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Ripening dynamics of fruit quality and bioactive compounds determine optimal harvest timing in Japanese plum cultivars

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Abstract

Harvest timing is one of the most critical factors influencing the quality attributes of plum fruits. This study aimed to evaluate the ripening-dependent changes in fruit characteristics of five Japanese plum (*Prunus salicina* L.) cultivars, namely ‘Black Amber’, ‘Black Diamond’, ‘Queen Rose’, ‘Obilnaja’, and ‘Angeleno’, at different maturity stages. Fruit samples were collected at three distinct ripening stages, and both quality parameters and biochemical traits were assessed in relation to maturity progression. Based on the overall mean of all cultivars from the initial to the final harvest stage, fruit weight (FW), total soluble solids (TSS), total phenolic content (TPC), antioxidant activity (AA), and total anthocyanin content (TAC) increased by 24.90%, 35.02%, 13.12%, 5.65%, and 4.5-fold, respectively. TSS content ranges from 14.76% (Black Amber) to 17.50% (Angeleno), titratable acidity (TA) content ranges from 0.74 (Black Diamond) to 2.35 (Obilnaja), and TP content ranges from 145.52 (Queen Rose) to 368.95

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(Angeleno), TAC between 9.89 (Black Amber) and 49.21 (Black Diamond), and AA content between 106.48 (Queen Rose) and 180.71 (Angeleno). In contrast, fruit flesh firmness (FFF), peel hue angle, and TA decreased by 62.84%, 50.96%, and 49.66%, respectively. Principal component analysis (PCA) revealed that the first two principal components accounted for 68.60% of the total variation among the evaluated traits, indicating a clear differentiation of quality attributes across ripening stages. The results demonstrated that early harvesting should be avoided to ensure superior fruit quality. The findings indicate that late-harvested fruits accumulate higher concentrations of bioactive compounds, thus enhancing nutritional and functional quality; however, simultaneous fruit softening imposes limitations on post-harvest processing and marketability. These results provide a cultivar-specific, multi-dimensional framework for optimizing harvest strategies to meet diverse marketing, storage, and health-conscious consumer demands for Japanese plum cultivars.

Keywords: Harvest maturity optimization, Postharvest quality dynamics, Anthocyanin accumulation, Multivariate analysis (PCA), Bioactive compounds

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1. Introduction

The genus *Prunus* comprises nearly 200 species predominantly distributed across the Northern Hemisphere (Avan 2015). Within this genus, plum species are taxonomically classified into three main groups: European–Asian, North American, and East Asian species (Özçağıran et al. 2011). Among the Far Eastern group, *Prunus salicina*, commonly referred to as Japanese plum, holds considerable commercial importance due to its early ripening characteristics and strong market appeal. Cultivars of *P. salicina* are widely preferred in global markets owing to their desirable organoleptic properties and early-season availability.

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Plums contribute significantly to human nutrition due to their high fiber content and antioxidant capacity (Usenik et al. 2008). They are rich in pectin, phenolic compounds, anthocyanins (Gündüz and Saraçoğlu 2012), flavonoids, and vitamins (Mahmoudi et al. 2022), making them an integral component of a healthy diet. With the growing emphasis on health-conscious consumption, there has been an increasing demand for nutritionally dense, plant-derived foods. In this context, plums have gained considerable attention due to their rich biochemical composition and high levels of health-promoting phytochemicals. Furthermore, they are consumed in both fresh and processed forms, including dried products, juices, jams, and functional food ingredients, owing to their favorable flavor profile and nutritional value (Stacewicz-Sapuntzakis 2013).

Despite their nutritional advantages, plums have a relatively short postharvest life and are highly susceptible to rapid quality deterioration (Minas et al. 2013). Both premature and delayed harvesting can result in substantial losses in fruit quality and storage performance (Adiletta et al., 2022; Xu et al. 2022). Accordingly, harvest timing has been identified as one of the most critical factors affecting plum fruit quality (Guerra and Casquero 2008). Achieving optimal harvest maturity is therefore essential for minimizing postharvest losses and maintaining both the organoleptic and nutritional quality of the fruit (Meng et al. 2021).

Plums, which exhibit climacteric characteristics, show a significant increase in respiration rate and ethylene production during ripening (Crisosto and Costa, 2008). For this reason, plums are harvested at commercial maturity, before they are fully ripe (Khan, 2016). The optimal stage of fruit ripening at harvest depends primarily on the fruit's intended use and cultivar (Westwood, 1993). As plums ripen, physiological changes occur in respiration rate, ethylene production, fruit firmness, and other physicochemical properties; these changes transform the ripe fruit from a

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hard, sour state with unacceptable texture, taste, and flavor to a state more suitable for consumption (Khan, 2016). In Japanese plum varieties, understanding the physiological changes that occur during growth and ripening determines the harvesting period for fruits with the best eating quality (Kader, 1999). The ripening process of plums and the planning of harvesting operations can vary depending on the cultivar and environmental factors. Quantifying changes in the ripening process of Japanese plum cultivars is critical not only for understanding metabolic processes but also for establishing objective criteria for determining the optimal harvest time.

As in many fruit crops, the determination of the appropriate harvest window in plums relies on a combination of fruit color, fruit size, pH, TSS, TA, and biochemical indicators. More recently, increasing attention has been directed toward biochemical traits, particularly TAC, TPC, and AA, which are considered key quality indicators due to their functional and health-related benefits (Ndou et al. 2019).

Considering these factors, the present study aimed to investigate the ripening-dependent dynamics of fruit quality, physicochemical properties, and major bioactive compounds in different Japanese plum cultivars (*P. salicina* L.). By tracking the precise physiological transitions from the early harvest stage to the late harvest stage, the aim is to elucidate the complex relationships between traditional maturity indices and functional biochemical characteristics. In conclusion, the information obtained from this research aims to provide variety-specific strategies to minimize post-harvest losses and determine the optimal harvest time for Japanese group plums, which have high nutritional and commercial value. Elucidating these dynamic changes will help determine the optimal harvest time, improve fruit quality management, and provide valuable insights for producers, consumers, and researchers.

