Should extra virgin olive oil production change the approach? A systematic review of challenges and opportunities to increase sustainability, productivity, and product quality

Alessio Cappelli, Lucrezia Lupori, Enrico Cini

Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence, Florence, Italy

Abstract

Extra virgin olive oil is constantly gaining interest for its outstanding health and nutritional properties. However, the production process generates roughly four times more waste than the quantity of oil. For this reason, improvements in extra virgin olive oil production and in the valorisation of olive mill by-products are urgently needed, thus motivating this work. The first aim of this review is to summarise current knowledge regarding machines, plants, and processes in extra virgin olive oil production. The second aim is to suggest specific innovations and improvement strategies to increase sustainability, productivity, profitability, and quality. This review clearly highlighted the copious advantages of modern production plants, which can control oxidation processes, avoid temperature increases, and significantly improve the quality of extra virgin olive oil. However, the production chain must face the monumental environmental sustainability challenge. In this direction, this review highlighted that scientific and technological research has made great strides in managing olive mill by-products, suggesting several strategies related to the recovery of polyphenols and applications in agriculture, feed, and food. However, to succeed in this ambitious project, harmonious teamwork between European policies, states, regions, and private companies is needed.

Introduction

The olive tree is native to the geographic region, which goes from South Caucasus (Iran) to Mesopotamia and Palestine (Lombardo, 2007). Moreover, with its majesty and elegance, it is the plant that best represents the countries facing the Mediterranean area. For this reason, it is widely cultivated in plains and hills territories. Until today, 95% of the world's olive growing surface is located in the Mediterranean basin zone and bordering. (Lombardo, 2007). The olive tree is a medium-sized evergreen arboreal plant (4-6 m in height) (Barone and Di Marco, 2007), able to withstand arid climate conditions (Rapoport *et al*., 2016; Patsios *et al*., 2020). Nevertheless, in modern intensive and super-intensive olive groves, the olive tree has a lower height (*i.e*., 2, 2.5 m) to simplify the mechanical harvesting (Rebufa *et al*., 2021). Although the availability of hundreds of olive tree cultivars have different shapes, sizes, phenolic content, and characteristics, the average composition of an olive drupe used for oil production is 22–25% oil, 50–60% vegetation water, 19–24% carbohydrates (pectin, cellulose, and hemicelluloses), 1.6–2% proteins and free nitrogen, and 1.5–2% minerals and ashes (Seçmeler and Galanakis, 2019).

The oil is mainly concentrated in the pulp of the drupe (Seçmeler and Galanakis, 2019). However, it is essential to highlight that the oil is also contained in the olive seed (OS) (Losito *et al*., 2021). Additionally, this oil is particularly interesting since it contains nuezhenide, another secoiridoid contained only in the oil of the OS (Losito *et al*., 2021). Although polyphenols are present in minimal amounts (mg/Kg) in extra virgin olive oil (EVOO), they play a key role in human health due to their powerful radical scavenging activity (Seçmeler and Galanakis, 2019; Losito *et al*., 2021). Moreover, they considerably affect the sensorial characteristics of the EVOO; in particular, oleuropein provides a bitter taste, and oleocanthal gives the typical chemesthetic sensation of spiciness (Seçmeler and Galanakis, 2019; Losito *et al*., 2021). The EVOO is also known for its very interesting nutritional properties, which allow counteracting the onset of several diseases (Romani *et al*., 2019). These proprieties are due to the high levels of mono

Correspondence: Alessio Cappelli, Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence, Piazzale delle Cascine 16, 50144, Florence, Italy.
Tel.: +39.055.2755876.
E-mail: alessio.cappelli@unifi.it

Key words: EVOO; olive mill waste water; by-product valorisation; circular economy; polyphenols; olive tree leaves.

Conflict of interest: the authors declare no potential conflict of interests.

Funding: none.

Availability of data and materials: data and materials are available by the authors.

Received for publication: 12 July 2022.
Revision received: 3 November 2022.
Accepted for publication: 23 November 2022.

Journal of Agricultural Engineering 2023; LIV:1479
doi:10.4081/jae.2023.1479

and polyunsaturated fatty acids and to the presence of phenolic compounds, phytosterols, tocopherols, and squalene (Romani *et al.*, 2019; Losito *et al.*, 2021).

As highlighted in earlier work (Cappelli *et al.*, 2021), the production of EVOO continues to increase. In particular, according to a European Commission report, approximately 3 million tons of olive oil are produced each year worldwide (European Commission, 2020; Cappelli *et al*., 2021). Two million tons are produced in the EU; in particular, the leading member states involved are Spain (66% of EU production); Italy (15%); Greece (13%); and Portugal (5%) (European Commission, 2020; Cappelli *et al.*, 2021). However, as reported by Espadas-Aldana *et al.* (2019) and Cappelli *et al.* (2021), 80% of the olive mass is composed of pulp, stones, and water; therefore, the production process of EVOO generates roughly four times more waste than the quantity of oil. Consequently, the management and disposal of olive mill by-products represent the most significant environmental problem in all Mediterranean countries. Moreover, these wastes are very harmful to the environment due to the high organic load, which contributes to the phytotoxic nature and antimicrobial effect (Cappelli *et al.*, 2021).

Furthermore, EVOO production generates additional adverse effects on the environment, like emissions and depletion of resources (Salomone and Ioppolo, 2012). In particular, Salomone and Ioppolo (2012), Banias *et al.* (2017), and Patsios *et al*. (2020) highlighted serious environmental impacts in the different phases of EVOO production through their life cycle assessment studies. These authors examined several unit operations like machines and tools in the farms, energy consumptions, and waste management flows. The results highlighted the need to rethink and overhaul this supply chain's approaches to increase sustainability, productivity, profitability, and quality, thus motivating this work. Therefore, the first aim of this review is to summarise current knowledge regarding machines, plants, and processes in the EVOO production chain. The second aim is to suggest specific innovations and improvement strategies to increase the sustainability, productivity, profitability, and quality of this essential production chain, with positive impacts on the environment.

Search strategy

The literature review explored three databases: Science Direct, PubMed, and the Web of Science. The search strings used were as follows:

(olive AND "washing water") OR "olive washing"

"olive crushing" OR ("olive paste" AND malaxing) OR ("olive paste" AND centrifugation) OR ("virgin olive oil" AND filtration)

"olive leaf" OR "olive mill waste water" OR "olive mill pomace" OR "waste olive seed"

No language, time, or publication status restrictions were imposed, and all duplicates were excluded. The initial results were screened by reading the title and abstract (articles that only consisted of an abstract and/or index were excluded at this point) and successively by a full-text reading. All articles concerning sustainability, production, and quality aspects of EVOO production were included, while those not relevant to this review were discarded. Figures 1, 2, and 3 summarise, in the form of a flow chart, the obtained results for Science Direct, PubMed, and the Web of Science, respectively.

Extra virgin olive oil production systems: traditional pressure olive oil mills versus modern productions plants

Traditional pressure olive oil mill

The oldest and most popular extraction method is based on pressure. It exploits mechanical movements able to exercise pressure on the olive paste to separate the oil from the solid phase

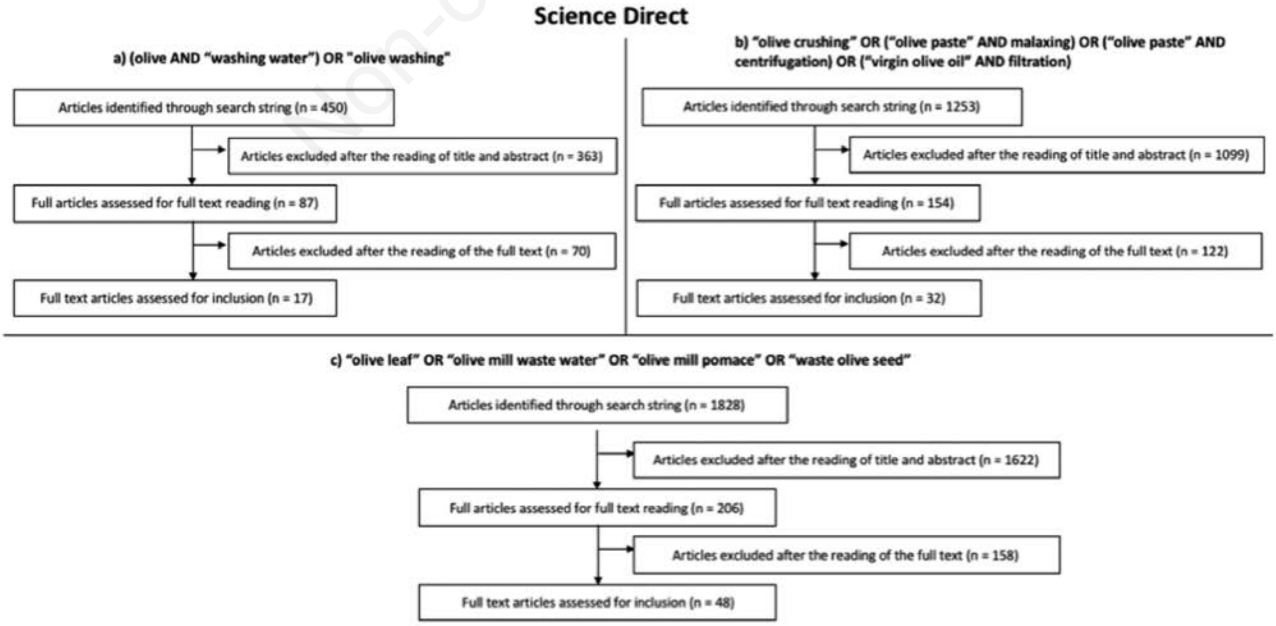

Figure 1. Flow charts pertaining to the selection process of papers on ScienceDirect, summarising the results of the systematic literature review.

