

Article

Assessing Optimal Olive Harvesting Time: A Comparison Between Visual Ripeness, Maturity Index, and Pulp Hardness

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Abstract

Optimal harvesting time is crucial for the quality and yield of extra virgin olive oil. Despite the widespread use of visual ripeness, maturity index, and pulp hardness, no study has compared their predictive ability for the quality and production parameters of extra virgin olive oil at industrial scale, thus motivating this work. Fifteen 300 kg olive samples (five replicates per harvesting date) were collected on 11 October, 29 October, and 25 November 2024 and processed within six hours at an industrial olive oil mill. One-way analysis of variance and Multiple Ordinary Least Squares regression were applied to evaluate harvest maturity indicators against primary quality, phenolic profile, yield, temperature, and sensory parameters. The former confirmed a significant main effect of harvesting time for most parameters, while the latter showed that visual ripeness systematically outperformed the maturity index and pulp hardness in seven out of eight models; pulp hardness was the sole exception, proving the strongest correlation with final oil temperature. These findings confirm that visual ripeness—a cost-free, immediately applicable parameter—seems to be the most strongly correlated indicator of the quality, phenolic content, and sensory attributes of extra virgin olive oil, while pulp hardness emerges as an innovative operative tool for optimizing temperature management in the production of extra virgin olive oil.

Keywords: extra virgin olive oil; olive ripeness; phenolic content; sensory attributes; olive maturity; visual ripeness; maturity index; pulp hardness; harvest timing; olive oil quality

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1. Introduction

Extra virgin olive oil (EVOO) is considered the worldwide standard bearer of the Mediterranean diet [1]. Its production is mainly concentrated in Europe [2]. Based on the latest European Commission report, 2.1 million tons of EVOO were produced in Europe during the 2024/2025 production season [2]. The primary EVOO producers are Spain (67% of EU production), Italy (12%), Greece (12%), and Portugal (8%) [2]. Furthermore, EVOO holds significant economic, nutritional, and social value; for these reasons, it is considered

worldwide as an essential food [3]. In Italy, EVOO industry is a pivotal sector of the national economy and one of its largest agri-food industries [3]. Moreover, due to its unique nutritional and health properties, EVOO represents the most prized and commercially valuable vegetable oil [4]; in particular, its richness in monounsaturated and polyunsaturated fatty acids, along with the presence of specific phenolic compounds like oleuropein and hydroxytyrosol, makes EVOO a globally unique product that plays an essential role in human health [4]. In addition, the specific phenolic profile of EVOO significantly affects the product's stability and sensorial characteristics. More precisely, oleuropein provides the bitter taste and oleocanthal gives the typical chemesthetic sensation of spiciness.

EVOO's quality is a direct expression of the freshness, integrity, and quality of the raw material, the olive. Consequently, the status of the olive drupe is one of the main factors affecting EVOO quality [5–7]. Accordingly, different authors have investigated the relationship between olive drupe quality and EVOO characteristics, testing different parameters like oil and water content, the distribution of oil and water within the drupe, visual ripeness, and pulp hardness. Monitoring the evolution of drupe composition during the ripening period is essential to define the optimal harvesting time and increase both EVOO yield and quality. Several methods and analytical techniques are currently employed to assess water, sugar, and oil evolution in olives. Gas chromatography (GC) is one of the most widely employed techniques for determining oil and fatty acid contents [6]. Nevertheless, high-resolution ^1H NMR spectroscopy represents an innovative technique that can determine, in a single spectrum, fatty acid and sugar contents in the olive drupe [8,9]. Nonetheless, this methodology has not yet been applied in the EVOO production chain, mainly due to cost and the need for highly specialized personnel.

Another interesting technique for the assessment of drupe composition evolution is based on hyperspectral imaging. González-Cabrera et al. (2018) [10] proposed a promising technique for evaluating olive drupe changes during ripening based on the application of micro-FTIR hyperspectral imaging. The results of the latter authors highlighted significant modifications during olive drupe ripening; in particular, a marked modification in cell wall polysaccharides in the flesh and the hypodermis during oil accumulation, a decrease in phenolic content as ripening progresses, and, finally, a decrease in pulp hardness with the increase in drupe ripening.

Other authors in the literature proposed different methods to identify optimal harvesting time based on NIR spectroscopy. Grassi et al. (2021) [11] proposed a novel approach based on NIR spectroscopy for rapidly predicting moisture, oil, soluble solid, and total phenolic content in olives with high model prediction accuracy. Cirilli et al. (2016) [12] proposed a novel approach based on the use of a portable NIR device for in-field monitoring of the textural properties of olives (flesh hardness) and the determination of other quality parameters like total phenolic, carotenoid, chlorophyll, and anthocyanin contents. The results of Cirilli et al. (2016) [12] are very interesting, showing an R^2 of 0.99 for flesh hardness predictive models and an R^2 ranging from 0.86 to 0.92 for total carotenoids, total anthocyanins, total chlorophyll, and rutin predictive models. Furferi et al. (2010) [13] and Khosravi et al. (2021) [14], in their respective papers, highlighted a significant advancement in the application of machine vision and artificial neural network-based techniques in understanding olive ripening progress. Finally, Tugnolo et al. (2021) [15] and Alamprese et al. (2021) [16] proposed similar approaches powered by a visible–near-infrared system based on image analysis to monitor the ripening stages of olive drupes with promising results.

Despite these approaches seeming to be the most interesting, fast, reliable, and green solutions for evaluating olive drupe quality and improving EVOO production processes, they present a significant increase in costs that olive growers and olive mills often cannot afford, given the lower investments and lower profitability of the sector compared, for

example, to the wine production chain. Furthermore, the literature review found two important gaps: no previous studies have directly correlated image data and/or NIR information with EVOO production parameters (yield and temperature) and EVOO characteristics (chemical, physical, and sensorial) at the industrial level; no authors in the literature have compared the effectiveness of the three most widely used methods to identify the optimal harvesting time of olives, namely the visual ripeness of olives, maturity index (International Olive Council official method), and pulp hardness, before directing scientific research efforts toward innovative technologies, thus motivating this work.

With respect to the three most widely used methods to identify the optimal harvesting time of olives (i.e., visual ripeness of olives, maturity index, and pulp hardness), despite their widespread use, each of the three maturity indicators presents specific limitations that have not been systematically addressed in the literature. Visual ripeness, while cost-free and immediately applicable in the field, is inherently subjective and operator-dependent, providing only a binary estimate of fruit color change without quantifying the progression of ripening within each color category and not considering the effective pulp maturity. The IOC maturity index, although more specific, requires trained personnel, a structured and time-consuming fruit classification procedure, and is difficult to standardize across different operators and production contexts. Finally, pulp hardness provides an objective and instrument-based measurement but requires dedicated equipment and has only been adopted sporadically in practical olive growing and mill operations, with very limited validation at the industrial scale. Critically, no previous study has directly and simultaneously compared the correlation of all three indicators against key EVOO production parameters—including oil yield, final extraction temperature, and the full phenolic and sensory profile—under real industrial processing conditions. This represents a fundamental gap in the literature, as the choice of maturity indicator has direct operative and economic consequences for olive growers and mill operators, yet no evidence-based framework exists to guide this decision at the industrial scale. As a result, the aim of this work is to assess which of the three most widely used approaches to identify optimal harvesting time of olives, i.e., visual ripeness of olives, maturity index, and pulp hardness, is most strongly associated with a group of key EVOO production processes and quality parameters, target phenolic compounds, total phenolic content, sensory defects, and positive attributes, at the industrial scale through the development of specific predictive models based on Multiple Ordinary Least Squares (MOLS) regression. It should be noted that optimal harvesting time is here intended as a multi-objective concept, as different production priorities—including oil yield maximization, phenolic content preservation, sensory quality, or technological efficiency—may lead to different optimal harvest moments. The aim of this study is therefore not to identify a single universally optimal harvest date, but rather to assess which maturity indicator is most reliably associated with each specific group of EVOO quality and process parameters, providing producers with an evidence-based framework to guide harvest timing decisions according to their specific objectives.

