set by the Water Framework Directive (2000/60/EC), requiring the achievement of the good qualitative and quantitative status of water bodies by 2027 [39,52]. At the same time, they could be a valuable tool to fit the sustainable development goals by 2030, especially sub-goals 6.4.1 (Water Stress) and 6.4.2. (Water Efficiency), the latter being far from fulfilled.

The data obtained from the LCA refer to the milling of 1000 kg of olives, thus to about 187 kg of oil for the two-phases process and 174 kg of oil for the three-phases process. These results, therefore, related to 1 kg of oil, lead to average values of 1.13 kg CO$_2$ eq per kg of oil for the two-phases process and 2.27 kg CO$_2$ eq per kg of oil for the three-phases process, showing how the former type of extraction is more sustainable than the latter, both in absolute terms and per kilo of the produced oil. Different LCA studies applied to olive cultivation have been published, following a “from cradle to grave” or “from cradle to farmgate” approach [19,20], mainly highlighting the agricultural phase and thus the contribution of fertilizers, pesticides, and water management. However, there is a paucity of works focusing on the employment of two-phase and three-phase extraction during the olive milling process. Studies investigating the olive milling process are relatively scarce, as most of them considered the entire supply chain, from olive growing to packaging [53]. In these cases, different assumptions and methodological frameworks, such as biomass conversion technologies, were considered [54]. Fernández-Lobato et al. considered both agricultural and industrial activities, based on a “from cradle to gate” approach, in the analysis of specific olive cultivars growing in Tunisia [7]. The same authors assessed the environmental compatibility of a cultivar in Spain, considering 1 kg of virgin oil (from cradle to gate) and an average impact of 1.93 to 3.00 kg CO$_2$ eq per kg, depending on the yield. [28]. Ben Abdallah et al., on the other hand, evaluated the harvest stage by considering nine production systems and comparing traditional, intensive, super-intensive, conventional, and organic systems [55]. Similarly, Romero-Gámez et al. compare eight traditional systems, three intensive systems, and one super-intensive system, considering
1 ton of olives as FU [36]. Guarino et al. propose an LCA for different production techniques (conventional and organic in the plains and hills), choosing a 0.75 L glass bottle of EVOO as FU and a “cradle to gate” perspective (from olive production to bottling) [10]. Similarly, De Luca et al. considered a cultivar growing in the South Italy area, by assuming a 0.75 L bottle of EVOO as FU and confining the analysis to “from cradle to the milling plant gate,” excluding distribution, sale, and use phase [5]. The results of their study range between 0.16–0.18 kg CO\(_2\) eq for the extraction phase and 5.11–5.13 kg CO\(_2\) eq for the agricultural phase. From the analysis of the literature related to LCA application in the olive sector, therefore, a comparison with other studies could lead to results that are not superimposable, mainly due to the different yields and different assumptions. Additionally, our aim was mainly focused on the industrial phase, highlighting the differences in impact between two and three-stage decanters. However, notable among the studies found is that of Iraldo et al., who analysed the environmental impacts of 1 kg of EVOO in Val di Cornia (Italy) with a three-step process, obtaining for the milling process alone a GWP of 3.63 kg CO\(_2\) eq, −59% compared to the results of our study [35]. However, the authors also employ sodium hydroxide and diesel in the milling process, since they also consider transport to the mill, which is excluded in the present evaluation. However, it is important to clarify some limitations of the performed study has led to the need for assumptions. Data for upstream and downstream processes were compiled from secondary data (retrieved from databases or based on global or regional averages), due to the lack of Italian databases, which will see the light of day in 2023 [56]. Thus, these data could not be always truly representative.

5. Challenges and Opportunities in the Elaio-Technical Sector

One of the biggest challenges related to olive oil production is the sustainable disposal of a large number of generated wastes. Specifically, OMWW, OP, and olive pomace hazel generate about 1550 kg of organic pollutants per 1000 kg of produced olive oil [57], thus resulting in an area of 150 m\(^3\) of municipal waste [58]. In the case of three-phase extraction, OMWW is composed by water (83–94% w/w), organic compounds (4–18% w/w), and inorganic compounds (0.4–2.5% w/w) [59], depending on the olive variety, maturity, water content, growing medium, harvest period, climate, and storage time of the fruit [17]. Typical parameters for characterizing OMWWs produced by the three-phase extraction process are chemical oxygen demand (COD), biological oxygen demand (BOD), pH, conductivity, total solids, lipids, and phenolic content, as reported in Table 3 [60]. These parameters highlight a significant amount of organic pollution associated with the triphasic OMWW and usually directly released into the surrounding environment, without any treatment. For example, OMWW, due to its high COD (54–318 g L\(^{-1}\)) and BOD (19–134 g L\(^{-1}\)) values, is considered one of the most polluting wastewaters [61,62]. In addition, it displayed reduced biodegradability, due to the massive presence of specific antioxidant compounds, such as polyphenol molecules.