2. Material and methods

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2.1. Plant material

The study was conducted in a plum orchard located at the Malatya Apricot Research Institute Directorate in the Eastern Anatolia Region of Türkiye (38°19′26″ N, 38°17′13″ E; 1005 m above sea level, the climatic characteristics of the study area are given in Figure 2). The plant material comprised five Japanese plum (*P. salicina* L.) cultivars, namely 'Black Amber', 'Black Diamond', 'Queen Rose', 'Obilnaja', and 'Angeleno' (Fig. 1). All trees were grafted onto Myrobalan 29-C clonal rootstock and planted at a spacing of 5 × 5 m. During the experimental period, the trees were seven years old and managed under standard horticultural practices, including routine pruning, irrigation, and fertilization. The experiment was designed in triplicate, with each replicate representing one tree, and a total of 100 fruit samples were collected from each replicate. Fruit samples were randomly collected from all parts of the tree. To evaluate fruit quality development during ripening, fruits were harvested at three distinct maturity stages. Plums with climacteric characteristics are harvested when they reach cultivar-specific color and size to extend post-harvest shelf life (Cristo et al., 1995). In this study, the harvest date for plums was determined as the period when they reached the variety-specific color and size criteria commonly used in the literature to determine plum harvest dates (Çetin and Saraçoğlu, 2023; Rymbai et al., 2024). Fruit samples were harvested at 14-day intervals. Harvest dates varied among cultivars, beginning on June 24 for 'Obilnaja', July 8 for 'Black Amber' and 'Queen Rose', July 22 for 'Black Diamond', and September 7 for 'Angeleno'.

Taxonomic identification of all plant materials was conducted by Prof. Dr. Ercan Yıldız. Voucher specimens were deposited in the Herbarium of Erciyes University under accession number 31625 and are accessible to the public for verification and future reference.

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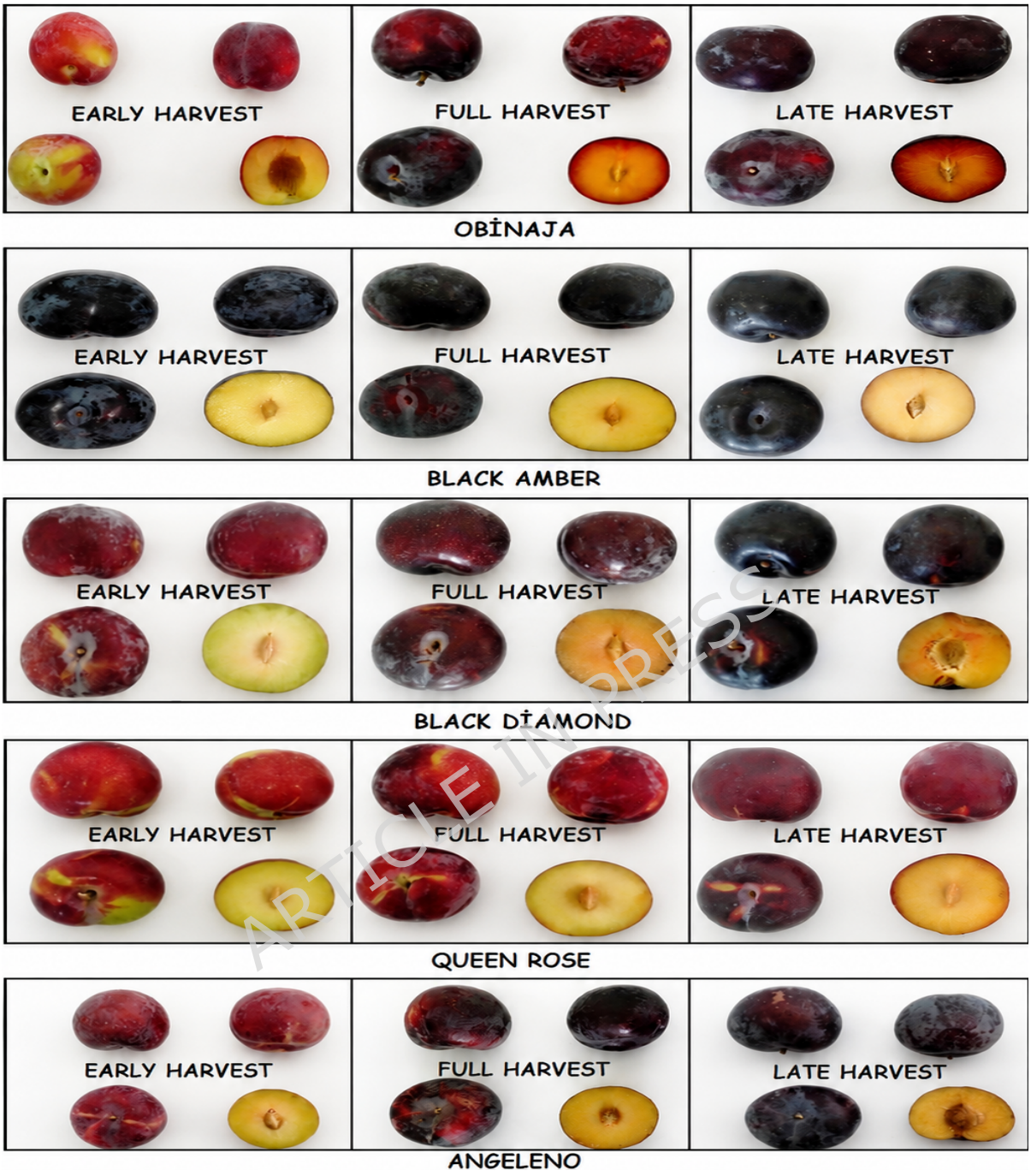


Fig. 1. Representative images of plum cultivars sampled at three different harvest stages. This photograph was captured as part of the present study and was provided by the second author, Prof. Dr. Ercan Yıldız. It is not subject to any third-party copyright restrictions.

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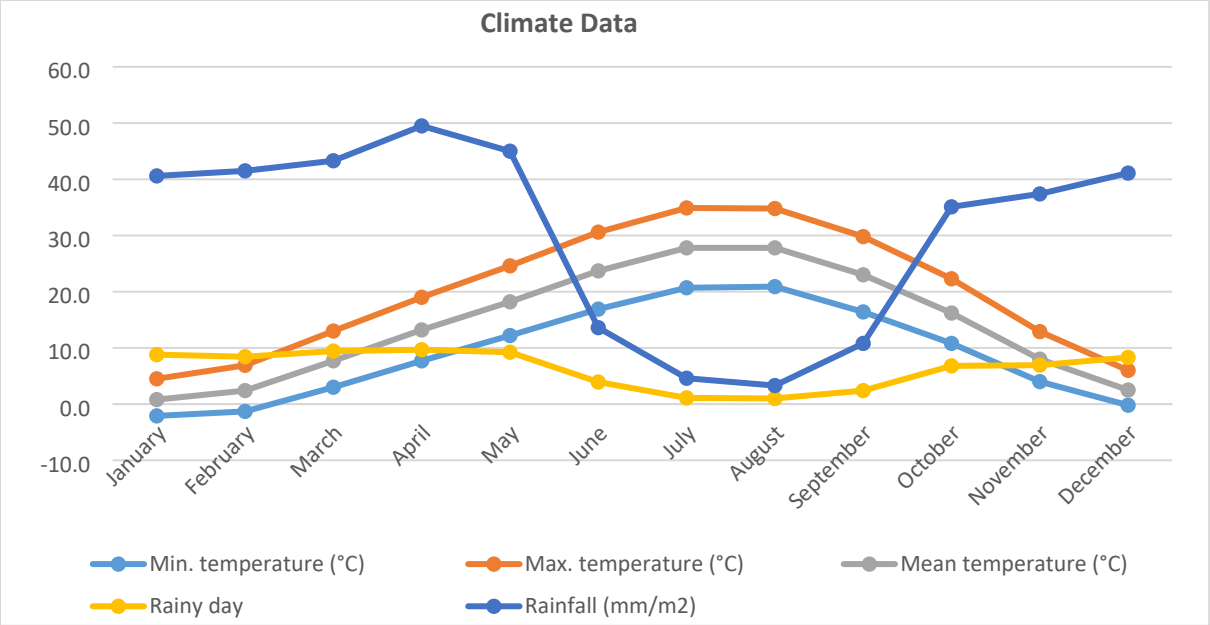