2. Materials and Methods

2.1. Raw Materials and Olive Sample Preparation

Fresh olives of Pendolino, Leccino, and Correggiolo cultivars were harvested on three different days, 11 October 2024, 29 October 2024, and 25 November 2024, at the Torre Bianca farm (San Casciano in Val di Pesa, Florence, Italy). The dates for olive harvesting were selected to cover the entire olive harvest period and depended on weather conditions. For every day of harvesting, five independent experimental samples of 300 kg each (one bin per sample) were prepared to obtain five statistical replicates. Olive sampling was performed randomly across trees of the three cultivars at each harvest date, following the standard farm practice for blend EVOO production, in which cultivars are harvested and

processed together. At each harvest date, the five independent 300 kg batches were constituted, ensuring full biological independence between replicates.

The five samples (300 kg each) were successively delivered to the olive oil mill of Torre Bianca farm to produce EVOO samples within six hours of olive harvesting (as described in detail in Section 2.3).

Each 300 kg sample of olives was created by filling one bin with the harvested olives contained in twelve perforated plastic boxes, each containing approximately 25 kg of olives. Before transferring the olives from the perforated plastic boxes to the bin, a representative sample of 3 kg was collected from the twelve plastic boxes to assess the visual ripeness of the olives (percentage of ripe fruits), maturity index (according to the IOC international standard), and pulp hardness, as described in Section 2.2. The 3 kg representative sample was obtained by randomly collecting approximately 250 g of olives from each of the twelve perforated plastic boxes, ensuring proportional and unbiased representation of the entire 300 kg batch. The twelve sub-samples were then pooled and thoroughly homogenized. Olives showing evident signs of damage, olive fruit fly (*Bactrocera oleae*) infestation, or other visible defects were discarded during homogenization. The resulting clean sample was subsequently divided into three equal subsamples of approximately 1 kg each, individually destined for the assessment of visual ripeness, maturity index, and pulp hardness, as described in detail in Section 2.2.

Successively, the five bins were taken to the oil mill for EVOO production. Each batch was processed separately through the industrial continuous-flow plant, and the resulting EVOO was independently sampled and analyzed. Cultivar was not treated as an independent experimental factor, as the three cultivars were co-harvested and co-processed following the standard farm practice for blend EVOO production. Figure 1 summarizes, in the form of a flow chart, the whole process of olive harvesting, sampling, and EVOO production.

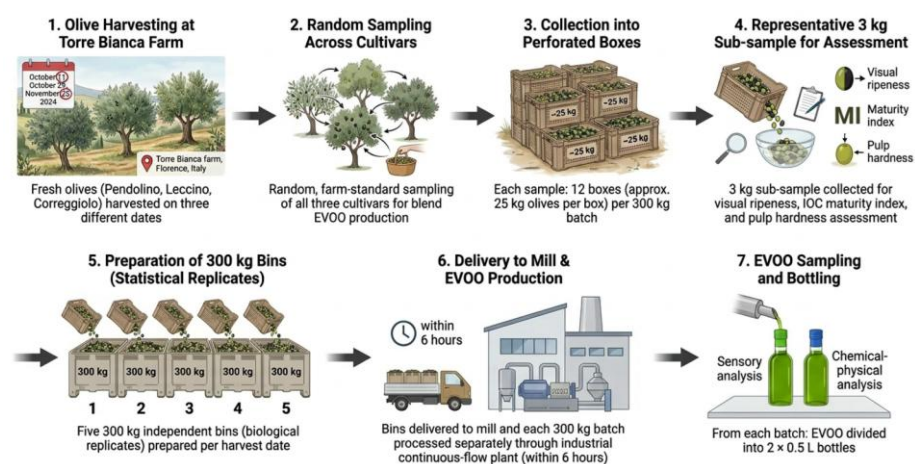


Figure 1. Graphical representation of olive harvesting, sampling, and EVOO production.

2.2. Assessment of Visual Ripeness, Maturity Index (IOC), and Pulp Hardness

Visual ripeness, evaluated by direct visual assessment, is the most widely used approach, since it is cost-free and relies on the widely accepted assumption in the technical and scientific literature that, in most cases, olive skin color reliably reflects the oil content and quality [17,18]. In particular, the current literature indicates that the optimal harvesting time of olives corresponds to an olive ripening level between 25 and 50% [17,18]. This range ensures the best compromise between oil yield and phenolic content. Specifically, visual ripeness was assessed by direct visual inspection of the 1 kg representative sample obtained from each batch (bin): each olive was individually examined and classified as

either ripe (i.e., showing any degree of skin color transition from green to yellow-green, purple, or black, indicating the onset of veraison) or unripe (fully green skin). The percentage of ripe fruits was then calculated as the ratio of ripe fruits to the total number of fruits in the sample, multiplied by 100. Although this binary classification does not distinguish between different stages of color development within the ripe category, it captures the onset and progression of veraison as a whole, which is the agronomically relevant threshold for harvest timing decisions in commercial olive growing. The proportion of fruits that have initiated color change, regardless of the specific stage reached, has been shown to reliably reflect the overall ripening status of the batch and its associated EVOO quality characteristics [19]. Furthermore, this approach differs fundamentally from the IOC maturity index, which requires the classification of each fruit into one of eight color categories (0–7) based on both skin and flesh color and calculates a weighted average score. Visual ripeness, by contrast, provides a rapid binary field estimate of the proportion of fruits that have entered the color-change phase, based exclusively on skin color observation, requiring no color chart, no equipment, and no laboratory procedure. This simplified, skin color-based visual approach is consistent with the method adopted by Salvador et al. (2001) [19], who assessed olive ripening stage through direct visual evaluation of fruit skin color as the primary field indicator of ripeness, demonstrating its strong correlation with key EVOO quality parameters across four consecutive crop seasons. Furthermore, this type of direct visual counting by trained operators has been documented in the literature as a recognized baseline assessment method. According to the harvesting dates (11 October 2024, 29 October 2024, and 25 November 2024) it was possible to obtain five samples with a visual ripeness between 7 and 15%, five samples with visual ripeness between 45 and 60%, and, finally, five samples with a visual ripeness $\geq 85\%$.

The maturity index (IOC official method) was determined strictly following the guidelines reported in the official IOC document [20]. In particular, the physiochemical influence of the ripening stage of olives was assessed using the maturity index, which classified olives into seven different categories: category 0: skin color deep green; category 1: skin color yellow-green; category 2: skin color green with reddish spots on less than half of the fruit surface and start of color change; category 3: skin color with more than half of the fruit surface turning reddish or purple and completion of color change; category 4: skin color black with white flesh; category 5: skin color black with less than half of the flesh turning purple; category 6: skin color black with not all the flesh purple to the stone; and category 7: skin color black with all the flesh purple to the stone. Figure 2 shows the physico-chemical impact of ripening on olives and the resulting olive oil [20].



