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Balancing Efficiency and Quality: Effects of Gradual Temperature Increase on Extra Virgin Olive Oil Extraction

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Abstract: This study examined the influence of malaxation temperatures on the extraction of extra virgin olive oil (EVOO) and its phenolic compound content, aiming to balance energy efficiency with final product quality. Extraction was tested at three temperatures of malaxation, 21 °C, 27 °C, and a gradual increase from 21 °C to 27 °C. Higher malaxation temperatures improved extraction yields and phenolic compounds. However, a gradual temperature increase produced promising results. The research found that yields like those obtained at 27 °C could be achieved using a lowered temperature of up to 6 °C for 15 min. The gradual temperature increase resulted in a 15% increase in phenolic compounds in comparison to low temperature extracted samples. The presence of beneficial aromatic compounds, such as (E)-2-hexenal, increased with higher temperatures, enhancing the fresh and fruity sensory notes of the oil. However, compounds linked to sensory defects, such as (E)-2-heptenal, increased at higher temperatures, indicating a need for careful modulation of extraction temperatures. In conclusion, adopting a gradually increasing temperature profile during malaxation represents an advantageous strategy for optimizing EVOO extraction, improving both the quality of the final product and operational efficiency, thus contributing to more sustainable and economical production.

Keywords: malaxation temperature; phenolic compounds; energy efficiency; aromatic compounds; sustainable production

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1. Introduction

One critical aspect of agricultural production affected by rising temperatures is thermal management. In various agricultural practices, maintaining specific temperature ranges has become increasingly crucial to ensure optimal growth, productivity, and quality of crops [1]. Extra virgin olive oil (EVOO) is typically extracted at temperatures below 27 degrees. This low temperature extraction process, known as "cold pressing", is critical for maintaining the quality and natural characteristics of the olive oil [2].

Temperature significantly affects yield during the kneading and centrifugation stages of olive oil extraction. Higher temperatures promote the coalescence of microscopic oil droplets in the olive paste, allowing them to merge into larger, more easily separable globules; this reduces the viscosity of the paste, facilitating the release and movement of the oil and enhances the transfer of substances from the aqueous phase to the oil phase, typically resulting in an increased yield [3].

Elevated temperatures decrease the viscosity of EVOO and the consistency of the olive paste, thereby enhancing the extraction process in the decanter [4]. During kneading, the slow agitation of the paste causes small oil droplets to coalesce into larger ones, resulting in a continuous liquid phase that is amenable to mechanical separation [5].

Temperature also significantly influences several quality parameters in EVOO. As temperatures increase, enzymatic reactions such as lipolysis and oxidation are intensified, which affects the phenolic and aromatic profiles. Moreover, the increased vapor pressure of volatile substances at higher temperatures may lead to a loss of aroma [6–8].

Phenolic compounds are essential indicators of EVOO quality due to their significant health benefits and impact on the oil's stability and flavor. High phenolic compounds content in EVOO is associated with enhanced antioxidant properties, which help protect the oil from oxidation, thereby prolonging its shelf life and preserving its nutritional value [5,9,10]. Furthermore, phenolic compounds, especially oleuropein and its derivatives, contribute to the characteristic bitterness and pungency of EVOO. These compounds are responsible for the sharp, peppery taste often associated with high-quality EVOO [11].

Studies have shown that temperature plays a critical role in the quality and yield of olive oil during its extraction process [12–14]. High temperatures can both positively and negatively impact the various stages of oil production. One study highlighted that a moderate increase in temperature, such as from 20 °C to 27 °C, can improve both the yield and quality of the olive oil. However, further increases to temperatures as high as 35 °C can lead to the formation of undesirable compounds associated with rancidity [15].

Given the critical role of temperature in the olive oil extraction process, we conducted an experiment to evaluate the impact of varying extraction temperatures. Our objective was to assess how temperature fluctuations in the malaxer influence the yield and quality of the extracted oil.

We initiated the experiment by setting the malaxer to an initial temperature of 21 °C. From this baseline, we incrementally increased the temperature to 27 °C.