(pomace) (Di Giovacchino, 2013). The oldest method for crushing the olives is employed in this traditional plant. It involves using old stone crushers that usually consist of a stone base and two or three upright rotating millstones with diameters between 100 and 140 cm (Di Giovacchino, 2013; Calabriso *et al*., 2015). This old crushing system is usually enclosed in a metal basin, often with scrapers and paddles to spread the olives under the stones and to circulate and expel the paste (Calabriso *et al.*, 2015). The olive crushing duration ranges from 20 to 30 min for a batch of olives (Di Giovacchino, 2013). Moreover, this crushing also provides a partial mixing of olive paste (malaxing) which favours the oil droplets' coalescence (Di Giovacchino, 2013).

After olive crushing and paste malaxing, a thin layer of paste is placed on circular mats. For every five mats, a circular metallic disk is inserted to ensure that the circular mats remain adequately stacked on top of each other (Di Giovacchino, 2013). Successively,

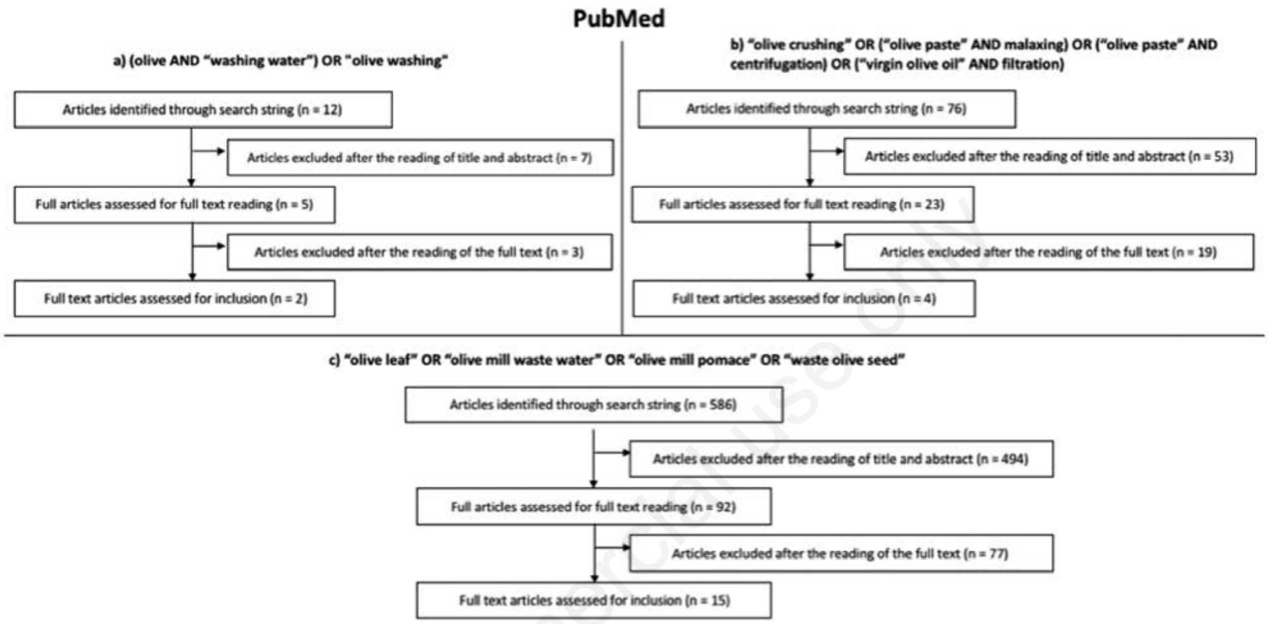

Figure 2. Flow charts pertaining to the selection process of papers on PubMed, summarising the results of the systematic literature review.

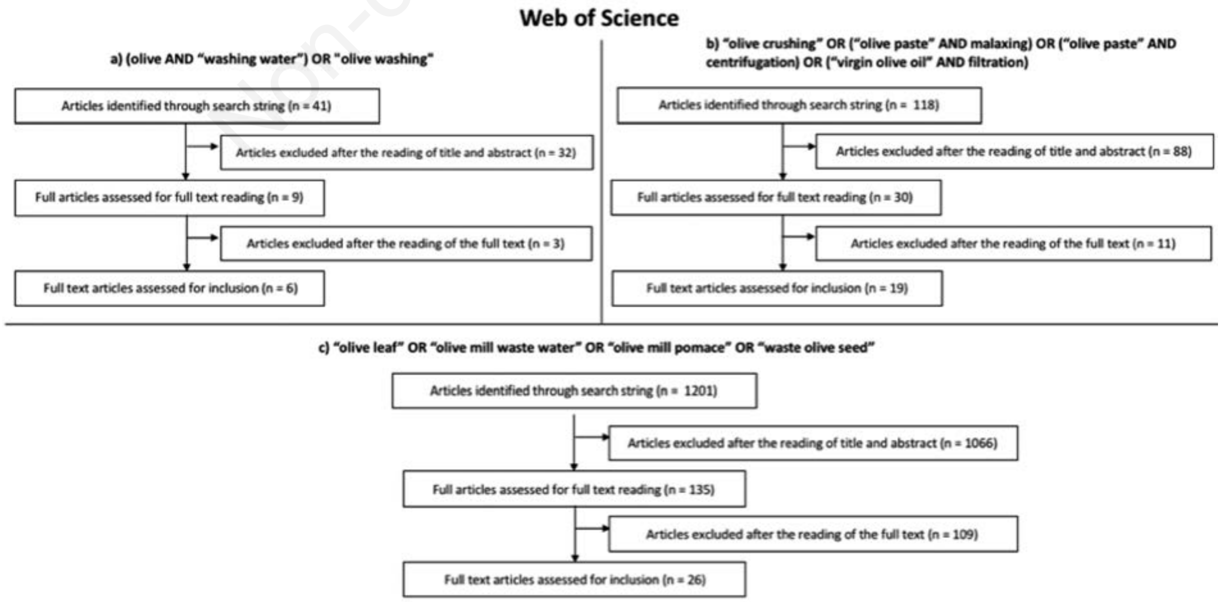

Figure 3. Flow charts pertaining to the selection process of papers on Web of Science, summarising the results of the systematic literature review.

by superimposing other mats and metallic disks with olive paste, strong pressure is applied to the thin layers of paste. Applying this force allows the extraction of the oily must (olive oil + vegetation water), which percolates out from the system. Finally, the oily must is collected at the bottom of the system in a specific collection tank. In more upgraded traditional olive oil mills, the oily must is sent to a vertical centrifuge, which improves the separation of EVOO from vegetation water (Di Giovacchino, 2013).

This traditional system discloses more disadvantages than advantages. The main advantages have been highlighted by Di Giovacchino (2013) and Calabriso *et al.* (2015). In particular, Calabriso *et al.* (2015) highlighted that the slow movement of the stone crushers could reduce the problem of paste heating during crushing, compared to other modern crushers. Furthermore, Di Giovacchino (2013) reported that the oil yield is higher in traditional olive oil mills due to longer crushing time and lower millstone speed. Despite these advantages, the traditional olive oil mills show several disadvantages and critical issues: firstly, this system does not allow a proper olive washing process to ensure the safety of the products (Cappelli *et al.*, 2019); secondly, machinery and plants are bulky, expensive, and slow (Di Giovacchino, 2013; Calabriso *et al.*, 2015); thirdly, the traditional plant has a low feed capacity, and the process is characterised by discontinuity (one of the biggest problem nowadays) (Di Giovacchino, 2013; Calabriso *et al.*, 2015); fourthly, the hygienic design of machines and plants makes washing and cleaning operations very difficult, with consequent hygienic issues; last but not least, traditional pressure olive oil mills present the massive problem that the olive paste is continuously exposed to oxygen for the entire production process with critical problems on chemical, physical, and sensorial characteristics of the obtained oils (Di Giovacchino, 2013; Calabriso *et al*., 2015).

Modern production plants based on lower oxygen exposure and olive paste centrifugation

EVOO production has grown in many European countries and in the United States, Argentina, Australia, and the Middle East, as the EVOO presents highly sought nutritional, antioxidant, and nutritional properties (Ochando-Pulido *et al*., 2012). Therefore, continuous and more efficient EVOO production plants were developed (Ochando-Pulido *et al.*, 2018). These modern plants functioning is based on olive washing and drying followed by olive crushing, paste malaxing and centrifugation, and, finally, EVOO filtration (Di Giovacchino, 2013; Clodoveo *et al*., 2015). These modern and continuous plants can guarantee an increased yield in oil, up to 20–25%, and a significant improvement in EVOO quality (Pulido, 2016). As highlighted by Cappelli *et al.* (2019), the washing stage of olives is a crucial unit operation for guaranteeing the safety and quality of EVOO. This essential stage should be performed using up-to-date washing machines with spray nozzles and air-blade blowing systems with laminar flow to dry the cleaned olives.

After the washing and drying of the olives, the olives are processed to produce the olive paste. As reported below, several types of olive crushers could be used: hammers, metal-toothed, and blades (or knives) crushers (Di Giovacchino, 2013). Among these, the knife crushers are the most suitable since they are able to reduce the increase in temperature, producing a paste with optimal particle size (Tsimidou *et al*., 2020). The main purpose of crushing is to reduce the size reduction of olive fruit tissues and the breakdown of vegetal cells to facilitate the release of oil from the elaioplasts (Clodoveo *et al*., 2015). More precisely, the main objectives of cell disruption are: i) the release of the maximum amount of oil present in the cells; ii) the release of the bioactive compounds and their subsequent dissolution in the oily phase; iii) the preservation of the product by limiting detrimental effects in the subsequent processing steps like emulsion formation, reduction of the oily drops diameter, excessive heating of olive paste, etc. (Clodoveo *et al.*, 2015).