Fig. 2. Climatic characteristics of the study area.

2.2. Physical and chemical fruit quality measurements

The physical and chemical quality attributes of plum fruits were determined using standardized analytical procedures and calibrated precision instruments. The analyses were performed in triplicate, with each replicate containing 30 fruits. Fruit and stone weights (SW) were measured using a digital analytical balance (±0.01 g accuracy; e.g., Sartorius Entris II, Germany). Fruit dimensions, including width (length between the two cheeks with the equatorial region in the middle), length (length between the stem cavity and the blossom end), and height (length between the equatorial region and the dorsal region), were recorded using a digital caliper (±0.01 mm precision; e.g., Mitutoyo, Japan). FFF was measured in Newtons (N) using a hand-held penetrometer (e.g., FT 327, Effegi, Italy) equipped with an 8 mm diameter probe. Measurements were taken at two opposite equatorial positions on each fruit after removing a small portion of the peel. Peel and flesh color parameters were determined using a chromameter (Minolta CR-200, Konica Minolta, Japan). Color measurements were recorded according to the CIELAB color

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space system and expressed as L* (lightness), C* (chroma), and h° (hue angle) values for both peel and flesh tissues. Following stone removal, fruit samples were homogenized using a laboratory blender (e.g., Waring Commercial, USA), and the resulting puree was filtered through cheesecloth to obtain clear juice for chemical analyses. TSS content was measured using a digital refractometer (e.g., Atago PAL-1, Japan) and expressed as Brix. The pH of the juice was determined using a calibrated digital pH meter (e.g., Hanna Instruments HI 2211, USA). TA was determined by diluting 10 mL of clarified juice with 90 mL of distilled water and titrating with 0.1 N NaOH to an endpoint of pH 8.1. Results were expressed as percentage (%) malic acid equivalents, which is the predominant organic acid in plum fruits. All measurements were performed in triplicate, and all instruments were calibrated prior to analysis to ensure accuracy, reliability, and reproducibility of the data.

2.3. Biochemical analysis

For the determination of biochemical traits, 40 fruits per replicate were homogenized using a laboratory blender (e.g., Waring Commercial, USA). Approximately 10 mL of the homogenate was transferred into 50 mL polypropylene centrifuge tubes (Falcon type). Each sample was extracted with 25 mL of HPLC-grade methanol and homogenized at 10,000 rpm for 2 min to ensure efficient extraction of bioactive compounds (e.g., IKA T25 digital Ultra-Turrax, Germany). The homogenates were incubated at 4°C in the dark for 16 h to minimize the degradation of light- and temperature-sensitive compounds. Following incubation, samples were centrifuged at 10,000 rpm for 20 min at 4°C using a refrigerated centrifuge (Elektromag M 4815 PR, Türkiye). The supernatants were carefully collected using micropipettes and filtered through Whatman No. 1 filter paper prior to spectrophotometric analysis. Quantitative analyses of TPC, TAC, and AA were performed using a UV–Vis spectrophotometer (Model T60U, PG

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Instruments, UK). All analyses were conducted in triplicate, and results were expressed on a fresh weight (FW) basis.

Total phenolic content: TPC was determined using the Folin–Ciocalteu colorimetric method following Singleton and Rossi (1965). Briefly, 0.5 mL of the extract was mixed with 2.5 mL of 10% (v/v) Folin–Ciocalteu reagent and allowed to react for 5 min. Subsequently, 2.0 mL of 7.5% (w/v) sodium carbonate solution was added. The mixture was incubated at room temperature in the dark for 30 min, and absorbance was measured at 765 nm. Results were expressed as mg gallic acid equivalents per g fresh weight (mg GAE/g FW).

Antioxidant activity: AA was evaluated using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay as described by Demirtaş et al. (2013). A 100 µL aliquot of extract was mixed with 3.9 mL of 0.1 mM DPPH solution prepared in methanol. After vortexing (e.g., Vortex-Genie 2, Scientific Industries, USA), the mixture was incubated at room temperature in the dark for 30 min. Absorbance was measured at 517 nm, and results were expressed as µmol Trolox equivalents per g fresh weight (µmol TE/g FW).

Total anthocyanin content: TAC was determined using the pH differential method described by Giusti et al. (1999). Briefly, 1 mL of extract was diluted with 9 mL of buffer solution prepared with 0.025 M potassium chloride (pH 1.0) and 0.4 M sodium acetate (pH 4.5). Absorbance was measured at 520 nm and 700 nm under both pH conditions. TAC was calculated based on the molar absorptivity and molecular weight of cyanidin-3-glucoside and expressed as mg cyanidin-3-glucoside equivalents per g fresh weight (mg cyanidin-3-gluc/g FW).

2.4. Statistical analysis

Data were checked for normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test) prior to analysis. The results showed that the data were suitable for parametric analysis. All

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quantitative data obtained in this study were subjected to one-way analysis of variance (ANOVA) according to the harvest times of the varieties using JMP Pro 17.0 statistical software (SAS Institute Inc., Cary, NC, USA). Significant differences among cultivars were determined using Tukey's Honestly Significant Difference (HSD) test at a significance level of $p < 0.05$. To further elucidate the relationships among the evaluated traits, multivariate statistical analyses were performed. PCA was conducted using OriginPro software (OriginLab Corporation, Northampton, MA, USA) to identify the major sources of variation among harvest stages and measured variables. Prior to PCA, all variables were standardized (z-score normalization) to eliminate the effects of differing measurement scales. Biplot graphs based on the first two principal components were generated to visualize the distribution of harvest stages and to illustrate the relationships among traits.