To ensure comprehensive analysis, we also performed extractions at constant malaxer temperatures of 21 °C and 27 °C throughout the process. These trials enabled us to directly compare the effects of fixed temperatures with those of a gradual temperature increase.

A comprehensive understanding of these effects can aid in optimizing the extraction process, ensuring higher quality and yield. Gradually increasing the temperature during extraction, rather than maintaining a constant high temperature, could help in balancing the benefits of improved yield and quality without introducing defects associated with excessive heat.

2. Materials and Methods

2.1. Olives

Handpicked Frantoio olives (*Olea europaea*) were collected in Bucine, Arezzo, Italy. Visual inspections by company technicians at the Frantoio dell' Olivone Loc. Le Mura/San Leolino Belvedere—Bucine (AR), Italy, confirmed that the fruits were in top sanitary and physical condition, free from insect or pest infestations and mechanical damage. The ripeness index was assessed at 4, indicating a predominantly purple to black skin color while the flesh remained white [16].

2.2. Experimental Conditions

A uniform batch of the "Frantoio" variety was divided into sub-batches and subjected to malaxation at three distinct temperature ranges. These ranges cover the full spectrum of temperatures used by the host company during production, as confirmed by a review of the literature [17]. All trials were performed in triplicate, yielding a total of 9 samples.

The olives were crushed at a speed of 3000 rpm in a continuous system, which matched the peripheral speed of the crushing elements. The resulting olive paste was then processed in a malaxation unit (MORI-TEM Srl, Via Leonardo da Vinci, 59, 50028 Barberino Tavarnelle (FI), Italy). It comprises five cylindrical malaxing units, each capable of holding up to 70 kg of paste, with thermal jackets that can operate either in series or parallel, depending on the configuration of the feeding pump system. The design supports continuous malaxation, thereby eliminating the need for a holding phase. It also makes cleaning more efficient through a 30° tilt, which permits the easy removal of the reel shaft from above and allows for straightforward access to internal surfaces for washing. The elongated and narrow design of the malaxing units improves heat transfer efficiency by expanding the heat transfer surface area relative to the volume of olive paste, thereby promoting a more uniform temperature distribution throughout the paste. Each malaxer is equipped with

temperature sensors located on the lower half of the tank, providing precise measurements of the average temperature during malaxation. The stirring action ensures that the paste in contact with the sensor is continuously refreshed, enhancing measurement accuracy. Malaxation was carried out in continuous cycles in the chambers for 25 min.

The tested malaxation temperatures were:

- 21 °C for the entire malaxation time (25 min), labeled Low Temperature
- 21 °C for the first 15 min, followed by 27 °C for the next 10 min, labeled Low–High Temperature.
- 27 °C for the entire malaxation time (25 min), labeled High Temperature

A two-phase decanter (MORI–TEM srl Via Leonardo da Vinci 59, 50028 Barberino Tavarnelle (FI), Italy) separated the oil from water and pomace at a rate of 840 kg h^{-1}. Finally, the oil that was produced was immediately filtered using a stainless steel prefilter and a filter press.

Table 1 shows the temperature settings that were monitored during the trials. It is important to note that the temperatures selected during the experimental design phase were maintained with very little variability. This confirms that the pilot malaxation system, as reported in a recent study [12], has a good heat transfer capability, minimizing energy losses and ensuring uniform distribution of heat.

Table 1. Mean Temperatures adopted during the trials and relative standard deviation.

Samples	Mean Temperature (°C)	Dev. Standard
Low Temperature	21.52	0.46
Low–High Temperature	21.8–27.8	0.55–0.45
High Temperature	26.81	0.41

2.3. Chemical Analysis

Oil samples from the trials were analyzed for free fatty acids (as % oleic acid), peroxide number (meq O_2 per kg of oil), and UV spectroscopic indices (K232, K270, and ΔK). [18]. Phenolic fractions were extracted and identified following the International Olive Council (IOC) official method [19]. Phenolic compounds were extracted using an 80:20 methanol solution and analyzed with an HP 1100 HPLC system equipped with DAD and MS detectors (Agilent Technologies, Santa Clara, CA, USA). Separation was achieved on a Poroshell 120 EC-C18 column with acetonitrile, water, and methanol as eluents, following the IOC gradient. The chromatogram was recorded at 280 nm, using syringic acid as an internal standard, and phenolic concentrations were reported in mg kg^{-1}.

