Chapter 2

Improvement of Olive Oil Mechanical Extraction: New Technologies, Process Efficiency, and Extra Virgin Olive Oil Quality

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Abstract

Most of the recent technological innovations applied to the mechanical oil extraction process are aimed at improving virgin olive oil quality and yield. Extra virgin olive oil (EVOO) quality is mainly based on the qualitative/quantitative composition of monounsaturated fatty acids, volatile and phenolic compounds that are strictly related to the health and sensory properties of the product, with particular attention given to the fraction of secoiridoid derivatives and C_5 and C_6 volatile compounds. The different levels of concentration of these compounds are due to some important variables: agronomic and technological. The chapter explains the recent approaches and innovations introduced in the oil extraction process to improve the working efficiency of the production system and to obtain high-quality extra virgin olive oils.

Keywords: EVOO quality, phenols, volatile compounds, EVOO processing, technological innovations

1. Introduction

Extra virgin olive oil (EVOO) is the main source of lipids in the Mediterranean diet. The marketable, healthy, and sensory quality of an EVOO has been ascribed to the presence of bioactive components such as monounsaturated and polyunsaturated fatty acids (MUFAs and PUFAs), squalene, phytosterols, phenolic, and volatile compounds [1–5]. Several factors such as the genetic and geographical origin of the olive fruit as well as agronomic practices and technological strategies affect the phenolic content and aromatic profile of EVOO.

Olives, EVOO, and the by-products of the mechanical extraction system such as olive vegetation water and pomace contain several phenolic compounds with recognized biological and health properties. These substances are considered the principal bioactive compounds of EVOO, showing a high antioxidant activity with an important role in the ratio between EVOO consumption and chronic degenerative events, mainly inflammatory and age-dependent diseases such as cardio-brain-vascular diseases and cancer [4–11].

Major phenolic compounds found in EVOO are phenolic acids, phenolic alcohols such as tyrosol (*p*-HPEA) and hydroxytyrosol (3,4-DHPEA), hydroxy-isocromans, flavonoids, lignans, and secoiridoids. This latter class of compounds is represented by the dialdehydic form of decarboxymethyl elenolic acid linked to 3,4-DHPEA or *p*-HPEA (3,4-DHPEA-EDA or *p*-HPEA-EDA), an isomer of oleuropein aglycon (3,4-DHPEA-EA) and the ligstroside aglycon (*p*-HPEA-EA). They arise from the secoiridoid glycosides (oleuropein, demethyloleuropein, and ligstroside) through the enzymatic action of β-glucosidase during the mechanical extraction process. Secoiridoids are exclusive compounds of olive leaves, fruits, EVOO, and milling by-products (olive vegetation water and pomace). The secoiridoid derivatives, along with lignans ((+)-1-acetoxypinoresinol and (+)-1-pinoresinol), are the most abundant hydrophilic phenols of EVOO [6, 12, 13].

The geographical and genetic origin of olive fruits, the choice of agronomic practices, and the technological conditions of EVOO production affect the wide variability in its phenolic and volatile composition and, therefore, its healthy and sensory quality. The variability range of the content of total phenols and oleuropein derivatives in over 700 industrial EVOO samples analyzed is illustrated in the box and whiskers plots of **Figure 1**. Based on these results, the contents of the total phenols and oleuropein derivatives show a median of 534 and 398 mg/kg, with values ranging between 187–997 and 77–112 mg/kg, respectively [14].

Health-promoting effects and organoleptic properties of EVOO have been mainly ascribed to its phenols content (hydroxytyrosol and secoiridoids, in particular) [5, 15]. Several epidemiological studies have in fact fully demonstrated the inflammatory, antioxidant, antimicrobial, anti-proliferative, antiarrhythmic, platelet antiaggregant and vasodilatory effects of EVOO phenolic compounds [4–6]. Furthermore, based on scientific evidence, Regulation (EU) No 432/2012 granted the health claim to the EVOO polyphenols, fixing the quantity of 5 mg as the daily amount of hydroxytyrosol and its derivatives (e.g. oleuropein complex and tyrosol) that should be ingested, with a moderate consumption of olive oil (20 g/day) to reduce cardiovascular disease [16].

It has been clearly known that phenolic compounds also have antioxidant activity; therefore, they play a pivotal role in the prolonging of EVOO shelf life [6]. Furthermore, from a sensory perspective, EVOO phenols are the compounds responsible for the characteristic notes of "bitterness" and "pungency". They stimulate the receptors of taste and the free endings of trigeminal nerve, which elicit the former the bitterness perception, the latter pungency and astringency interaction [15].

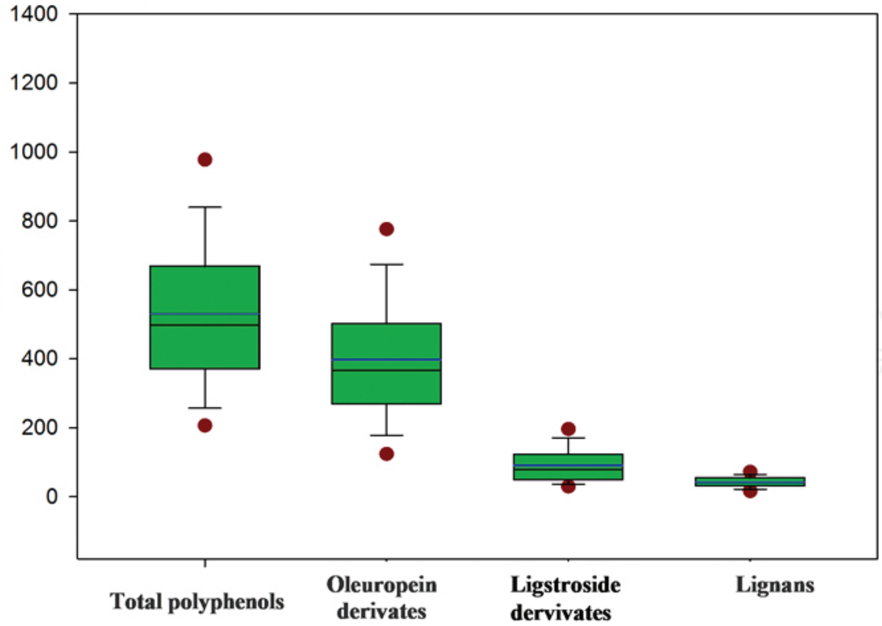

Figure 1. Box and whisker plots of variability (mg/kg) of phenolic compounds evaluated over 700 extra virgin olive oil samples analyzed [14]. Percentile limits in: box = lower 25th, upper 75th; whiskers = lower 10th, upper 90th; the red points = lower 5th, upper 95th; blue and black lines in the box represent the median and the average, respectively.