3. Results and Discussion

3.1. Fruit physical characteristics

Changes in the physical characteristics of Japanese plum cultivars across different ripening stages are presented in Fig. 3. Significant differences ($p < 0.05$) were observed among for all evaluated traits. At the final ripening stage, the lowest fruit weight was recorded in the 'Obilnaja' cultivar, whereas the highest value was observed in 'Black Diamond'. Fruit weight exhibited a continuous increasing trend from the initial to the final sampling stage, with the greatest increase detected in 'Black Amber' (43.62%). According to harvest-time averages, FW ranged from 34.17 g (Obilnaja) to 70.83 g (Black Diamond) (Supplementary Table S1). Fruit dimensional traits showed a generally increasing, yet slightly fluctuating, trend throughout the ripening period. On average, Fwi, FL, and FH increased by 5.16%, 10.23%, and 7.47%, respectively. Previous studies evaluating physical changes during fruit development have primarily focused on

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variations in fruit size and weight. Ergun (2016) reported increases of 35% and 65% in FW in 'Stanley' and 'Sugar' cultivars, respectively, along with relatively minor changes in fruit dimensions. Similarly, Altuntaş et al. (2020) observed increases of 6%, 3%, and 2% in FW, FL, and Fwi, respectively, in the 'President' cultivar across three maturity stages. Sezer and Çetin (2021) reported a 3.7-fold increase in FW, accompanied by increases of 35% and 39% in FL and Fwi, respectively, in the 'Papaz' cultivar over a one-month ripening period. However, although a linear increase is often reported, several studies have demonstrated non-linear or fluctuating growth patterns. Usenik et al. (2008) reported irregular increases in fruit weight and size in *Prunus domestica*, attributing this variation to asynchronous ripening on the tree. Similarly, Famiani et al. (2012) observed a temporary slowdown in fruit growth during specific developmental phases in Japanese plums. Cetin and Saraçoğlu (2023) reported no significant increase in fruit size at advanced ripening stages in certain *P. domestica* cultivars. Rymbai et al. (2024) further indicated that FW in *P. jenkinsii* increases until full maturity, followed by a decline during over-ripening, accompanied by similar trends in fruit size and seed characteristics. The increase in fruit size and weight is primarily attributed to cell division and cell expansion processes (Atkinson and MacRae 2007), which are regulated by plant growth hormones such as auxins and gibberellins (He and Yamamuro 2022; Rymbai et al. 2024). These physiological processes promote cell enlargement and elongation, leading to increased fruit mass up to a certain developmental stage (Wongmetha et al. 2015). However, depending on the species and developmental stage, fruit growth may slow down or cease during the transition from growth to ripening (Forlani et al. 2019). As in many fruit species, fruit size is a key determinant of marketability and consumer preference in plums. In addition to genetic factors, environmental conditions, cultural practices (e.g., irrigation, fertilization, and pruning), tree age, and crop load

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are known to influence fruit size characteristics. According to harvest-time averages, SW ranged from 0.95 g (Black Amber) to 1.56 g (Queen Rose) (Supplementary Table S1). SW exhibited a pattern similar to FW, increasing progressively during ripening. At the final harvest stage, the highest SW was recorded in 'Queen Rose' (1.63 g), while the lowest value was observed in 'Black Amber' (1.02 g). Previous studies have reported comparable values, including 0.80 g ('Obilnaja') and 1.78 g ('Angeleno') (Balık 2005), as well as ranges between 0.84–1.04 g (Bilgü and Seferoğlu 2005) and 1.40–1.52 g (Subaşı 2013). SW is a critical parameter influencing the flesh-to-stone ratio, which directly affects overall fruit quality. The consistency between the present findings and previous studies confirms the reliability of the obtained results. However, the genetic backgrounds of the varieties examined in the studies and differences in experimental conditions are the primary reasons for the variations observed among the studies. FFF is a key quality parameter, particularly in relation to postharvest handling, storage, and transport. According to harvest-time averages, FFF ranged from 25.50 kg-force (Obilnaja) to 35.96 kg-force (Angeleno) (Supplementary Table S1). In all cultivars, the highest FFF values were recorded at early harvest stages, followed by a significant decline toward full maturity. At the final sampling stage, the lowest FFF was observed in 'Obilnaja', whereas the highest value was recorded in 'Angeleno'. The greatest reduction in FFF was observed in 'Obilnaja' (72.89%), while the lowest decrease occurred in 'Angeleno' (42.61%). FFF is strongly influenced by ripening stage (Martinez-Espla et al. 2014), genetic variability (Usenik et al. 2014), storage conditions (Davarynejad et al. 2015), and pre- and postharvest treatments (Erkan and Eksi 2012; Ozturk et al. 2015). The decline in FFF during ripening is associated with fruit softening, which results from cell wall degradation mediated by hydrolytic enzymes (Atkinson and MacRae 2007; Botton et al. 2019). Overall, the results clearly demonstrate that fruit firmness decreases as

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ripening progresses, which is consistent with previous findings reported in the literature (Altuntaş 2020; Alvarez-Herrera et al. 2021; Cetin and Saraçoğlu 2023; Famiani et al. 2012; Khalili et al. 2020; Ndou et al. 2019; Sarıdaş et al. 2016). Variations among studies are likely attributable to differences in environmental conditions and cultural practices.

