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Investigation of the Color Development Process and Changes in Antioxidant Properties of Five Pomegranate Cultivars During the Growing Season

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ABSTRACT

Red color is considered the main quality index in most commercial pomegranates. Many studies have investigated the type and concentration of anthocyanins in pomegranate cultivars; however, changes in color development in Iranian native cultivars have received less attention. In this study, color changes and physicochemical properties of the peel and arils of five native Iranian cultivars (Agha Mohammad Ali, Alak-e Torsh, Pooste Siah, Pooste Sefid, and Shirin-e Saveh) were evaluated under the climatic conditions of Karaj. Results showed that as the growing season progressed, fruit weight and diameter increased in all cultivars; among them, Pooste Sefid exhibited the highest values, while Pooste Siah showed the lowest. The L* index of arils decreased in all cultivars, whereas it increased in the peel. The a* index of arils and peel increased in most cultivars, except Pooste Siah, and intensified in the final stages, with Alak-e Torsh ultimately exhibiting the highest a* value. The hue angle decreased in most cultivars, with Pooste Siah showing the lowest values. Arils of Alak-e Torsh contained the highest levels of anthocyanins, phenolic compounds, and antioxidant capacity, whereas the peel of Pooste Siah showed the greatest color intensity. Trends of total phenol and antioxidant capacity increased in most cultivars, but decreased in Pooste Sefid at the end of the experiment. Anthocyanin of arils increased in all cultivars during fruit development. Correlation analysis also revealed significant and distinct relationships among peel and aril color indices, as well as between these indices and bioactive compounds.

1-Introduction

Color, flavor, and texture are the three principal quality attributes that determine consumer acceptance, among which color exerts the greatest influence on consumer judgment. Color is one of the most important visual features in human perception and image data analysis, playing a fundamental role in environmental interpretation, cognitive decision-making, and product quality control. Humans naturally perceive color as a critical criterion for evaluating food quality, freshness of agricultural products, and visual appeal [1].

Humans are capable of distinguishing up to 10 million colors; however, color memory remains relatively weak. Color perception among individuals with normal color vision is generally consistent, although approximately 8% of men and 0.5% of women exhibit physiological deficiencies that alter color perception. In general, color results from the interaction between the light source, the object, and the observer. When visible light with different wavelengths strikes an object, part of the light is absorbed while another portion is reflected. A specific combination of these reflected wavelengths reaches the human retina, and the brain interprets these signals as the subjective perceptual sensation known as color. The human eye is a complex system that receives and processes light to enable color perception. Light enters through the cornea, passes through the aqueous humor and vitreous humor, and is ultimately focused on the retina. The human retina contains two types of photoreceptor cells: rods and cones. The macula, a small and highly sensitive region of the retina (approximately 5 mm in diameter), is responsible for precise central vision (Figure 1). This yellow-orange region contains a high concentration of the carotenoids lutein and zeaxanthin, which may protect it against photic damage. At the center of the macula lies the fovea (approximately 2 mm in diameter), characterized by a high density of cone cells responsible for color vision under daylight conditions. Three types of cone cells are present, each sensitive to a different portion of the visible spectrum: L-cones (sensitive to red light in the range of 560–580 nm), M-cones (sensitive to green light around 530 nm), and S-cones (sensitive to blue light around 420 nm). According to the Color Opponent Theory, red, green, and blue signals are transformed in the brain into one luminance signal (lightness–darkness) and two chromatic signals (red versus green and blue versus yellow) [2, 3]. These mechanisms constitute the foundation for the development of color spaces.