Oil extraction yields were calculated in two ways: as the actual yield (OY) and as the Extractability Index (EI).

$$\mathrm{OY} = \frac{\text{extracted olive oil (g)}}{\text{olive paste (g)}} \times 100 \quad (1)$$

$$\mathrm{EI} = \frac{\text{extracted olive oil (g)}}{\text{content of the olive paste (g)}} \times 100 \quad (2)$$

The content of the olive paste (g) was determined from the oil content of the olive fruits (%).

Water content was assessed via the gravimetric method. To determine the total oil content in both olive paste and pomace, hexane extraction was performed using an automatic Randall extractor (model 148, Velp Scientifica, Milan, Italy). Results were expressed as a percentage of the total weight.

2.4. Volatile Organic Compounds Analysis

Volatile organic compounds (VOCs) were identified and quantified using headspace solid-phase microextraction (SPME) combined with gas chromatography–mass spectrometry (GC-MS) and the multiple internal standard method. Oil samples (4.3 g) and 0.1 g of an internal standard mix were placed in 20 mL vials sealed with PTFE/silicone septa. After 5 min at 60 °C, a 50/30 µm DVB/CAR/PDMS SPME fiber was exposed to the headspace for 20 min while shaking at 500 rpm. The fiber was then desorbed for 2 min at 260 °C in splitless mode in the gas chromatograph. VOCs were identified and quantified (mg kg^{-1}) by comparing their mass spectra and retention times to those of the internal standard mix, which contained 11 compounds. Calibration was performed using the internal standard mix.

A VOC analysis was performed using a Trace GC-MS (Thermo Fisher Scientific, Waltham, MA, USA) with a ZBFFAP column. The temperature program was: 36 °C for 10 min, ramped to 156 °C at 4 °C/min, then to 260 °C at 10 °C/min, and decreased to 250 °C at 10 °C/min, with a 2-min hold. Helium was the carrier gas (0.8 mL/min), and the ion source and transfer line were at 250 °C. Mass detection was in scan mode (30–330 Th) with 70 eV ionization. The external standard mix contained 71 analytes in refined oil, chosen based on previous studies of Italian virgin olive oils.

2.5. Sensory Analysis

The sensory evaluation of EVOO samples was carried out by a panel of eight trained evaluators, using the organoleptic assessment method established by the IOC, in accordance with the regulations set forth by the EEC Department of Early Education and Care [18]. The evaluation was carried out across three separate sessions, with the samples being randomly distributed among the assessors.

2.6. Statistical Analysis

A one-way ANOVA was employed to assess significant differences across temperature ranges, with a significance threshold set at $p < 0.05$. To further investigate differences between mean values, Tukey's honestly significant difference (HSD) test was performed as a post-hoc analysis where necessary. The findings are reported with means and standard deviations. All statistical computations were carried out using R software (version 4.4.1).

3. Results

The gradual increase in temperature during extraction was tested on an industrial scale to demonstrate its effectiveness in balancing the benefits of improved yield and quality while avoiding defects associated with excessive heating. No issues related to the operation of the plant were observed.

3.1. Quality Parameters in EVOO

For the EVOO samples, both the oil extraction yield and the legal chemical parameters are reported in Table 2. No significant effect of the extraction temperatures was observed for the free fatty acids content, the peroxide number, the K232, and the K270 UV spectroscopic indexes. However, temperature significantly influenced the extraction yields. The OY increased from approximately 16.4% at 21 °C to 17.2% at 27 °C, with an intermediate value corresponding to the gradual increase in temperature (low–high). Similarly, EI values increased from approximately 71% at 21 °C to 76% at 27 °C, with the same high value recorded in the low–high temperature range.

Table 2. Parameters of EVOO extracted by malaxation at different temperatures (Low Temperature, Low–High Temperature, High Temperature) for 25 min. Means and (±) Standard deviations. Different letters represent a statistically significant difference ($p < 0.05$) based on the Tukey HSD post-hoc test.