Another important part of EVOO flavor is characterized by many different olfactory notes, such as "cut grass," "floral," "green apple," "tomato" and "almond," which are often related to many volatile substances such as aldehydes, alcohols, esters, and hydrocarbons. In particular, C_6 and C_5 compounds, especially C_6 linear unsaturated and saturated aldehydes, alcohols, and esters, represent the key odorants responsible for those perceptions of positive aroma [17–19]. When the olive is intact, the concentration of those volatile compounds is still low. They greatly increase when the cell structures rupture during the mechanical extraction process and with the consecutive activation of the lipoxygenase (LOX). The C_6 and C_5 compounds are synthesized from linoleic (LA) and linolenic (LnA) acids by the enzymatic activities included in the lipoxygenase (LOX) pathway, and their concentrations depend on the level and the activity of each enzyme involved in this LOX pathway. **Figure 2** depicts a schematic illustration of the LOX pathway, which was extensively studied and discussed [18, 19].

However, it is worth mentioning that even though the main pathways are known for the formation of olive oil volatiles, the only correlation that has been proved is that between the "cut grass" aroma and C_5 and C_6 aldehydes (saturated and unsaturated) [18, 20].

EVOO processing includes a series of mechanical operations for extracting the oil from olive drupes by physical means only, according to Regulation (EU) No 1348/2013 [21]. Among them, the most important as regards quality is the crushing of the olives, which allows the release of the droplets of oil from the vacuoles, breaking down the cellular structure of the olive fruit; the malaxation of the olive paste, which promotes the coalescence of the oil droplets, with the simultaneous release of phenolic compounds into the oil phase and the increase of EVOO aroma; the mechanical recovery of the oil by centrifugation (continuous process) or pressing (discontinuous process); and lastly, filtration, used for removing suspended particles and eliminating residual water responsible for EVOO oxidation and the onset of off-flavors during its shelf life.

Many studies have been already developed during the last 10 years in order to optimize all the mechanical extraction steps that play a crucial role in the qualitative/quantitative composition of phenolic and volatile profile and, consequently, the sensory characteristics of the resulting EVOOs. Technological innovations have led to new extraction plants designed to improve the quality of oils obtained from olives with different genetic, geographical, and agronomic characteristics.

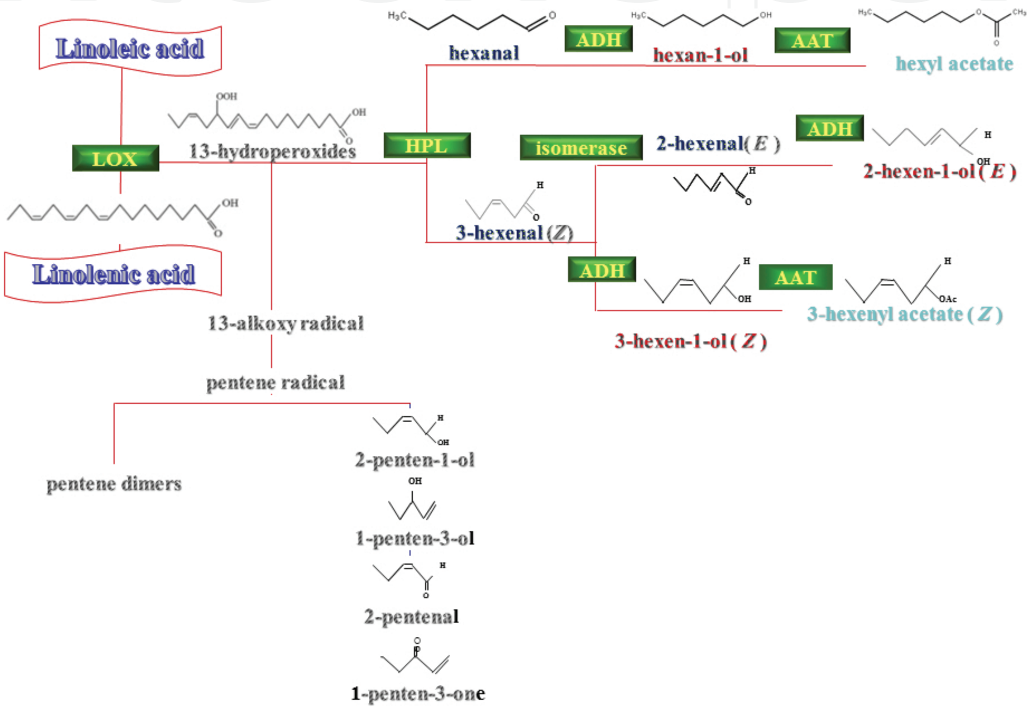

Figure 2. The lipoxygenase pathway on polyunsaturated fatty acids for the synthesis of main volatile compounds in EVOO according to Angerosa et al. [18] and Servili et al. [19]. LOX, lipoxygenase; HPL, hydroperoxide lyases; ADH, alcohol dehydrogenase; AAT, alcohol acetyl transferases.

One of the major challenges in the olive oil field will be the improvement of plant engineering performance in terms of sustainability, efficiency, modularity, and flexibility, reducing production costs, with attention to EVOO quality and yield.

In this regard, the next chapter emphasizes the effects of the recent new approaches and innovations in the olive oil field.

2. Crushing impact on minor components of EVOO

In recent years, several studies have been performed to elucidate the impact of technological operations applied during the mechanical extraction on EVOO yield and on its minor compounds, in particular [14, 22–26].