An essential parameter to preserve the nutritional content in EVOO is the contact with the oxygen during the main unit operations such as crushing, malaxing, centrifugation, and filtration (Clodoveo *et al.*, 2015). In particular, several authors highlighted the key importance of the strategic control of oxygen concentration in the olive paste, notably in olive crushing and malaxing processes, but also in the subsequent unit operations. In particular, the double-edged sword is related to the fact that if a high amount of air is in contact with the olive paste, it causes a significant deterioration of EVOO quality due to the oxidation of polyphenols and fatty acids. On the other hand, in case of no contact with air, the lipoxygenase (LOX) pathway cannot generate the mild oxidation of polyunsaturated fatty acids (PUFA), which allows obtaining desired flavours in EVOO such as fruity, grass, and artichoke. That is why a little (and controlled) amount of air is let into the system via the crushing system. Another essential parameter to be controlled is the olive paste temperature. In particular, during the whole production process, the temperature must never exceed 30°C (better if lower than 27°C) in order not to incur the deterioration of the product (Parenti et al., 2008; Clodoveo *et al*., 2015; Catania *et al*., 2016).

After olive crushing, the paste is sent to the malaxing machine for paste malaxing (Di Giovacchino, 2013). The aims of this unit operation are: i) the complete disintegration of mesocarp cells to increase the oil extraction via the mechanical action of the malaxer and through enzymatic activity; ii) the formation of bigger oil droplets (by the reunion of little oil droplets) leading to the formation of a continuous phase which will be more easily separated in the centrifugation stage by the decanter. The latter phenomenon is called coalescence. Successively, the malaxed paste is sent to the decanter. The extraction process by centrifugation allows the separation of oil from vegetation water and insoluble solids (Souilem *et al*., 2017). The separation is performed by a horizontal centrifuge, called a decanter (Clodoveo *et al*., 2015), composed of a power supply unit rotating at differential speed and by a drum. The separation of phases is favoured by the centrifugal force developed in the drum (Souilem *et al.*, 2017). The centrifugation system can have two or three outputs (Clodoveo *et al*., 2015). In the case of three outputs, at the end of the process, it is possible to obtain oil, olive mill waste water (OMWW), and olive pomace (OP) (Clodoveo *et al.*, 2015); while, in the case of two outputs, at the end of the centrifugation process, it is possible to collect oil and wet OP (Clodoveo *et al*., 2015). As Clodoveo *et al*. (2015) highlighted, the decanter with two outputs could present higher advantages like a minor waste of water, reduced production of OMWW, and higher content in phenols and flavours in the obtained oils. However, in both cases, the obtained oil is cloudy and needs to be filtered to ensure its stability during storage.

The presence of suspended solid particles of vegetable tissue and vegetation water in the oil is the main responsible for the turbidity of the oils outgoing the decanter. In particular, during storage, the oil can undergo several reactions, such as hydrolysis of polyphenols, hydrolysis of triglycerides, and chemical oxidation of fatty acids (Di Giovacchino, 2013). Furthermore, if the EVOO remains in contact with the aqueous layer for a long time, it can acquire organoleptic defects; therefore, the oil must be filtered immediately after centrifugation (Bakhouche *et al*., 2014). The filtration systems used in the EVOO are the following: i) systems based on the use of organic or inorganic filtration adjuvants in combination with filtration equipment; ii) membrane filtration; iii) new filtration systems proposed as alternative processes (such as the polypropylene filter bag system and filtration based on the flow of inert gas); iv) filtration with cellulosic boards inserted in a filter press (Bubola *et al.*, 2017). In conclusion, the modern production plants show copious advantages compared to the traditional discontinuous plants, such as continuity of production, higher oil yield, improved quality of the obtained EVOO, higher polyphenol content, the possibility to control the temperature during the whole production process, lower air exposure of the olive paste, and the possibility to modulate the characteristics of the oils to be produced (in the crushing process).

Main findings

Results of the systematic literature review

The initial dataset consisted of 5565 initial items. This was reduced to 169 after applying the selection criteria previously reported (search strategy). Removing duplicates left a total of 67 items: 11 book chapters, 10 reviews, and 46 research papers. Figures 1, 2, and 3 summarise, in the form of flow charts, the selection process, consistent with the PRISMA statement (Moher *et al.*, 2009). In particular, Figures 1, 2, and 3 report the results obtained for Science Direct, PubMed, and the Web of Science, respectively.

Innovations and improvement strategies in olive washing and in olive washing water management

The harvested olives might be contaminated by microorganisms and by impurities like leaves, sprigs, ground, or rock fragments (Di Giovacchino *et al.*, 2002). Therefore, the impurities must be removed to prevent damage to the production plants and to avoid negative influences on the EVOO quality (Di Giovacchino, 2013). For this reason, most olive washing machines are composed of three blocks named defoliator, debranching, and finally, the washing machine. Olive washing is a hygienic operation to preserve the natural and nutritional characteristics of the olive oil that, according to the International Olive Council (T. 33/Doc. n. 2-4 2006), must be performed using drinking water.

As highlighted by Cappelli *et al.* (2019), olive washing is a critical phase that has been slightly neglected or, leastwise, did not experience the same involvement, regarding experimental research efforts, despite representing one of the crucial steps for the quality of the finished product and for the reduction of the environmental impacts. Therefore, the latter authors developed and tested an innovative washing machine able to improve the olive washing stage. Moreover, the tested washing machine proved to reduce the processing time and consumption of energy and water (Cappelli *et al.*, 2019). This machine comprises a stainless-steel tray, a conveyor belt, two washing nozzle lines, and three air-blade blowing systems with a laminar flow for olives drying (Cappelli *et al.*, 2019). As a result, the new washing machine was able to clean the olives and significantly reduced processing time and water consumption (from 210 L/h to 150 L/h) (Cappelli *et al.*, 2019). In particular, the above-mentioned reduction in water consumption and the processing time is mainly related to the more usable and quicker cleaning system introduced in the suggested washing machine.

Other authors investigated the topics of reducing water consumption and olive washing water (OWW) recovery. In particular, water recovery is becoming a key factor in developing new innovations and improvement strategies to achieve a circular economy (Cifuentes-Cabezas *et al.*, 2021). In this direction, Maza-Márquez *et al.* (2017) suggest the most interesting approach, which uses a photobioreactor for OWW treatment. The system can treat up to 3926 L of OWW per day and consists of an activated-carbon pre-treatment column and a tubular photobioreactor unit (80 tubes, 98.17 L volume, 2 m height, 0.25 m diameter) (Maza-Márquez *et al.*, 2017). The latter authors found that photobioreactor was an effective and environmentally friendly method for removing phenols, COD, BOD, turbidity, and colour from OWW, with an efficiency close to 95% (Maza-Márquez *et al.*, 2017). Finally, Maza-Márquez *et al.* (2017) highlighted the essential role of interplay between green algae, cyanobacteria, and Proteobacteria in OWW bioremediation.

Innovations and improvement strategies in extra virgin olive oil production

The EVOO is produced from olives only through mechanical procedures. Nevertheless, all these operations can influence the nutritional content, flavour, and overall final quality of EVOO (Clodoveo *et al.*, 2015). The most critical phases are olive crushing and paste malaxing; however, also centrifugation and filtration play an essential role (Reboredo-Rodríguez *et al.*, 2014). Therefore, in recent years, several innovations improved the EVOO production chain, increasing the yield and the final quality of the product (Taticchi *et al.*, 2021). The following sub-paragraphs summarise the most interesting innovations and improvement strategies in the four major stages of EVOO production: olive crushing, paste malaxing, paste centrifugation, and EVOO filtration.

Innovations and improvements in olive crushing

The hammers crusher

Several types of metal crushers might be used in EVOO production. Among these, the hammers crusher is widely employed in the EVOO production chain. The hammers crusher is composed of a circular crushing chamber positioned vertically where a variable number of hammers rotate at high speed to crush and hurl the olives against a metal screen (Calabriso *et al.*, 2015; Tsimidou *et al.*, 2020). The produced paste passes through the holes of the metal screen and is successively pumped in the malaxing machine (Tsimidou *et al.*, 2020). Veillet *et al.* (2009) highlighted that EVOO obtained using a hammers crusher had a significantly higher content of polyphenols and an improved quality compared to the EVOO obtained using a traditional stone crusher. Despite these expected results, the hammers crusher presents several disadvantages.

Calabriso *et al.* (2015) and Tsimidou *et al.* (2020) highlighted that the high rotational speed of the hammers creates more emulsification of the oil and water within the paste. Moreover, the latter authors found that the hammers crusher generates a significant increase in the olive paste temperature (up to 13-15°C) that considerably worsens the chemical and sensorial composition of the obtained oil. In particular, this process causes a higher oxidative degradation (Tsimidou *et al.*, 2020). For this reason, the manufacturers tried to solve the problem by equipping the hammers crusher with a jacket that allows the passage of a refrigerant (Tsimidou *et al.*, 2020). In the case of correct management of hammers rotational speed and reducing the increase in olive paste temperature, the use of the hammers crusher might presents some advantages as high output, compact size, and low cost (Calabriso *et al.*, 2015).