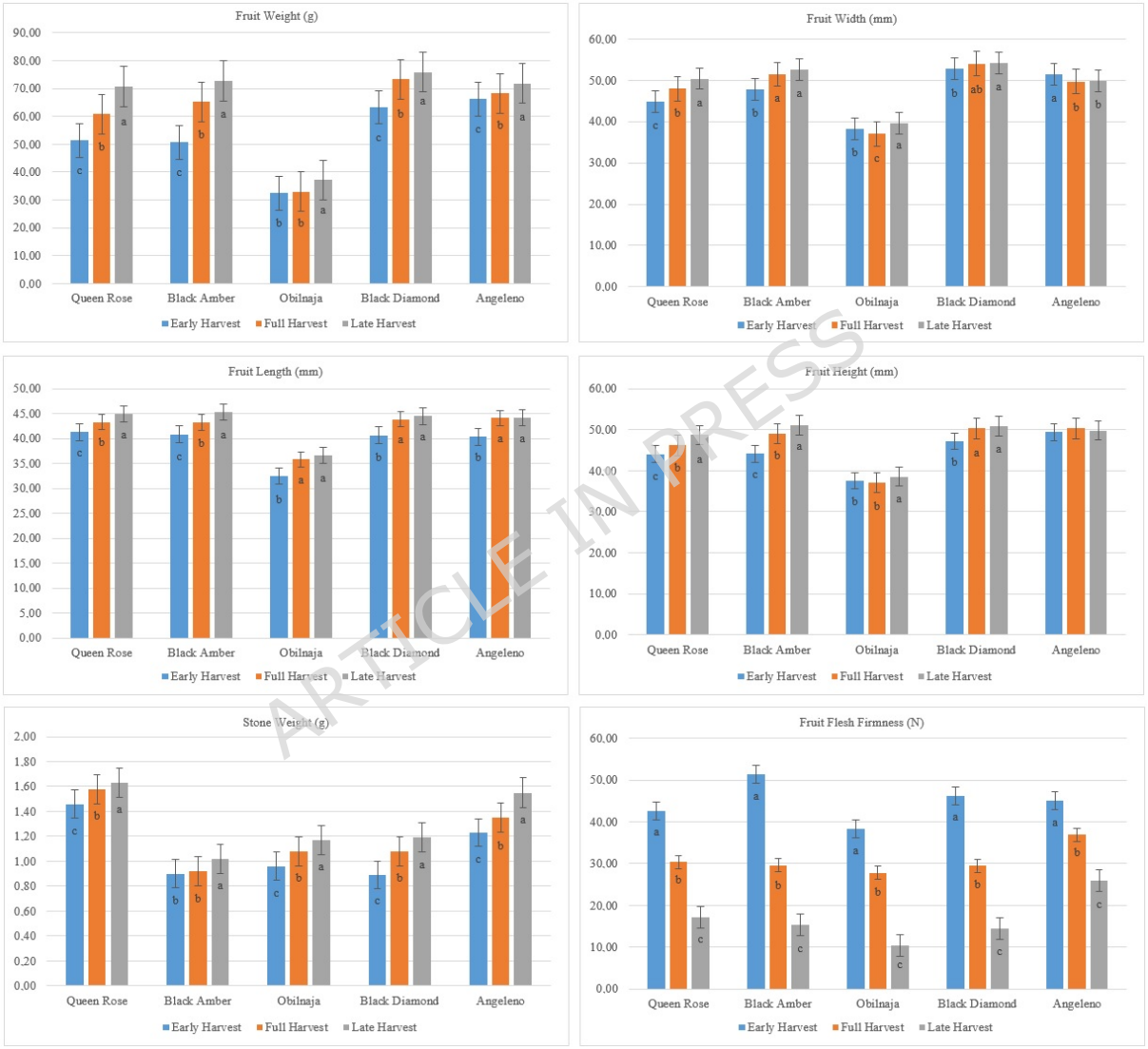


Fig. 3. Effects of harvest maturity stages on the morphological characteristics of plum cultivars (The values followed by a lowercase letter are statistically significantly different).

3.2 Peel and flesh color characteristics

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Fruit peel and flesh color are among the most critical quality attributes for determining harvest maturity and influencing consumer preferences in plums. In all evaluated cultivars, statistically significant changes ($p < 0.05$) in colorimetric parameters were observed throughout the ripening process (Supplementary Table S2). A general decreasing trend in color parameters was recorded as ripening progressed, although the magnitude of change varied among cultivars. On average, peel L*, chroma (C*), and hue angle (H°) values decreased by 14.60%, 50.54%, and 50.96%, respectively. Similarly, flesh L*, C*, and H° values declined by 12.92%, 13.24%, and 18.68%, respectively (Fig. 4). The results indicated that peel color progressively shifted toward a reddish-purple hue during ripening. Moreover, color changes were first observed in the peel and subsequently in the flesh. Flesh color transitioned from green to yellow and, in certain cultivars such as 'Obilnaja' and 'Black Diamond', to reddish tones at advanced ripening stages. Chroma (C*) reflects color intensity or saturation, and its decline indicates a shift toward darker and less vivid coloration (less saturated and more grayed color). Hue angle (H°), which defines the basic color tone (Civil 2009), decreases as red pigmentation increases (Ozturk et al. 2015). Hue angle (H°), which defines the basic color tone (Civil 2009), decreases as red pigmentation increases (Ozturk et al. 2015). The observed changes in fruit color during ripening are consistent with previous studies (Alvarez-Herrera et al. 2021; Cetin and Saraçoğlu 2023; Ndou et al. 2019; Rybai et al. 2024; Sarıdas et al. 2016). The increase in red coloration is associated with decreasing L* and hue angle values (Diaz-Mula et al. 2009). However, it is well established that the extent and pattern of color changes vary depending on species, cultivar, and maturity stage (Avcı et al. 2023; Farcuh et al. 2022; Li et al. 2022; Ndou et al. 2019). The color transition observed during ripening is primarily attributed to the degradation of chlorophyll and the concomitant accumulation of anthocyanins. This process is accompanied by the synthesis of

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carotenoid and anthocyanin pigments, which play a key role in fruit coloration (Majeed and Jawandha 2016). The characteristic reddish-purple coloration in plum fruits is mainly due to anthocyanins, which mask the underlying chlorophyll and carotenoid pigments (Infante et al. 2011).