Traditional stone mills, hammers, blade and disc crushers, and destoning machines are the crushers currently available for industrial equipment operations [25]. Every crusher exerting different mechanical action to break down the olive tissue elicits several effects due to variation induced in the olive paste, in terms of temperature, granulometry of fragments, and exposure to atmospheric oxygen. These variations play a crucial role for endogenous enzymatic activities, affecting the final amount of the EVOO as well as its phenolic and volatile profile [27, 28]. During this phase, in fact, the entire heritage of olive fruit endogenous enzymes (cellulases, hemicellulases, pectinases, polygalacturonases, lipase, β-glucosidase, polyphenoloxidase (PPO), peroxidase (POD), and lipoxygenase (LOX)) is activated and involved in the subsequent phases of the extraction process and the formation and transformation of phenolic and volatile compounds in EVOO [29, 30]. Among them, the most important endogenous enzymes involved in EVOO quality are β-glucosidase, PPO, POD, and LOX. On the other hand, temperature and time become key parameters (to be checked continuously) when oxygen availability is not a limiting factor for the enzymatic activity of oxidoreductases [17, 20]. Many studies have been focused on the thermal stabilities of PPO, POD, and the enzymes pool of the LOX pathway [26, 29, 30]. According to the data found by Taticchi et al. [30] for the Moraiolo cultivar, the activity of PPO and POD varies according to temperature, with a maximum at 50°C and at 34.7°C, respectively. The maximum LOX activity has been observed at 30°C [20]. Hyperoxide lyase (HPL) is a heat-labile enzyme characterized by maximum activity at 15°C, while at 30°C its activity shows a partial inhibition [31].

Therefore, olive crushing is not just a simple physical process; it also represents an EVOO quality key factor.

Several studies carried out on the distribution of olive fruit endogenous enzymes in its constitutive parts (pulp, stone and seed) have shown that the seed is particularly rich in POD, while the phenolic compounds are most concentrated in the pulp [28, 32]. In particular, in olive pastes and the produced oil the decrease of phenols is due to their oxidation catalyzed by the POD and the PPO together. Whereas the LOX, contained in the seed, through the aforementioned cascade pathway, produces only a small amount of volatile compounds, which are mainly generated by the same enzyme of the pulp responsible for the production of C_5 and C_6 saturated and unsaturated aldehydes, alcohols and esters [14]. These findings are fundamental for the innovative use of a hammer with a selective effect on the different constitutive parts of the olive. Blade or tooth crushers, pre-crusher or destoning machines, for example, reduce the degradation of seed tissues, limiting the release of POD in the pastes. This involves in an increase in phenolic concentration, because their enzymatic oxidation is prevented (**Figure 3**) [32, 33]. As concerns aroma, the use of a hammer mill or other crushers causes the pulp tissues to be ground more violently, bringing about an increase of the olive paste temperature and a reduction of HPL activity [18, 27] (**Table 1**). Olive stoning in pre-crushing increases the phenolic concentration in EVOO [32, 34] and, at the same time, positively modifies the composition of the volatile compounds [27, 32].

Nowadays, strategic approaches in the olive oil field are based on the choice of plant engineering systems and operating conditions aimed at the control of these endogenous enzymes [26, 30].

Inarejos-García and co-workers [22] evaluated the effect of stronger (e.g. hammer crushers using small hole grid diameter and high rotation speed) or milder (e.g. hammer crushers using large hole grid diameter, blade crusher, etc.) crushing conditions on minor components (phenolic and volatile fraction, in particular) of olive paste and EVOO. The results obtained showed that the stronger crushing produced an increase of phenols and a decrease of volatile compounds in olive pastes and corresponding EVOO, while milder crushing produced an opposite effect [22]. These findings are in agreement with results reported by other authors [23, 24, 28]. The relationship between pressure and an overheating of the olive paste can explain these data: energetic milling action yields significant shredding of the olive oil tissues. The crushing conditions produce deep changes in the composition of EVOO hydrophilic phenols. This aspect is due to the activity of enzymes such as β-glucosidase and esterase that catalyze the transformation of secoridoids into aglycon forms, which are characterized by greater solubility in the oily phase. In EVOO, the oleuropein derivatives are the most abundant phenols due to both their partition coefficients between the oil and water phases and their different stability [22].

Further, comparative investigations have indicated that the hammer crusher or a partial destoner produces a significantly larger amount of small oil droplets, extending the malaxation time, hence promoting the loss of phenols and volatile compounds [24, 35].

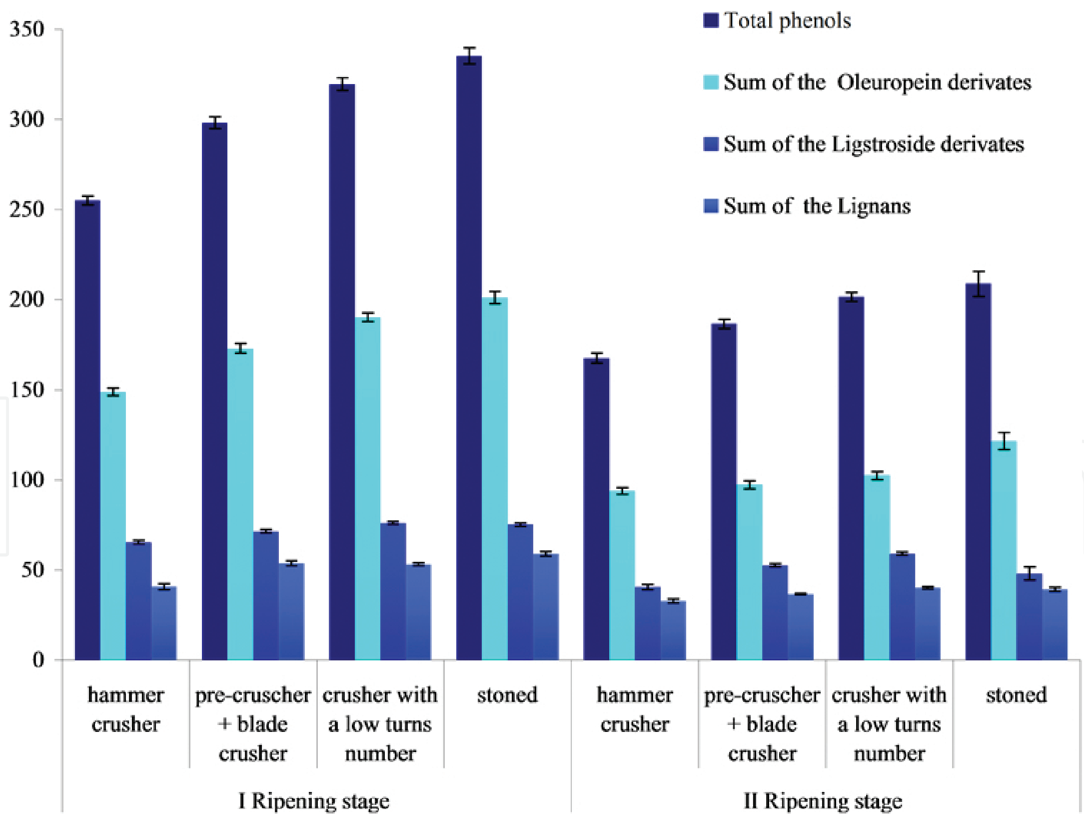

Figure 3. Phenolic composition (mg/kg) of EVOOs (*Frantoio* Cv.) obtained by different crushing methods [32]. The phenols' concentration was evaluated by HPLC previously reported by Montedoro et al. [36]. Results are mean value of three independent determinations ± standard deviation.

