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Multidimensional Fruit Quality Profiling of 24 Olive (*Olea europaea* L.) Cultivars from Longnan, Gansu

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Abstract: The quality profiles of olive cultivars introduced into non-traditional growing regions remain insufficiently characterized, particularly when fruit morphological, oil-related, fatty acid, and phenolic traits are considered together. In this study, 24 olive cultivars grown in a common high-altitude demonstration orchard in Longnan, Gansu Province, China, were evaluated for fruit phenotypic traits, moisture content, dry-pulp oil content, basic physicochemical properties, fatty acid composition, and major phenolic compounds. Significant cultivar-associated variation was observed in SFW (0.64–9.27 g), the O/L ratio (1.89–23.66), and oleuropein content (0.11–2.63 mg/g). Correlation analysis was used to examine associations and potential trade-offs among fruit morphological, oil-related, fatty acid, and phenolic traits, while principal component analysis and hierarchical cluster analysis were applied to characterize cultivar-specific quality profiles. Six principal components explained 83.24% of the total variance, indicating that the evaluated quality variation involved multiple complementary dimensions. Within the present evaluation framework, composite scoring identified XBYXPG, MXGXPG, PXL, HJBLK, and EZ8H as relatively high-ranking cultivars. XBYXPG exhibited a favorable combination of fruit and selected phenolic traits, whereas PXL and NXT showed relatively favorable fatty acid profiles. These cultivars may therefore serve as candidates for further evaluation of fruit-oriented, dual-purpose, or oil-oriented utilization. The findings provide a preliminary basis for multidimensional olive fruit quality assessment and utilization-oriented germplasm screening under the conditions of the Longnan orchard.

45 **Keywords:** Olive; High-Altitude Introduction; Fruit Quality; Fatty Acid Composition;

46 Phenolic Compounds; Comprehensive Evaluation

47

1. Introduction

Olive (*Olea europaea* L.) is an important fruit and oil crop originating from the Mediterranean Basin and is increasingly cultivated in non-traditional production regions. The commercial, nutritional, and processing value of olive germplasm is determined by the coordinated performance of fruit morphology, pulp proportion, oil accumulation, fatty acid composition, and phenolic profile. Oleic acid and phenolic compounds are particularly relevant to the nutritional characteristics, sensory properties, and potential oxidative stability of olive-derived products [1−3]. However, the concentration and composition of these components vary considerably among cultivars and can be affected by growing conditions and harvest environment [4−6]. With the expansion of olive cultivation beyond traditional Mediterranean regions, including Gansu, Sichuan, and Yunnan in China, the local evaluation of introduced cultivars has become increasingly important for effective germplasm utilization [7, 8].

Olive fruit traits and chemical composition are influenced by cultivar, environmental conditions, fruit developmental stage, and the interaction between genotype and environment [9, 10]. Temperature, water availability, radiation, and harvest conditions can affect fruit growth, oil accumulation, fatty acid metabolism, and the accumulation of phenolic compounds. In particular, variation in the relative proportions of oleic and linoleic acids may result in substantial differences in the oleic acid/linoleic acid (O/L) ratio and other fatty-acid-related indices among cultivars and growing regions [11, 12]. Phenolic compounds such as oleuropein may also show pronounced cultivar specificity and environmental responsiveness, and their

accumulation patterns cannot be fully represented by total phenolic or total flavonoid contents alone [3−13−14]. Consequently, the evaluation of olive germplasm introduced into non-traditional growing regions should consider multiple quality dimensions rather than relying on a single trait, such as fruit size, oil content, or total phenolic content.

The Bailong River Valley in Longnan, Gansu Province, is an emerging olive-growing region in China. The experimental orchard used in this study is located at an elevation of 1048 m and is characterized by a relatively large diurnal temperature range during fruit development, together with comparatively cool and dry autumn conditions. These agroecological characteristics differ from those of many traditional Mediterranean olive-growing areas and may influence fruit development, lipid accumulation, and phenolic metabolism [15, 16]. Nevertheless, the independent effects of altitude, climate, and cultivar cannot be separated in a single-site and single-year experiment. Therefore, cultivar performance observed in the present study should be interpreted as cultivar-associated variation under the Longnan environment rather than direct evidence of high-altitude adaptation. Previous studies have evaluated olive fruit quality or oil-related characteristics in Longnan and other emerging olive-growing regions, but many have focused on individual traits or a limited number of chemical components. A common-orchard comparison integrating fruit morphology, oil content on a dry pulp basis, fatty acid composition, basic physicochemical properties, and targeted phenolic profiles across a relatively broad set of cultivars remains limited [17, 18]. Such an integrated evaluation could help

distinguish cultivars with different utilization-oriented quality profiles, including fruit-oriented, oil-oriented, and phenolic-oriented characteristics.

Accordingly, this study evaluated 24 olive cultivars grown in the same high-altitude demonstration orchard in Longnan, China. Fruit phenotypic traits, moisture content, oil content on a dry pulp basis, basic physicochemical properties, fatty acid composition, and major phenolic compounds were determined under a common-orchard experimental condition. The objectives were to: (1) characterize cultivar-associated variation in fruit, lipid, and phenolic traits under the Longnan environment; (2) examine relationships and potential trade-offs among fruit morphology, oil-related traits, fatty acid composition, and phenolic profiles; and (3) use multivariate analysis to identify cultivar-specific quality combinations and candidate cultivars for different utilization purposes. Rather than defining a universally superior cultivar or directly demonstrating functional-food efficacy, this study aimed to provide a preliminary basis for utilization-oriented germplasm screening and for the subsequent validation of oil quality, oxidative stability, phenolic bioaccessibility, and functional-food ingredient potential.

2. Materials and methods

2.1. Experimental site and plant materials

The experiment was conducted in 2024 at the Dabao Olive Science and Technology Demonstration Orchard of the Longnan Economic Forest Research Institute, Gansu Province, China (33°24′13″N, 104°53′28″E; altitude, 1048 m). The

region is located in a transitional zone from a northern subtropical semi-humid monsoon climate to a warm temperate climate. The annual mean temperature is approximately 14.5–15.3 ℃, annual precipitation is approximately 400–470 mm, and annual sunshine duration is approximately 1800–1950 h. During the critical period of fruit development (August–October), the diurnal temperature range can reach 10–15 ℃.

A total of 24 olive cultivars growing in the same orchard were used in this study (Table 1). The materials originated from Greece, Spain, Italy, France, Algeria, Albania, and Chinese breeding programs. The selected trees were healthy and showed relatively uniform vigor under consistent orchard management. A completely randomized block design was adopted, with three biological replicates for each cultivar. Fruits were harvested in late October when they reached commercial maturity. Fruits without visible mechanical damage, pests, or diseases were selected and transported to the laboratory under low-temperature conditions. Samples were divided into two groups: one group was used for fresh fruit phenotypic and moisture measurements, while the other was pitted, frozen in liquid nitrogen, ground, and freeze-dried to prepare powder for physicochemical, fatty acid, and phenolic analyses.

2.2. Measurement of fruit phenotypic traits

For each cultivar, 30 fruits were randomly selected from the fresh samples, with 10 fruits considered as one biological replicate. Single fruit weight (SFW) was measured using an electronic balance. Fruit longitudinal diameter (LD) and transverse diameter (TD) were measured using a digital vernier caliper. The pulp was then

completely separated from the stone, and single stone weight was recorded. Pulp ratio (SC, %) was calculated as follows: SC (%) = (SFW − stone weight)/SFW × 100.

2.3. Determination of moisture content

Moisture content (MC) was determined based on the difference between fresh and dry pulp weight. For each biological replicate, fresh intact fruits were pitted, and the fresh weight of the pulp was recorded [19]. The pulp was then vacuum freeze-dried to constant weight, and the dry weight was measured. MC was calculated as follows: MC (%) = (fresh weight − dry weight)/fresh weight × 100.