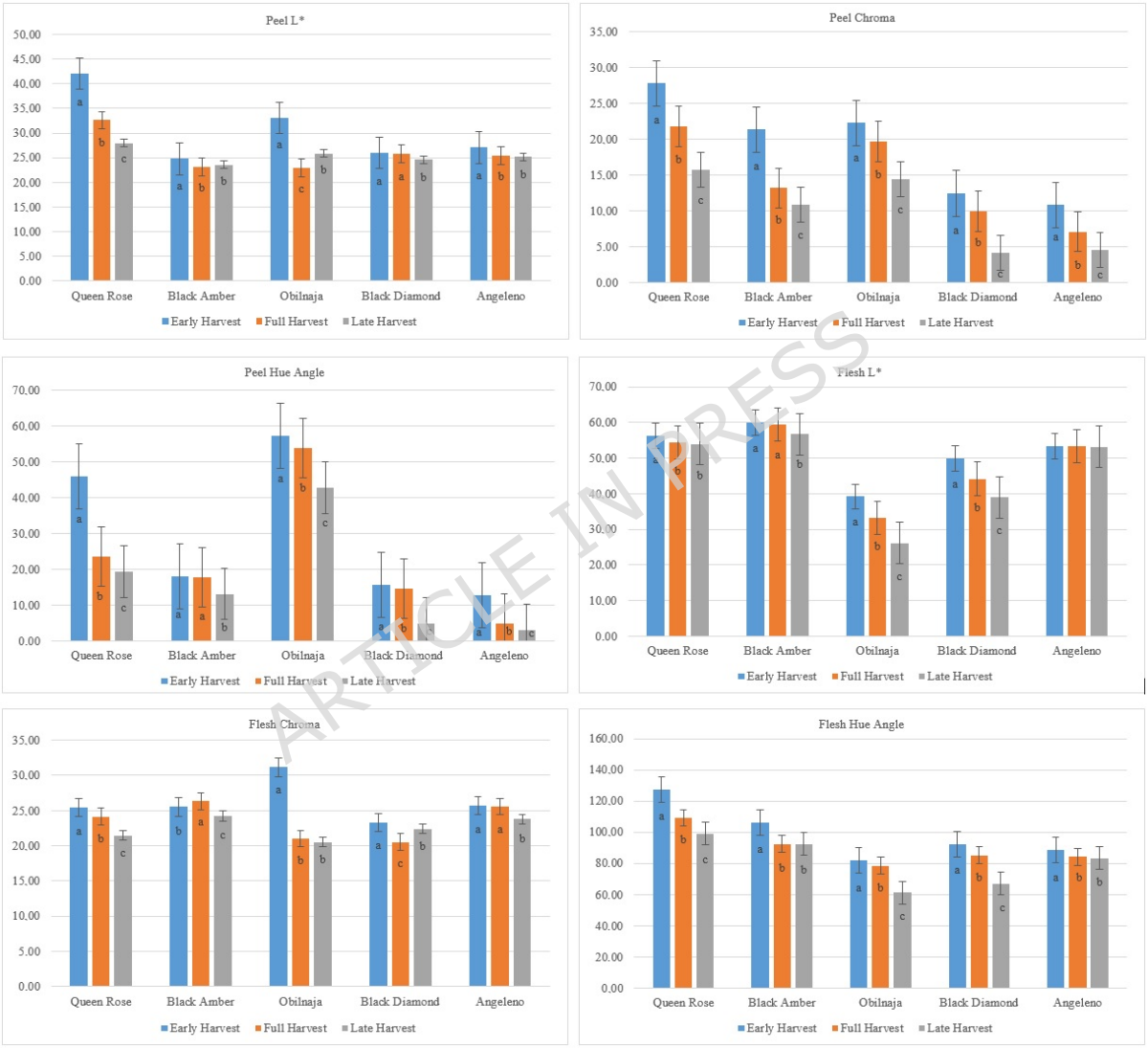


Fig. 4. Effects of harvest maturity stages on peel and flesh color characteristics of plum cultivars (The values followed by a lowercase letter are statistically significantly different).

3.3 Chemical and biochemical characteristics

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Fruit ripening is a dynamic process characterized by complex metabolic changes that lead to the development of taste, aroma, and health-promoting compounds. Harvest time had a statistically significant effect ($p < 0.05$) on all evaluated chemical and biochemical parameters (Fig. 5). According to harvest time averages, TSS content varied between 14.76% (Black Amber) and 17.50% (Angeleno), and TA between 0.74% (Black Diamond) and 2.35% (Obilnaja) in plum varieties (Supplementary Table S3). In all plum cultivars, fruit pH and TSS increased progressively from the initial to the final ripening stage, whereas TA decreased. On average, pH and TSS increased by 13.27% and 35.02%, respectively, while TA decreased by 49.66%. The increase in TSS ranged from 14.22% ('Angeleno') to 43.90% ('Queen Rose'), whereas the reduction in TA varied between 33.94% ('Angeleno') and 64.32% ('Queen Rose'). The decline in organic acid content during ripening is primarily attributed to their utilization as respiratory substrates, which contributes to energy production (Batista-Silva et al. 2018; Saltveit 2019). The reduction in TA can also be associated with enhanced metabolic activity and the concurrent synthesis of sugars and secondary metabolites (Jiang et al. 2019). As ripening progresses, organic acids are metabolized and partially converted into sugars, leading to increased sweetness and improved flavor (Jimenez et al. 2011). Consequently, TSS and TA are considered key indicators of fruit quality, as they directly influence sweetness, taste balance, and consumer acceptability, as well as processing suitability (Rymbai et al. 2023). The present findings are consistent with previous reports in plum species (Alvarez-Herrera et al. 2021; Cetin and Saraçoğlu 2023; Kim et al. 2015; Martinez-Espla et al. 2014; Ndou et al. 2019; Rymbai et al. 2024; Zhang et al. 2025), as well as in other fruit species, where ripening is associated with increased TSS and decreased acidity (Lin and Lay 2013; Ndou et al. 2019). Biochemical compounds exhibited significant variation among cultivars and harvest stages. According to

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harvest time averages, TP content varied between 145.52 mg GAE/g (Queen Rose) and 368.95 mg GAE/g (Angeleno), TAC between 9.89 mg cyn-3-gluc/g (Black Amber) and 49.21 mg cyn-3-gluc/g (Black Diamond), and AA between 106.48 µmol TE/g (Queen Rose) and 180.71 µmol TE/g (Angeleno) in plum varieties (Supplementary Table S3). TPC showed an overall increasing trend during ripening, although the rate of increase varied among cultivars. On average, TPC increased by 13.12%, with the highest increase observed in 'Obilnaja' (23.23%) and the lowest in 'Black Amber' (7.77%). AA, showing an overall increase of 5.65%, with the greatest increase observed in 'Black Diamond' (13.92%). The accumulation of anthocyanins represents a key biochemical indicator of ripening in plums. In parallel with color development, TAC increased substantially, with an average 4.5-fold increase during ripening. The lowest increase was observed in 'Black Diamond' (approximately 1-fold), whereas the highest increase occurred in 'Black Amber' (approximately 7.5-fold). These findings are in agreement with previous studies reporting increases in biochemical compounds during fruit ripening in both plum and other fruit species, including *Rubus* spp. (Nisar et al. 2025), peach (Remorini et al. 2008), strawberry (Pineli et al. 2011), blackberry (Montaya et al. 2010), and mulberry (Polat 2013), as well as in plum (Cetin and Saraçoğlu 2023; Khalili et al. 2020; Rymbai et al. 2024; Usenik et al. 2013). Plum fruits are recognized as valuable sources of phenolic compounds, anthocyanins, antioxidants, and other bioactive substances with significant nutritional and functional properties (Kim et al. 2003; Zhu et al. 2023). The presence of phenolics such as anthocyanins and flavonoids largely influences antioxidant capacity (Rymbai et al. 2023). These compounds play a crucial role in neutralizing free radicals and reducing oxidative stress, thereby contributing to the prevention of chronic diseases (Isabelle et al. 2010; Miralakbari and Shahidi 2008; Kasnak and Palamutoğlu 2015). Overall, the results indicate that full ripening enhances the accumulation of bioactive

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compounds and improves the nutritional quality of plum fruits. Therefore, harvesting at optimal maturity is essential not only for achieving desirable sensory attributes but also for maximizing the potential health benefits associated with plum consumption. The biochemical composition of fruits is highly dynamic and influenced by several factors, including genotype, environmental conditions, and most importantly, the stage of ripeness at harvest (Cetin and Saraçoğlu, 2023).