Samples	Low Temperature	Low–High Temperature	High Temperature
Free Fatty Acids (%)	0.28 ± 0.01 a	0.28 ± 0.01 a	0.29 ± 0.01 a
Peroxide number (meq O_2 kg^{-1})	4.82 ± 0.58 a	5.44 ± 0.35 a	5.99 ± 0.64 a
K232	1.77 ± 0.04 a	1.79 ± 0.01 a	1.81 ± 0.03 a
K270	0.13 ± 0.00 a	0.12 ± 0.00 a	0.13 ± 0.00 a
ΔK	0.00 ± 0.00 a	0.00 ± 0.00 a	0.00 ± 0.00 a
OY (%)	16.43 ± 0.24 b	16.76 ± 0.20 ab	17.18 ± 0.27 a
EI (%)	71.10 ± 0.71 b	75.96 ± 1.34 a	75.35 ± 1.39 a

3.2. Phenolic Compounds, VOCs Concentration and Sensory Description

The total phenolic compounds content of the olive oil increased markedly with higher final extraction temperatures (Table 3). Specifically, olive oil samples extracted at 21 °C exhibited a significantly lower phenolic compounds content, approximately 34% less, compared to those extracted at 27 °C. This increase in phenolic compounds concentration at higher temperatures can be attributed to the enhanced solubility and extraction efficiency of phenolic compounds [20].

Table 3. Phenolic compounds concentrations (mg kg^{-1}) of EVOO extracted by malaxation at different temperatures (Low Temperature, Low–High Temperature, High Temperature) for 25 min. Means and (±) Standard deviations. Different letters represent a statistically significant difference ($p < 0.05$) based on the Tukey HSD post-hoc test.

Samples	Low Temperature	Low–High Temperature	High Temperature
Hydroxytyrosol	2.15 ± 0.16 b	2.10 ± 0.11 b	2.78 ± 0.19 a
Tyrosol	4.06 ± 0.07 b	3.99 ± 0.06 b	4.90 ± 0.08 a
Tyrosyl acetate	3.31 ± 1.74 a	4.10 ± 1.79 a	1.82 ± 1.22 a
Vanillic acid + Caffeic acid	2.61 ± 0.16 b	2.25 ± 0.15 b	3.39 ± 0.01 a
Vanillin	2.12 ± 0.19 a	1.74 ± 0.10 b	2.35 ± 0.07 a
Para-coumaric acid	2.03 ± 0.18 b	1.87 ± 0.24 b	2.96 ± 0.21 a
Hydroxy tyrosyl acetate	0.47 ± 0.10 b	0.57 ± 0.07 ab	0.69 ± 0.09 a
Ferulic acid	5.61 ± 0.12 b	3.09 ± 0.19 c	7.19 ± 0.10 a
Ortho-coumaric acid	1.24 ± 0.30 a	1.19 ± 0.51 a	1.84 ± 0.20 a
Cinnamic acid	3.24 ± 0.38 a	4.82 ± 1.44 a	2.66 ± 0.38 a
Decarboxy methyl oleuropein aglycone, oxidised dialdehyde	1.27 ± 0.43 a	1.40 ± 0.35 a	1.64 ± 0.89 a
Oleuropein	7.70 ± 2.89 a	9.69 ± 2.40 a	6.69 ± 2.36 a
Oleuropein-aglycone mono-aldehyde (3,4-DHPEA-EA)	21.16 ± 2.14 b	22.73 ± 0.82 b	33.11 ± 2.27 a
Oleuropein-aglycone di-aldehyde (3,4-DHPEA-EDA)	100.81 ± 1.13 c	122.21 ± 3.04 b	161.77 ± 6.99 a
Oleuropein aglycone, oxidised aldehyde and hydroxylic	6.55 ± 2.12 a	6.10 ± 1.52 a	6.76 ± 0.38 a
Oleuropein aglycone, aldehyde and hydroxylic	26.50 ± 0.14 a	24.22 ± 1.05 ab	20.89 ± 1.23 b