Figure 2. Visual reference of the different olive ripening stage categories based on skin and flesh color evolution and the corresponding color variations in the extracted olive oil (adapted from IOC [20]).

The maturity index was calculated using the following formula:

$$M.I. = \frac{A0 + B1 + C2 + D3 + E4 + F5 + G6 + H7}{100}$$

where A, B, C, D, E, F, G, and H represent the number of fruits in color categories 0, 1, 2, 3, 4, 5, 6, and 7, respectively. This formula determines the maturity index of a representative sample of 100 olives. Finally, pulp hardness was measured on 100 olives per sample, carefully selected from the 1 kg representative subsample collected from each 300 kg batch (bin), as described above and illustrated in Figure 1. Olive selection was performed to ensure that the proportion of ripe fruits within the 100-olive set reflected the actual percentage of veraison observed in the original batch, thus maintaining the representativeness of the sample. Selection criteria included the exclusion of damaged fruits, olives showing signs of olive fruit fly (*Bactrocera oleae*) infestation, or fruits affected by other visible defects; only intact and healthy drupes were retained for measurement. Each olive was individually placed on a dedicated flat support to ensure stability during measurement. Pulp hardness was assessed using a Digital Shore durometer (type C) (China) equipped with a 2.5 mm spherical indenter, and the results are expressed on the Shore hardness scale (0–100 HC; resolution 0.5 HC). The reading was taken immediately upon stable contact between the indenter and the olive surface. To ensure methodological consistency and comparability across all samples, measurements were always taken at the same anatomical position on each drupe, specifically at the equatorial region of the fruit, avoiding both the styler and peduncular ends. The final hardness value for each sample was calculated as the mean of the 100 individual measurements, in accordance with previous studies [21].

2.3. Extra Virgin Olive Oil Production

As described in Section 2.1, fifteen olive samples of 300 kg each were delivered to the olive oil mill of Torre Bianca farm to produce EVOO samples within six hours of olive harvesting. The EVOO production plant (Mori TEM, Tavarnelle Val di Pesa, Florence, Italy) consisted of the following machines: (I) the DLE SUPER T unit (Mori TEM), which is an olive cleaning line consisting of a debrancher to remove twigs, stones, and other solid debris, followed by a defoliator, a washing machine, and a drying system; (II) a FR 350 knife crusher (Mori TEM), operating at 3000 rpm to produce the olive paste; (III) two sealed vertical malaxers, model CULTIVAR (Mori TEM), with controlled air–paste contact and oxygen exposure, operating at a temperature below 27 °C for 20 min; (IV) a DMT 30 decanter (Mori TEM), with a capacity of 2500–3000 kg/h, operating at 3400 rpm without any addition of water; and (V) a filtration group, model JOLLY FILTERS 10–20 (Mori TEM), using 20 cellulose filters arranged in sequence within the filtration unit. All the processing parameters were carefully monitored and kept constant to avoid any differences among the samples due to variations arising from the mill’s operational settings instead of the investigated factors. For each 300 kg olive sample, EVOO was collected in duplicate after the filtration system and stored in 0.75 L dark glass bottles specifically designed for EVOO, featuring a non-refillable cap. Subsequently, fifteen samples of EVOO were sent to the Analytical Food Laboratory (Florence, Italy) for EVOO characterization, and analyses were performed following approved, official methods (Section 2.4); the other fifteen EVOO samples (0.75 L bottles) were sent to the University of Messina (Sicily, Italy) for EVOO sensory analysis, as described in Section 2.5.

2.4. Extra Virgin Olive Oil Characterization and Analysis

The analytical characterization of the EVOO samples was carried out following the standard methods defined by the European Commission Implementing Regulation (EU)

2022/2105 of 29 July 2022, which lays down rules on conformity checks of marketing standards for olive oil and methods of analysis of the characteristics of olive oil. According to this regulation (and its current consolidated version), the following parameters were assessed by the accredited private laboratory Analytical Food (Florence, Italy): (1) Primary quality parameters: The determination of free acidity (expressed as % of oleic acid), peroxide value ($\text{meq O}_2 \text{ kg}^{-1}$) and UV spectrophotometric constants (K_{232} , K_{270} , and ΔK) was performed to assess the standard quality indices and the legal category of the oil. (2) Total phenolic content: Total phenolic content was quantified through a colorimetric assay using the Folin–Ciocalteu reagent, with the final concentrations expressed as milligrams of gallic acid equivalents per kilogram of oil (mg/kg). (3) Specific phenolic profile: Specific phenolic compounds were identified and quantified using High-Performance Liquid Chromatography (HPLC) coupled with a Diode Array Detector (DAD), in accordance with the IOC official method (COI/T.20/Doc. No. 29). This analysis specifically targeted the secoiridoid fraction, including oleuropein, oleuropein aglycone (3,4-DHPEA-EA), the dialdehydic form of oleuropein aglycone, the dialdehydic form of decarboxymethyl oleuropein aglycone (3,4-DHPEA-EDA, oleacein), hydroxytyrosol (3,4-DHPEA), ligstroside aglycone (p-HPEA-EA), ligstroside aglycone dialdehydic form, the dialdehydic form of decarboxymethyl ligstroside aglycone (p-HPEA-EDA, oleocanthal), and tyrosol (p-HPEA).

2.5. Extra Virgin Olive Oil Sensory Analysis

Sensory analysis of the EVOO samples was conducted by the institutional panel of the Department of Veterinary Sciences of the University of Messina. The sensory panel consisted of 16 participants (10 males and 6 females) aged between 25 and 60 years. The panel was formed according to the International Olive Council guidelines [22–24]. All participants signed an informed consent under the principles outlined by the Declaration of Helsinki. The evaluations were carried out between 10:00 a.m. and 12:00 p.m. in individual booths under controlled lighting conditions. The EVOO samples were served in standardized dark glasses with randomized order among participants and sessions. Water and unsalted crackers were provided as palate cleansers between samples.

The descriptors were validated using reference standards, allowing panel members to calibrate their sensory perceptions and maintain consistency in the use of descriptors across different sessions. Positive (fruity, bitter, pungent) and negative (such as fusty/muddy sediment, musty/humid/earthy, winey/vinegary, and rancid) attributes were used in the sensory analysis. The intensity of attributes was defined using a 10 cm continuous linear scale from 0 (no sensation) to 10 (maximum intensity). The median value was calculated for each attribute listed in the profile sheet. Data collection was performed using a computerized registration system (FIZZ Biosystèmes ver. 2.00 M, Couteron, France).

2.6. Statistical Analysis

The effect of the olive harvesting date was assessed using a one-way ANOVA to evaluate the general experimental results and establish statistical significance. Three levels were tested based on the harvesting dates (11 October, 29 October, and 25 November 2024). The significance level was set at $\alpha = 0.05$. In cases of statistically significant results ($p < 0.05$), Tukey's HSD post hoc test was performed. Furthermore, a Principal Component Analysis (PCA) was performed as an unsupervised multivariate approach to explore the overall distribution of EVOO samples according to harvesting date. The PCA matrix included harvest maturity indicators, process parameters, and selected EVOO quality-related variables, namely visual ripeness, maturity index, pulp hardness, EVOO yield, final EVOO temperature, free acidity, total phenolic content, and selected secoiridoid-related

compounds. Before PCA, data were log-transformed and autoscaled by mean-centering and division by the standard deviation to reduce scale effects and give all variables comparable weight in the multivariate model. PCA was carried out using MetaboAnalyst V.6 (2026). Variable loadings for PC1 and PC2 were also extracted and plotted to identify the variables mainly contributing to sample separation. To support the interpretation of the PCA dimensionality, parallel analysis was additionally performed by comparing the observed PCA eigenvalues with eigenvalues generated from randomly simulated datasets with the same dimensionality.