The blades (or knives) crusher

This type of crusher can cut the pulp and seed of the olive, exploiting the rotational speed of the knives (Morrone *et al.*, 2017; Guerrini *et al.*, 2017; Tsimidou *et al*., 2020). Therefore, the use of the knives crusher has several advantages compared to the other metal crushers (Morrone *et al*., 2017; Guerrini *et al*., 2017; Tsimidou *et al*., 2020): i) lower increase in paste temperature and higher quality of the obtained oils; ii) possibility to modulate more easily the granulometry of the paste according to the crushing speed and the dimension of the holes of the metal screen; iii) release of more desirable volatiles compounds and improved sensorial characteristics of the obtained EVOO (Morrone *et al*., 2017; Tsimidou *et al.*, 2020).

In particular, Morrone *et al*. (2017) tested (in comparison) two types of crushers, hammers, and blades in the production of EVOO from olives at four stages of ripeness to analyse the effect of these two factors on oil quality indices. The results reported by the latter authors found that ripeness exerted a stronger influence on EVOO quality. Despite this, according to the results reported in Table 1 by Morrone *et al*. (2017), the EVOO obtained using a blades crusher has lower free acidity and peroxide values. Guerrini *et al*. (2017) confirmed this, which highlighted the importance of correctly managing the crushing speed during olive crushing with knives crusher. In particular, the analysis of variance analysis found a strong relationship between crusher speed and oil quality, highlighting that faster crushing significantly increases chlorophyll and total polyphenols content (Guerrini *et al*., 2017). Secoiridoids are particularly affected, and concentrations of 3,4-DHPEA-EDA and p-DHPEA-EDA significantly varied in oils produced at different crushing speeds (Guerrini *et al*., 2017). From the lowest to the highest speed, a difference of roughly 50 mg/kg (on about 400 mg/kg) for total polyphenols and about 40 mg/kg of 3,4-DHPEA-EDA was found (Guerrini *et al*., 2017). Finally, panel testing found higher bitterness and astringency scores in oils produced at a higher speed, confirming the earlier results (Guerrini *et al*., 2017).

The metal-toothed crusher

The metal-toothed crusher (or disks crusher) is composed of two toothed disks; one is stationary while the other is revolving (Tsimidou *et al*., 2020). In this type of crusher, the olives are fed into the crusher through a short screw conveyor. The disks tear the olives apart, and the resulting paste drops into a hopper or is directly pumped to be transferred into the malaxing machine. As highlighted by Caponio *et al*. (2003) and Tsimidou *et al*. (2020), the metal-toothed crusher causes a minor increase in the temperature of the paste compared to the hammers crusher. In particular, the results of Caponio *et al*. (2003) highlighted that oxidative degradation in oils obtained from hammer-crushed olives was significantly higher than in those obtained from disks-crushed olives.

Moreover, a significant inverse correlation was found between the Rancimat induction time values and the amounts of oxidised triacylglycerols (Caponio *et al*., 2003). In conclusion, consistent with Caponio *et al*. (2003) and Tsimidou *et al*. (2020), the hammers crusher causes a more significant increase in olive paste temperature and a higher level of oxidative degradation in EVOO compared to the disks crusher. Finally, it is important to highlight the lack in the literature of a research paper aimed to compare hammers, knives, and disks crushers regarding the increase of paste temperature during crushing (despite being widely known in the practice that knives crusher is less affected by this problem).

Innovations and improvements in olive paste malaxing

The olive paste malaxing is an essential and critical unit operation that allows to increase the oil extraction and yield, facilitate the coalescence of little oil droplets in bigger ones, and, if properly managed, improve the characteristics of the EVOO (Catania *et al*., 2016). In particular, this unit operation allows: firstly, to increase the oil extraction via the mechanical action of the malaxer and through enzymatic activity; and secondly, to form bigger oil droplets (by the reunion of little oil droplets) leading to the formation of a continuous phase which will be more easily separated in the centrifugation stage by the decanter. The latter phenomenon takes the name of coalescence.

This operation consists of a slow and continuous mixing of the paste for about 30–60 minutes at a temperature of 28–30°C (Clodoveo *et al*., 2015). It is important to highlight that nowadays, in current practice, the malaxing process has been definitely shortened to 15-20 min (or even lower) to avoid the outbreak of defects in EVOO. For the same reason, the paste temperature during malaxing must be kept under 30°C (better under 27°C) (Parenti *et al*., 2008). The following subparagraph summarises the most interesting innovations and improvement strategies aimed to upgrade the olive paste malaxing.

Airtight malaxer machines with atmospheric headspace control

In the newest EVOO production plants, the malaxer is an airtight machine that presents a confined or controlled atmosphere in the headspace to properly manage the amount of oxygen during the olive paste malaxing process (Amirante, 2018). The use of airtight malaxer allows, firstly, to limit the contact between air and olive paste and, secondly, to increase the content of antioxidants, safeguarding precious elements like polyphenols and other aromatic components (Amirante, 2018). However, as previously reported and as highlighted by Amirante (2018), in case of no contact with air, the LOX pathway cannot generate the mild oxidation of PUFA, which allows obtaining desired flavours in EVOO. This might result in EVOO with high polyphenols content but with poor flavours (Catania *et al*., 2016; Amirante, 2018). This is confirmed by the results of Pastore *et al*. (2014), which highlighted that excessive reduction of O_2 concentration in the malaxing chamber significantly affected the formation of all the examined volatile compounds. Particularly, lowering oxygen levels hindered the formation of lipoxygenase-derived volatiles weakening odours and flavours of artichoke, fresh fruity, and fresh-cut grass (Pastore *et al*., 2014). As a result, during the malaxing process, it is essential to control the amount of air in contact with the paste, performing a short malaxing process and avoiding the increase of olive paste temperature over 27°C (Parenti *et al*., 2008; Catania *et al*., 2016; Amirante, 2018). Some studies tested airtight malaxer machines containing inert gas (nitrogen and argon) in the headspace (Clodoveo *et al*., 2015). However, the olive paste malaxing with inert gas presents a high cost and entails losses in the oil flavours (Clodoveo *et al*., 2015). Furthermore, as highlighted by Tamborrino *et al*. (2010), the presence of a small oxygen concentration is essential, especially in the initial part of malaxation, to develop the typical aromas appreciated in the best EVOO. In conclusion, as highlighted by Tamborrino *et al*. (2014), the best innovation to improve the management of the headspace during paste malaxing, and, consequently, the whole malaxing process, is to develop and implement automatically controlled malaxer machines able to manage the most important parameters like the amount of oxygen, malaxing time, and paste temperature (Parenti *et al.*, 2008).

Use of ultrasounds, microwaves, and megasonic technologies in malaxing systems

Clodoveo *et al.* (2013), Leone *et al.* (2014), Leone *et al.* (2017) and Tamborrino *et al.* (2021) investigated the effects of innovative technologies, like microwaves and ultrasounds, on the olive paste malaxation process. The working principle of ultrasounds allows to break down the cell walls of the plant tissue, releasing oil, phenols, tocopherols, chlorophylls, and carotenoids (Clodoveo *et al.*, 2013). Furthermore, Leone *et al*. (2014) found that microwaves reduce the paste's conditioning time from 40 minutes (traditional approach) to a few seconds. In particular, the direct heating system presented by the authors led to a more uniform time-temperature profile, avoiding overheating the olive paste and reducing the complexity of the EVOO plant. Therefore, the application of these technologies in malaxation is very appealing not only for the advantages mentioned above but since the application of ultrasound and microwave can replace the traditional malaxation process, which represents a bottleneck of the EVOO production process. As a result, their application in malaxation allows them to obtain a continuous process and other additional benefits like the reduction of energy consumption, costs, and, finally, an easier cleaning (Clodoveo *et al*., 2013).

In this direction, Tamborrino *et al*. (2021) tested an innovative prototype of an integrated tube-in-tube heat exchanger with a rotating spiral coil and microwave module to replace traditional malaxation processes in an industrial EVOO production plant. The nominal mass flow rate showed that the prototype was perfectly integrated into the plant (Tamborrino *et al*., 2021). In particular, thanks to the transport activity of the rotating spiral coil, the prototype did not affect the feed pressure of the paste from the crusher to the malaxer (Tamborrino *et al*., 2021). The heat exchanger reduced the malaxing time by 50% without decreasing oil extraction (Tamborrino *et al*., 2021). Additionally, the microwave module increased oil extractability and enhanced the quantitative and qualitative composition of hydrophilic phenols without altering legal quality parameters (Tamborrino *et al*., 2021).

Similar results were obtained by Leone *et al.* (2017). In particular, the latter authors evaluated the ability of microwave heating to substitute the malaxation process without and with megasonic treatment of the paste. For this reason, an industrial microwave and a megasonic prototype were installed in a commercial EVOO plant (Leone *et al*., 2017). As a result, oil yields showed increased extractability (1.98% and 2.25%, respectively) after exposing the microwave-treated and malaxed paste to a megasonic field (Leone *et al*., 2017). In conclusion, the study of Leone *et al*. (2017) confirmed the ability of microwaves to substitute the malaxation and, for the first time, demonstrates the effectiveness of a subsequent megasonic intervention to increase oil yield.

Vacuum-assisted malaxing systems

High vacuum technology has been incorporated into an innovative assisted extraction system applied to EVOO production by Taticchi *et al*. (2021). The vacuum system changed the mechanical and structural properties of the olive cells, increasing the coalescence of the oil droplets due to substantial cellular and intracellular mass transfer during the process (Taticchi *et al*., 2021). Moreover, the application of this technology almost doubled the phenolic content in the obtained EVOO (Taticchi *et al*., 2021). On the other hand, the content of volatile compounds responsible for the EVOO flavours significantly decreased (Taticchi *et al*., 2021). The use of this new extraction technique involving high vacuum had a positive impact on EVOO phenolic content but, in contrast, significantly reduced the volatile compounds as a function of processing temperature (Taticchi *et al*., 2021).