Table 3. *Cont.*

Samples	Low Temperature	Low–High Temperature	High Temperature
Decarboxymethyl ligstroside aglycone, oxidised dialdehyde	17.22 ± 0.96 a	18.14 ± 1.18 a	18.94 ± 1.86 a
Ligstroside-aglycone mono-aldehyde (p-HPEA-EA)	9.34 ± 3.13 a	9.81 ± 0.78 a	6.71 ± 0.39 a
Ligstroside-aglycone di-aldehyde (p-HPEA-EDA)	35.30 ± 1.03 c	45.55 ± 3.61 b	62.44 ± 3.88 a
Ligstroside aglycone, oxidised aldehyde and hydroxylic	14.31 ± 2.41 a	17.24 ± 1.63 a	15.86 ± 0.99 a
Ligstroside aglycone, aldehyde and hydroxylic	7.38 ± 0.68 a	5.59 ± 0.88 b	4.80 ± 0.31 b
Pinoresinol	15.52 ± 1.20 b	22.80 ± 1.15 a	16.67 ± 0.88 b
Luteolin + Methyl-luteolin	14.15 ± 1.08 b	21.66 ± 1.45 a	21.61 ± 1.31 a
Apigenin	1.35 ± 0.42 a	1.74 ± 0.11 a	2.01 ± 0.41 a
Total phenolic compounds	305.39 ± 3.21 c	354.61 ± 5.61 b	410.49 ± 15.12 a

The content of the dialdehydic form of decarboxymethyl oleuropein aglycone, known as 3,4-DHPEA-EDA, and the most prevalent phenolic compound in EVOO was observed to rise significantly with increasing temperature (Table 3). This temperature-dependent increase in phenolic content aligns with previous findings [13,15].

Additionally, an increase in p-HPEA-EDA associated with a rise in temperature was also recorded.

Concerning the volatile aromatic compound's concentration, it emerged as an effect of temperature as shown in Table 4. The temperature of malaxation also showed an effect on aromatic compounds. Higher temperatures during extraction and malaxation can enhance the extraction of compounds associated with positive notes such as "fresh" and "fruity", particularly C6 compounds that ranged from 26.8 (mg kg^{-1}) at low temperature to 32.6 (mg kg^{-1}) at high temperature. The Low–High temperature has shown a value similar to the High temperature value.

Table 4. Class of Aromatic Volatile concentrations (mg kg^{-1}) of EVOO extracted by malaxation at different temperatures (Low Temperature, Low–High Temperature, High Temperature) for 25 min. Means and (±) Standard deviations. Different letters represent a statistically significant difference ($p < 0.05$) based on the Tukey HSD post-hoc test.

Samples	Low Temperature	Low–High Temperature	High Temperature
C5	0.58 ± 0.13 a	0.68 ± 0.08 a	0.69 ± 0.03 a
C6	26.79 ± 1.63 b	31.74 ± 0.46 a	32.63 ± 2.76 a
Derived from microbial metabolites	8.18 ± 0.67 b	9.95 ± 0.26 a	10.21 ± 0.53 a
Others	11.28 ± 0.35 b	11.24 ± 0.15 b	14.47 ± 1.41 a

A similar trend was also observed with the concentration of compounds derived from microbial activity. In fact, the trend indicates that an increase in temperature leads to the formation of a greater number of compounds, not all of which are positive.

The concentrations of representative compounds from this class, such as (E)-2-Hexenal, clearly demonstrate the effect of temperature, as reported in Figure 1. Additionally, (E)-2-Heptenal, a volatile compound linked to rancidity [5,21] was notably significant in the EVOO samples extracted at high temperature.