Finally, the influence of the three most widely used methods to identify optimal harvesting time of olives—visual ripeness of olives (in percentage), maturity index (IOC official method), and pulp hardness—on the chemical and sensory characteristics of EVOO was investigated using Multiple Ordinary Least Squares (MOLS) regression. MOLS models were developed to assess the relationship between the selected harvest maturity indicator of olives (dependent variables) and specific groups of independent parameters, including primary EVOO quality indices, total phenolic content, specific phenolic compounds, EVOO yield, final EVOO temperature, and sensory attributes.

The model equation is as follows:

$$Y = \beta^0 + \beta^1 X^1 + \beta^2 X^2 + \dots + \beta_n X_n + \varepsilon$$

where

Y is the harvest maturity indicator (visual ripeness, maturity index, or pulp hardness);

β_0 is the intercept;

$\beta_1 \dots \beta_n$ are the regression coefficients representing the effect of each EVOO quality or process parameter on the dependent variable;

ε is the error term.

For models including a single predictor (total phenolic content, EVOO yield, and final EVOO temperature), the equation simplifies to the simple linear regression form:

$$Y = \beta_0 + \beta_1 X + \varepsilon.$$

Specifically, the following regression models were investigated:

- (I) Harvest maturity indicators vs. primary EVOO quality parameters (free acidity, peroxide value, and UV spectrophotometric constants).
- (II) Harvest maturity indicators vs. total phenolic content.
- (III) Harvest maturity indicators vs. oleuropein and its direct derivatives (3,4-DHPEA-EA, 3,4-DHPEA-EDA, hydroxytyrosol).
- (IV) Harvest maturity indicators vs. ligstroside and its direct derivatives (p-HPEA-EA, p-HPEA-EDA, tyrosol).
- (V) Harvest maturity indicators vs. total specific phenolic profile (sum of oleuropein, ligstroside, and their derivatives).
- (VI) Harvest maturity indicators vs. EVOO yield.
- (VII) Harvest maturity indicators vs. final EVOO temperature.
- (VIII) Harvest maturity indicators vs. positive sensory attributes (fruity, bitter, and pungent).

It should be noted that each MOLS model includes a single harvest maturity indicator as the sole dependent variable; the three indicators are therefore compared across separate, independent models and are never entered simultaneously into the same regression equation. Furthermore, prior to all statistical analyses, including one-way ANOVA and MOLS regression, the normality of the data distribution was verified, and homoscedasticity was assessed using Bartlett's test, as is standard and mandatory practice before applying par-

ametric statistical methods. All statistical analyses were performed using R software (version 4.5.0).

3. Results and Discussion

3.1. Experimental Results

3.1.1. Harvest Maturity Indicators

The results for visual ripeness of olives, maturity index, and pulp hardness are summarized in Table 1. The one-way ANOVA found a significant main effect for the factor “harvesting date” for all the tested methods to identify optimal harvesting time ($p < 0.001$). As shown in Table 1, the percentage of ripe olives and the maturity index significantly increased as the harvesting date progressed; this is consistent with Camposeo et al. (2013) [25], who highlighted that, from early October to late November, olive skin color changed from green to yellow-green, then to red-virescent and, finally, to black, due to a progressive chlorophyll and carotenoid degradation and the simultaneous anthocyanin synthesis. Conversely, pulp hardness significantly decreased as the harvesting date progressed. This is mainly due to ripening-associated modifications in cell wall composition and olive structure, as well as to the increased enzymatic activity. More precisely, Diarte et al. (2021) [26] found that the yields of alcohol-insoluble residue and calcium content in fruit pericarp decreased during ripening. Furthermore, despite cultivar-specific differences, the reduction in pulp hardness is mainly related to the decrease in pectin methylesterase activity, the reduction in calcium content, the increase in ascorbate content, and, finally, the increase in α -l-arabinofuranosidase and β -galactosidase activities [26].

Table 1. Harvest maturity indicators (visual ripeness, maturity index, and pulp hardness) for each sample.

Sample	Olive Harvesting Date	Visual Ripeness of Olives (%)	Maturity Index (I.O.C.)	Pulp Hardness (HC)
Sample 1–5	HD1	12.4 ± 3.7^a	1.27 ± 0.39^a	67.62 ± 11.03^a
Sample 6–10	HD2	52.0 ± 5.7^b	2.45 ± 0.36^b	58.33 ± 6.76^a
Sample 11–15	HD3	90.0 ± 0.0^c	3.89 ± 0.16^c	43.82 ± 4.12^b

Samples 1–5, 6–10, and 11–15 correspond to the five independent 300 kg batches processed on 11 October, 29 October, and 25 November, respectively. Data are presented as the mean ($\pm$ SD) of five replicates. Different letters represent statistically significant differences ($p < 0.05$). HD1 = 11 October 2024; HD2 = 29 October 2024; HD3 = 25 November 2024.

3.1.2. Primary EVOO Quality and Process Parameters (EVOO Yield and Temperature)

Table 2 shows the results for free acidity, peroxide value, K_{232} , K_{270} , ΔK , EVOO yield, and temperature. With respect to free acidity, the one-way ANOVA did not find any statistically significant differences. This is consistent with D’Imperio et al. (2010) [27], who highlighted that the increase in free acidity is mainly due to oxygen exposure during EVOO production and storage. Regarding peroxide value, despite a slight increase alongside harvesting date progression, the one-way ANOVA did not find any statistically significant differences for the reasons previously discussed with respect to free acidity. Concerning K_{232} and K_{270} , the one-way ANOVA found a significant main effect for the factor “harvesting date” ($p < 0.001$). The significant decrease in K_{232} and K_{270} values observed with advancing fruit maturation can be attributed to the reduction in lipoxygenase enzymatic activity, which affects both primary and secondary oxidation products during the ripening process [28,29]. Finally, with respect to ΔK , the one-way ANOVA did not find any statistically significant differences.

Table 2. Primary EVOO quality and process parameters.

Sample	Olive Har-vesting Date	Free Acidity (% of Oleic Acid)	Peroxide Value (meq O ₂ kg ⁻¹)	K ₂₃₂	K ₂₇₀	ΔK	EVOO Yield (%)	EVOO Temperature (°C)
Sample 1–5	HD1	0.18 ± 0.03	4.83 ± 0.89	1.9 ± 0.07 ^a	0.2 ± 0.01 ^a	0.008 ± 0.004	7.20 ± 0.0 ^a	26.22 ± 1.02 ^a
Sample 6–10	HD2	0.14 ± 0.02	5.22 ± 0.77	1.8 ± 0.05 ^b	0.1 ± 0.01 ^b	0.004 ± 0.005	9.44 ± 0.29 ^b	26.08 ± 0.54 ^a
Sample 11–15	HD3	0.18 ± 0.06	5.84 ± 1.04	1.7 ± 0.02 ^c	0.1 ± 0.01 ^b	0.002 ± 0.004	12.62 ± 0.53 ^c	23.70 ± 0.58 ^b

Samples 1–5, 6–10, and 11–15 correspond to the five independent 300 kg batches processed on 11 October, 29 October, and 25 November, respectively. Data are presented as the mean (±SD) of five replicates. Different letters represent statistically significant differences ($p < 0.05$). HD1 = 11 October 2024; HD2 = 29 October 2024; HD3 = 25 November 2024.