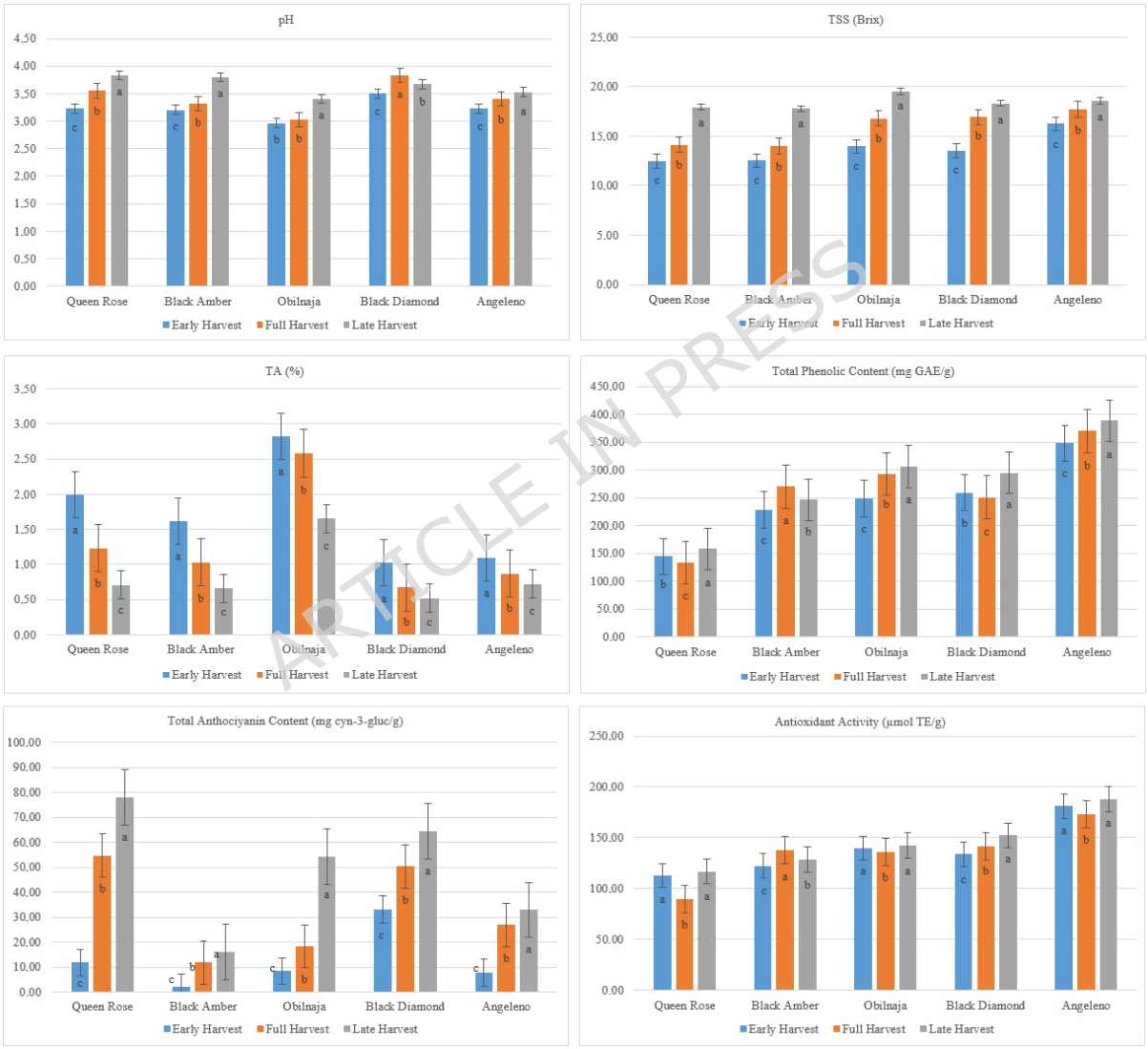


Fig. 5. Effects of harvest maturity stages on the chemical and biochemical characteristics of plum cultivars (The values followed by a lowercase letter are statistically significantly different).

3.4. Principal component analysis

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PCA is a powerful statistical method used to reduce complexity in multivariate datasets and identify key sources of variation. This analysis allows for the visualization of relationships between variables and the grouping of observations (plum cultivars and harvest stages) by projecting high-dimensional data onto a lower-dimensional space. The PCA biplot visualizes the distribution of plum varieties and harvest maturity stages based on fruit characteristics (Fig. 5). The first two principal components (PC1 and PC2) explained 44.20% and 24.40% of the total variance, respectively, accounting for a cumulative variance of 68.60%. PC1 shows a strong positive correlation with traits such as FW, FH, TSS, TAC, TP, and AA. The vectors of these traits are located on the positive side of PC1. This finding indicates that PC1 primarily reflects chemical components associated with ripeness and fruit size. The 'Queen Rose', 'Angeleno', and 'Black Diamond' varieties in the 'Full Harvest' and 'Late Harvest' groups are on the positive side of PC1; this sitation indicates that these varieties and harvest stages generally have larger fruits and higher maturity parameters. PC2 appears to be particularly associated with peel color (Peel C*, Peel H°) and flesh color (Flesh C*, Flesh H°). The 'Early Harvest' group and the 'Obilnaja' variety are associated with PC2, and traits such as Flesh H°, Flesh L*, Flesh C*, FFF, and Peel C* are on the positive side of PC2. The early harvest group is generally associated with lower TSS, TAC, TP, and AA values. Full harvest and late harvest groups are located on the positive side of PC1. During the full harvest and late harvest periods, the fruits generally had higher fruit weight, diameter, TSS, TAC, TP, and AA values. Varieties such as 'Queen Rose', 'Angeleno', and 'Black Diamond' are closely associated with the full harvest and late harvest groups, indicating that these varieties achieve optimum quality characteristics full harvest or late harvest. In the biplot representation, variables are depicted as vectors, where vector length reflects the relative contribution of each variable to overall variability, and the angle between vectors indicates the

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degree of correlation among traits. Acute angles represent strong positive correlations, whereas obtuse or near-180° angles indicate negative relationships (Garazhian et al. 2020; Hair et al. 2010; Sümbül 2025). The spatial proximity of harvest stage points indicates similarity in trait composition, while greater distances reflect increased dissimilarity. The characteristics FW, Fwi, FL, FH, TAC, AA, TSS, TP, pH and SW, located in the positive direction of PC1, exhibit a positive correlation, showing vector characteristics in the same direction. Similarly, shell and flesh color values show a positive correlation with each other, while being negatively correlated with the FW, Fwi, FL, FH, TAC, AA, TSS, TP, pH and SW characteristics. Overall, the PCA results provide strong evidence that ripening induces coordinated changes in physical, chemical, and biochemical traits, enabling the identification of optimal harvest stages based on multidimensional quality criteria. These findings are consistent with previous studies (Khalili et al. 2020; Zhang et al. 2025).