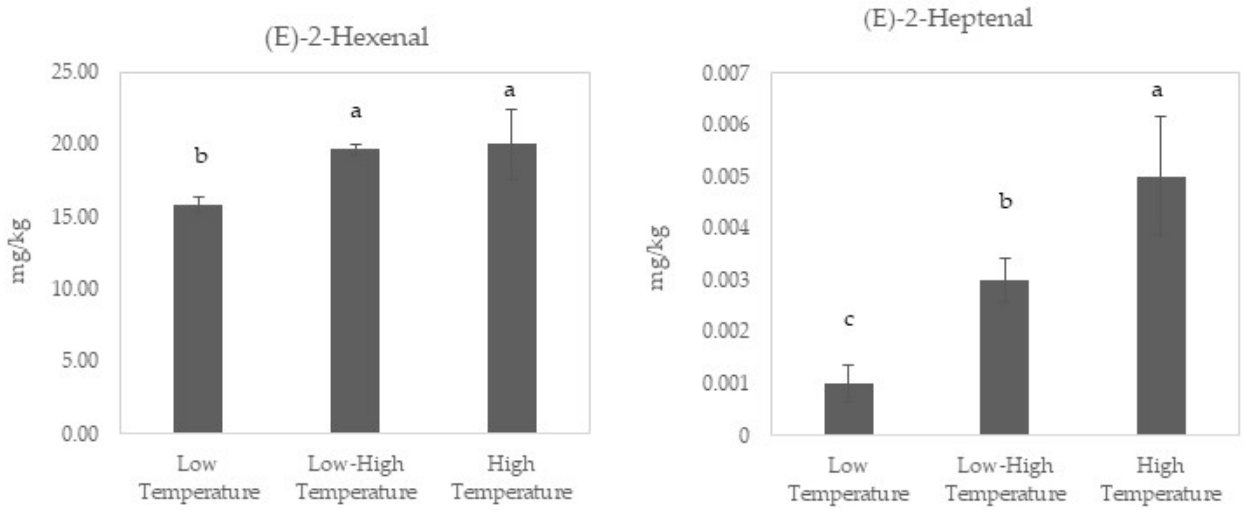

Figure 1. VOCs concentrations of (E)-2-hexenal and (E)-2-heptenal, (mg kg^{-1}) in EVOO extracted by malaxation at different temperatures (Low Temperature Low–High Temperature, High Temperature) for 25 min. Means and Standard deviations. Different letters represent a statistically significant difference ($p < 0.05$) based on the Tukey HSD post-hoc test.

Regarding the sensory evaluation, no significant differences were found for the fruity and bitter descriptors, nor for the rancid defect. This was expected, as the selected temperatures are suitable for enhancing the quality of olive oil.

4. Discussion

This study explores the potential for a gradual increase in malaxation temperature to enhance extraction yields and phenolic compound content, while also providing a balance between high yields and energy costs.

The qualitative chemical parameters analyzed did not show differences between the extraction temperatures.

The factors K232 and K270 are key indicators for assessing the degree of oxidation, which directly impact the freshness and quality of the oil, as they are associated with the presence of conjugated dienes and trienes.

The factor ΔK is a critical parameter for evaluating the purity of the oil and detecting potential adulteration or blending with refined oils.

The data show a clear positive correlation between temperature and both oil yield (OY) and extraction yield (EI), with values of 0.86 and 0.85 respectively. As the temperature increases, both yields improve, indicating that higher temperatures can enhance the efficiency of the extraction process.

A notable finding was that similar yields to those achieved at 27 °C could be obtained at a lower temperature (approximately 6 °C less) over a duration of 15 min.

These results agree with previous studies [15,22], which indicate that higher malaxation temperatures are associated with increased extraction yields. This effect is due to several factors:

Enhanced Enzyme Activity: Slightly higher temperatures can improve the activity of enzymes responsible for breaking down cell walls, facilitating the release of oil [23].

Reduced Viscosity: Higher temperatures lower the viscosity of the olive paste, allowing the oil to separate more easily during the extraction process [24].

The ability to obtain comparable results at lower temperatures represents a significant advantage in terms of resource optimization.

The content of total phenolic compounds in the olive oil significantly increased with higher final extraction temperatures.

At elevated temperatures, the cell walls of the olives become softer, and the enzymatic activity is improved, leading to a more efficient release of phenolic compounds into the

oil [25]. Consequently, the higher extraction temperature facilitates better extraction of these bioactive compounds, resulting in a higher concentration of phenolic compounds in the final product [22]. The temperature range tested, which involves a gradual increase from 21 °C to 27 °C over a 25-min malaxation period, showed promising results. This gradual increase approach provided an intermediate value between the two extremes of extraction temperature: the high temperature (27 °C) and the low temperature (21 °C).