2.4. Determination of oil content on a dry pulp basis

Oil content on a dry pulp basis was determined using the Soxhlet extraction method [20]. Briefly, 1.0 g of freeze-dried pulp powder was accurately weighed, wrapped in filter paper, and placed in a Soxhlet extractor. Petroleum ether (50 mL) was used as the extraction solvent, and continuous reflux extraction was performed at 55 ℃ for 12 h. After extraction, residual solvent was removed from the flask in an oven, and the flask was cooled and weighed. Oil content on a dry pulp basis was calculated as the ratio of extracted oil mass to freeze-dried pulp powder mass and expressed as a percentage.

2.5. Determination of physicochemical properties

Freeze-dried pulp powder was used for the determination of basic physicochemical traits. Total sugar content was determined by the anthrone-sulfuric acid colorimetric method and expressed as glucose equivalents (mg GE/g DW) [21]. Soluble protein content was determined using the Coomassie Brilliant Blue G-250

158 method and expressed as bovine serum albumin equivalents (mg BSAE/g DW) [22].
159 Total phenolic content (TPC) was determined using the Folin-Ciocalteu method and
160 expressed as gallic acid equivalents (mg GAE/g DW). Total flavonoid content (TFC)
161 was determined using the aluminum nitrate colorimetric method [6] and expressed as
162 rutin equivalents (mg RE/g DW). The contents of all measured compounds were
163 calculated from standard calibration curves.

164 *2.6. Determination of fatty acid composition*

165 Fatty acid methyl esters were prepared according to the alkaline-catalyzed
166 method described in *GB 5009.168-2016*, and quantitative analysis was performed
167 using an internal standard method. Olive oil sample (60.0 mg) was accurately
168 weighed into a stoppered glass tube, followed by the addition of 1.0 mL undecanoic
169 acid (C11:0) internal standard solution and 4.0 mL isooctane. After the oil was
170 completely dissolved, 0.2 mL of 2 mol/L KOH-methanol solution was added, and the
171 mixture was shaken for 30 s. Approximately 1.0 g of sodium bisulfate was then added
172 to neutralize excess KOH, and the upper clear phase was collected after centrifugation
173 for analysis.

174 Chromatographic separation was performed using an HP-88 capillary column.
175 The oven temperature program was as follows: initial temperature of 140 ℃, held for
176 6 min; increased to 240 ℃ at 2 ℃/min; and held for 10 min. High-purity nitrogen was
177 used as the carrier gas at a flow rate of 1.0 mL/min. The injector and flame ionization
178 detector temperatures were both set at 250 ℃. The injection volume was 1.0 μL, with
179 a split ratio of 10:1. Fatty acids were identified by comparing retention times with

those of standards and quantified using the internal standard method. The sums of saturated fatty acids (SFA), unsaturated fatty acids (UFA), monounsaturated fatty acids (MUFA), and polyunsaturated fatty acids (PUFA), as well as the O/L and MUFA/PUFA ratios, were subsequently calculated.

2.7. Determination of phenolic compounds

Major phenolic compounds were extracted and quantified using high-performance liquid chromatography with diode-array detection (HPLC-DAD), following the method of Talhaoui et al[2]. with appropriate modifications. Freeze-dried pulp powder (0.1 g) was accurately weighed and extracted with 5 mL of 70% methanol at 60 °C for 60 min. The mixture was centrifuged at 4000 rpm for 10 min, and the supernatant was collected. The residue was extracted once more under the same conditions. The combined extracts were adjusted to 10 mL, concentrated to dryness by rotary evaporation at 55 °C, redissolved in the initial mobile phase, and filtered through a 0.22 μm organic-phase-compatible membrane filter before HPLC analysis.

Chromatographic separation was performed on a C18 reversed-phase column (250 mm × 4.6 mm, 5 μm). The mobile phase consisted of methanol (A) and 0.1% formic acid in water (B), using gradient elution. The flow rate was 1.0 mL/min, the column temperature was 25 °C, and the injection volume was 10 μL. Oleuropein, hydroxytyrosol, and tyrosol were detected at 280 nm, while caffeic acid, luteolin glycoside, and quercetin were detected at 330 nm. Compounds were identified by comparison with authentic standards and quantified using the external standard

method. Authentic standards of oleuropein, hydroxytyrosol, tyrosol, caffeic acid, luteolin glycoside, and quercetin were purchased from Jiangxi Baicaoyuan Biotechnology Co., Ltd. (Jiangxi, China), with HPLC purity of ≥98%. Stock solutions of each standard were prepared in methanol and serially diluted to construct calibration curves for quantitative analysis.

2.8. Statistical analysis

All indicators were measured with three biological replicates, and the results are expressed as mean ± standard deviation (SD). Statistical analyses were performed using SPSS 26.0. One-way analysis of variance (ANOVA) was used to evaluate differences among cultivars, followed by Duncan's multiple range test at $P < 0.05$. Spearman correlation analysis was used to explore relationships among traits. Prior to PCA and HCA, all data were standardized using Z-score transformation to eliminate the effects of different units and scales. HCA was performed based on the Z-score-standardized trait matrix using Euclidean distance and Ward's minimum variance linkage method. PCA and HCA were performed using GraphPad Prism and R software. A comprehensive evaluation model was established by weighting each principal component according to the ratio of its variance contribution to the cumulative variance contribution of the selected components [17].

3. Results

3.1. Variation in fruit phenotypic traits

Significant differences were observed among the 24 olive cultivars for all

measured fruit phenotypic traits ($P < 0.001$; Table S1,Table 2). SFW ranged from 0.64 to 9.27 g, TD from 3.53 to 24.18 mm, LD from 10.81 to 31.01 mm, stone weight from 0.25 to 1.39 g, and pulp ratio from 26.30% to 84.20%.

The coefficient of variation differed among phenotypic traits. SFW exhibited the highest variation (CV = 53.72%), followed by stone weight (CV = 35.57%) and TD (CV = 29.08%). In contrast, the CV of pulp ratio and LD were relatively lower, at 22.28% and 22.63%, respectively. These results indicate clear inter-cultivar differences in fruit size and fruit structure, with SFW representing the most variable phenotypic trait among the tested materials.

3.2. Variation in fruit quality-related physicochemical traits

The 24 cultivars differed significantly in MC, oil content on a dry pulp basis, total sugar, soluble protein, TPC, and TFC ($P < 0.001$; Table 2). TFC ranged from 67.13 to 321.42 mg/g, TPC from 34.54 to 105.11 mg/g, total sugar from 293.31 to 627.40 mg/g, soluble protein from 15.49 to 60.47 mg/g, oil content on a dry pulp basis from 10.67% to 22.72%, and MC from 44.49% to 76.98%.

Among these traits, TFC exhibited the greatest inter-cultivar variation (CV = 39.67%), followed by soluble protein (CV = 33.02%) and TPC (CV = 28.02%). MC showed the lowest variation (CV = 12.09%). These results indicate that chemical quality traits, particularly flavonoids, phenolics, and soluble proteins, were more variable among cultivars than moisture content.

3.3. Fatty acid composition

A total of 14 fatty acid components were detected in the oils of the 24 olive

246 cultivars, and significant differences were observed among cultivars for all fatty acids
247 and derived indices ($P < 0.001$; Table 2; Table S2). Oleic acid was the dominant fatty
248 acid, ranging from 50.17% to 78.68%, followed by palmitic acid and linoleic acid,
249 with mean values of 13.87% and 10.28%, respectively. These results indicate that the
250 oils of the tested cultivars were generally characterized by a high proportion of
251 monounsaturated fatty acids.

252 Among the major fatty acids, linoleic acid exhibited a relatively high *CV*
253 (54.67%), which was markedly greater than that of oleic acid (10.21%) and palmitic
254 acid (16.18%). Among minor fatty acids, nervonic acid (C24:1) showed the highest
255 *CV* (58.89%). The fatty acid ratio indices also differed considerably among cultivars.
256 The MUFA/PUFA ratio ranged from 1.82 to 19.37. CG32 had the lowest
257 MUFA/PUFA ratio (1.82), while NXT had the highest value (19.37) (Fig. 1). These
258 results suggest that differences in PUFA-related indices were major contributors to
259 fatty acid differentiation among cultivars.