Despite this, Taticchi *et al*. (2021) highlighted that the extraction process carried out at the lowest malaxation temperature (20°C) showed a limited reduction in the volatile compounds, minimising the negative impact on the sensory quality of the EVOO. In addition, the high vacuum treatment also causes significant stripping of molecules not involved with positive sensory notes, such as ethanol, ethyl acetate, and acetic acid (Taticchi *et al*., 2021). This effect needs to be confirmed and further investigated to evaluate the possibility of a remarkable reduction of the volatile compounds responsible for alterations and decreases in the sensory quality of EVOO. In conclusion, despite the interesting results reported by Taticchi *et al*. (2021), the application of this technology to EVOO production needs further investigation.

Use of pulsed electric fields in malaxing systems

The impacts of pulsed electric field technology on EVOO production have been investigated by Puértolas and De Marañón (2015). In particular, the application of pulsed electric fields (2 kV/cm; 11.25 kJ/kg) to the paste significantly increased the extraction yield by 13.3% compared to the control (Puértolas and De Marañón, 2015). Moreover, using pulsed electric fields technology significantly increased total phenolic content, total phytosterols, and total tocopherols, which were 11.5%, 9.9%, and 15.0% higher, respectively (Puértolas and De Marañón, 2015). In addition, Puértolas and De Marañón (2015) did not highlight the negative effects on chemical and sensory characteristics of the EVOO in relation to the application of pulsed electric fields. Therefore, this technology could be considered very promising in improving EVOO production.

In conclusion, Puértolas and De Marañón (2015) highlighted the following advantages in the case of pulsed electric fields application: i) enrichment in human-health-related compounds, such as polyphenols, phytosterols, and tocopherols; ii) increased and facilitated EVOO production, with subsequent increase of profits; iii) no negative effects on the chemical and sensory characteristics of EVOO. However, although the application of pulsed electric fields technology seems to be very promising, further investigations are needed to clarify, in more depth, the mechanism of action and to realise comparative studies with other emerging technologies like microwaves and ultrasounds.

Innovations and improvements in olive paste centrifugation

Nowadays, improved decanters use an automatic system to adjust the operative parameters (Souilem *et al*., 2017). In particular, as highlighted by Amirante (2018), a decanter with computerised control of the differential speed between the drum and the auger and of the couple exercised by the auger on the paste during the extraction phase might considerably improve the centrifugation process. These systems allow optimising the operating performances of the machine, choosing the optimal feed flow rate, determining the optimal position of the paste discharge pipe inside the decanter, correctly managing the differential speed of the auger with respect to the drum, and, finally, controlling the water and oil discharge levels (Amirante, 2018). As found by Amirante (2018), in these innovative decanters, the extraction yield is always higher, even in the case of a low dilution of the paste. Moreover, using these innovative decanters considerably reduces oil losses in the pomace, improving the qualitative characteristics of the final product (Amirante, 2018). However, further innovations and improvement strategies were tested and introduced in the olive paste centrifugation stage; Masella *et al*. (2012) compared conventional vertical centrifugation in contact with air with vertical centrifugation under inert gas. The results of centrifugation under inert gas provided a significant reduction of the oil oxygenation in terms of reduced dissolved oxygen concentration and oxidative indexes (Masella *et al*., 2012). However, with respect to minor compounds like chlorophyll, total polyphenols, and volatile compounds, the latter authors did not find any statistically significant differences (Masella *et al*., 2012). In conclusion, the technical implementation of inert gases in vertical separators seems practicable to preserve EVOO quality traits and extend the product's shelf-life. Moreover, this solution can be easily implemented by the olive mill owner with homemade adjustments of the existing machines and by industrial plant manufacturers.

Innovations and improvements in EVOO filtration

Unfiltered oil is cloudy due to the presence of suspended solid particles of vegetable tissue and vegetation water emulsified in the oil (Bubola *et al*., 2017). The sensorial and lipidic degradation, performed in unfiltered oil mainly by yeast and enzymes, leads to several deterioration reactions such as hydrolysis of polyphenols, hydrolysis of triglycerides, and chemical oxidation of fatty acids (Di Giovacchino, 2013; Bubola *et al*., 2017). This generates sensorial defects easily perceivable by consumers, in addition to the severe nutritional impoverishment of the product. For these reasons, the filtration of EVOO is an essential unit operation to ensure stability during shelf-life. Currently, in the most modern EVOO production plants, oil filtration is performed using cellulosic boards inserted in a filter press (Bubola *et al*., 2017). Contrarily, in industrial plants, oil filtration is carried out using conventional systems based on the use of organic or inorganic filtration adjuvants in combination with filtration equipment (Bubola *et al*., 2017). However, scientific and technological research has greatly improved EVOO filtration stage. Thus, the following subparagraph summarises the most interesting innovations and improvement strategies aimed to improve EVOO filtration.

Cross-flow and membrane filtration

Based on the knowledge of the EVOO characteristics, Lozano-Sánchez *et al*. (2010) highlighted that microfiltration and ultrafiltration have also been used to filter EVOO. In this case, different commercial inorganic membranes with tubular mono- or multichannel configuration might be used. However, Bottino *et al.* (2004) tested membrane cross-flow filtration as a different and innovative filtration process for EVOO. The results reported by the authors showed that the removal of damaging substances through membrane filtration could be achieved in a single step without the addition of filter aids (Bottino *et al*., 2004). Moreover, membrane filtration does not alter the filtered EVOO's chemical composition (Bottino *et al*., 2004). Despite the fact that Bottino *et al*. (2004) showed the applicability of membrane filtration in the EVOO production chain, further investigation is needed, particularly regarding the fouling of the membranes, which represent one of the biggest problems in these filtration systems.

Filtration system based on the flow of inert gases

The University of Bologna has patented this filtration system (World Patent Application no. WO 2009/107096; Kind Code: A2 of September, 3, 2009). The system is based on the flow of inert gases in the filtration equipment divided into two modules (Lozano-Sánchez *et al*., 2010). The first module consists of a tank where the olive oil is introduced, and the filtration process is carried out (Lozano-Sánchez *et al*., 2010). The second module is the storage tank of inert gases used as a filter aid (nitrogen and argon) (Lozano-Sánchez *et al*., 2010). The distinctive trait of this system is that the second module has an insertion dispositive connected by the bottom filter tank that introduces a constant inert gas flow directly in the centre of EVOO mass (Lozano-Sánchez *et al.*, 2010). The gas insertion generates a circular movement of the oil mass that facilitates the precipitation of the suspended solids, avoiding using any organic materials (Lozano-Sánchez *et al.*, 2010). Moreover, at the end of the filtration step, the EVOO is already in an environment saturated with inert gases; this provides more suitable storage conditions to extend EVOO shelf-life (Lozano-Sánchez *et al.*, 2010).

Addition of a steel pre-filter before the filtration with cellulosic boards

Among filter systems, plate filter presses equipped with cellulosic boards are the most used systems in small and medium companies because the filters are cheap, and the technique does not impair the sensory and chemical traits of the EVOO (Guerrini *et al*., 2015). However, plate filter presses have some disadvantages: their operating capacity is low, they require a lot of manpower, and filter sheets trap part of the processed oil (Guerrini *et al*., 2015). Furthermore, a considerable cost is associated with the exhausted cellulosic board disposal (Guerrini *et al*., 2015). Therefore, Guerrini *et al*. (2015) tested the insertion of a steel pre-filter into the filtration system to retain part of the suspension. The results of the latter authors highlighted that the plate filter press with the added pre-filter was able to process about 1.8 times the amount of oil typically processed in a batch (Guerrini *et al*., 2015). As a result, the operative capacity was improved, and the amount of oil trapped in the sheets was reduced (Guerrini *et al*., 2015). Moreover, the number of required filter sheets was almost halved (the same applies to their purchase and disposal costs) (Guerrini *et al*., 2015).

Concerning the pre-filter efficacy and efficiency, a surface fouling mechanism is seen in the traditional filter press configuration. At the same time, particle retention in the new system is due to depth fouling, demonstrating that adding a pre-filtration step leads to the more effective use of filter sheets (Guerrini *et al*., 2015). In conclusion, Guerrini *et al*. (2015) found that adding a pre-filtration step in EVOO production improves the filtration cycle. Specifically, the pre-filtration step can double the duration of the cellulosic boards (Guerrini *et al*., 2015). Consequently, the consumption of filter sheets in the traditional plate filter press can be halved. Moreover, Guerrini *et al*. (2015) highlighted that the amount of oil lost in the sheets is significantly reduced. Finally, with respect to EVOO chemical composition, the latter authors did not find any statistically significant differences, highlighting the suitability of this application for EVOO filtration.

Management of olive oil mill by-products

As highlighted by Cappelli *et al*. (2021), approximately eighty percent of the olive mass is composed of pulp, stones, and water. Therefore, the production process of EVOO generates four times more waste than the quantity of oil (Cappelli *et al*., 2021). Consequently, the disposal of olive mill wastes [mainly OWW, OMWW, olive seed (OS), and pomace] represents a significant environmental problem in all Mediterranean countries (Cappelli *et al*., 2021). In particular, these olive oil mill wastes are very harmful to the environment due to the high organic load, which contributes to the phytotoxic nature and antimicrobial effect of the olive wastes (Cappelli *et al*., 2021). Therefore, the recovery of these by-products, particularly polyphenols could lead to double advantages for human health and the environment. As a result, in the following subparagraph, the most interesting innovations and improvement strategies aimed to valorise EVOO by-products were summarised in detail.