The gradual increase of heat during the malaxation phase resulted in an enhancement of phenolic compounds by approximately 15%, significantly boosting the levels of antioxidant compounds compared to extraction conducted at low temperatures.

This intermediate result suggests that gradually increasing the temperature during malaxation can be effective in balancing the benefits of both extreme temperatures. In other words, this method offers a compromise between the higher extraction yields achieved at higher temperatures and the energy savings and potential advantages associated with lower temperatures.

A notable effect has been observed with an increase in the concentration of certain phenolic compounds, particularly p-HPEA-EDA. This compound is commonly revealed as a positive quality indicator that may suggest a higher presence of beneficial phenolic compounds [25]. Phenolic compounds, including those derived from oleuropein and ligstroside, are known for their antioxidant properties and contribute to the stability and longevity of the oil [26]. This increase, which follows the trend already described for total phenolic compounds, is attributable to enhanced enzymatic activity and increased solubility of the phenolic compounds.

Regarding the volatile organic compounds, higher temperatures during extraction and malaxation can enhance the extraction of compounds associated with positive notes such as “fresh” and “fruity”, particularly C6 compounds.

This increase of nearly 20% indicates that optimizing the temperature profile during extraction can improve the sensory qualities of the oil, potentially leading to a more aromatic and appealing final product. This approach could be advantageous for producers aiming to enhance the flavor profile of their olive oil while managing energy consumption efficiently.

About the compounds derived from microbial metabolites (in particular: 1butanolo 2 methyl + 3 methyl, acetic acid, hexyl ester, acetic acid, phenol, 2-methoxy-,phenol, phenol, 4-ethyl-2-methoxy-, 4 ethyl phenol, 2-butanone, methyl propionate, butanal 2- methyl, butanal, 3-methyl, ethanol, propanoic acid, ethyl ester, 2-butanol), we observed a correlation between their concentration and the increase in temperature (correlation value 0.89). This effect can be demonstrated by examining the concentration of these compounds across different temperature conditions. Specifically, in the low-to-high temperature extraction process, where the duration at low temperatures is longer than at high temperatures, the concentration of microbial metabolites increases with temperature. This indicates that higher temperatures enhance the presence of these microbial metabolites in the oil.

For the class of compounds associated with defects in EVOO, (E)-2-heptenal—a volatile compound linked to rancidity—was notably prominent in the EVOO samples extracted at high temperature. This compound was detected in all EVOO samples, and its concentration increased with temperature following the heating of the malaxed olive paste. However, there were significant differences between the high temperature (27 °C) and the controlled gradual temperature increase, which showed an intermediate concentration value, while the lowest value was observed at 21 °C, with a very low presence of this compound.

The measured concentrations of (E)-2-heptenal, as shown in Figure 1, ranged approximately from 0.001 to 0.005 mg kg^{-1}. The concentration at which this compound begins to be perceived is generally around 0.005 mg kg^{-1} in olive oils [27,28]. This means that levels below this concentration are hardly noticeable, while higher concentrations can be easily detected as rancid or defective.

This study shows that a gradual increase in temperature not only optimizes resource use but enhances the sensory and antioxidant properties of the final product, thereby contributing to both quality and sustainability in olive oil production.

5. Conclusions

This study reveals that gradually increasing malaxation temperature can significantly enhance extraction yields and phenolic compound content while balancing yield improvements with energy efficiency. This method optimizes resource use and improves the sensory and antioxidant properties of olive oil.

Key findings include the ability to achieve similar yields at a lower temperature (approximately 6 °C less) for 15 min compared to 27 °C, demonstrating a reduction in energy consumption without compromising the quality of the olive oil. The gradual temperature increase also results in an approximate 15% boost in phenolic compounds compared to the samples extracted at low temperatures, enhancing the oil's antioxidant properties.

Moreover, this approach improves the concentration of desirable aromatic compounds, such as C6, which contribute to fresh and fruity notes. However, it also raises the concentration of (E)-2-heptenal, a compound linked to rancidity. It highlights the importance of carefully managing temperature profiles to optimize quality. A gradually increasing temperature profile during malaxation offers an effective strategy to improve the efficiency and quality of olive oil extraction, while also reducing the environmental impact.

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