| Parameter                  | Range of Values |
|----------------------------|-----------------|
| pH                         | 2.24–5.90       |
| Conductivity (\(\mu\)S cm\(^{-1}\)) | 5–81            |
| COD (g L\(^{-1}\))        | 16.5–190.0      |
| BOD (g L\(^{-1}\))        | 13.4–37.5       |
| Dry residue (g L\(^{-1}\)) | 11.5–102.5      |
| Organic matter (g L\(^{-1}\)) | 16.7–81.6   |
| Lipids (g L\(^{-1}\))     | 1.64–9.80       |
| Phenolic compounds (g L\(^{-1}\)) | 0.5–24.0   |

COD: Chemical Oxygen Demand; BOD: Biological Oxygen Demand.

Making a comparison with municipal wastewater, it has been estimated that the polluting power of OMWW is two hundred times higher. Thus, due to the high organic load
and phytotoxic/antibacterial phenolic substances, OMWW is considered one of the main pollutant effluents produced by agro-food industries. In contrast, the pollution parameters of biphasic OMWW are negligible since the production of liquid effluent from this extraction process is minimal (about 3%) [63]. Regarding OP, those derived from the three-phase and two-phase systems, on the other hand, displayed a very different composition, especially in terms of moisture, residual oil, and phenol content. For three-phase OP these parameters are in the following range: moisture, 45–55%; oil, 3.5–4.5%; and phenolic compounds, 200–300 mg per 100 g; while two-phase OP parameters are in the range 65–75 (moisture), 3–4% (oil), and 400–600 mg per 100 g (phenolic compounds) [64]. Triphasic OP has the consistency of moist soil, while biphasic OP is a dense sludge, with a pasty consistency, difficult to transport, store, and handle. Therefore, sustainable management of these wastes could be important for the sustainable growth of specific sectors of the food industry. Among the three by-products obtained during olive oil production, the reuse of the OP was chosen to be explored. Olive pomace represents more than 50% of the waste obtained in olive oil production [7] and it contains a remarkable added value, useful employment to generate energy from a renewable source, according to Directive 2009/28/EC [65]. Typically, OP was exploited in pomace factories for the extraction of residual oil using organic and hydrophobic solvents (such as n-hexane), but this type of oil has over time lost market to better quality seed oils sold at cheaper prices. This has led to the closure of many pomace factories, while the disposal of the OP has become a significant environmental issue. Therefore, a scenario analysis was accomplished to assess what might be preferable end-of-life for the valorisation of OP to mitigate the impacts of the disposal of waste deriving from the elaio-technical sector. Therefore, two valorisation opportunities were evaluated to be applied in the agriculture (composting) and energy (biogas production) fields, both applied to the two-step and three-step processes.

In these regards, four scenarios are therefore proposed:

1. Two-phases extraction process with final composting of the OP (including compost application) (S1);
2. Two-phases extraction process with final bio-gasification of the OP (S2);
3. Three-phases extraction process with final composting of the OP (including the application of compost) (S3);
4. Three-phases extraction process with final bio-gasification of the OP (S4).

It was assumed not to consider the intermediate process of extracting and refining the OP oil because of the lack of data. Moreover, some of these inputs are considered negligible for the purpose of the analysis. Finally, although the oil extraction would have been more cost-effective, the process is carried out using organic solvents and thus through an unsustainable process [66], contrary to the objective of our study. Further scenarios for the disposal or reuse of OMWW and OP will be considered in a subsequent study.