Opportunities related to olive tree leaves reuse

Olive tree leaves represent one of the most interesting olive mill by-products. This by-product is obtained by olive tree pruning and by the production of EVOO, where olive leaves represent approximately 10% in weight of the raw materials conferred to the olive oil mill for EVOO production (Talhaoui *et al*., 2015). In several countries of the Mediterranean area, there is, unfortunately, the common illegal practice of burning olive tree leaves (with other by-products such as olive tree branches and twigs), significantly increasing fire risks and environmental pollution (Cappelli *et al*., 2021). As suggested by a few authors in the literature, to valorise this important waste, one of the most interesting strategies could be related to the extraction of polyphenols from the olive tree leaves (Talhaoui *et al*., 2015; Cappelli *et al*., 2021). This allows the removal of pollutant elements obtaining extracts rich in polyphenols (mainly oleuropein) with high commercial value (Borjan *et al*., 2020; Cappelli *et al*., 2021).

A significant number of extraction methods have been developed to obtain phenolic extracts from olive tree leaves (Talhaoui *et al*., 2015). The most widely used extraction methods are based onsolid–liquid extraction by maceration of the olive tree leaves (dried and powdered) in a solvent (Talhaoui *et al*., 2015). Common extraction solvents used are methanol, ethanol, acetone, ethyl acetate, and diethyl ether, as well as aqueous alcohol mixtures (Talhaoui *et al*., 2015). However, more modern, rapid, and green techniques have been developed. In particular, as highlighted by Talhaoui *et al*. (2015) and Putnik *et al*. (2017), microwave-assisted extraction, pressurised liquid extraction, supercritical fluid extraction, and ultrasound-assisted extraction seem to be the most interesting innovative approaches. On the other hand, polyphenol extraction from olive tree leaves requires significant economic investments (Talhaoui *et al*., 2015; Cappelli *et al*., 2021). That is why alternative approaches, like mixing olive tree leaves with other by-products to produce high-quality compost, were suggested in the literature (Cappelli *et al*., 2021). Although the use of polyphenol extracts from olive tree leaves in cosmetic and pharmaceutical applications seems to be the most interesting strategy, other innovative implementations were found in the literature. For example, phenolic extracts from olive tree leaves might be used in the food industry as food preservatives with a double ability to prevent lipid oxidation and to add nutritional value to foods (Putnik *et al*., 2017). However, the use of phenolic extracts has a limited application in the food industry since these compounds have a very pungent and bitter taste that consumers do not always appreciate (Flamminii *et al*., 2020). Another interesting possibility is suggested by Moudache *et al*. (2016) and Flamminii *et al*. (2020), which tested the incorporation of bioactive compounds present in olive tree leaves, such as oleuropein, luteolin, and hydroxytyrosol, into edible films or food packaging materials to maximise their antioxidant capacity. The results of the latter authors showed that olive tree leaves extracts could eliminate free radicals from the package's headspace (Moudache *et al.*, 2016). In conclusion, the results of Moudache *et al*. (2016) showed that active film containing olive tree leaf extracts can be used in food packaging to improve and extend the shelf-life of the products (and not only to store foods as in current packaging properly).

Challenges and opportunities related to olive mill waste water treatment

Among the olive mill by-products, OMWW is the most investigated in the literature. This could be because the most polluting and phytotoxic elements derive from OMWW, although they represent the most plentiful source of bioactive compounds (Souilem *et al*., 2017). The literature review highlighted that the most widely used systems for OMWW treatment are: physical/chemical methods; biological digestion or inactivation processes; advanced chemical oxidation processes; and, finally, filtration and membrane separation processes (Ioannou-Ttofa *et al*., 2017).

As Ioannou-Ttofa *et al*. (2017) highlighted, physical methods cannot reduce the toxicity of the OMWW to acceptable limits. However, biological treatment systems, like anaerobic bioreactors, can convert OMWW organic content into biogas for energy production (Ioannou-Ttofa *et al*., 2017). Cerrone *et al.* (2011) suggested a solution for OMWW treatment based on biological agents, such as *Panus tigrinus, Trametes versicolor,* and *Funalia trogii*. However, the effective use of this solution is possible only after OMWW dilution to reduce the pollutant load (Cerrone *et al*., 2011). Moreover, as highlighted by Cerrone *et al*. (2011), dilution is illegal in most olive oil-producing countries, and it would be problematic due to the massive amount of water consumed in the process. Another approach in OMWW treatment is the advanced oxidation process. This system is based on creating very reactive species, such as hydroxyl radicals, to quickly break down a wide range of organic/inorganic compounds and eliminate effluents' toxicity (Ioannou-Ttofa *et al*., 2017). However, given the high content and value of polyphenols in OMWW (even higher than in EVOO), the filtration and membrane separation techniques seem to be the most valuable systems to valorise this by-product.

In this direction, Bazzarelli *et al*. (2016) tested an innovative process for water recovery and polyphenols encapsulation from OMWW. The system combined conventional pressure-driven processes, such as microfiltration and nanofiltration, and "relatively" new membrane operations like reverse osmosis and membrane emulsification (Bazzarelli *et al*., 2016). The process was based on a first acidification step to remove suspended solids followed by nanofiltration to obtain water from the permeate side and a concentrated polyphenolic solution from the retentate side (Bazzarelli *et al*., 2016). In particular, the retentate was treated via reverse osmosis, and the concentrated polyphenolic extract was encapsulated in a water-in-oil emulsion by membrane emulsification (Bazzarelli *et al*., 2016). As a result, the integrated membrane system was efficient in all the operating units with high fluxes compared with other literature data (60 and 7 L/m^{2}h for microfiltration and nanofiltration, respectively) (Bazzarelli *et al*., 2016).

Additionally, high polyphenols rejections were measured for the nanofiltration membrane (Bazzarelli *et al*., 2016). More specifically, considering the process mass balance, the treatment of 1000 L of OMWW allowed us to obtain 1463 g of polyphenols (85% of the initial content) and 800 L (80% of the initial volume) of purified water. In conclusion, Bazzarelli *et al*. (2016) proved the efficacy and efficiency of membrane separation techniques and the emulsification process, suggesting a highly innovative technique for the valorisation of OMWW.

Opportunities related to olive mill pomace reuse

As highlighted by Di Giovacchino (2013), the most ancient and traditional method for reusing OP is olive pomace oil production. This oil is extracted using a solvent (hexane) from specialised establishments. Successively, the oil extracted from the pomace is refined and mixed with a small amount of EVOO (approximately 5%) (Di Giovacchino, 2013). However, the OP oil production process generates, as production waste, vast amounts of pomace that must be found in sustainable reuse. For this reason, the literature review found different approaches, consistent with the current circular economy and sustainability policies, to reuse OP. A few authors in the literature suggested a possible reuse of OP for polyphenols extraction; however, the latter authors did not suggest the potential reuse of the residual wastes. For this reason, only the following strategies related to agriculture, feed, and food applications, have been considered.

With respect to applications in agriculture, Lacolla *et al*. (2021) tested the OP as an alternative organic fertiliser on cereal crops. In particular, the latter authors tested the effects of OP fertilisation on grain yield, protein, and polyphenol content of emmer wheat crop (cv *Giovanni Paolo*) cultivated in the south of Italy (Lacolla *et al*., 2021). The results showed that applying OP at 140 Mg per hectare in the first year and 70 Mg per hectare in the second year gave the best grain yield (Lacolla *et al*., 2021). However, fertilisation treatments did not significantly affect polyphenol content, while ferulic acid in the emmer grain fertilised with OP showed a significant increase (Lacolla *et al*., 2021). Regarding feed applications of OP, Herrero-Encinas *et al*. (2020) investigated the effects of supplementing broiler diets with a bioactive OP extract on growth performance, digestibility, gut microbiota, bile acid composition, and immune response. The latter authors concluded that the inclusion of 750 ppm of OP extract containing a minimum of 10% total triterpenes and 2% polyphenols positively affects growth in broiler chickens (Herrero-Encinas *et al*., 2020).

Finally, with respect to food applications, Simonato *et al*. (2019) and Balli *et al*. (2021) tested the enrichment of pasta with different percentages of OP. Simonato *et al*. (2019) found that fortification with OP significantly increased the total phenolic content and antioxidant capacity in both cooked and raw pasta. Moreover, it increased the swelling index, water absorption, cooking loss, and firmness of the final product (Simonato *et al*., 2019). On the other hand, OP incorporation decreased the optimum cooking time (Simonato *et al*., 2019). Balli *et al*. (2021) found similar results on tagliatelle enriched with OP pâté, highlighting an additional increase of 3% in the pasta fibre content. These results show that pasta fortified with OP could represent a healthy product and a potential technological alternative for the food industry.

Additional use of OP in foods is suggested by Ribeiro *et al*. (2021). The latter authors tested the incorporation in yoghurt of liquid-enriched powder and pulp-enriched powder obtained from OP. The addition of these powders (2% and 1% respectively) into yoghurt allowed to reach the claim “good source of fibre” and provided 5 mg of hydroxytyrosol in a standard yoghurt (120 g) (Ribeiro *et al*., 2021). Moreover, also yoghurts’ unsaturated fatty acids profile was positively influenced (Ribeiro *et al.*, 2021). According to these results, OP powders can be considered a key source of dietary fibre, polyphenols, and unsaturated fatty acids (Ribeiro *et al*., 2021). In conclusion, given the enormous amount of OP produced annually, their incorporation into dairy products could be a straightforward way to increase the economic and environmental sustainability of the EVOO production chain (Ribeiro *et al*., 2021).