260 *3.4. Phenolic compounds*

261 Significant differences were observed among cultivars for the major phenolic
262 compounds ($P < 0.001$; Table S1). Among the detected compounds, oleuropein
263 showed the widest range, from 0.11 to 2.63 mg/g. Hydroxytyrosol ranged from 0.28
264 to 3.63 mg/g, and tyrosol ranged from 0.13 to 0.70 mg/g.

265 The degree of variation differed considerably among phenolic compounds.
266 Oleuropein exhibited the highest *CV* (94.63%), followed by caffeic acid (62.69%) and
267 luteolin glycoside (55.56%). In contrast, quercetin showed limited variation, with a

CV of only 3.20% and values concentrated between 0.45 and 0.51 mg/g. These findings indicate strong cultivar specificity in the accumulation of certain phenolic compounds, particularly oleuropein.

3.5. Spearman correlation analysis

Spearman correlation analysis revealed several associations among the measured traits (Fig. 2). Among phenotypic traits, SFW was significantly and positively correlated with stone weight, TD, and LD ($P < 0.001$), indicating that larger fruit size was generally accompanied by increased longitudinal and transverse growth and greater stone weight. MC was also positively correlated with SFW and TD.

For fatty acid-related traits, MUFA was significantly negatively correlated with PUFA ($r = -0.927$). The MUFA/PUFA ratio was strongly positively correlated with the O/L ratio ($r = 0.998$), while the O/L ratio was significantly negatively correlated with PUFA ($r = -0.990$). These results suggest a strong compositional trade-off between monounsaturated and polyunsaturated fatty acids, with linoleic acid playing an important role in determining the O/L and MUFA/PUFA ratios. In addition, positive correlations were observed between soluble protein and caffeic acid, as well as between stone weight and tyrosol, although these relationships require further validation across additional years and environments.

3.6. Principal component analysis and hierarchical cluster analysis

PCA was performed to integrate the measured traits and evaluate multidimensional quality differences among the 24 cultivars. Six principal components with eigenvalues greater than 1 were extracted, explaining 28.02%,

19.00%, 13.18%, 9.57%, 7.15%, and 6.33% of the total variance, respectively (Table 3). Together, these components accounted for 83.24% of the total variance, indicating that they captured most of the information contained in the dataset.

The loading results showed that LD, TD, and SFW contributed substantially to PC1 (Fig. 3), suggesting that PC1 mainly represented fruit size-related variation. PC2 was mainly influenced by MC, caffeic acid, SFW, and MUFA, whereas PC3 was primarily associated with TFC, oleuropein, oil content on a dry pulp basis, tyrosol, and TPC. The PCA score plots further illustrated the distribution of cultivars in the principal component space (Fig. 4).

Considering the different variance contributions of the six principal components, a comprehensive evaluation model was established using the ratio of each component's variance contribution to the cumulative contribution as the weight:

$$Y = 0.3366Y_1 + 0.2283Y_2 + 0.1583Y_3 + 0.1150Y_4 + 0.0859Y_5 + 0.0760Y_6.$$

The composite scores ranged from −1.5806 to 1.9281. XBYXPG had the highest composite score, whereas QMLE had the lowest. The top nine cultivars were XBYXPG, MXGXPG, PXL, HJBLK, EZ8H, LX, KLD, XL-3, and PGE, all with composite scores greater than 0.74 (Table 4). HCA based on the Z-score-standardized integrated fruit quality traits divided the 24 cultivars into two major groups using Euclidean distance and Ward’s minimum variance linkage method (Fig. 5). The Z-score radar charts further showed the core trait patterns of the top nine cultivars; XBYXPG showed standardized values greater than 1.5 for SFW, pulp ratio, and TPC, while PXL showed a high Z-score for the O/L ratio (approximately 2.0) (Fig. 6).

4. Discussion

4.1. Fruit phenotypic variation and its association with physicochemical traits

Fruit phenotypic traits are important components of olive fruit quality because they characterize fruit size and structure and may be relevant to fruit-oriented processing [2, 11]. In the present study, all measured phenotypic traits differed significantly among the 24 cultivars/accessions. SFW showed the greatest variation (*CV* = 53.72%), followed by stone weight (*CV* = 35.57%) and transverse diameter (*CV* = 29.08%). In contrast, pulp ratio and longitudinal diameter showed lower coefficients of variation. This variation indicates that the evaluated materials encompassed diverse fruit-size and structural profiles under the conditions of the Longnan orchard. Similar cultivar-associated variation in olive fruit traits has been reported in Mediterranean and non-traditional growing regions [1−18−23].

SFW was positively correlated with longitudinal diameter, transverse diameter, and stone weight, indicating that larger fruits generally had greater dimensions and heavier stones. SFW and transverse diameter were also positively associated with MC. However, SFW was not significantly associated with oil content on a dry-pulp basis or with most of the quantified phenolic compounds. This pattern suggests that fruit size and several compositional traits represented partly distinct dimensions of quality in the evaluated collection. The association between fruit size and MC may indicate that water content contributed to variation in fresh fruit mass, but this interpretation is specific to the sampled site, year, and harvest conditions; it does not establish that the

Longnan environment or high altitude caused greater water accumulation.

These findings are consistent with the view that olive fruit quality reflects the combined effects of cultivar, developmental stage, and growing conditions, and that fruit size alone may not predict compositional characteristics [24, 25]. From a utilization perspective, larger fruits and a higher pulp ratio may be relevant to fruit-oriented processing. However, these traits do not, on their own, demonstrate higher oil productivity or a more favorable phenolic profile. The results therefore support evaluating fruit morphology, pulp ratio, moisture, dry-pulp oil content, fatty acid composition, and phenolic traits jointly, with the relative importance of each trait determined by the intended use.

4.2. Fatty acid composition and the O/L ratio

Fatty acid composition was an important compositional dimension for differentiating the evaluated cultivars. Oleic acid was the predominant fatty acid, with a mean proportion of 67.61%, while linoleic acid showed greater relative variation (CV = 54.67%) than oleic acid (CV = 10.21%). The cultivars also differed in derived indices, including the O/L and MUFA/PUFA ratios. Together, these results indicate that fatty acid variation in this collection was associated not only with the relative abundance of oleic acid, but also with differences in linoleic acid and the overall distribution of fatty acid classes [26, 27].

MUFA and PUFA were strongly negatively correlated. Because fatty acid results were expressed as relative percentages, this association may partly reflect the compositional constraint that an increase in the proportion of one component or group

356 is accompanied by a decrease in the relative proportion of others. It should therefore
357 not be interpreted solely as evidence of cultivar-specific differences in fatty acid
358 metabolism or desaturation. Similarly, the strong correlations between MUFA/PUFA,
359 O/L, and PUFA are partly expected because these indices are calculated from
360 overlapping fatty acid components. They are useful for describing relative profiles,
361 but they are not independent lines of evidence. Cultivar-associated variation in olive
362 lipid composition has also been reported in previous studies [12, 28]. The O/L and
363 MUFA/PUFA ratios can help describe the relative balance between monounsaturated
364 and polyunsaturated fatty acids. Cultivars with relatively high values may therefore be
365 considered candidates for further oil-oriented evaluation. A higher relative proportion
366 of oleic acid and a lower proportion of linoleic acid are compositional characteristics
367 that may be associated with reduced susceptibility to oxidation [11, 29]. Accordingly,
368 the present results indicate fatty-acid-profile characteristics relevant to subsequent oil
369 evaluation, rather than confirmed differences in oxidative stability.