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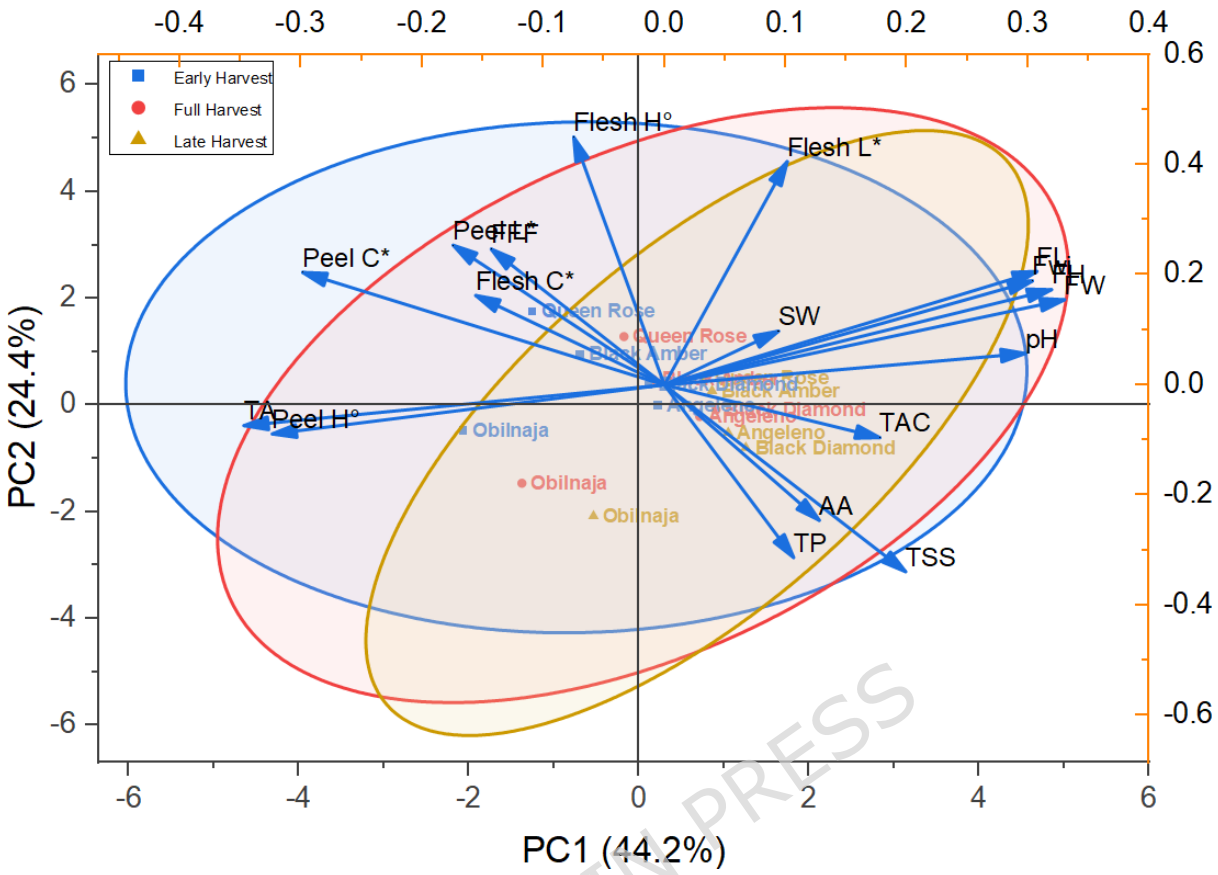


Fig. 6. PCA biplot of fruit traits of plum cultivars across harvest maturity stages.

4. Conclusions

Determining the optimal harvest time is critical for maintaining fruit quality and minimizing both pre- and postharvest losses. Therefore, accurate identification of harvest maturity is of paramount importance for both producers and supply chain management.

This study comprehensively investigated the ripening-driven dynamics of quality characteristics and bioactive compounds in five Japanese plum (*Prunus salicina* L.) cultivars: ‘Black Amber’, ‘Black Diamond’, ‘Queen Rose’, ‘Obilnaja’, and ‘Angeleno’. The aim of the study was to elucidate changes among different ripening stages to determine the optimal harvest timing, which is crucial for maximizing fruit quality and marketability. As ripening progressed, fruit weight, dimensional traits, and stone weight increased, whereas FFF and color parameters (L*,

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C*, h°) decreased. Concurrently, significant changes were observed in chemical attributes, with increases in pH and TSS and a marked decline in TA.

In terms of biochemical composition, TPC, TAC, and AA exhibited generally increased levels during ripening, indicating enhanced accumulation of bioactive compounds. However, the reduction in FFF and changes in color parameters highlight the importance of balancing textural integrity with biochemical quality when determining the optimal harvest stage.

Overall, the findings demonstrate that harvest timing plays a decisive role in shaping both the physicochemical and functional quality of plum fruits. The results clearly demonstrate that early harvesting should be avoided to ensure superior fruit quality, as many desirable biochemical characteristics are still developing. While the increase in bioactive compounds as ripening progresses is beneficial for nutritional value, the simultaneous decrease in fruit firmness presents a critical challenge for post-harvest processing and consumer acceptance. Therefore, determining the optimum harvest time is essential to strike a balance between maximizing nutritional quality and maintaining sufficient physical integrity for marketability and storage potential. This information provides producers with valuable practical information on minimizing post-harvest losses, maximizing health-promoting phytochemicals, and meeting evolving consumer demands in global plum markets.

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Declarations

Ethics approval and consent to participate: Not Applicable

Research involving Human Participants and, or Animals: Not applicable

Informed consent: Not applicable

Statement specifying permissions

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For this study, we acquired permission to study plum issued by the Agricultural and Forestry Ministry of the Republic of Türkiye.

Statement on experimental research and field studies on plants

The either cultivated or wild-growing plants sampled comply with relevant institutional, national, and international guidelines and domestic legislation of Türkiye.

Consent for publication: Not applicable

Availability of data and materials

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

Conflict of Interest Statement

The authors declare that they have no conflict of interest regarding the publication of this manuscript. There are no financial, personal, or institutional relationships that could have influenced the work reported in this study.

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Author's Contributions

All authors contributed to the conception and design of the study. MB, EY, AS, and MY experimented and collected data. AS and YT analyzed data, wrote and edited the manuscript. All authors read and approved the final manuscript.

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