	Hammer		Blade + pre-crusher		Low turn number crusher		Stoned	
Aldehydes*								
Pentanal	236.5	(4.0)	273.4	(2.1)	17.9	(1.0)	66.5	(6.7)
Hexanal	280.0	(2.9)	511.4	(35.7)	533.7	(0.3)	579.6	(5.3)
2-Pentanal *(E)*	10.7	(0.3)	13.2	(0.9)	94.8	(1.8)	16.6	(1.0)
2-Hexanal *(E)*	43600.6	(327.0)	44718.9	(207.8)	39811.6	(587.4)	52228.1	(521.0)
2,4-Esadyenal *(E,E)*	19.4	(0.1)	42.0	(3.5)	341.6	(14.4)	88.9	(5.4)
2-Heptanal *(E)*	0.0	(0.0)	0.0	(0.0)	158.2	(10.0)	72.0	(3.7)
Alcohols								
1-Pentanol	167.0	(5.2)	94.5	(4.7)	23.3	(0.7)	62.6	(1.4)
2-Penten-1-ol *(E)*	166.0	(11.3)	91.4	(5.1)	52.4	(3.5)	104.0	(7.4)
1-Penten-3-ol	960.3	(53.2)	899.0	(43.3)	522.0	(49.2)	300.0	(28.2)
1-Hexanol	1788.0	(57.0)	2152.0	(74.0)	521.0	(41.0)	1501.0	(56.0)
3-Hexan-1-ol *(Z)*	88.4	(22.2)	103.6	(10.1)	49.2	(2.3)	77.0	(5.1)
3-Hexan-1-ol *(E)*	22.2	(0.2)	20.2	(0.1)	9.9	(0.2)	20.4	(0.5)

The volatile compounds were determined in duplicate by HS-SPME-GC-MS as reported by Esposto et al. [37].

*Results are the mean value of three independent determinations; standard deviation is reported in parentheses.

Table 1. Volatile composition (μg/kg) of EVOOs (*Frantoio* Cv.) obtained by different crushing methods [32].

3. Malaxation impact on minor components of EVOO

In recent years, the impact of malaxation on EVOO minor compounds has been investigated at length by several authors [30, 38]. During this phase, a slow, continuous mixing up and a gradual temperature increase of olive paste take place. This has the effect of breaking up the water-oil emulsion formed in the previous step and favoring, at the same time, the coalescence of the oil droplets into drops of greater sizes. Furthermore, a reduction of the product viscosity and endogenous enzymatic activities also occurs. Malaxation and the related selective control of enzymes such as PPO, POD and LOX are therefore other critical points of the mechanical extraction process of EVOO [14, 26].

Recently, the optimization of the best operative parameters for the malaxation process, such as time, temperature and oxygen concentration, that can guarantee the correct balance between the yield and the quality of extracted EVOOs (in terms of the amount of phenolic and volatile compounds) has been extensively investigated [39].

The newest malaxer machines ensure a hermetic sealing. To avoid the negative effects of POD and PPO activities on phenols, the O_2 availability in the malaxer headspace is modulated by valves for inert gas (nitrogen or argon). Other authors have proposed to exploit the emission of carbon dioxide (CO_2) from olive paste coupled with the oxygen depletion during malaxation under sealed conditions, in order to solve the problem of oxidative phenomena without using inert gases [40–42]. The saturation of the malaxation chamber with CO_2 offers a two-fold benefit for the cost of inert gas and for the POD and PPO inactivation. However, the amount of O_2 incorporated during crushing of the olive pastes seems to be for developing volatile compounds from LOX pathway [28].

Through the control of O_2 concentration in the malaxer headspace, it is possible to regulate the content of phenolic and volatile compounds in the end products (**Figure 4** and **Table 2**).

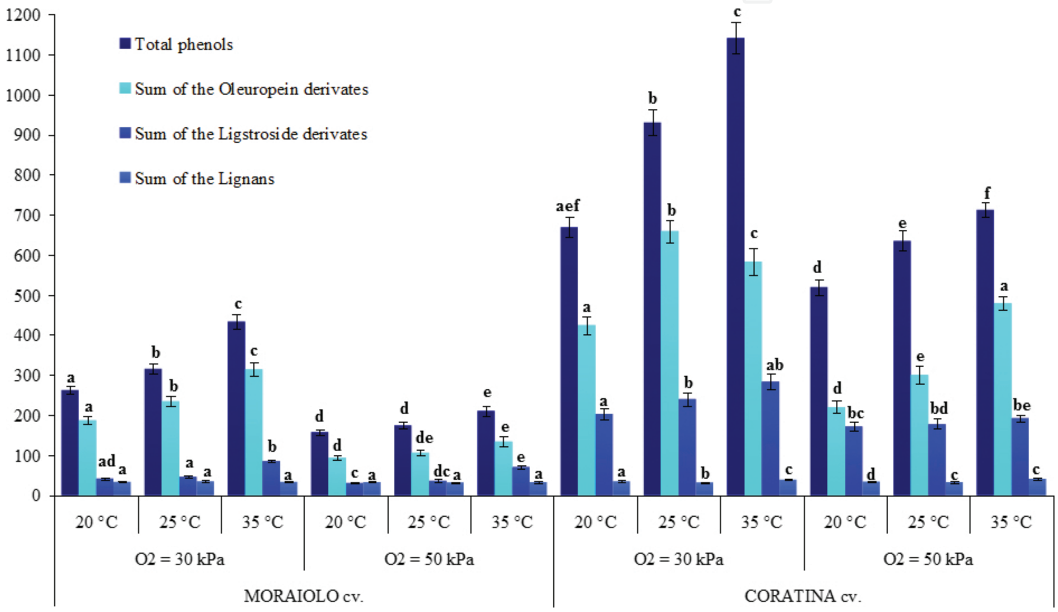

Figure 4. The phenolic composition (mg/kg) of EVOOs obtained malaxing at different temperatures and in different initial atmosphere compositions [30]. The phenols' concentration was evaluated by HPLC previously reported by Montedoro et al. [36]. Data are the mean value of two independent experiments analyzed in duplicate ± standard deviation. The values in each row having different letters (a–f) are significantly different from one another ($p < 0.05$).