Regarding EVOO yield, the one-way ANOVA showed a significant main effect for the factor “harvesting date” ($p < 0.001$). The significant increase in EVOO yield observed with advancing fruit maturation is mainly due to the progressive accumulation of triglycerides in the mesocarp tissue and the reduction in moisture content, which concentrates the oil fraction [29,30]. Finally, with respect to EVOO temperature, the one-way ANOVA found a significant main effect for the factor “harvesting date” ($p < 0.001$). The significant decrease in final EVOO temperature observed in the samples obtained from olives harvested on 25 November can be attributed to the progressive reduction in olive pulp hardness (softening of the olive mesocarp), which results from extensive cell wall disassembly driven by polysaccharide solubilization and neutral sugar loss [31]. This ripening-related reduction in fruit firmness leads to decreased mechanical friction during the olive crushing and malaxation processes, generating less heat and resulting in lower final EVOO temperatures.

3.1.3. Total Phenolic Content and Individual Phenolic Composition

Table 3 summarizes the results for total phenolic content, oleuropein aglycone, and its direct derivatives, while Table 4 shows the contents of ligstroside aglycone and its direct derivatives. With respect to total phenolic content, the results of the one-way ANOVA found a significant main effect of the factor “harvesting date” ($p < 0.001$). As widely reported in the literature, the total phenolic content of EVOO is negatively correlated with olive fruit ripeness, declining progressively from early (October) to late harvest (November). This pattern is driven by the progressive enzymatic hydrolysis of oleuropein and related secoiridoids—carried out by endogenous β-glucosidases activated during fruit senescence in vivo and further amplified by oxidative enzymatic activity during mechanical extraction—resulting in a net decrease in the intact glycosidic phenolic pool in the final product [32].

Table 3. Total phenolic content, oleuropein, and its direct derivatives.

Sample	Olive Harvesting Date	Total Phenolic Content (mg/kg)	Oleuropein (mg/kg)	Oleuropein Aglycone (3,4-DHPEA-EA) (mg/kg)	Dialdehydic Form of Oleuropein Aglycone (mg/kg)	Decarboxymethyl Oleuropein Aglycone (mg/kg)	Hydroxytyrosol (3,4-DHPEA) (mg/kg)
Sample 1–5	HD1	591.2 ± 51.3 ^a	18.22 ± 10.40	85.23 ± 9.46 ^a	86.21 ± 8.19 ^a	74.51 ± 14.94	1.98 ± 1.16
Sample 6–10	HD2	346.1 ± 36.9 ^b	11.47 ± 6.02	52.72 ± 16.15 ^b	25.73 ± 5.81 ^b	90.83 ± 16.62	1.81 ± 0.36
Sample 11–15	HD3	290.1 ± 36.4 ^c	6.65 ± 2.69	39.82 ± 18.36 ^b	24.39 ± 8.31 ^b	56.07 ± 7.28	1.65 ± 0.79

Samples 1–5, 6–10, and 11–15 correspond to the five independent 300 kg batches processed on 11 October, 29 October, and 25 November, respectively. Data are presented as the mean (±SD) of five

replicates. Different letters represent statistically significant differences ($p < 0.05$). HD1 = 11 October 2024; HD2 = 29 October 2024; HD3 = 25 November 2024.

Table 4. Ligstroside aglycone and its direct derivatives.

Sample	Olive Harvesting Date	Ligstroside Aglycone (p-HPEA-EA) (mg/kg)	Dialdehydic Form of Ligstroside Aglycone (mg/kg)	Decarboxymethyl Ligstroside Aglycone (p-HPEA-EDA) (mg/kg)	Tyrosol (p-HPEA) (mg/kg)
Sample 1–5	HD1	26.56 ± 8.75 ^a	35.20 ± 9.67 ^a	43.87 ± 7.10	3.07 ± 0.55
Sample 6–10	HD2	8.07 ± 5.26 ^b	5.17 ± 1.42 ^b	38.10 ± 5.93	2.64 ± 0.59
Sample 11–15	HD3	9.43 ± 3.51 ^b	4.20 ± 1.31 ^b	32.47 ± 7.53	4.67 ± 0.66

Samples 1–5, 6–10, and 11–15 correspond to the five independent 300 kg batches processed on 11 October, 29 October, and 25 November, respectively. Data are presented as the mean (±SD) of five replicates. Different letters represent statistically significant differences ($p < 0.05$). HD1 = 11 October 2024; HD2 = 29 October 2024; HD3 = 25 November 2024.

Concerning oleuropein content, despite a similar decreasing trend with advancing harvesting date, the one-way ANOVA did not find any statistically significant differences. Nevertheless, regarding oleuropein aglycone (3,4-DHPEA-EA), ligstroside aglycone (p-HPEA-EA), and the dialdehydic forms of oleuropein aglycone (3,4-DHPEA-EDA) and ligstroside aglycone (p-HPEA-EDA or oleocanthal) contents, the one-way ANOVA showed a significant main effect for the factor “harvesting date” ($p < 0.001$). As highlighted by Diamantakos et al. (2020) [32], individual secoiridoid derivatives also decrease significantly in EVOO with advancing fruit maturity (and harvesting date), a pattern consistently observed from the beginning of October to the end of November harvest due to the progressive enzymatic hydrolysis of oleuropein and related secoiridoids, increased by oxidative enzymatic activity during olive crushing and paste malaxation. Finally, with respect to decarboxymethyl oleuropein aglycone, decarboxymethyl ligstroside aglycone, hydroxytyrosol (3,4-DHPEA), and tyrosol (p-HPEA) contents, the results of the one-way ANOVA did not find any statistically significant differences.

3.1.4. Positive Sensory Attributes of EVOO

Table 5 summarizes the results for the positive sensory attributes of the EVOO samples. Notably, the organoleptic assessment conducted by the institutional panel confirmed the absence of defects in all fifteen EVOO samples throughout the sessions. Consequently, only positive sensory attributes, such as fruitiness, pungency, and bitterness intensities, were assessed with the one-way ANOVA and Multiple Ordinary Least Squares (MOLS) regression (Section 3.2). With respect to fruitiness and bitterness intensities, despite a decreasing trend as the harvesting date advanced, the one-way ANOVA did not find any statistically significant differences. In contrast, the result of the one-way ANOVA shows a significant main effect of the factor “harvesting date” ($p < 0.001$) in the case of pungency intensity. As shown in Table 5, it is possible to observe a significant decrease in pungency with increasing fruit maturity. This result is consistent with the phenolic profile discussed in Section 3.1.3, where oleuropein aglycone (3,4-DHPEA-EA), ligstroside aglycone (p-HPEA-EA), and their respective dialdehydic forms (3,4-DHPEA-EDA and oleocanthal) all declined significantly as the harvesting date advanced. Furthermore, this significant reduction in pungency intensity and oleocanthal content is consistent with the well-established role of oleocanthal as the primary compound responsible for the pungent sensation in EVOO, acting as a non-selective inhibitor of cyclooxygenase enzymes in a manner analogous to ibuprofen, as first described by Beauchamp et al. (2005) [33].

Table 5. Results of sensory analysis (positive attributes).