5.1. S1 and S3: Agricultural Use—Composting of Spent Pomace

Pomace can be used as such or after composting in a mixture with other technically and economically suitable biomasses, such as poultry manure to considerably increase the nitrogen content. However, the soil conditioner must meet standard limits of organic matter > 40%, C/N ratio < 30, pH in the range of 6.0–8.5, absence of pathogens, low levels of heavy metals, and inert and glass materials [67]. The use for agricultural purposes has been mainly favoured by the loss of organic matter in soils, a recurring problem especially in Italy, typically in southern regions, where organic matter decomposes more rapidly. Such depletion can cause profound changes in the physical, chemical, and biological characteristics of the soil, resulting in degenerative phenomena of which erosion and loss of fertility are the most obvious features. Oil by-products due to their high content of potassium, nitrogen, and phosphorus, must be uniformly spread on the ground to replenish the loss of organic matter in the soil.
5.2. S2 and S4: Energy Destination—Biogas Production

Another particularly interesting valorisation scenario for olive pomace could be its bio-gasification to produce biofuel (biogas), consisting mainly of methane and carbon dioxide. Spent pomace, from a regulatory point of view, represents biomass that can be used for energy purposes [65]. As OP takes origin during an exclusively mechanical extraction process, it does not contain additives or foreign chemicals, but only natural organic and inorganic compounds. It follows that its chemical composition is suitable for bio-gasification. Biogas represents an excellent fuel for small-scale valorisation plants aimed to apply a circular economy model and a valuable resource to develop a system to ensure energy autonomy for medium-sized olive oil mills. The use of pomace for biogas production creates a new virtuous and economically viable circuit for a by-product that has lost value over time.

The results of the scenario analysis are depicted in Figure 5. Considering the whole production process, and thus also considering the disposal scenarios, regarding the GWP (Figure 5A) the two-step extraction process (S1 and S2) turns out to be more sustainable than the three-step process (S3 and S4) in both valorisation scenarios. If the OP was to be composted and applied to the soil, in the two-step process (S1) a reduction of 205 kg of CO\textsubscript{2} was recorded, while in the three-step process (S3) this increase was less consistent (140 kg CO\textsubscript{2} eq). However, this reduction could be even greater if the OP was bio-gasified, with a CO\textsubscript{2} reduction of 1745 kg CO\textsubscript{2} eq in the two-step process (S2) and 1199 kg CO\textsubscript{2} eq in the three-step process (S4). The reduction in CO\textsubscript{2} in both disposal processes is mainly related to the use of compost as a soil amendment, avoiding the production of synthetic fertilizers (and related emissions) [68]. On the other hand, biogas production could limit the exploitation of additional fossil fuels and the resulting emissions [69,70].

Regarding SOD, OFHH, FPMF, OFTE, and TA, it is necessary to consider that the emissions of PM\textsubscript{2.5}, SO\textsubscript{2}, and NO\textsubscript{X}, along with other generated gases (CH\textsubscript{4}, hydrocarbons) in the anaerobic digestion and bio-gasification stages, are not vented to the atmosphere. Although the inventory data in the various databases in SimaPro refer to average processes and technologies, in Italy, composting plants are equipped with bio cells with a suction system. This technical aspect, together with the presence of adequate piping, means that the gases present, along with water vapor, are conveyed to suitable biofilters that have the function of retaining all emissions from the aerobic composting stages [71]. Therefore, the data related to SOD, OFHH, FPMF, OFTE, and TA are to be considered negligible because PM\textsubscript{2.5}, CFCs, NO\textsubscript{X}, and SO\textsubscript{2} are not released into the atmosphere.