This opportunity of regulating the content of phenolic and volatile compounds, obtained by using adequate amounts of O_2 during malaxation, is an important aspect to be taken into account. The influence of malaxing temperature on the olive PPO and POD activities has been studied by Taticchi et al. [30]. The outcomes showed that PPO is characterized by a lower thermal stability than the POD, which explains the variation of phenolic concentrations in the olive paste during processing as a function of temperature. The malaxation temperature promotes the release of phenols from cell wall polysaccharides catalyzed by endogenous hemicellulases and polygalacturonases and improves the solubility of phenols in the oil phase [43]. However, for many Italian autochtone cultivars, temperatures above 30°C led to a strong decrease in the aromatic profile of oils. Hence, the enzymes involved in the LOX pathway are characterized by different temperature optima between 15 and 30°C, while a reduction in their activity level is observed above 30°C [15]. The processing temperature affects the concentration of aldehydes: the lowest amounts have been observed at 35°C, while the highest concentration occurs at 25°C. Esters also showed the same behavior as the aldehydes; in fact, high malaxation temperatures provoke a decay of esters and of *cis*-3-hexen-1-ol, which are responsible for positive sensorial notes [17, 19, 20].

With regard to the alcohols, their concentration increased with the malaxation temperature. Several authors observed an accumulation of hexan-1-ol and *trans*-2-hexen-1-ol, both associated with odor not completely agreeable [17, 19, 20]. These results suggested that, according to the genetic characteristics of the cultivar, the optimal malaxation temperature could be set at about 28 or 30°C [15]. Other studies have demonstrated that the extending malaxation time shows a decrease in the typical "green" sensory note and all the other pleasant sensations [18, 20].

Therefore, particular emphasis has been placed on optimizing temperature and oxygen concentration during malaxation for obtaining high-quality EVOOs, but always taking into account the olive cultivar [39].

	O_2 = 0 kPa		**O_2 = 30 kPa**		**O_2 = 50 kPa**		**O_2 = 100 kPa**	
Aldehydes[*]								
2-Pentanal *(E)*	548.5	(16.3)ab	509.7	(5.8)b	636.7	(17.9)c	613.0	(51.2)ac
Hexanal	1187.0	(9.9)a	1624.3	(30)bc	1532.1	(27.3)b	1744.0	(121.2)c
2-Hexanal *(E)*	51565.0	(827.3)a	52900.0	(565.7)ab	54340.5	(355.7)b	53920.0	(333.1)b
Alcohols								
1-Pentanol	40.0	(5.7)a	54.3	(5)b	39.4	(5)a	48.0	(3.2)ab
2-Penten-1-ol (E)	87.5	(0.7)a	67.0	(0.2)b	105.8	(5.7)c	105.0	(8.3)c
1-Penten-3-ol	890.0	(2.8)a	82.0	(1.2)b	1093.5	(33.5)c	1185.0	(91.2)c
1-Hexanol	2326.0	(49.5)a	3694.2	(2)b	1788.0	(57.2)b	2170.0	(123.1)a
3-Hexan-1-ol *(E)*	25.5	(0.7)ab	31.6	(3.8)a	20.0	(1.9)b	21.0	(1.9)b
3-Hexan-1-ol *(Z)*	561.0	(4.2)a	513.6	(9.6)b	486.3	(11.1)b	498.0	(31.2)b
2-Hexan-1-ol *(E)*	3654.5	(30.4)a	5905.0	(321)b	3350.1	(80.5)c	4185.0	(35.6)d

The volatile compounds were determined in duplicate by HS-SPME-GC-MS as reported by Esposto et al. [37].

[*] Data are the mean values of three independent experiments; standard deviation is reported in parentheses. Values in each row having different letters (a–d) are significantly different from one another at $p < 0.01$.

Table 2. Volatile composition (μg/kg) of EVOOs (*Coratina* Cv.) obtained after malaxation in different initial atmosphere compositions [42].

4. New approaches: emerging techniques

In the olive oil field, the current scientific research is focused on the improvement of its quality, with particular attention given to the optimization of the working efficiency of the extraction plant and to reducing malaxation time. Attempts have been made for converting the traditional malaxation batch process into a continuous one, obtaining a simultaneous positive effect on both the oil yield and the working times [38]. The traditional malaxer is a heat exchanger characterized by a low thermal transfer efficiency, because the ratio of surface area to volume is disadvantageous. In principle, malaxation is distinguished into two steps, with the "pre-heating" phase, defined as the time required for the olive paste to reach the process temperature (about 27°C), and "actual malaxation". The duration of the "pre-heating" phase is about 45% of the total process time [44]. In order to reduce this phase and optimize the phenolic and volatile compounds related to EVOO healthy and sensory properties, different technological solutions can be adopted during olive paste conditioning: microwave energy (from 300 MHz to 300 GHz) [45, 46], mechanical vibrations (under 200 Hz) [47], pulsed electric field (PEF) [48, 49], ultrasounds (US) [50-52], and heat exchangers [37, 53, 54].

4.1. Microwave technology

Leone and co-workers [45] have built and adjusted a new apparatus in an industrial olive oil extraction plant that is based on microwave technology for the continuous conditioning of the olive paste. It replaces the malaxer, with the purpose of assuring the continuity of the process. The capability of microwaves to generate a thermal and a non-thermal effect on the olive paste is exploited for the purpose of increasing the temperature and the vacuole desegregation, respectively. These combined effects promoted the coalescence that is directly related to extraction efficiency. Tamborrino et al. [46] investigated in a subsequent study the impact of the microwave apparatus on phenolic and volatile compounds of olive oil. The microwave technology is responsible for a reduction in the olive paste conditioning time of around 88% compared to the conventional system, and a significant increase in the extraction yields, without compromising the EVOO marketable parameters. However, the authors observed that the EVOOs obtained from microwave treatment were characterized by low amounts of secoiridoid derivatives, specifically 3,4-DHPEA-EDA, *p*-HPEA-EA, and *p*-HPEA-EDA, compared to the EVOOs extracted with traditional systems. By reducing the time needed for the activation period of the depolymerizing enzymes, the microwave treatment led to a decrease of phenolic concentration in EVOOs. This does not occur with the traditional, slow malaxing process. On the other hand, the EVOOs obtained from rapid microwave conditioning compared with those obtained from traditional malaxation showed the largest increase of volatile compounds due to the shorter overall conditioning time. At the same time, a positive effect on the different activity levels of the LOX pathway is seen. These results are in good agreement with the findings of Angerosa et al. [18] and Esposto et al. [37]. One advantage of exploiting a shorter conditioning time is the reduction of the partial inactivation of the HPL, promoting an accumulation of the C_6 aldehydes [55]. Therefore, microwave technology could be potentially used in olive oil extraction plants to improve the olive oil extraction process and to overcome the bottlenecks of malaxation by guaranteeing a continuous process [45, 46].