370 *4.3. Cultivar specificity of phenolic compound accumulation*

371 Phenolic measurements provided a further dimension for characterizing
372 cultivar-associated fruit quality. In the present study, total flavonoid content (TFC)
373 varied substantially among cultivars (CV = 39.67%), while oleuropein showed
374 particularly pronounced variation (CV = 94.63%). Caffeic acid and luteolin glycoside
375 also had relatively high coefficients of variation (62.69% and 55.56%, respectively),
376 whereas quercetin varied comparatively little (CV = 3.20%). These differences
377 indicate that the degree of cultivar-associated variation was compound-specific and

that individual phenolic compounds may distinguish cultivars differently from aggregate phenolic indices.

Total phenolic and flavonoid measurements and targeted phenolic compounds provide complementary information: aggregate indices describe broad compositional characteristics, whereas compound-specific measurements reveal differences in individual constituents. This distinction is relevant because phenolic accumulation in olive fruit can vary with genotype, maturity, environment, and their interactions [30, 31]. The marked variation in oleuropein in this study suggests that it may be informative for preliminary cultivar discrimination under the evaluated orchard conditions. However, results from one site and one harvest year do not establish stable cultivar-specific accumulation across environments or years[2, 13].

The cultivar-level results further suggest that phenolic profiles were not identical across compounds. XL-3 showed relatively high levels of several quantified phenolic compounds, including oleuropein, hydroxytyrosol, tyrosol, and luteolin glycoside, whereas XBYXPG showed favorable values for selected traits but was not uniformly highest across the measured phenolics. These patterns, if supported by the corresponding cultivar-level data, indicate that phenolic-oriented selection should consider the target compound or profile rather than rely on a single total-phenolic measure. XL-3 may therefore be considered a candidate for further evaluation of a broader phenolic profile, while XBYXPG may be of interest for the particular phenolic traits in which it performed favorably [32, 33].

4.4. Implications of multivariate evaluation for cultivar selection

The results indicate that the quality of the evaluated olive fruits was multidimensional: fruit size, moisture, dry-pulp oil content, fatty acid composition, and phenolic traits did not vary as a single coordinated set. PCA summarized the measured variation in six components, which together explained 83.24% of the total variance. PC1 was mainly associated with SFW, longitudinal diameter, and transverse diameter and therefore represented a fruit-size-related dimension. PC2 and PC3 captured additional variation involving moisture, fatty acids, oil content, and phenolic traits. The PCA thus supports the use of multiple complementary dimensions to describe the cultivar profiles, rather than treating one trait as a proxy for overall fruit quality.

Within the present PCA-based evaluation framework, XBYXPG, MXGXPG, PXL, HJBLK, and EZ8H received the highest composite scores. These scores should be interpreted as exploratory summaries of the measured, standardized traits rather than as definitive rankings of commercial or biological quality. The results point to different potential strengths among cultivars: XBYXPG showed a favorable combination of fruit and selected phenolic traits; PXL showed a relatively favorable fatty acid profile; and XL-3 had a phenolic-oriented profile despite its smaller fruit size. NXT also illustrates the value of trait-specific screening: although it was not among the five highest composite-scoring cultivars, it had the highest MUFA/PUFA ratio in the collection. The HCA and PCA therefore provide complementary ways of describing differences in quality profiles, but do not establish that any cultivar is universally superior.

The interpretation of composite scores depends on the traits included, their standardization, the weighting procedure, and the direction assigned to each trait. In PCA, the signs of principal-component loadings and scores are arbitrary, and higher values do not automatically represent better quality. Moreover, traits with overlapping information such as MUFA, PUFA, O/L, and MUFA/PUFA may contribute related information to a composite assessment. Consequently, the ranking should be presented as an exploratory result of the current evaluation framework, not as an objective, use-independent quality index. Future applications should define trait desirability separately for each intended use, justify the inclusion and direction of each indicator, and test the robustness of rankings to alternative weighting schemes. Independent and multi-environment datasets will also be needed to determine whether the identified quality profiles are repeatable [17−18−23].

4.5. Limitations and future perspectives

This study provides a comparative assessment of fruit phenotypic traits, dry-pulp oil content, physicochemical properties, fatty acid composition, and phenolic profiles in 24 olive cultivars/accessions grown in the Longnan orchard. Accordingly, the observed differences do not establish stable performance across environments or years, and may be influenced by variation in fruit maturity. In addition, oil oxidative stability and the bioaccessibility or functional effects of phenolic compounds were not directly evaluated. Future studies should validate the identified quality profiles through multi-year, multi-location trials with standardized maturity criteria, and directly assess oil stability and phenolic bioaccessibility.

5. Conclusions

This study provided a multidimensional characterization of fruit phenotypic traits, dry-pulp oil content, physicochemical properties, fatty acid composition, and major phenolic compounds in 24 olive cultivars grown in a common orchard in Longnan, China. The evaluated materials showed substantial variation in fruit morphology and in several compositional traits, including flavonoid content, linoleic acid proportion, the oleic acid/linoleic acid (O/L) ratio, and oleuropein content. Correlation analysis revealed coordinated variation among fruit size-related traits and among fatty acid indices, whereas associations between fruit morphology and compositional traits were generally more limited. These patterns suggest that olive fruit quality is multidimensional and cannot be adequately represented by fruit size or any single compositional indicator.

Multivariate analysis and composite scoring provided an exploratory means of distinguishing cultivar-specific quality profiles. Within the present evaluation framework, XBYXPG, MXGXPG, PXL, HJBLK, and EZ8H received relatively high composite scores. XBYXPG showed a favorable combination of fruit traits and selected phenolic characteristics, while PXL and NXT exhibited relatively favorable fatty acid profiles. These results identify materials that merit further, utilization-specific evaluation; they do not establish universally superior cultivars. Instead, cultivar selection should be guided by the intended use and by the relevant combination of fruit, oil-related, fatty acid, and phenolic traits.

Overall, this study provides a preliminary basis for comparative fruit-quality

assessment and utilization-oriented germplasm screening under the conditions of the Longnan orchard. Because the evaluation was conducted at a single site and in one harvest year, the findings should not be interpreted as evidence of stable cultivar performance, high-altitude adaptation, confirmed oil oxidative stability, or functional-food efficacy. Multi-year and multi-location trials, standardized analyses of oil quality and oxidative stability, sensory evaluation, and further investigation of phenolic bioaccessibility and functional properties are needed to validate the stability and utilization potential of the identified quality profiles.

CRediT authorship contribution statement

Kangli Xie: Project administration, Methodology, Data curation, Validation, Visualization, Writing-original draft. **Min Zhang**: Methodology, Data curation, Visualization, Writing-original draft, review & editing. **Jiali Xie**: Data curation, Writing-original draft, Writing-review & editing. **Yongxing Yang**: Resources, Conceptualization, Writing-review & editing. **Wenwen Zhang**: Data curation, Visualization, Writing-review & editing. **Fatao Hu**: Data curation, Visualization, Writing-review & editing. **Zhengwu Zhang**: Resources, Conceptualization, Writing-review & editing. **Wanming Bai**: Resources, Conceptualization, Writing-review & editing. **Junyi Ma**: Project administration, Conceptualization. **Ji Zhang**: Project administration, Funding acquisition, Conceptualization. **Weibao Kong**: Methodology, Resources, Funding acquisition, Formal analysis, Validation, Project administration, Conceptualization, Writing-review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Figure captions

Fig. 1. Distribution of MUFA/PUFA ratios among olive cultivars. MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids.