Sample	Olive Harvesting Date	Fruitiness Intensity	Pungency Intensity	Bitterness Intensity
Sample 1–5	HD1	6.6 ± 0.5	4.6 ± 0.5 ^a	3.8 ± 0.8
Sample 6–10	HD2	6.6 ± 0.5	3.8 ± 0.4 ^b	2.8 ± 0.8
Sample 11–15	HD3	6.0 ± 0.7	2.8 ± 0.4 ^c	2.8 ± 0.4

Samples 1–5, 6–10, and 11–15 correspond to the five independent 300 kg batches processed on 11 October, 29 October, and 25 November, respectively. Data are presented as the mean (±SD) of five replicates. Different letters represent statistically significant differences ($p < 0.05$). HD1 = 11 October 2024; HD2 = 29 October 2024; HD3 = 25 November 2024.

3.2. Principal Component Analysis (PCA)

Figure 3 shows the Principal Component Analysis score plot of EVOO samples according to harvesting date.

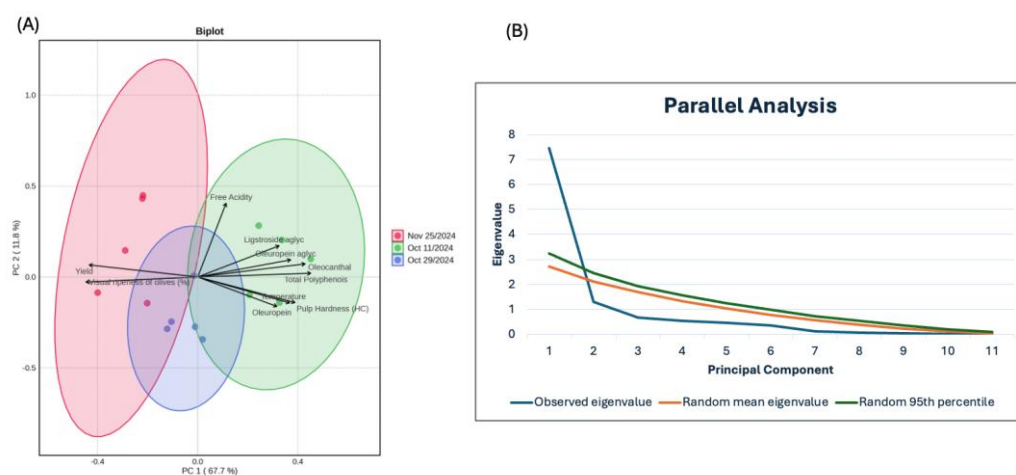


Figure 3. PCA and parallel analysis of EVOO samples according to harvesting date. (A) PCA biplot showing sample distribution and variable loadings on PC1 and PC2. Samples harvested on 11 October, 29 October, and 25 November are shown in green, blue, and red, respectively. PC1 explained 67.7% of the total variance, whereas PC2 explained 11.8%. Arrows represent variable loadings and indicate the contribution of each variable to sample separation. (B) Parallel analysis comparing observed PCA eigenvalues with eigenvalues generated from randomly simulated datasets with the same dimensionality. PC1 was confirmed as the dominant non-random component, whereas PC2 was retained as a secondary descriptive axis to visualize residual structured variability among samples.

PCA was performed on the standardized matrix including EVOO yield, final oil temperature, total phenolic content, selected secoiridoid-related compounds, harvest maturity indicators, pulp hardness, and free acidity. The first two principal components explained 79.5% of the total variance, with PC1 accounting for 67.7% and PC2 for 11.8%.

The PCA biplot showed a clear separation of samples according to harvesting date, mainly along PC1. Samples harvested on 11 October were positioned on the positive side of PC1, whereas samples harvested on 25 November were located on the negative side. Samples from 29 October showed an intermediate distribution, indicating a progressive multivariate shift during olive ripening. Variable loadings confirmed that positive PC1 values were mainly associated with total phenolic content, oleocanthal, oleuropein aglycone, ligstroside aglycone, oleuropein, pulp hardness, and final EVOO temperature. Con-

versely, negative PC1 values were associated with visual ripeness, maturity index, and EVOO yield. Therefore, PC1 can be interpreted as a ripening-related axis, separating early-harvest samples characterized by higher phenolic content and firmer pulp from late-harvest samples characterized by greater ripeness and higher oil yield.

Parallel analysis confirmed PC1 as the dominant non-random component, supporting the robustness of the main ripening-related axis observed in the PCA. Although PC2 did not exceed the random eigenvalue threshold, it was retained as a secondary descriptive axis because it improved the visualization of residual structured variability among samples and, together with PC1, accounted for 79.5% of the total variance.

3.3. MOLS Regression Models

The results of the MOLS regression models are summarized in Table 6.

Table 6. Results of the MOLS regression models. Nss indicates the non-statistical significance of the model.

MOLS Model	p-Value	Adjusted R ²
visual ripeness of olives vs. primary quality parameters	<0.001	0.78
maturity index vs. primary quality parameters	0.007	0.67
pulp hardness vs. primary quality parameters	0.006	0.68
visual ripeness of olives vs. total phenolic content	<0.001	0.80
maturity index vs. total phenolic content	<0.001	0.71
pulp hardness vs. total phenolic content	0.002	0.50
visual ripeness of olives vs. oleuropein and its direct derivatives	<0.001	0.82
maturity index vs. oleuropein and its direct derivatives	0.003	0.72
pulp hardness vs. oleuropein and its direct derivatives	0.017	0.59
visual ripeness of olives vs. ligstroside and its direct derivatives	<0.001	0.80
maturity index vs. ligstroside and its direct derivatives	<0.001	0.77
pulp hardness vs. ligstroside and its direct derivatives	0.06	0.38
visual ripeness of olives vs. specific phenolic profile	0.01	0.85
maturity index vs. specific phenolic profile	0.02	0.82
pulp hardness vs. specific phenolic profile	nss	nss
visual ripeness of olives vs. EVOO yield	<0.001	0.96
maturity index vs. EVOO yield	<0.001	0.90
pulp hardness vs. EVOO yield	<0.001	0.58
visual ripeness of olives vs. final EVOO temperature	<0.001	0.58
maturity index vs. final EVOO temperature	<0.001	0.57
pulp hardness vs. final EVOO temperature	<0.001	0.61
visual ripeness of olives vs. positive sensory attributes	<0.001	0.77
maturity index vs. positive sensory attributes	0.002	0.66
pulp hardness vs. positive sensory attributes	0.008	0.54

Parameter groups included in the MOLS models: primary quality parameters (free acidity, peroxide value, K232, K270, ΔK); total phenolic content (TPC); Oleuropein and derivatives (oleuropein, oleuropein aglycone, 3,4-DHPEA-EA, 3,4-DHPEA-EDA, hydroxytyrosol); Ligstroside and derivatives (ligstroside aglycone, p-HPEA-EA, p-HPEA-EDA/oleocanthal, tyrosol); specific phenolic profile (all nine compounds above); EVOO yield; final EVOO temperature; positive sensory attributes (fruitiness, bitterness, pungency).