Opportunities related to olive seed reuse

The OS mainly consists of lignocellulosic materials such as hemicellulose, cellulose, and lignin (Rodríguez *et al*., 2008). However, it also contains proteins, fats, phenols, and free sugars; given this composition, the recovery and valorisation of OS seem to be very interesting. Different approaches in OS reuse have been found in the literature: as fuel to produce electricity or heat, as plastic filler, as a source of squalene and polyphenols in cosmetic/pharmaceutical industries, as animal feed, and, finally, as a raw material for resin production (Rodríguez *et al*., 2008). However, one of the widest application is related to the use of OS as fuel to produce heat in olive oil mill (and not only) since it is available in abundance, can be easily separated from pomace, and have reduced emissions of NO_x and SO_2 given the low content of nitrogen and sulphur (Rodríguez *et al*., 2008). In addition, its calorific value (4,075 Kcal/Kg) is very close to the pellets used in stoves (Rodríguez *et al*., 2008; Parenti *et al*., 2014).

Rodríguez *et al.* (2008) highlighted many other strategies to reuse OS. It can be used as active carbon (due to its microporous structure), which could be used to remove undesirable colours, dyes, flavours, or contaminants such as arsenic or aluminium (Rodríguez *et al*., 2008). Moreover, Rodríguez *et al*. (2008) reported that OS could be hydrolysed in furfural production to obtain fertiliser. A very interesting (and eco-friendly) application is related to using OS as plastic filler. Rodríguez *et al*. (2008) reported that OS can be mixed with polypropylene to produce a new thermoplastic polymer that can produce industrial films and other homogeneous polymeric compounds. Regarding applications in the food industry, Bolek (2020) highlighted that the wasted OS can be used as a functional ingredient to enrich foods due to their polyphenols and fibre content. The latter author tested the substitution of wheat flour with 0, 5, 10, and 15% of OS powder for the production of biscuits (Bolek, 2020). The results of Bolek (2020) highlighted that wheat flour replacement with olive stone powder significantly increased antioxidant activity, fat, and fibre content in the tested biscuits. In particular, the biscuits prepared with 15% olive stone powder had 30.44±0.03% DPPH radical scavenging activity, 11.22±0.09% crude fiber, and 26.32±0.22% fat (Bolek, 2020). Moreover, Bolek (2020) performed a sensory evaluation which gave a positive opinion to the substitution of up to 15% with OS powder.

Conclusions and future trends

This review has highlighted the urgent need for changes in the EVOO production chain. Starting from the comparison between traditional pressure olive oil mills and modern productions plants, this review clearly highlighted the copious advantages of modern EVOO production plants, which can control oxidation processes, avoid temperature increases, and, finally, significantly improve the quality of EVOO both from a nutritional and sensory point of view. Moreover, several innovations and improvement strategies to improve EVOO production, like the use of knives crushers for olive paste production, the employment of ultrasounds, microwaves, and pulsed electric fields to improve paste malaxing in airtight malaxing machines, and the use of inert gases to improve the centrifugation and filtration processes, were previously suggested.

However, the EVOO production chain has to face another big issue: the monumental challenge of environmental sustainability. As highlighted above, approximately eighty percent of the olive mass is composed of pulp, stones, and water; therefore, the production process of EVOO generates four times more waste than the quantity of oil. According to the current circular economy and sustainability policies, these by-products must be valorised both to reduce environmental pressures and provide an additional income source for olive oil mills (which usually work intensively only 3-4 months per year). In this direction, the review highlighted that scientific and technological research has made great strides in the management of EVOO by-products, suggesting several strategies related to the recovery of polyphenols and applications in agriculture, feed, and food. Despite the fact that this topic needs further investigation, we can state that by implementing some of the suggested innovations and improvement strategies, it is possible to achieve remarkable progress for this essential production chain.

Nevertheless, olive oil mills cannot be left alone to fight this monumental challenge since they lack the funds to implement the suggested by-product valorisation strategies. For this reason, we suggest a political intervention at the European, national, and regional levels aimed at funding the creation of cooperatives or regional by-products management centres that, thanks to the profits obtained from the sale of phenolic extracts and other products, will remain operative in the territory. This approach will have positive effects not only on the environment but also on the productivity and profitability of the entire region. Moreover, other potentially positive effects on the territory, such as improvement to the landscape and attractiveness of rural areas and the increase of job opportunities and employability, are expected from the application of this approach. In conclusion, a harmonious teamwork between European policies, states, regions, and private companies is needed to succeed in this ambitious project.

References

Amirante P. 2018. Dalle olive all'olio: evoluzione delle tecnologie. Available from: https://www.researchgate.net /publication/323078812_DALLE_OLIVE_ALL%27OLIO_EVOLUZIONE_DELLE_TECNOLOGIE.

Bakhouche A., Lozano-Sánchez J., Ballus C.A., Bendini A., Gallina-Toschi T., Fernández-Gutiérrez A., Segura-Carretero A. 2014. A new extraction approach to correct the effect of the apparent increase in secoiridoid content after filtration of virgin olive oil. Talanta. 127:18-25.

Balli D., Cecchi L., Innocenti M., Bellumori M., Mulinacci, N. 2021. Food by-products valorisation: grape pomace and olive pomace (pâté) as sources of phenolic compounds and fiber for enrichment of tagliatelle pasta. Food Chem. 355:129642.

Banias G., Achillas C., Vlachokostas C., Moussiopoulos N., Stefanou M. 2017. Environmental impacts in the life cycle of olive oil: a literature review. J. Sci. Food. Agric. 97:1686-97.

Bazzarelli F., Piacentini E., Poerio T., Mazzei R., Cassano A., Giorno L. 2016. Advances in membrane operations for water purification and biophenols recovery/valorization from OMWWs. J. Membrane. Sci. 497:402-9.

Barone and Di Marco. Fiorno P. (ed). 2007. Caratteristiche generali della pianta. Olea trattato di olivicoltura, Bologna, Edagricole, 2007, pag 14. Available from: https://www.edagricole.it/wp-content/uploads/2020/03/4938-Olea-SFOGLIA. pdf.

Bolek S. 2020. Olive stone powder: a potential source of fiber and antioxidant and its effect on the rheological characteristics of the biscuit dough and quality. Innov. Food. Sci. Emerg. Technol. 64:102423.

Borjan D., Leitgeb M., Knez Ž., Hrnčič M. K. 2020. Microbiological and antioxidant activity of phenolic compounds in olive leaf extract. Molecules. 25:5946.

Bottino A., Capannelli G., Comite A., Ferrari F., Marotta F., Mattei A., Turchini A. 2004. Application of membrane processes for the filtration of extra virgin olive oil. J. Food. Eng. 65:303-9.

Bubola K.B., Lukić M., Mofardin I., Butumović A., Koprivnjak O. 2017. Filtered vs. naturally sedimented and decanted virgin olive oil during storage: effect on quality and composition. LWT – Food. Sci. Technol. 84:370-7.

Calabriso N., Scoditti E., Pellegrino M., Carluccio M.A. 2015. Olive oil. In The Mediterranean Diet (pp. 135-142). London, UK: Academic Press.

Caponio F., Gomes T., Summo C., Pasqualone A. 2003. Influence of the type of olive-crusher used on the quality of extra virgin olive oils. Eur. J. Lipid. Sci. Tech. 105:201-6.

Cappelli A., Menditto N., Cini E. 2021. Innovative olive tree leaves shredder prototype for the valorization of wasted leaves: an application to high-quality compost production. Sustainability. 13:9421

Cappelli A., Parretti C., Cini E., Citti P. 2019. Development of a new washing machine in olive oil extraction plant: A first application of usability-based approach. J. Agric. Eng. 50:134-42.

Catania P., Vallone M., Farid A., De Pasquale C. 2016. Effect of O2 control and monitoring on the nutraceutical properties of extra virgin olive oils. J. Food. Eng. 169:179-88.

Cerrone F., Barghini P., Pesciaroli C., Fenice M. 2011. Efficient removal of pollutants from olive washing wastewater in bubble-column bioreactor by Trametes versicolor. Chemosphere. 84:254-9.

Cifuentes-Cabezas M., Carbonell-Alcaina C., Vincent-Vela M.C., Mendoza-Roca J.A., Álvarez-Blanco S. 2021. Comparison of different ultrafiltration membranes as first step for the recovery of phenolic compounds from olive-oil washing wastewater. Process. Saf. Environ. Protection. 149:724-34.

Clodoveo M.L., Camposeo S., Amirante R., Dugo G., Cicero N., Boskou D. 2015. Research and innovative approaches to obtain virgin olive oils with a higher level of bioactive constituents. In: Boskou D. (ed). Olive and Olive Oil Bioactive Constituents. Urbana, Illinois: AOCS Press. pp.179-215.

Clodoveo M.L., Durante V., La Notte D. 2013. Working towards the development of innovative ultrasound equipment for the extraction of virgin olive oil. Ultrason. Sonochem. 20:1261-70.

Di Giovacchino L. 2013. Chapter 3: technological aspects. In: Aparicio R., Harwood J (eds). Handbook of olive oil: analysis and properties. Boston, MA: Springer. pp. 86-9.

Di Giovacchino L., Sestili S., Di Vincenzo D. 2002. Influence of olive processing on virgin olive oil quality. Eur. J. Lipid Sci. Tech. 104:587-601.

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 Prod. Consump. 19:216-30.

European Commission. 2020. Olive oil: an overview of the production and marketing of olive oil in the EU. 2020. Available online: https://ec.europa.eu/info/food-farming-fisheries/plants-and-plant-products/plant-products/olive-oil

Flamminii F., Di Mattia C.D., Nardella M., Chiarini M., Valbonetti L., Neri L., Pittia P. 2020. Structuring alginate beads with different biopolymers for the development of functional ingredients loaded with olive leaves phenolic extract. Food. Hydrocolloids. 108:105849.

Guerrini L., Masella P., Migliorini M., Cherubini C., Parenti A. 2015. Addition of a steel pre-filter to improve plate filter-press performance in olive oil filtration. J. Food. Eng. 157:84-7.