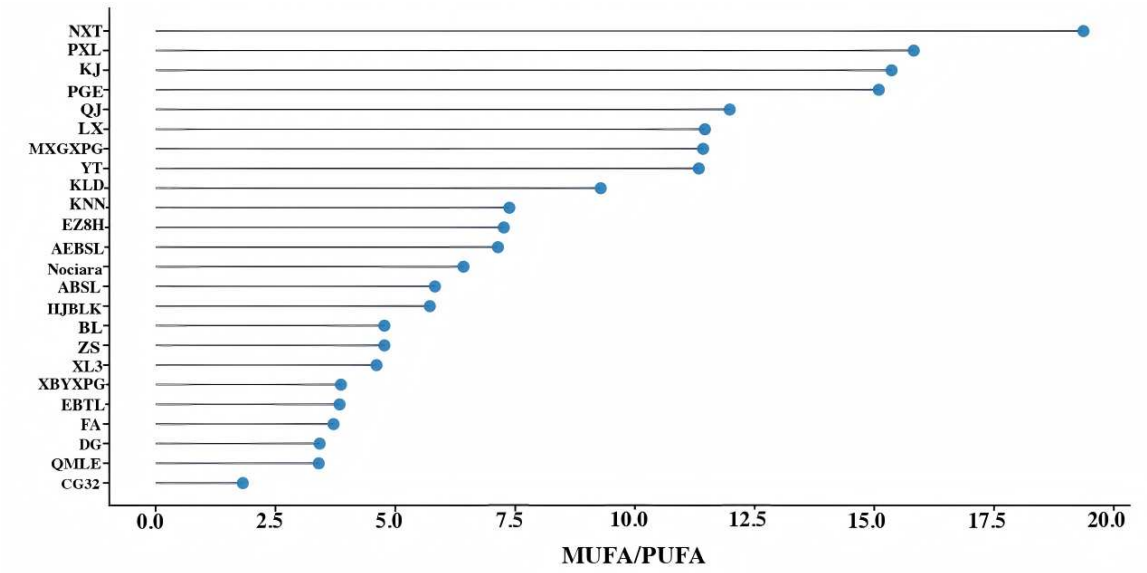
Fig. 2. Spearman correlation heatmap among fruit phenotypic traits, fatty acid composition, and phenolic compounds($P < 0.001$).The lower triangular matrix presents pairwise correlation coefficients; red and blue indicate positive and negative correlations, respectively, with color intensity and square size proportional to the absolute correlation coefficient. Pale colors and smaller squares indicate weak associations, whereas dark colors and larger squares indicate stronger associations. The diagonal represents self-correlations. SFA, saturated fatty acids; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids; O/L, oleic acid/linoleic acid ratio.

Fig. 3. PCA loading plot.

Fig. 4. PCA score plots of olive fruit traits: (a) PC1 versus PC2; (b) PC1 versus PC3. Different colors indicate different cluster groups, and ellipses indicate the distribution range of samples within each group.

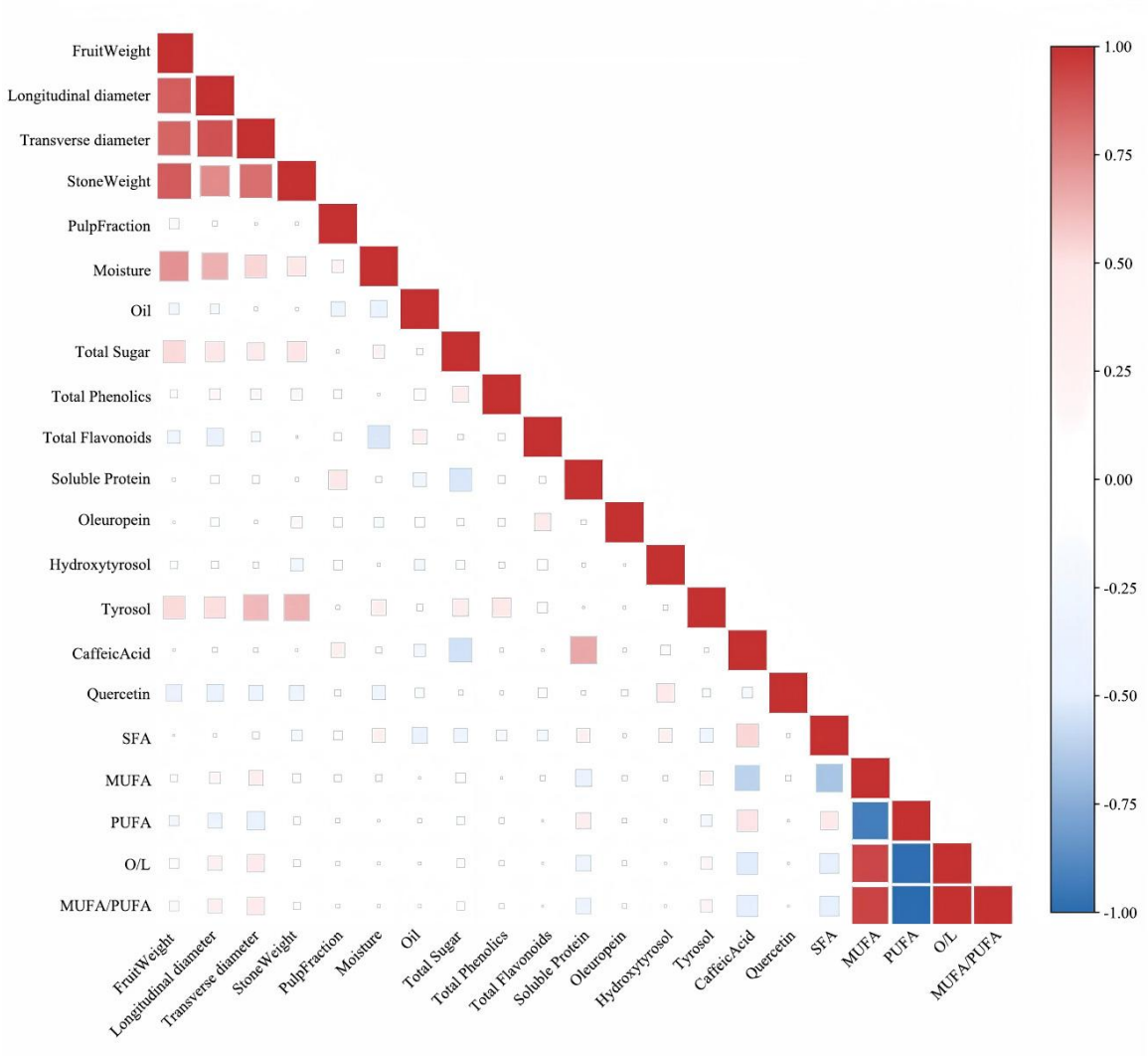
Fig. 5. Hierarchical clustering dendrogram of the 24 olive cultivars.

Fig. 6. Radar charts of major traits in the top nine olive cultivars: (a) XBYXPG; (b) MXGXPG; (c) PXL; (d) HJBLK; (e) EZ8H; (f) LX; (g) KLD; (h) XL-3; (i) PGE. MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids; O/L, oleic acid/linoleic acid ratio.


NXT
PXL
KJ
PGE
QJ
LX
MXGXPG
YT
KLD
KNN
EZ8H
AEBSL
Nociara
ABSL
IIJBLK
BL
ZS
XL3
XBYXPG
EBTL
FA
DG
QMLE
CG32
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
MUFA/PUFA