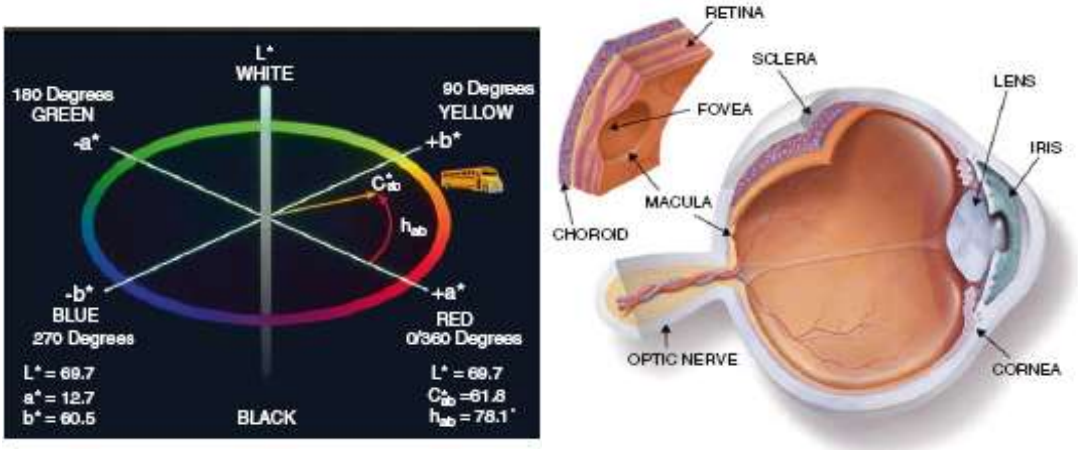


Figure 1. Structure of the human eye in relation to color perception (right) and the CIE 1976 L*a*b* color space (left) (Wrolstad & Smith, 2017).

Color spaces were designed to provide a numerical and comparable representation of colors, where each color is described by a set of coordinates within a three-dimensional space [4, 5]. These systems enable quantitative color measurement, sample comparison, and image data processing. One of the most fundamental color spaces is the RGB color space, which is based on the trichromatic theory of human vision. In this model, each color is defined by combining different intensities of the three primary components, red, green, and blue, typically within a range of 0 to 255. The RGB model is extensively used in monitors, digital cameras, and electronic display systems. Nevertheless, because the RGB color space is non-linear relative to human color perception, another color space known as CIE XYZ was developed in 1931 by the International Commission on Illumination (CIE: Commission Internationale de l'Éclairage) based on the RGB framework. In this system, each color is represented by three components, X, Y, and Z, which describe the relative contributions of red, green, and blue stimuli [6]. Although this space became an international standard, it exhibited limitations in perceptual uniformity, meaning that equal numerical changes did not always correspond to equal perceptual changes in human vision. To address this issue, Richard S. Hunter introduced the Hunter Lab model during the 1940s–1950s. Although Hunter Lab represented a significant advancement, it still lacked complete perceptual uniformity and exhibited deficiencies in certain regions of the color spectrum, particularly in saturated yellow and blue hues. Subsequently, in 1976, the CIE introduced a new color space known as CIELAB (L*a*b*) to further improve perceptual uniformity (Figure 2). In the LAB color space, the L* component represents lightness, a* denotes the red–green axis, and b* corresponds to the yellow–blue axis, thereby aligning closely with human visual perception. Owing to its relative perceptual uniformity and device independence, this space is considered one of the most accurate models for color analysis in various industries, including agriculture and food processing [1,4,7]. Indeed, it is currently the most widely used color space in the food industry. Subsequently, the *CIE LCH color space was proposed, in which L* represents lightness, C* denotes chroma (color intensity), and H* refers to hue angle. Hue corresponds to the dominant color that humans instinctively recognize as "color" and is based on the dominant wavelength of light. Chroma indicates the intensity or saturation of a color and can be calculated using the following equations [5]:

$$Hue° = \arctan\left(\frac{b*}{a*}\right)$$

$$C* = \sqrt{a*^2 + b*^2}$$

Another widely used formula for color comparison is the ΔE equation, which represents the numerical difference between two colors (i.e., two objects, 1 and 2, or an object relative to a standard reference) within the CIE L*a*b* color space. This parameter is extensively employed in the food industry and quality control applications for precise color comparison. The smaller the ΔE value (approximately equal to 1), the more similar the two colors appear; conversely, larger ΔE values (greater than 5) indicate more pronounced color differences [5].

$$\Delta E^*_{ab} = \sqrt{\{(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2\}}$$

Iran, recognized as the primary center of origin of pomegranate (*Punica granatum* L.), is considered one of the world's largest producers and exporters of this fruit and possesses cultivars with extensive genetic and phenotypic diversity. The peel and aril color of Iranian pomegranate cultivars ranges from white to deep red, among which the red coloration is regarded as the principal indicator of quality and consumer acceptance [8].