Guerrini L., Migliorini M., Giusti M., Parenti A. 2017. The influence of crusher speed on extra virgin olive oil characteristics. Eur. J. Lipid. Sci. Tech. 119:1600156.

Herrero-Encinas J., Blanch M., Pastor J.J., Mereu A., Ipharraguerre I.R., Menoyo D. 2020. Effects of a bioactive olive pomace extract from Olea europaea on growth performance, gut function, and intestinal microbiota in broiler chickens. Poultry. Sci. 99:2-10.

Lacolla G., Rinaldi M., Savino M., Russo M., Caranfa D., Cucci G. 2021. Effects of organic fertilization from wet olive pomace on emmer wheat (Triticum dicoccum Shrank) grain yield and composition. J. Cereal. Sci. 102:103369.

Ioannou-Ttofa L., Michael-Kordatou I., Fattas S. C., Eusebio A., Ribeiro B., Rusan M., Amer A.R.B., Zuraiqi S., Waismand M. Linder C. Wiesman Z., Gilron J.,Fatta-Kassinos D. 2017. Treatment efficiency and economic feasibility of biological oxidation, membrane filtration and separation processes, and advanced oxidation for the purification and valorization of olive mill wastewater. Water. Res. 114:1-13.

Leone A., Romaniello R., Tamborrino A., Xu X.Q., Juliano P. 2017. Microwave and megasonics combined technology for a continuous olive oil process with enhanced extractability. Innov. Food Sci. Emerg. Technol. 42:56-63.

Leone A., Tamborrino A., Romaniello R., Zagaria R., Sabella E. 2014. Specification and implementation of a continuous microwave-assisted system for paste malaxation in an olive oil extraction plant. Biosyst. Eng. 125:24-35.

Lombardo N. 2007. Parte prima: Aspetti generali dell'olivicoltura. In: Fiorino P. Olea trattato di olivicoltura. Bologna: Edagricole. p. 3.

Losito I., Abbattista R., De Ceglie C., Castellaneta A., Calvano C.D., Cataldi T.R. 2021. Bioactive secoiridoids in italian extra-virgin olive oils: impact of olive plant cultivars, cultivation regions and processing. Molecules. 26:743.

Lozano-Sánchez J., Cerretani L., Bendini A., Segura-Carretero A., Fernández Gutiérrez A. 2010. Filtration process of extra virgin olive oil: effect on minor components, oxidative stability and sensorial and physicochemical characteristics. Trends. Food. Sci. Tech. 21:201-11.

Masella P., Parenti A., Spugnoli P., Calamai L. 2012. Vertical centrifugation of virgin olive oil under inert gas. Eur. J. Lipid. Sci. Tech. 114:1094-6.

Maza-Márquez P., González-Martínez A., Rodelas B., González-López J. 2017. Full-scale photobioreactor for biotreatment of olive washing water: structure and diversity of the microalgae-bacteria consortium. Bioresource Technol. 238:389-98.

Moher D., Liberati A., Tetzlaff J., Altman D.G. 2009. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. Ann. Intern. Med. 151:264–9.

Morrone L., Pupillo S., Neri L., Bertazza G., Magli M., Rotondi A. 2017. Influence of olive ripening degree and crusher typology on chemical and sensory characteristics of Correggiolo virgin olive oil. J. Sci. Food. Agr. 97:1443-50.

Moudache M., Colon M., Nerín C., Zaidi F. 2016. Phenolic content and antioxidant activity of olive by-products and antioxidant film containing olive leaf extract. Food Chem. 212:521-7.

Ochando-Pulido J.M., Corpas-Martínez J.R., Martinez-Ferez A. 2018. About two-phase olive oil washing wastewater simultaneous phenols recovery and treatment by nanofiltration. Process Saf. Environ. Protection. 114:159-68.

Ochando-Pulido J.M., Stoller M., Bravi M., Martinez-Ferez A., Chianese A. 2012. Batch membrane treatment of olive vegetation wastewater from two-phase olive oil production process by threshold flux based methods. Sep. Purif. Technol. 101:34-41.

Parenti A., Masella P., Guerrini L., Guiso A., Spugnoli P. 2014. Energetic and economic viability of olive stone recovery as a renewable energy source: a Southern Italy case study. JAE. 45:60-3.

Parenti A., Spugnoli P., Masella P., Calamai L. 2008. The effect of malaxation temperature on the virgin olive oil phenolic profile under laboratory□scale conditions. Eur. J. Lipid. Sci. Tech. 110:735-41.

Pastore G., D'Aloise A., Lucchetti S., Maldini M., Moneta E., Peparaio M., Raffo A., Sinesio, F. 2014. Effect of oxygen reduction during malaxation on the quality of extra virgin olive oil (Cv. Carboncella) extracted through "two-phase" and "three-phase" centrifugal decanters. LWT –Food. Sci. Technol. 59:163-72.

Patsios S.I., Kontogiannopoulos K.N., Banias G.F. 2020. Environmental impact assessment in agri-production: a comparative study of olive oil production in two European countries. In: Bio-Economy and Agri-Production. London, UK: Academic Press. pp. 83-116.

Puértolas E., de Marañón I.M. 2015. Olive oil pilot-production assisted by pulsed electric field: Impact on extraction yield, chemical parameters and sensory properties. Food. Chem. 167:497-502.

Pulido J.M.O. 2016. A review on the use of membrane technology and fouling control for olive mill wastewater treatment. Sci. Total. Environ. 563:664-75.

Putnik P., Barba F.J., Španić I., Zorić Z., Dragović-Uzelac V., Kovačević D.B. 2017. Green extraction approach for the recovery of polyphenols from Croatian olive leaves (Olea europea). Food. Bioprod. Process. 106:19-28.

Rapoport H.F., Fabbri A., Sebastiani L. 2016. Olive biology. Olive Tree Genome. 13-25.

Reboredo-Rodríguez P., González-Barreiro C., Cancho-Grande B., Simal-Gándara J. 2014. Improvements in the malaxation process to enhance the aroma quality of extra virgin olive oils. Food. Chem. 158:534-45.

Rebufa C., Pinatel C., Artaud J., Girard F. 2021. A comparative study of the main international extra virgin olive oil competitions: their impact on producers and consumers. Trends. Food. Sci. Technol. 107:445-54.

Ribeiro T. B., Bonifácio-Lopes T., Morais P., Miranda A., Nunes J., Vicente A.A., Pintado M. 2021. Incorporation of olive pomace ingredients into yoghurts as a source of fibre and hydroxytyrosol: Antioxidant activity and stability throughout gastrointestinal digestion. J. Food. Eng. 297:110476.

Rodríguez G., Lama A., Rodríguez R., Jiménez A., Guillén R., Fernández-Bolanos J. 2008. Olive stone an attractive source of bioactive and valuable compounds. Bioresource. Technol. 99: 5261-9.

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, 11:1776.

Salomone R., Ioppolo G. 2012. Environmental impacts of olive oil production: a life cycle assessment case study in the province of Messina (Sicily). J. Clean. Prod. 28:88-100.

Seçmeler Ö., Galanakis C.M. 2019. Olive fruit and olive oil. In: Galanakis C. Innovations in Traditional Foods. Swaston, UK: Woodhead Publishing. pp. 193-220.

Simonato B., Trevisan S., Tolve R., Favati F., Pasini G. 2019. Pasta fortification with olive pomace: effects on the technological characteristics and nutritional properties. LWT – Food. Sci. Technol. 114:108368.

Souilem S., El-Abbassi A., Kiai H., Hafidi A., Sayadi S., Galanakis C.M. 2017. Olive oil production sector: environmental effects and sustainability challenges. In: Galanakis C.M. Olive mill waste. London, UK: Academic Press. pp. 1-28.

Talhaoui N., Taamalli A., Gómez-Caravaca A.M., Fernández-Gutiérrez A., SeguraCarretero A. 2015. Phenolic compounds in olive leaves: analytical determination, biotic and abiotic influence, and health benefits. Food. Res. Int. 77:92-108.

Tamborrino A., Clodoveo M.L., Leone A., Amirante P., Paice A.G. 2010. The malaxation process: influence on olive oil quality and the effect of the control of oxygen concentration in virgin olive oil. In: Olives and olive oil in health and disease prevention. London, UK: Academic Press. (pp. 77-83). Available from: https://www.uniba.it/it/docenti/clodoveo-maria-lisa/malaxationoxygen.pdf

Tamborrino A., Pati S., Romaniello R., Quinto M., Zagaria R., Leone A. 2014. Design and implementation of an automatically controlled malaxer pilot plant equipped with an in-line oxygen injection system into the olive paste. J. Food. Eng.141:1-12.

Tamborrino A., Veneziani G., Romaniello R., Perone C., Urbani S., Leone A., Servili M. 2021. Development of an innovative rotating spiral heat exchanger with integrated microwave module for the olive oil industry. LWT – Food. Sci. Technol. 147:111622.

Taticchi A., Esposto S., Veneziani G., Minnocci A., Urbani S., Selvaggini R., Sordini B., Daidone L., Sebastiani L., Servili, M. 2021. High vacuum-assisted extraction affects virgin olive oil quality: impact on phenolic and volatile compounds. Food. Chem. 342:128369.

Tsimidou M.Z., Mastralexi A., Özdikicierler O. 2020. Cold pressed virgin olive oils. In: Ramadan M.F. (ed). Cold Pressed Oils Green Technology, Bioactive Compounds, Functionality, and Applications. London, UK: Academic Press. pp. 547-573

Veillet S., Tomao V., Bornard I., Ruiz K., Chemat F. 2009. Chemical changes in virgin olive oils as a function of crushing systems: stone mill and hammer crusher. CR. Chim. 12:895-904.