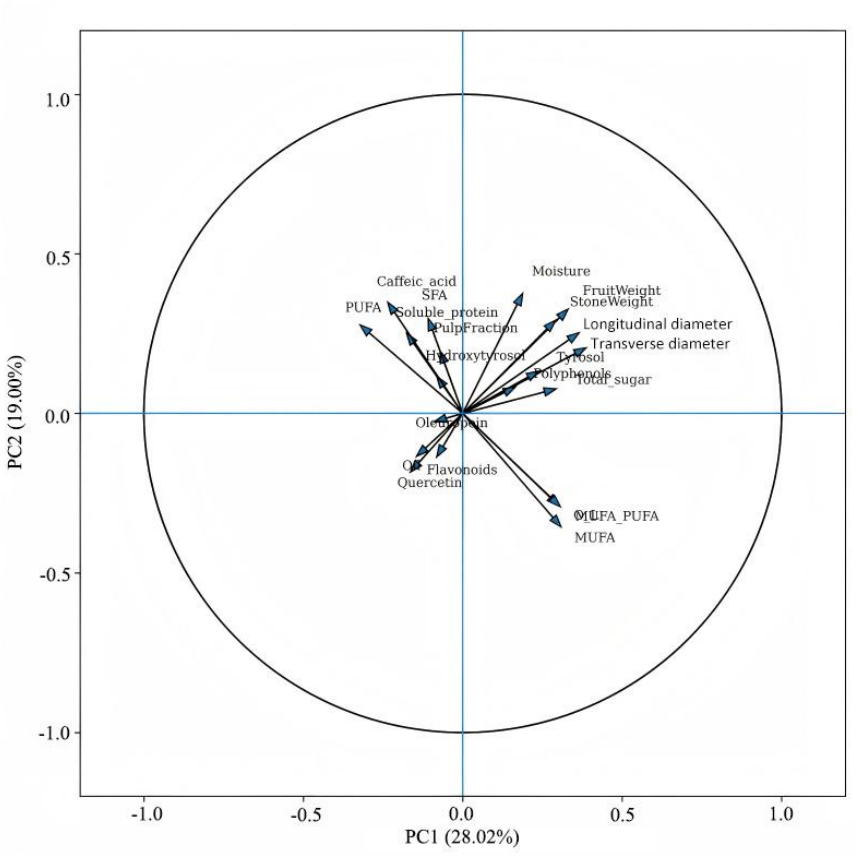
642

643 **Fig. 1**.


FruitWeight
Longitudinal diameter
Transverse diameter
StoneWeight
PulpFraction
Moisture
Oil
Total Sugar
Total Phenolics
Total Flavonoids
Soluble Protein
Oleuropein
Hydroxytyrosol
Tyrosol
CaffeicAcid
Quercetin
SFA
MUFA
PUFA
O/L
MUFA/PUFA
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00

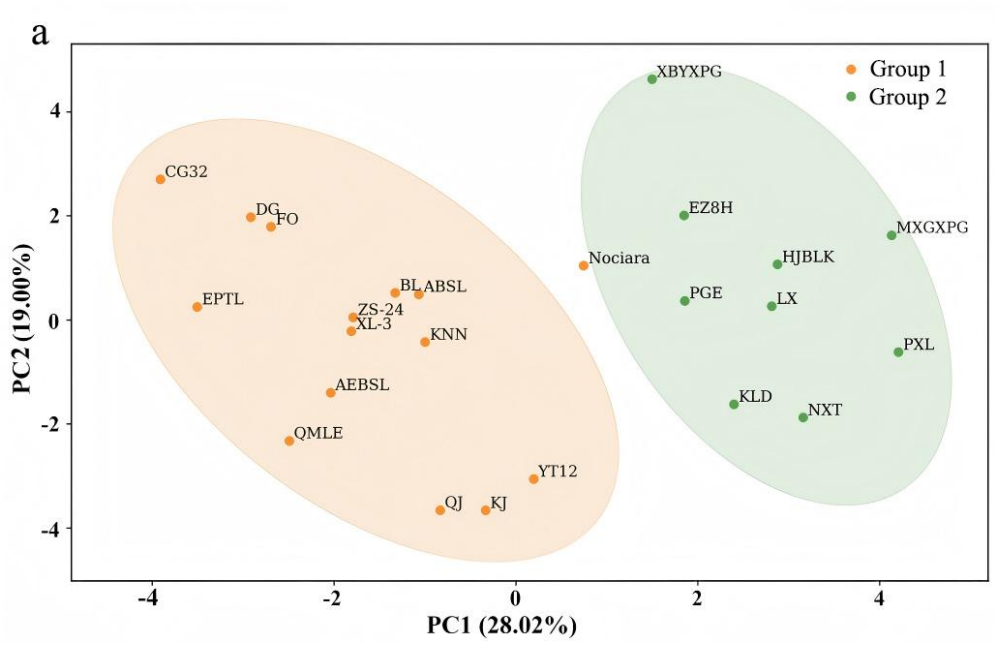
644

645 **Fig. 2**.


1.0
0.5
0.0
-0.5
-1.0
PC2 (19.00%)
-1.0
-0.5
0.0
0.5
1.0
PC1 (28.02%)
Caffeic_acid
SFA
PUFA
Soluble_protein
PulpFraction
Hydroxytyrosol
Moisture
FruitWeight
StoneWeight
Longitudinal diameter
Transverse diameter
Tyrosol
Polyphenols
Total_sugar
Oleuropein
Flavonoids
Quercetin
MUFA

646

647 **Fig. 3**.


a
Group 1
Group 2
XBYXPG
CG32
DG
FO
EZ8H
MXGXPG
Nociara
HJBLK
BL
ABSL
PGE
LX
EPTL
ZS-24
XL-3
KNN
PXL
AEBSL
KLD
NXT
QMLE
YT12
QJ
KJ
PC2 (19.00%)
PC1 (28.02%)

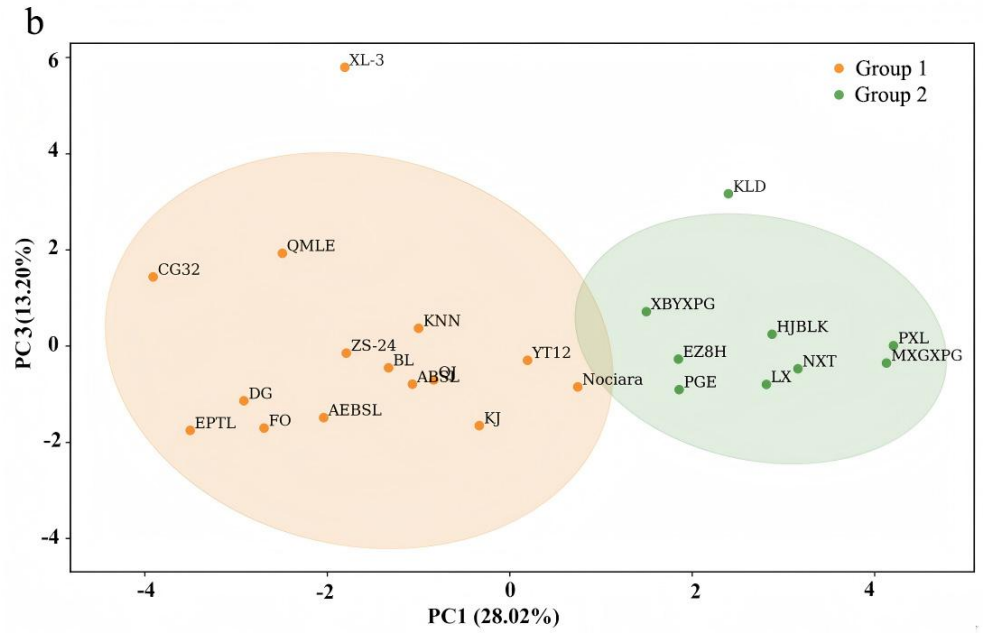
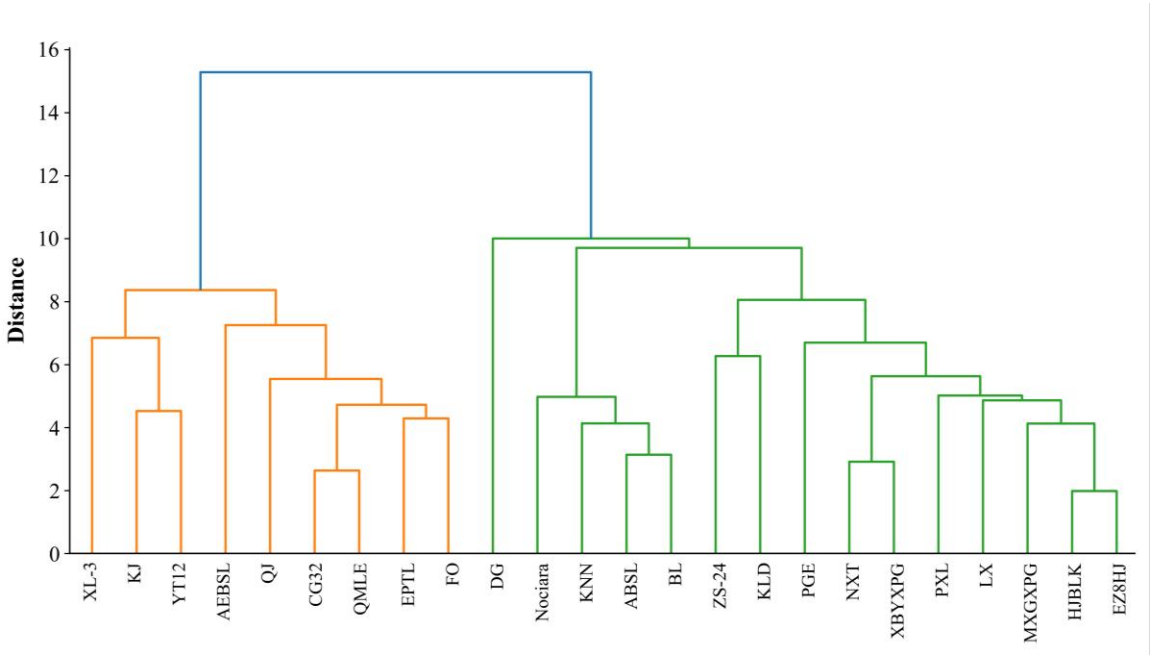