The red color of pomegranate is mainly attributed to the presence of anthocyanins

(glycosylated flavonoid compounds) in the peel and arils [9]. Early studies conducted by Du et al. [10] demonstrated that pomegranate contains six major anthocyanin compounds, including cyanidin 3-glucoside, cyanidin 3,5-diglucoside, delphinidin 3-glucoside, delphinidin 3,5-diglucoside, pelargonidin 3-glucoside, and pelargonidin 3,5-diglucoside. However, the predominant pigment type has been reported to vary among different tissues [11, 12]. Investigations on Iranian pomegranate cultivars identified all six aforementioned anthocyanins, although significant differences were observed among cultivars in terms of total anthocyanin content and anthocyanin composition [13, 14]. Despite numerous studies focusing on the identification and quantification of anthocyanins in pomegranate, limited information is available regarding the pattern of color development and anthocyanin accumulation during fruit ripening, particularly in native Iranian cultivars.

Therefore, the present study aimed to investigate the changes in peel and aril color, as well as antioxidant properties and physical characteristics, in five pomegranate cultivars grown under the climatic conditions of Karaj, Iran.

2-Materials and Methods

In the present study, the trend of peel and aril color changes in five pomegranate cultivars, namely Agha M. Ali (AMA), Alake Torsh (AT), Poste Siah (PS), Poste Sefid (PSF), and Shirine Saveh (SS), was investigated on five sampling dates: 1 July, 27 July, 21 August, 16 September, and 7 October 2021. Fruit samples were collected from the pomegranate collection orchard of the Horticultural Research Center, College of Agriculture and Natural Resources, University of Tehran, located in Mohammadshahr, Karaj, Iran. The geographical coordinates of the sampling site were 50°55′49″ E longitude and 35°46′36″ N latitude, at an altitude of 1320 m above sea level.

For each cultivar and sampling date, nine fruits were harvested as three replicates (from the same tree and different canopy orientations). Following the evaluation of fruit weight and diameter, arils were separated and juice extraction was performed for the determination of color characteristics and antioxidant properties.

Fruit weight was measured using a digital balance with an accuracy of 0.01 g (AND, Japan), while fruit diameter was determined using a digital caliper.

The CIE L*, a*, and b* color parameters of peel and arils were measured using a Minolta colorimeter (CR-300 model, Japan), and hue angle values were calculated according to the corresponding equations [5].

Anthocyanin content of the aril extract was determined using the pH differential method. For this purpose, 25 mM potassium chloride buffer (pH = 1.0) and 0.4 M sodium acetate buffer (pH = 4.5) were prepared. The aril extract was first centrifuged at 9800 × g at 4°C for 15 min. The supernatant was collected, and 0.5 mL of the extract was mixed with 4.5 mL of each buffer solution. The absorbance of each solution was measured at 510 and 700 nm using a spectrophotometer (PerkinElmer, Lambda-25 model). Anthocyanin concentration was calculated using the following equation [15]:

$$\text{Anthocyanin content (mg/L)} = \frac{[(\text{ABS 510nm} - \text{ABS700nm})\text{pH 1} - (\text{ABS 510nm} - \text{ABS700nm})\text{pH 4.5}] \times \text{MW} \times \text{DF}}{\text{MA}}$$

In this equation, ABS represents the absorbance value of the sample; MW denotes the molecular weight of cyanidin 3-glucoside, considered the predominant anthocyanin in pomegranate (449.2 g mol^{-1}); df is the dilution factor (10); and MA refers to the molar absorptivity coefficient of the predominant pomegranate anthocyanin (26,900 L mol^{-1} cm^{-1}).