Regarding the depletion of abiotic resources, for the MRS category (Figure 5B), the results again showed that the preferable scenario is S2 because a reduction of 0.77 kg Cu eq induces greater savings of mineral resources than the other scenarios (−0.49 kg Cu eq for S1, −0.33 kg Cu eq for S3 and −0.53 kg Cu eq for S4). Regarding the FRS category (Figure 5C), similar results were obtained. S2 (−756 kg oil eq) is preferable as compared to the other scenarios (−554 kg oil eq for S1, −380 kg oil eq for S3, and −519 kg oil eq for S4) because of the resources that would be saved for fossil gas production [72]. Further, for WC (Figure 5D), S2 induces less water wastage (0.73 m\textsuperscript{3} of water) than the other valorisation pathways. Therefore, the results of the scenario analysis show that in the entire production process, the two-step process is more sustainable than the three-step process, either in the case of composting treatment or in the case of biogas production. In addition, between the two valorisation scenarios, the bio-gasification process appears to be more sustainable than the composting process since it induces greater CO\textsubscript{2} reduction in both scenarios for all impact categories. Therefore, in the elaio-technical sector, the preferable process might be the two-step decanter process, where OP is bio-gasified (S2), while the least preferable, although it still induces a positive benefit for ecosystems, is the three-step extraction with final composting (S4). However, within the two-step extraction process, there are still some challenges that lead olive farmers to prefer the three-step process. The three-stage decanter, although found to be less sustainable than the two-stage decanter, remains the most widely used for several reasons, mainly economic. Most of the oil mill
industries are small and medium-sized companies and it is considered not convenient to remodel their plants concerning the cost incurred in switching the decanter from three to two stages. In this case, the investment would be not justified, due to the difficulty to amortize the expense for a two-stage decanter [53]. In the case of companies with large turnovers, it might be convenient, but the high-water content of biphasic pomace oil could make pomace oil extraction more expensive, difficult, and impactful, due to the high use of organic solvents and energy [73]. In addition, pomace management requires specific facilities (such as storage tanks with special valves, pumps, and tankers) [74]. Therefore, two-phase technology could transfer the problem of the olive waste disposal of the olive mill factory to the seed oil refineries. For these reasons, there is still often a tendency to prefer the three-phase system.

![Figure 5. GWP (A), MRS (B), FRS (C), and WC (D) for the four scenarios considered. S1: 2-step extraction and composting of olive pomace, S2: 2-step extraction and bio-gasification of olive pomace, S3: 3-step extraction and composting of olive pomace, S4: 3-step extraction and bio-gasification of olive pomace.](image)

### 6. Conclusions

This research proposes a life cycle assessment approach to compare two different methods of EVOO extraction, a two-phase process vs. a three-phase one. The recorded results show that among the two processes, the two-phases system resulted to be more sustainable than three-phase extractions, with lower values in all considered impact categories. This finding appears mainly related to the extra addition of water, usually required in the three-phase system. Water extraction requires a relevant amount of energy, as well as relevantly increases the volume of the residue to be disposed of. Specifically, the two-phase extraction process induces 46% CO$_2$ savings (212 kg CO$_2$ eq) compared to the three-phase
process, and changes in the range of 5–26% in the other impact categories were recorded as well, thus showing preference over the three-phase extraction process. In this framework, it could be worth enhancing greater efforts in terms of energy efficiency and water productivity, thus ensuring a rationalized and sustainable production by a unit of input. In particular, the adoption of a two-phase decanter could advantage mill owners in terms of continuous and automated labour, more compact machinery, OMWW reduction and disposal problems, and better composition and shelf-life of the obtained oil (aspect being also valuable for consumers). All considered, the broader application of the two-phase extraction method should be promoted also with the support of National and/or European funds to sustain the higher costs of adoption. This will result in environmental benefits in the long term and a global collective advantage in terms of resource-saving and reduced environmental pollution. However, one of the main challenges of the sector also includes the management of the by-products with a much higher environmental load compared to the extraction technology itself. To this purpose, some of the most promising solutions could be the possibility of introducing innovative technologies that can improve energy efficiency, and the valorisation of olive oil by-products (e.g., pomace). Bio-gasification and composting technologies were evaluated as possible useful scenarios for the reuse of OP. Specifically, the first one appears the best available technology for bioenergy production, since it induces greater benefits in terms of CO₂ savings. For example, bio-gasification of OP induces savings of −1756 kg CO₂ eq in the two-step compared to the same end-of-life in the three-step process (−205 kg CO₂ eq) and, in turn, greater savings than composting (−140 kg CO₂ eq for the two-step vs. −1199 for the three-step), savings of −0.77 kg Cu eq (two-phase), greater than the −0.49 kg Cu eq of the three-phase, and −756 kg oil eq (two-phase), greater than the −554 kg oil eq of the three-phase. For these reasons, it emerges that bio-gasification is the preferable process. Anyway, it should be underlined that the olive oil sector waste management is a very complex issue, related partly to the chemical features of these by-products, but also to economic, technological, regulatory, and organizational aspects that many times prevent the real adoption of very exciting research purposes by geographically scattered small–medium mills. In this scenario, the LCA approach surely represents an extraordinary tool to evaluate each technology/best practice and its environmental sustainability. However, it should be considered only the starting point leading the way to a more integrated approach involving academia, producers, and decision-makers to switch from a huge problem to an environmental and economic gain.

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