b
Group 1
Group 2
XL-3
KLD
QMLE
CG32
XBYXPG
KNN
HJBLK
ZS-24
YT12
EZ8H
PXL
BL
NXT
MXGXPG
Nociara
PGE
LX
DG
AEBSL
KJ
EPTL
FO
PC3(13.20%)
PC1 (28.02%)

Fig. 4.


Distance
16
14
12
10
8
6
4
2
0
XL-3
KJ
YT12
AEBSL
QJ
CG32
QMLE
EPTL
FO
DG
Nociara
KNN
ABSL
BL
ZS-24
KLD
PGE
NXT
XBYXPG
PXL
LX
MXGXPG
HJBLK
EZ8HJ

651

652 **Fig. 5**.

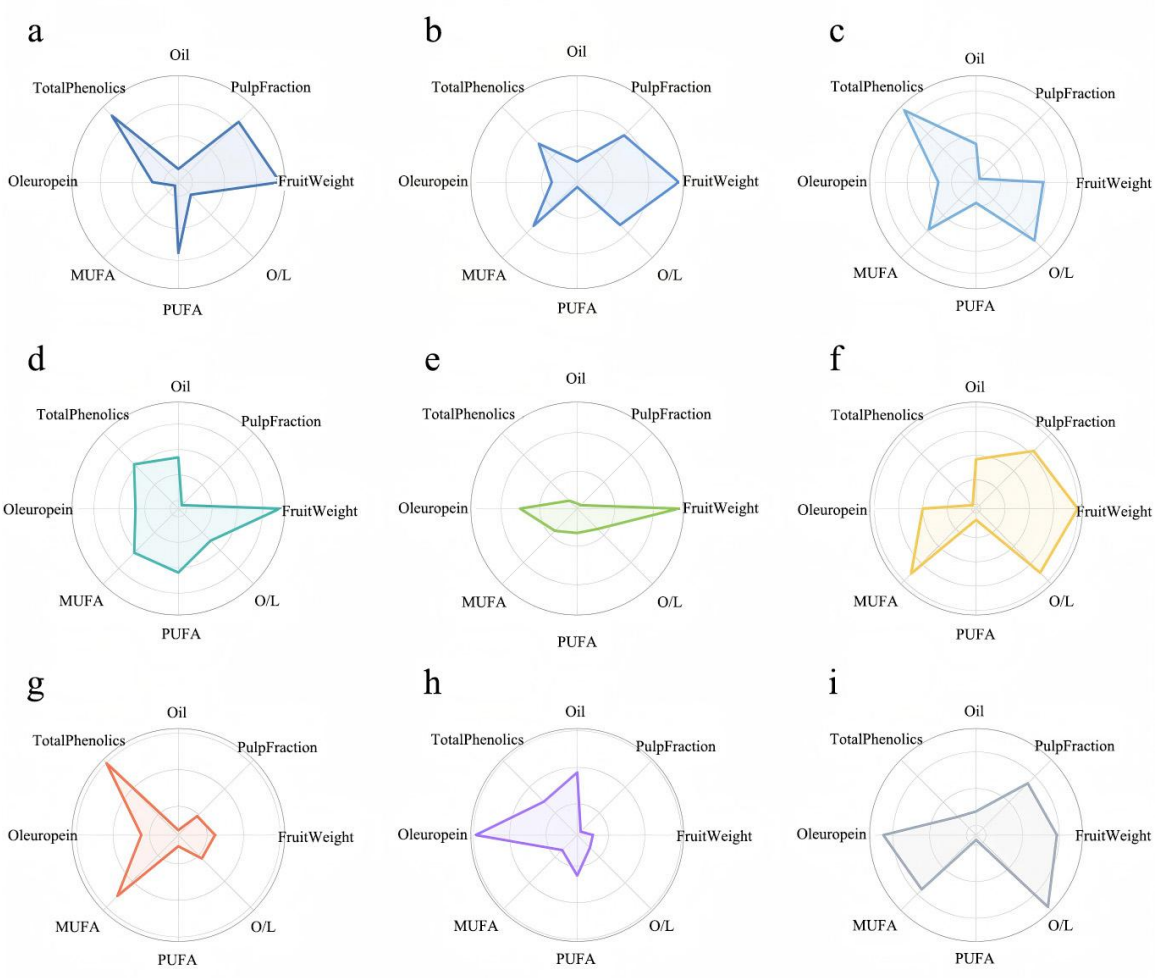

a
b
c
d
e
f
g
h
i
Oil
PulpFraction
FruitWeight
O/L
PUFA
MUFA
Oleuropein
TotalPhenolics

Fig. 6.

Table 1. Information on the 24 olive (*Olea europaea* L.) cultivars used in this study.

No.	Code	Cultivar	Reported origin	No.	Code	Cultivar	Reported origin
1	KJ	Koroneiki	Greece	13	AEBSL	Arbosana	Spain
2	XBYXPG	Manzanilla	Spain	14	HJBLK	Hojiblanca	Spain
3	PGE	Picual	Spain	15	EPTL	Empeltre	Spain
4	LX	Leccino	Italy	16	FO	Frantoio	Italy
5	PXL	Picholine	Spain	17	QMLE	Chemlal de Kabylie	Algeria
6	EZ8H	Ezhi-8	Hubei, China	18	NXT	Nisiot	France
7	ZS-24	Zhongshan 24	Jiangsu, China	19	XL-3	Greek-3	Greece
8	DG	Arbequina	Spain	20	KLD	Coratina	Albania
9	QJ	Qiji	Croatia	21	YT12	Yuntai 12	Spain
10	MXGXPG	Manzanilla	Mexico	22	Nociara	Nociara	Italy
11	CG32	Chenggu 32	Shaanxi, China	23	KNN	Canino	Greece
12	BL	Berat	Albania	24	ABSL	Arbosana	Spain

Table 2. Descriptive statistics and variation analysis of major quality traits in the 24 olive cultivars.