In addition, 1 g of fruit peel was

extracted with 10 mL of acidified methanol, and after centrifugation, the absorbance of the supernatant was measured at 520 nm using a spectrophotometer.

Antioxidant capacity was determined using the DPPH assay. Briefly, aril extract was prepared and centrifuged (9800 × g, 4°C, 15 min), after which the supernatant was collected. For the reaction, 10 µL of the supernatant was mixed with 2 mL of DPPH solution (1 mM) and kept in darkness for 45 min to allow complete reaction. Subsequently, absorbance was measured at 515 nm using a spectrophotometer, and antioxidant capacity was calculated based on the reduction in absorbance relative to the control sample [15].

DPPH inhibition (%)=[1-
(Absorbance of sample + DPPH
/Absorbance of DPPH solution)× 100

Total phenolic content was determined using the Folin–Ciocalteu method [16]. For this purpose, 5 mL of distilled water was mixed with 0.5 mL of fruit extract. Subsequently, 0.5 mL of Folin–Ciocalteu reagent was added, and after 5 min, 0.5 mL of 20% sodium carbonate solution was incorporated into the mixture. Absorbance of the samples was recorded after 1 h at 760 nm, and total phenolic content was calculated based on a tannic acid standard prepared simultaneously with the samples.

The experiment was conducted as a split-plot design in time based on a completely randomized design with three replications. Cultivar was considered the main factor, while sampling date represented the subplot factor. Data were analyzed after normality assessment using SAS software (version 9.3.1), and mean comparisons were performed using the Least Significant Difference (*LSD*) test at the 5% probability level.

3- Results

3.1. Fruit weight and diameter

The trend of changes in fruit weight and diameter followed a similar pattern among the five pomegranate cultivars throughout the growth period. In all cultivars, fruit weight and diameter increased progressively with the advancement of the growing season. Among the cultivars, PSF exhibited the highest fruit weight and diameter during the entire growth period, whereas the lowest values for these traits were recorded in PS. The cultivars SS, AMA, and AT showed intermediate values for fruit weight and diameter; however, SS ultimately produced larger fruits compared with the other two cultivars (Figure 2).