Prior to the comparative analysis of the MOLS regression models, the pairwise Pearson correlations among the three harvest maturity indicators were computed to assess the degree of shared information. Visual ripeness and maturity index showed a very strong positive correlation ($r = 0.95$, $p < 0.001$), consistent with the fact that both indicators are

based on olive skin color observations. Pulp hardness showed a strong negative correlation with both visual ripeness ($r = -0.805$, $p < 0.001$) and maturity index ($r = -0.802$, $p < 0.001$), reflecting the well-documented inverse relationship between fruit softening and color-change progression during olive ripening. Despite these significant correlations, the three indicators are not interchangeable: approximately 35% of the variance in pulp hardness is not shared with either color-based indicator, confirming that pulp hardness captures a biologically distinct and complementary dimension of olive ripening rather than simply reflecting the same color-change gradient measured by visual ripeness and maturity index.

3.3.1. Relationship Between Harvest Maturity Indicators and Primary Quality Parameters

The relationship between harvest maturity indicators and primary quality parameters shows substantial differences in explanatory power across the three harvest maturity indicators. Starting with the model “visual ripeness of olives vs. primary quality parameters”, the MOLS regression model shows a p -value < 0.001 and a strong correlation with an adjusted R^2 of 0.78. Furthermore, the MOLS regression models “maturity index vs. primary quality parameters” and “pulp hardness vs. primary quality parameters” achieved p -values of 0.007 and 0.006, with an adjusted R^2 of 0.67 and 0.68, respectively. Consequently, given an adjusted R^2 of 0.78, the visual ripeness of olives seems to be the most suitable parameter for identifying the optimal harvesting time, followed by the pulp hardness and, finally, the maturity index. These results are supported by Salvador et al. (2001) [19], who highlighted that the olive fruit ripening stage, assessed using visual skin ripeness, is strongly associated with primary oil quality parameters—including free acidity, peroxide value, and spectrophotometric indices—across four consecutive crop seasons.

3.3.2. Correlation of Harvest Maturity Indicators with Total Phenolic Content, Oleuropein, Ligstroside, and Their Direct Derivatives

Regarding the results of the MOLS regression models evaluating the relationship between harvest maturity indicators and total phenolic content, statistically significant differences were found in the explanatory capacity of the three harvest maturity indicators. The model “visual ripeness of olives vs. total phenolic content” shows a p -value < 0.001 and the strongest correlation, with an adjusted R^2 of 0.80. Moreover, the “maturity index vs. total phenolic content” model shows a p -value < 0.001 with a good correlation (adjusted R^2 0.71). Finally, the “pulp hardness vs. total phenolic content” model yielded a p -value of 0.002 with an adjusted R^2 of 0.50. As a result, based on an adjusted R^2 of 0.80, the visual ripeness of olives emerges as the most suitable parameter for identifying the optimal harvesting time, followed by the maturity index and, finally, pulp hardness. These findings are consistent with Yousfi et al. (2006) [34], who found that olive ripeness (skin color) is strongly correlated with changes in olive and EVOO phenolic content across different cultivars and harvesting seasons.

Concerning the correlation between harvest maturity indicators and oleuropein and its direct derivatives, MOLS regression models show significant differences in their ability to explain variance across the three harvest maturity indicators. In particular, the model “visual ripeness of olives vs. oleuropein and its direct derivatives” shows a p -value < 0.001 and the strongest correlation, with an adjusted R^2 of 0.82. Additionally, the “maturity index vs. oleuropein and its direct derivatives” model shows a p -value of 0.003 with a good correlation (adjusted R^2 0.72). Lastly, the “pulp hardness vs. oleuropein and its direct derivatives” model yielded a p -value of 0.017 with an adjusted R^2 of 0.59.

Similar results were observed for the models evaluating the correlation between harvest maturity indicators and ligstroside and its direct derivatives; the model “visual ripe-

ness of olives vs. ligstroside and its direct derivatives” shows a p -value < 0.001 and the highest correlation, with an adjusted R^2 of 0.80. Additionally, the “maturity index vs. ligstroside and its direct derivatives” model shows a p -value < 0.001 with a strong correlation (adjusted R^2 0.77). Finally, the “pulp hardness vs. ligstroside and its direct derivatives” model yielded a non-statistically significant result (p -value of 0.06) with a very low adjusted R^2 (0.38).

The limited explanatory capacity of pulp hardness for polyphenol-related parameters can be explained by the distinct biochemical pathways underlying cell wall degradation and phenolic metabolism in olive drupes. Pulp softening is primarily driven by the enzymatic disassembly of cell wall polysaccharides—including pectin solubilization and neutral sugar loss—mediated by polygalacturonase, pectin methylesterase, and cellulase activities [25,30]. In contrast, the biosynthesis and catabolism of secoiridoid-related phenolic compounds, particularly oleuropein and its derivatives, are regulated by β -glucosidase and peroxidase enzymatic activities, which are more closely associated with the overall ripening trajectory, as captured by color-based indicators such as visual ripeness and maturity index [31]. These two processes occur in parallel during olive ripening, but are mechanistically decoupled, meaning that cell wall degradation and phenolic turnover do not share a direct biochemical link. Consequently, while pulp hardness effectively captures the mechanical changes associated with ripening and therefore is strongly associated with process-related parameters such as final EVOO temperature, it is not a direct proxy for phenolic metabolism, which explains its comparatively lower explanatory capacity for polyphenol-related EVOO quality parameters.

In conclusion, based on an adjusted R^2 of 0.82 for oleuropein and derivatives and 0.80 for ligstroside and derivatives, the visual ripeness of olives stands out as the most suitable indicator of all of the examined phenolic fractions. These findings are consistent with Diamantakos et al. (2020) [32], who found that the visual ripeness of olives has a strong correlation with EVOO secoiridoids and their derivatives, highlighting a significant decrease in their content as ripening progresses across multiple cultivars.

3.3.3. Relationship Between Harvest Maturity Indicators and the Specific Phenolic Profile

With respect to the results of the MOLS regression models evaluating the relationship between harvest maturity indicators and the specific phenolic profile, which represents the sum of oleuropein, ligstroside, and their derivatives, significant differences in explanatory power across the three harvest maturity indicators were found. More precisely, the model “visual ripeness of olives vs. specific phenolic profile” shows a p -value of 0.01 and the highest correlation, with an adjusted R^2 of 0.85. Furthermore, the “maturity index vs. specific phenolic profile” model shows a p -value of 0.02 with a good correlation (adjusted R^2 0.82). Finally, the “pulp hardness vs. specific phenolic profile” model yielded a non-statistically significant result (p -value of 0.17) with a low adjusted R^2 (0.48). As highlighted in Section 3.3.2, these results are supported by Yousfi et al. (2006) [34] and Diamantakos et al. (2020) [32], who found that the olive ripeness degree is strongly correlated with changes in olive and EVOO phenolic content, confirming that the visual ripeness of olives represents the most reliable and strongly correlated indicator of both total and specific phenolic content, as it is able to identify the optimal harvesting time.

3.3.4. Effect of Harvest Maturity Indicators on EVOO Yield and Final EVOO Temperature

Examining the relationship between harvest maturity indicators and two key operative parameters, i.e., EVOO yield and temperature, the results of the MOLS regression models show statistically significant differences in the explanatory capacity of the three harvest maturity indicators. Specifically, the model “visual ripeness of olives vs. EVOO

yield” shows a p -value < 0.001 and a very strong correlation, with an adjusted R^2 of 0.96. Furthermore, the “maturity index vs. EVOO yield” model shows a p -value < 0.001 and a strong correlation, with an adjusted R^2 of 0.90. Finally, the “pulp hardness vs. EVOO yield” model yielded a p -value < 0.001 with an adjusted R^2 of 0.58. As a result, based on an adjusted R^2 of 0.96, the visual ripeness of olives showed the strongest association with EVOO yield, and consequently seems to be the most suitable indicator for identifying the optimal harvesting time. These results are consistent with Dag et al. (2011) [35], who highlighted that olive maturation degree, assessed using visual skin color changes, is strongly correlated with EVOO yield, confirming that the visual ripeness of olives represents a reliable tool for optimizing harvest timing and EVOO production.