4.2. Mechanical vibrations

A further innovative approach based on a vibration system to reduce the malaxation time, always overlooking the EVOO yield and quality, has been recently developed by Gallina Toschi and co-workers [47]. The influence of mechanical vibrations, at frequencies between 5 and 200 Hz, applied in the resonant conditions of the olive paste as pre-treatment and in combination

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with traditional malaxation, was investigated. The results obtained suggested that this technological approach breaks down the olive cells to improve the next phase of the EVOO extraction process. Gallina Toschi et al. [47] found that the optimal frequencies of excitation of the olive pastes fall between 50 and 80 Hz.

4.3. Pulsed electric field (PEF)

Among the emerging techniques recently proposed, the application of pulsed electric fields (PEF) during olive oil extraction could be also interesting in the olive oil technological panorama [48, 49]. The study at the pilot scale in an industrial oil mill was conducted by Puértolas and Martínez de Marañón [48] on Arroniz cultivars to assess the effect on the extraction yield and oil quality obtained through the application of a PEF treatment (2 kV/cm; 11.25 kJ/kg) on the crushed olive paste before malaxation. The exposure to electric fields for microseconds causes the formation of pores in cell membranes. This electroporation mechanism increasing the permeability of the vegetable cells promoted the diffusion of solutes through their membranes. This leads to an increase of 13.3% in the yield extraction. The PEF treatment not only showed no negative side effects on the sensory and chemical characteristics of EVOO but also increased the amount of human-health-related compounds, such as phenols, phytosterols, and tocopherols, assuring the EU marketable parameters of highest quality EVOO [49]. Hence, the application of PEF could also represent a good alternative for enhancing the phenolic content in EVOO.

4.4. Ultrasound (US) technology

With the aim of exploiting the technological environmental sustainability for improving EVOO extraction yields, the application of ultrasound (US) technology in olive paste pre-treatment has been tested in the laboratory by Jiménez et al. [51]. The effects of high-power ultrasound, applied directly by probe horn (105 W, 12 cm, and 24 kHz) and indirectly by ultrasound-cleaning bath (150 W and 25 kHz), on olive pastes were observed and compared to conventional malaxation from a sensory and chemical characteristic perspective.

The results of research focusing on the use of new ultrasonic extraction technologies in the EVOO industry should lead to meaningful technological advances in EVOO production. Following experimental trials, the results were employed to suggest innovative scaling-up solutions of the EVOO mechanical extraction process [50]. Briefly, the ultrasound produces mechanical and thermal effects. The mechanical effect is due to the cavitation phenomena, causing the rupture of a part of the uncrushed oil cells. The thermal effect is related to ultrasonic energy: as an acoustic wave propagates through a plant tissue, a part of it is absorbed and converted to heat in the olive paste [52].

More recently, in a pilot-scale plant, Clodoveo and Hachicha Hbaieb [44] compared ultrasound and microwave treatments of olive paste with traditional malaxation to evaluate their capability to increase environmental sustainability by improving EVOO extraction yields. The results demonstrated that a significant reduction of the malaxation pre-heating stage and improvement in the extraction yield were observed in EVOOs obtained from both ultrasound and microwaves systems [44]. Furthermore, in terms of energy consumption, the ultrasound technology was more sustainable than microwaves and the traditional system, with energy efficiencies of 93.05% (ultrasounds), 42.3% (microwaves), and 49.41% (traditional system). [44].

4.5. Flash thermal conditioning (FTC)

Veneziani et al. [53] carried out a line of research previously studied by Esposto et al. [37], evaluating the impact of a new technology, based on heat exchangers placed after the crashing phase of extraction process, on the quality of EVOO [37, 53, 54]. Crushed olive pastes from five Italian cultivars—Coratina, Ottobratica, Moraiolo, Peranzana, and Cellina di Nardò—were immediately brought to 25 or 30°C by flash thermal conditioning (FTC) by means of a tubular heat exchanger with counter current flow of hot water. After this phase, 15 or 20 minutes of malaxation was applied at the same temperature as the treated pastes (25 and 30°C) [53]. A conventional extraction was done on the same cultivar applying traditional malaxation at temperatures of 25 and 30°C for 30 minutes for non-pretreated crushed pastes. The results obtained indicated that the FTC treatment brings about an increase in phenols in the EVOO for each cultivar studied, as shown in **Figure 5**. Furthermore, the main differences in terms of phenolic composition with respect to the traditional malaxation have been observed in EVOOs