Trait	Maximum	Minimum	Mean	SD	CV (%)
Fruit transverse diameter (mm)	24.18	3.53	14.63	4.16	29.08
Fruit longitudinal diameter(mm)	31.01	10.81	20.63	4.57	22.63
Single fruit weight (g)	9.27	0.64	3.52	1.85	53.72
Stone weight (g)	1.39	0.25	0.71	0.25	35.57
Pulp ratio (%)	84.20	26.30	56.90	12.40	22.28
Moisture content (%)	76.98	44.49	62.03	7.50	12.09
Oil content on dry pulp basis(%)	22.72	10.67	14.92	3.26	21.82
Total sugar content (mg/g DW)	627.40	293.31	445.72	101.31	22.73
Soluble protein content (mg/g DW)	60.47	15.49	38.15	12.60	33.02
Total phenolic content (mg/g DW)	105.11	34.54	62.28	17.45	28.02
Total flavonoid content (mg/g DW)	321.42	67.13	132.24	52.45	39.67
Hydroxytyrosol (mg/g DW)	3.63	0.28	1.56	0.75	47.95
Tyrosol (mg/g DW)	0.70	0.13	0.34	0.17	51.49
Caffeic acid (mg/g DW)	0.18	0.01	0.07	0.05	62.69
Luteolin glycoside (mg/g DW)	0.13	0.02	0.05	0.03	55.56
Oleuropein (mg/g DW)	2.63	0.11	0.57	0.54	94.63
Quercetin (mg/g DW)	0.51	0.45	0.46	0.01	3.20
Myristic acid, C14:0 (%)	0.03	0.01	0.01	0.00	32.50
Palmitic acid, C16:0 (%)	17.26	8.24	13.87	2.24	16.18
Palmitoleic acid, C16:1 (%)	0.19	0.06	0.09	0.03	33.54
Stearic acid, C18:0 (%)	4.04	1.39	2.44	0.84	34.40
Oleic acid, C18:1 (%)	78.68	50.17	67.61	6.90	10.21
Linoleic acid, C18:2 (%)	26.52	3.24	10.28	5.62	54.67
Linolenic acid, C18:3 (%)	1.41	0.69	0.97	0.18	19.08
Arachidic acid, C20:0 (%)	0.58	0.28	0.38	0.08	22.55
Eicosenoic acid, C20:1 (%)	0.48	0.23	0.30	0.05	17.62
Eicosadienoic acid, C20:2 (%)	0.03	0.01	0.02	0.01	36.64
Behenic acid, C22:0 (%)	0.19	0.07	0.12	0.03	24.46
Erucic acid, C22:1 (%)	0.25	0.05	0.12	0.05	46.65
Lignoceric acid, C24:0 (%)	0.11	0.04	0.07	0.02	27.64
Nervonic acid, C24:1 (%)	1.26	0.10	0.56	0.33	58.89

Table 3. Principal component loadings of fruit quality-related traits.

Eigen vector	Principal factor					
	1	2	3	4	5	6
Single fruit weight	0.3040	0.3008	-0.0003	-0.0701	0.0161	0.0089
Fruit transverse diameter	0.3342	0.2317	0.0091	-0.0877	-0.0437	0.1092
Fruit longitudinal diameter	0.3536	0.1882	0.0804	0.0526	-0.1221	0.0676
Stone weight	0.2647	0.2657	0.1223	-0.0777	-0.2179	-0.1148
Pulp ratio	-0.0582	0.1603	-0.2268	0.3226	-0.1113	-0.3560
Moisture content	0.1713	0.3426	-0.1420	0.1861	0.1717	0.1250
Oil content on dry pulp basis	-0.1175	-0.1091	0.3460	-0.2437	-0.3211	0.0773
Total sugar	0.2567	0.0675	0.1209	-0.3441	0.2610	-0.1409
Total phenolics	0.1315	0.0662	0.3143	-0.0626	0.3081	-0.2272
Total flavonoids	-0.0625	-0.1043	0.4905	0.3155	-0.0569	-0.0600
Soluble protein	-0.1546	0.2212	-0.1533	0.2909	-0.2348	-0.4001
Oleuropein	-0.0530	-0.0154	0.3909	0.2765	-0.2100	0.3604
Hydroxytyrosol	-0.0604	0.0861	0.2010	0.4084	0.4749	0.2147
Tyrosol	0.2056	0.1142	0.3234	0.2052	0.0474	-0.2865
Caffeic acid	-0.2144	0.3173	0.0111	0.1592	-0.1761	-0.0114
Quercetin	-0.1391	-0.1556	-0.0416	0.0571	0.4623	-0.2579
Luteolin glycoside	-0.0726	0.1346	-0.1624	-0.1394	0.0445	0.2019
SFA	-0.0956	0.2627	-0.2136	0.0801	0.0126	0.4889
MUFA	0.2837	-0.3270	-0.0444	0.1398	-0.0143	-0.0491
PUFA	-0.2939	0.2532	0.1566	-0.2235	-0.0431	-0.1429
O/L	0.2743	-0.2635	-0.1388	0.2055	-0.1362	0.0138
MUFA/PUFA	0.2793	-0.2665	-0.1366	0.2048	-0.1264	0.0081
Eigenvalue	6.1409	4.1627	2.8873	2.0961	1.5676	1.3861
Variance contribution rate	0.2802	0.1900	0.1318	0.0957	0.0715	0.0633
Cumulative contribution rate	0.2802	0.4702	0.6020	0.6976	0.7692	0.8324

Table 4. Composite scores of the 24 olive cultivars based on the PCA model.

Cultivar	PC1	PC2	PC3	PC4	PC5	PC6	Composite score	Rank
XBYXPG	1.4961	4.6291	0.7211	0.7831	2.4209	-0.5804	1.9281	1
MXGXPG	4.1300	1.6306	-0.3466	-0.4406	-0.1966	0.0220	1.6418	2
PXL	4.2067	-0.6177	0.0131	-1.1252	1.4129	0.8234	1.3320	3
HJBLK	2.8748	1.0701	0.2497	-3.1375	0.6020	0.5665	0.9858	4
EZ8H	1.8477	2.0121	-0.2669	-0.5161	-1.4502	1.1533	0.9427	5
LX	2.8125	0.2658	-0.7916	0.1295	-0.2619	0.7850	0.9342	6
KLD	2.3971	-1.6190	3.1700	0.5474	0.4035	-2.9822	0.8103	7
XL-3	-1.8099	-0.2148	5.8024	2.4638	0.4680	2.3684	0.7635	8
PGE	1.8568	0.3702	-0.9026	2.8693	-1.7763	0.0562	0.7480	9
NXT	3.1592	-1.8736	-0.4664	1.1908	-1.4904	-1.0948	0.4877	10
Nociara	0.7445	1.0473	-0.8446	0.3444	0.0329	-1.4415	0.2888	11
BL	-1.3298	0.5235	-0.4465	-0.0271	0.3569	0.9037	-0.3027	12
ABSL	-1.0680	0.4967	-0.7900	0.4099	-1.7385	1.5137	-0.3585	13
KNN	-0.9980	-0.4238	0.3751	0.4586	0.0494	-0.9810	-0.3909	14
DG	-2.9146	1.9790	-1.1352	0.2274	0.8333	-0.3365	-0.6371	15
ZS-24	-1.7915	0.0521	-0.1402	-0.4314	-0.2047	-0.1140	-0.6892	16
YT12	0.1949	-3.0542	-0.2910	-1.8267	0.2768	1.3977	-0.7574	17
FO	-2.6938	1.7936	-1.7001	0.0562	-0.8272	-0.0829	-0.8376	18
CG32	-3.9101	2.7058	1.4429	-1.4589	-2.3539	-0.9324	-0.9113	19
AEBSL	-2.0389	-1.3958	-1.4854	0.0013	1.2357	1.1826	-1.0439	20
QJ	-0.8332	-3.6536	-0.6994	0.4292	1.1883	0.2530	-1.0543	21
KJ	-0.3344	-3.6553	-1.6509	1.4798	-0.6866	-0.3983	-1.1273	22
EPTL	-3.5046	0.2533	-1.7494	0.8439	2.4037	-1.0093	-1.1721	23
QMLE	-2.4934	-2.3213	1.9325	-3.2711	-0.6981	-1.0722	-1.5806	24

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