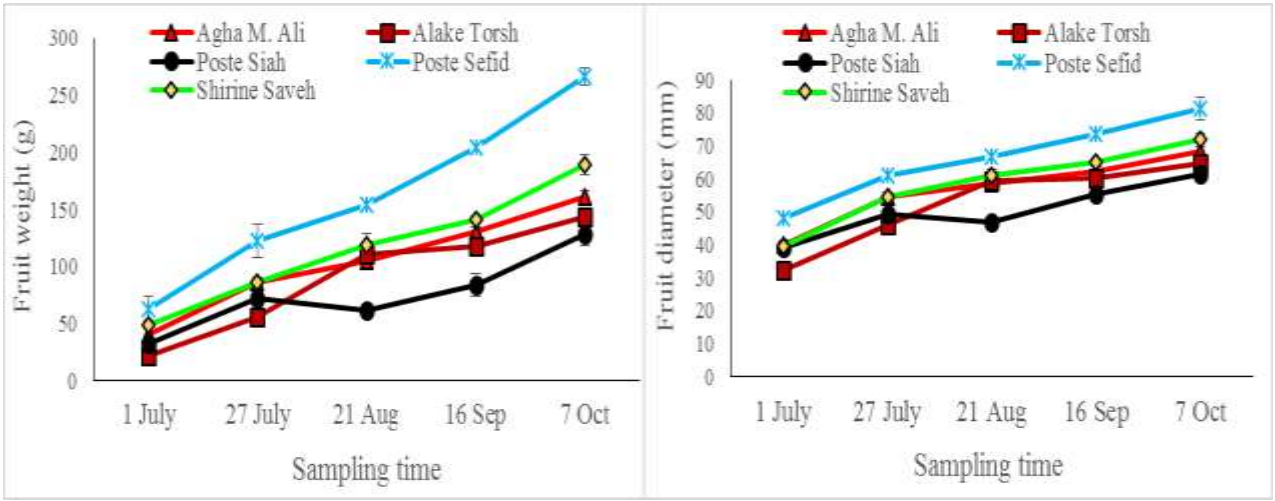


Figure 2. Changes in weight and diameter of five pomegranate cultivars during growth period in Karaj climatic conditions

3.2. Color characteristics

According to the results, at the first sampling date, the lowest aril lightness index (L*) was observed in PS. In addition, peel L* values in AMA were lower than those of the other cultivars. With the progression of the growth period, aril L* values decreased in all cultivars, although the magnitude of reduction differed among cultivars. At the final sampling date, the lowest aril L* value was recorded in AT, whereas the highest value was observed in SS (Figure 3).

Peel L* values exhibited an increasing trend throughout the experimental period in most cultivars. In this regard, the lowest peel L* values at all sampling dates were consistently recorded in PS. Furthermore, peel L* values in PSF and SS were significantly higher than those in AT and AMA during the growth period (Figure 3).

Evaluation of the aril a* index revealed that at the first harvest date, all cultivars except PS exhibited negative values for this parameter. In PS, no substantial change in aril a* values was observed throughout the growth period. In contrast, a* values increased progressively in the remaining cultivars, with a particularly pronounced increase during the final stage of fruit development. Among the cultivars, AMA exhibited the lowest aril a* values, whereas no significant differences were observed among the other cultivars for this trait (Figure 3).

Despite slight fluctuations, peel a* values in PS did not show substantial changes during the growth period. Conversely, this index increased progressively in the other cultivars, with the highest final value recorded in AT and the lowest in PSF. It is noteworthy that peel a* values in PSF and SS remained negative until the 16 September sampling date, indicating the persistence of green coloration in the peel of these two cultivars up to this stage of fruit development; however, the values became positive at the end of the experimental period (Figure 3).

From the perspective of aril hue angle, PS exhibited the lowest value compared with the other cultivars, and its value increased during the growth period. In contrast, the aril hue angle in the other cultivars showed a continuous decreasing trend, which became more pronounced close to the ripening stage. However, in most harvesting dates, no significant differences were observed among the other cultivars regarding this parameter (Figure 3).

The results also showed that the lowest peel hue angle at all growth stages belonged to PS, with no noticeable changes throughout the growth period. In contrast, the peel hue angle in the other cultivars showed a continuous decreasing trend. Among these cultivars, the highest final value of this index belonged to PSF, while the lowest value belonged to AT. Furthermore, the peel hue angle in SS was significantly higher than that in AMA (Figure 3).

3.3. Anthocyanin content

Due to the non-juicy nature of the arils, anthocyanin measurement of the extract (as well as antioxidant capacity and total phenolic content) was not possible on 1 July. On 27 July, only samples of the cultivar PSF yielded extractable juice. After this date, all samples became assessable.

Evaluation of anthocyanin content in the aril extract indicated that, despite an increasing trend of this parameter in all cultivars, significant differences among cultivars were limited until 16 September. However, the greatest increase in anthocyanin content was observed at the final stage of fruit development in all cultivars. At the end of the experimental period, the results showed that AT had significantly the highest anthocyanin content, whereas AMA exhibited the lowest value among the studied cultivars. Furthermore, although anthocyanin content in SS was significantly higher than in PSF and PS, no significant difference was observed between PSF and PS (Figures 4 and 5).

Based on the results, peel extract color intensity increased gradually throughout

the growth period in all cultivars. Among them, PS showed significantly the highest color intensity among all studied cultivars. In addition, AT also exhibited higher peel extract color intensity compared with the other three cultivars (PSF, AMA, and SS) (Figures 4 and 5).