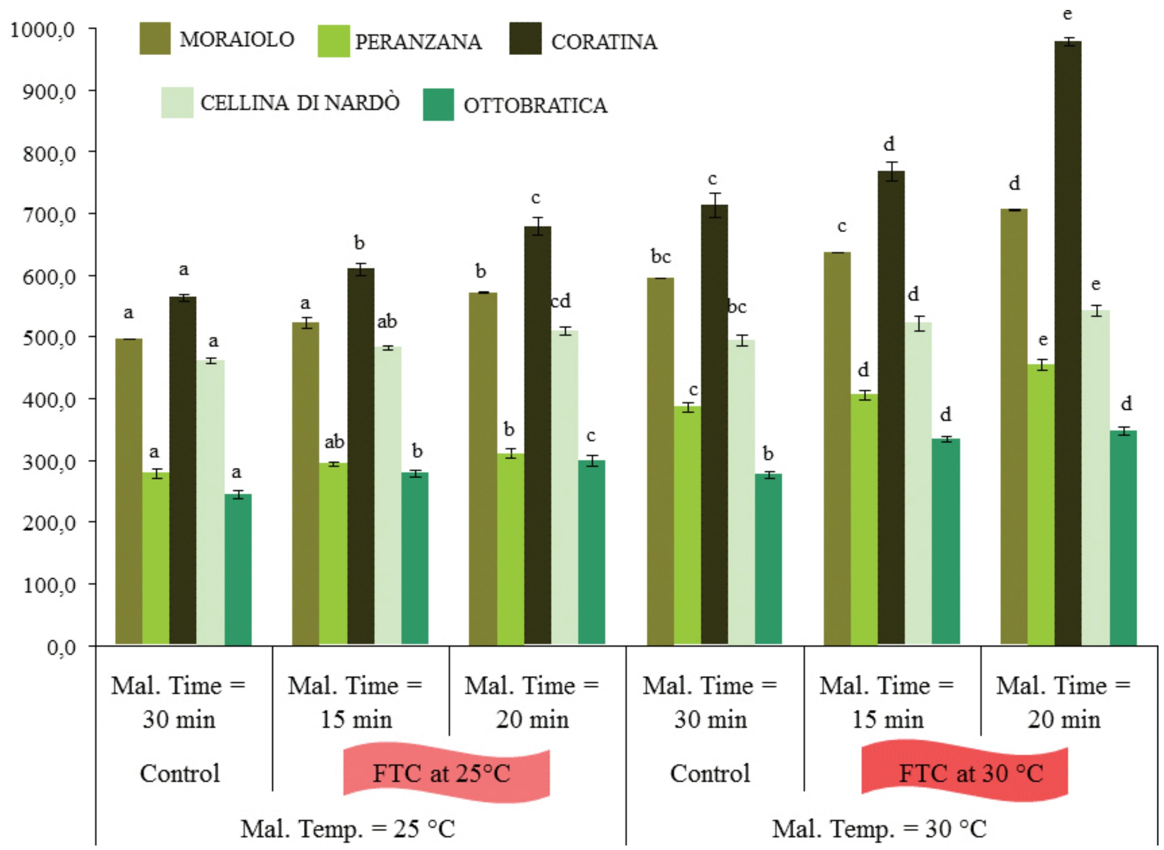

Figure 5. Evaluation of phenolic composition (mg/kg) of EVOO Control and FTC obtained at different temperatures and times of malaxation[a] [53]. The evaluations were carried out by HPLC according to the method reported by Selvaggini et al. [55]. [a] Data are the mean of three independent analytical determinations ± SD. The values in each row having different letters (a–d) are significantly different from one another ($p < 0.05$).

when a lengthy malaxation (20 minutes) followed the FTC treatment, in both the temperature range investigated (25°C and 30°C). These findings were then repeated also for the Peranzana and Coratina cultivars, with the latter characterized by the highest levels of phenolic concentrations [53]. Ottobratica EVOOs were less affected by the FTC pre-treatment of the crushed pastes [53].

The FTC treatment always allowed an increase of total phenols, which ranged from 3.7 to 21.5%, with the higher values obtained when malaxation was longer than 15 minutes. These results confirmed those previously found by Esposto et al. [37]. The minimum time required to determine the cell wall degradation catalyzed by the endogenous depolymerizing enzymes, which are involved in the release of phenols in the oily phase. The differences in terms of phenolic compounds are mainly related to the oleuropein derivatives (3,4-DHPEA-EDA, and 3,4-DHPEA-EA) and to a lesser extent *p*-HPEA and *p*-HPEA-EDA. These increases appear to be influenced not only by the heat treatment but also by the genetic origins of five cultivars tested [53].