Regarding the correlation assessment between harvest maturity indicators and the final EVOO temperature, the model “visual ripeness of olives vs. final EVOO temperature” shows a p -value < 0.001 and a good correlation, with an adjusted R^2 of 0.58. Moreover, the “maturity index vs. final EVOO temperature” model shows similar results, with a p -value < 0.001 and an adjusted R^2 of 0.57. Lastly, and crucially, the model “pulp hardness vs. final EVOO temperature” shows a p -value < 0.001 and the strongest correlation, with an adjusted R^2 of 0.61. Based on an adjusted R^2 of 0.61, pulp hardness showed the strongest association with final EVOO temperature.

This result is supported by the findings reported in Section 3.1.2 from the one-way ANOVA, which highlighted that the statistically significant decrease in final EVOO temperature is attributable to the progressive reduction in olive pulp hardness due to extensive cell wall disassembly driven by polysaccharide solubilization and neutral sugar loss. This structural softening leads to decreased mechanical friction during olive crushing and malaxation processes, generating less heat and resulting in lower final EVOO temperatures. However, while an adjusted R^2 of 0.61 indicates a good correlation for biological and agronomic parameters, the remaining variance suggests that the thermal dynamics of the extraction process are multifactorial. Since operational parameters such as knife crusher speed and malaxing time were strictly kept constant, it is evident that, alongside pulp hardness, other intrinsic and environmental variables—such as ambient temperature, the initial temperature of the olive batches, and olive moisture content—inevitably contribute to the final EVOO temperature. Nevertheless, consistent with the one-way ANOVA results from Diarte et al. (2021) [26] and Diarte et al. (2022) [31], pulp hardness represents an innovative and reliable operative parameter whose monitoring could optimize EVOO production—reducing the risk of the heated or burnt sensory defect—given the strong correlation with final EVOO temperature.

3.3.5. Impact of Harvest Maturity Indicators on Positive Sensory Attributes

With respect to the correlations between harvest maturity indicators and positive sensory attributes (fruitiness, pungency, and bitterness intensities), the MOLS regression models show statistically significant differences in the explanatory power of the three harvest maturity indicators. Notably, the model “visual ripeness of olives vs. positive sensory attributes” shows a p -value < 0.001 and the strongest correlation, with an adjusted R^2 of 0.77. Furthermore, the “maturity index vs. positive sensory attributes” model shows a p -value of 0.002 and a good correlation, with an adjusted R^2 of 0.66. Finally, the “pulp hardness vs. positive sensory attributes” model yielded a p -value of 0.008 with an adjusted R^2 of 0.54. Therefore, based on an adjusted R^2 of 0.77, the visual ripeness of olives is confirmed as the most strongly correlated indicator of the intensity and type of positive attributes (green fruity, ripe fruity, bitter, and pungent), since the phenological progression of the fruit systematically determines both the phenolic composition and the volatile profile of the extracted oil [36].

4. Conclusions

Among the three indicators examined, visual ripeness seems to be the most cost-effective and operationally accessible option. Unlike the maturity index, which requires trained operators, standardized lighting, and a time-consuming counting procedure, and pulp hardness, which needs a standardized protocol and specific instrumentation, visual ripeness relies exclusively on olive skin color observation, requiring no instrumentation, no laboratory reagents, and no specialized personnel. Given no additional gain offered by the other two indicators in most models, the cost-benefit ratio strongly favors visual ripeness as the primary field-applicable tool for olive growers and oil mill operators. On the other hand, from an applicative point of view, the interesting correlation between pulp hardness and final EVOO temperature suggests that online monitoring of olive pulp hardness could represent a practical tool for optimizing the EVOO production process, reducing the risk of heated sensory defects. Furthermore, the strong correlation between visual ripeness and EVOO yield confirms that this cost-free parameter can be profitably integrated into production planning tools to support farm management, optimal harvesting time identification, and olive oil milling for scheduling and processing decisions.

In conclusion, despite the limitations associated with using data from a single year and the inclusion of only three Italian cultivars, the visual ripeness of olives proved to be the most promising and cost-free indicator of EVOO quality across the broadest range of chemical, phenolic, and sensory parameters, with adjusted R^2 values ranging from 0.77 to 0.96; furthermore, although optimal harvest time dynamically varies depending on the specific cultivar and seasonal variability, a visual ripeness range between 25% and 50% represents an optimal technological window to maximize both the phenolic content and the green sensory attributes of high-quality EVOO. It should be emphasized, however, that the concept of optimal harvest time inherently reflects a trade-off between competing production objectives. Early-harvest EVOO is characterized by higher total phenolic content, greater oleuropein and its derivatives concentration, and more intense pungency and bitterness, at the cost of lower oil yield and consequently higher production costs per unit. Mid-season harvest represents a balanced compromise between phenolic richness, sensory quality, and acceptable oil yield. Late-harvest EVOO, obviously within certain time limits, progressively shifts toward higher oil yield, but lower phenolic content and attenuated green sensory attributes. The identification of the optimal harvest date should therefore be guided by the producer's primary objectives—whether maximizing phenolic content and sensory complexity, oil yield, or economic return—and by market positioning, as premium high-polyphenol EVOOs command significantly higher market prices that can offset the lower yield of early harvesting.

Moreover, the influence of cultivar background warrants consideration. Individual cultivars are well-known to exhibit distinct phenotypic ripening rates and varying accumulation patterns of target phenolic compounds. Although the design of this industrial-scale study relied on the co-processing of three different cultivars into a commercial blend, the high explanatory capacity achieved by the visual ripeness models (adjusted R^2 up to 0.96) is significant. It demonstrates that a holistic visual assessment of a mixed olive batch can effectively integrate and smooth out the baseline differences among constituent cultivars, providing a robust, cost-free tool for real-world olive mill management.

In contrast, although final EVOO temperature may also be influenced by fruit temperature, ambient conditions, and other processing factors, pulp hardness emerged as a promising indicator that was strongly correlated with final EVOO temperature, opening innovative perspectives for the optimization of temperature management strategies in the EVOO production process. Future research should extend this experimental approach to a broader set of cultivars and multi-year datasets to assess the cultivar-specific robustness and inter-annual stability of the developed predictive models, which could also be improved with the integration of EVOO process variables such as malaxation time, temper-

ature, and decanter rotational speed, among others. Moreover, it is important to note that this study was conducted in a specific orchard (specific area). While this approach rigorously isolated the processing variables from external pedoclimatic interferences, future research across multiple years and different regions could be useful to further validate the generalizability of these absolute values. Finally, the results of this study could guide the development of image-based systems—relying on machine vision, RGB analysis, or hyperspectral imaging [10–13]—capable of providing automated, real-time and operator-independent estimates of olive ripeness directly in the field or at the mill intake, overcoming the subjectivity and time constraints associated with manual visual assessment. In parallel, the integration of low-cost, portable vis-NIR devices could enable the simultaneous non-destructive assessment of pulp hardness and phenolic content, providing olive growers and mill operators with a comprehensive, rapid, and cost-effective toolkit for optimizing harvest timing and EVOO production across diverse cultivars and production contexts.

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