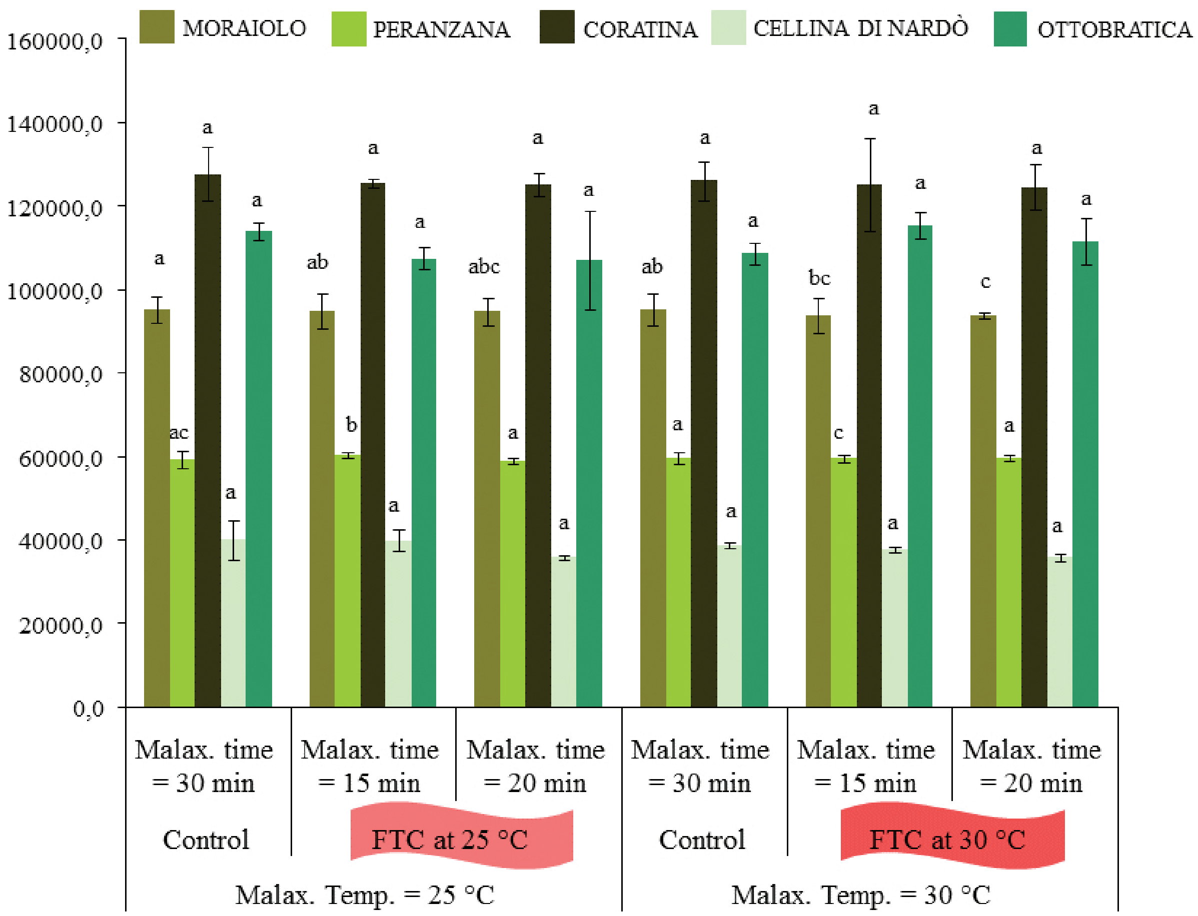

Figure 6. Evaluation of C_5–C_6 volatile compounds (μg/kg) of EVOO Control and FTC obtained at different temperatures and times of malaxation[a] [53]. The evaluations were carried out by HS–SPME–GC/MS according to the method reported by Esposto et al. [37]. [a]Data are the mean of three independent analytical determinations ± SD. The values in each row having different letters (a–c) are significantly different from one another ($p < 0.05$).

The profile of volatile compounds, which highly influence the positive attributes of EVOO aroma, did not show univocal behavior ascribable to the application of FTC treatment to the crushed pastes, according to the cultivars. In Moraiolo cv., significant differences were observed only for EVOOs receiving FTC treatment and subsequent malaxation at 30°C. In Peranzana cv. EVOO, only small variations were seen for EVOO from FTC malaxed for 15 minutes (**Figure 6**) [53]. For the other three cultivars studied, non-significant differences were observed. These results obtained by Veneziani et al. [53] make it possible to highlight the variability according to the cultivar in the formation of volatile compounds during processing, linked to the different activity levels of each enzyme involved in the LOX pathway. A higher accumulation of C_6 saturated and unsaturated aldehydes was observed in the EVOO treated with FTC compared to that in the traditional process (**Figure 6**). The elimination of the stop period at the maximum temperature could account for the reduction of HPL partial inactivation [56].

5. Separation systems

This last phase provides for the separation of oily must from the malaxed paste by different extraction technologies, such as pressure, centrifugation, and selective filtration (i.e., "surface tension" or "percolation"). Over time, the innovation of the oil extraction phase has led to the replacement of traditional discontinuous lines using the pressure system extraction with the continuous lines, using different generations of decanters: two-phase, three-phase, and three-phase with water-saving system decanters [57–60].

The different decanters play an important role particularly in the hydrophilic composition of EVOO. Most of the phenols are effectively flushed away with the olive mill vegetation waters (OMVW) produced, instead of remaining in the oil. In general, the three-phase decanter provides a dilution of malaxed pastes with water (0.2–0.5 m^3/t of olives) producing 50–90 l of OMVW/100 kg of olive paste and 50–60 kg of olive pomace/100 kg of olive paste [15, 28]. However, the addition of water prior to oil separation in order to reduce the paste viscosity can explain the decrease in the phenols and C_6 alcohols, hexan-1-ol and *trans*-2-hexen-1-ol, in particular [18, 28]. In fact, adding water to olive paste gives rise to a loss in oleuropein and ligstroside derivatives, while lignans seem not to be affected by water addition. Indeed, the secoiridoids are amphiphilic in their nature, with a higher solubility in water than in the oil phase [61]; thus, when partitioned, most of them end up in olive oil co-products such as OMVW and/or pomaces.

The development of this machine has led to two-phase and three-phase centrifugal separations with low water consumption. The two-phase system is generally characterized by greatly reduced water consuming during the extraction process, producing 70 kg of olive pomace/100 kg of olive paste [28]. The new decanters produce EVOO characterized by a higher phenolic concentration compared with those extracted by the traditional centrifugation process, and the loss of these hydrophilic compounds in OMVW is reduced [58].

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6. Filtration

Filtration is the last step of the EVOO mechanical extraction process before bottling. In the EVOO industry, several filtration systems have been applied: conventional filtration systems (filter tanks and filter presses) and cross-flow filtration (tangential flow filtration). Recently, the new filtration systems, based on a filter bag and inert gas (nitrogen or argon) flow, have been proposed as innovative techniques [62].

Filtration is required to remove the residual water present as water-in-oil emulsions or dispersions, and solid particles deriving from olive pulp and peel. These suspended particles are rich in enzymes and sugars, which can lower EVOO quality by promoting hydrolysis and/or oxidation reactions. They also form unpleasant volatile components responsible for the muddy defect due to microbial fermentation, with consequent shortening of EVOO shelf life [18, 63, 64]. The effects of the filtration on EVOO shelf life are not unique. Several investigations have been carried out in order to evaluate the benefits and drawbacks of filtration in terms of changes of phenolic and volatile composition of olive oil and its stability over time [65, 66]. A number of research papers have shown that in filtered oils, the levels of hydroxytyrosol and tyrosol, which are formed by the hydrolysis rate of their secoiridoid derivatives, had decreased, and these oils showed a more rapid loss in total phenolic compounds compared to unfiltered oils [28, 66]. This change in the profile of the EVOO phenolic fraction implies a lowering of end-product stability [66]. EVOO filtration could help extend shelf life, thus reducing the rate of hydrolysis of the triacylglycerol matrix, especially in oils with higher initial free fatty acidity [66]. From the sensory point of view, filtration removes unwanted particles that cause hydrolysis, lipid oxidation, and microbial fermentation, which would lead to the producing of sensory defects during storage [18]. Positive attributes such as pungency, fruitiness, and bitterness may also be affected, depending on the type of filtration system. Research results differ greatly on the sensory impacts of filtration, which are highly dependent on the sensorial attributes of the unfiltered oil, the type of filtration used, and the time in storage [62].

7. Conclusion

The new technologies, applied to mechanical olive oil extraction systems, are process innovations adaptable to most of the oil extraction plants commonly used, characterized by different purchase costs and different results of application. The increase in oil yield, the transformation into a continuous extraction process, the reduction of processing times, and the greater versatility of some new plants, united by the same goal of high-quality virgin olive oil production, are all elements that aim toward greater economic growth in the olive oil industry.

The application of new technologies properly dimensioned according to the producer's necessities is a valid tool for reaching an optimal compromise between plant performance and VOO quality, according to the olives' characteristics.

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