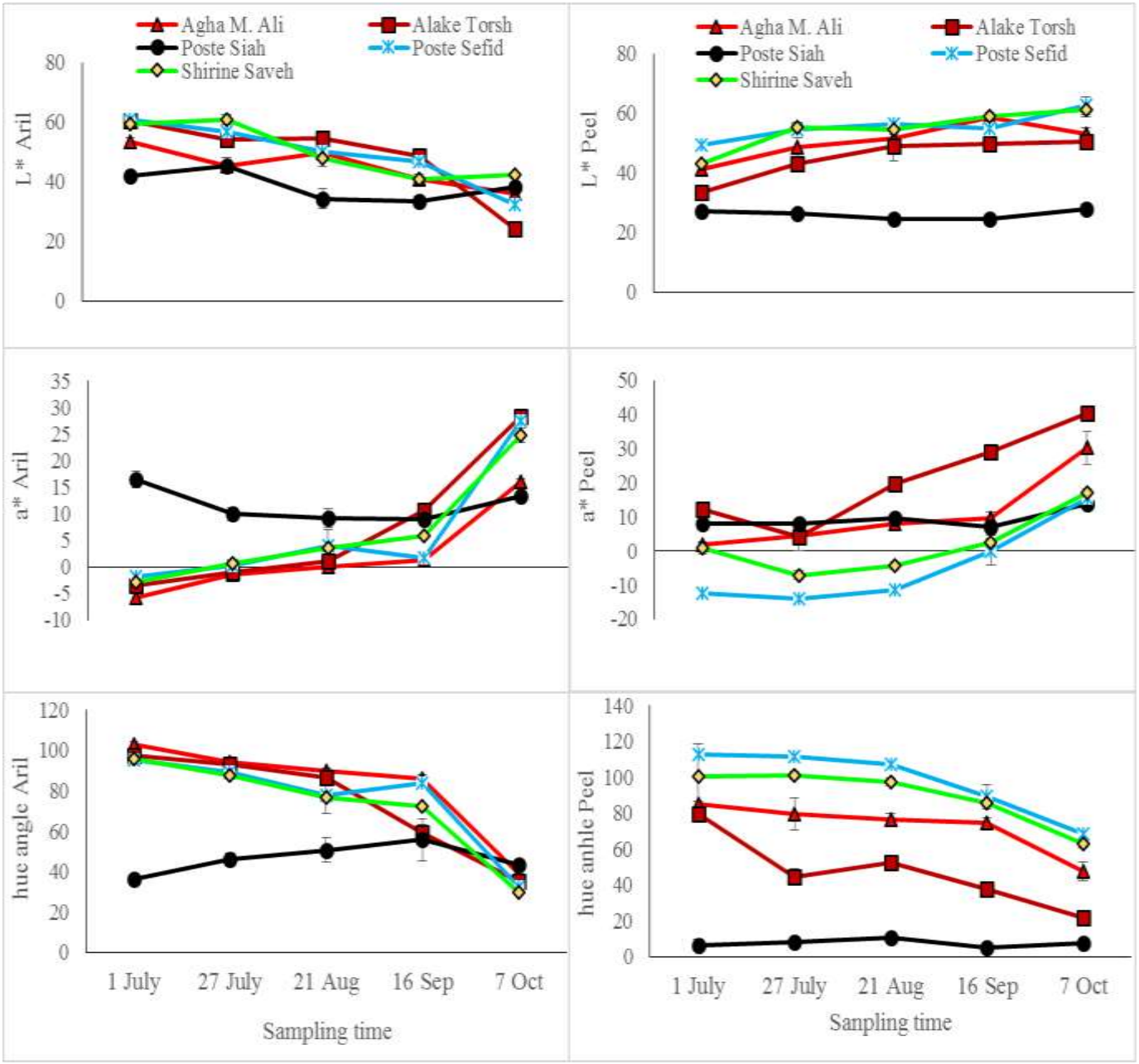
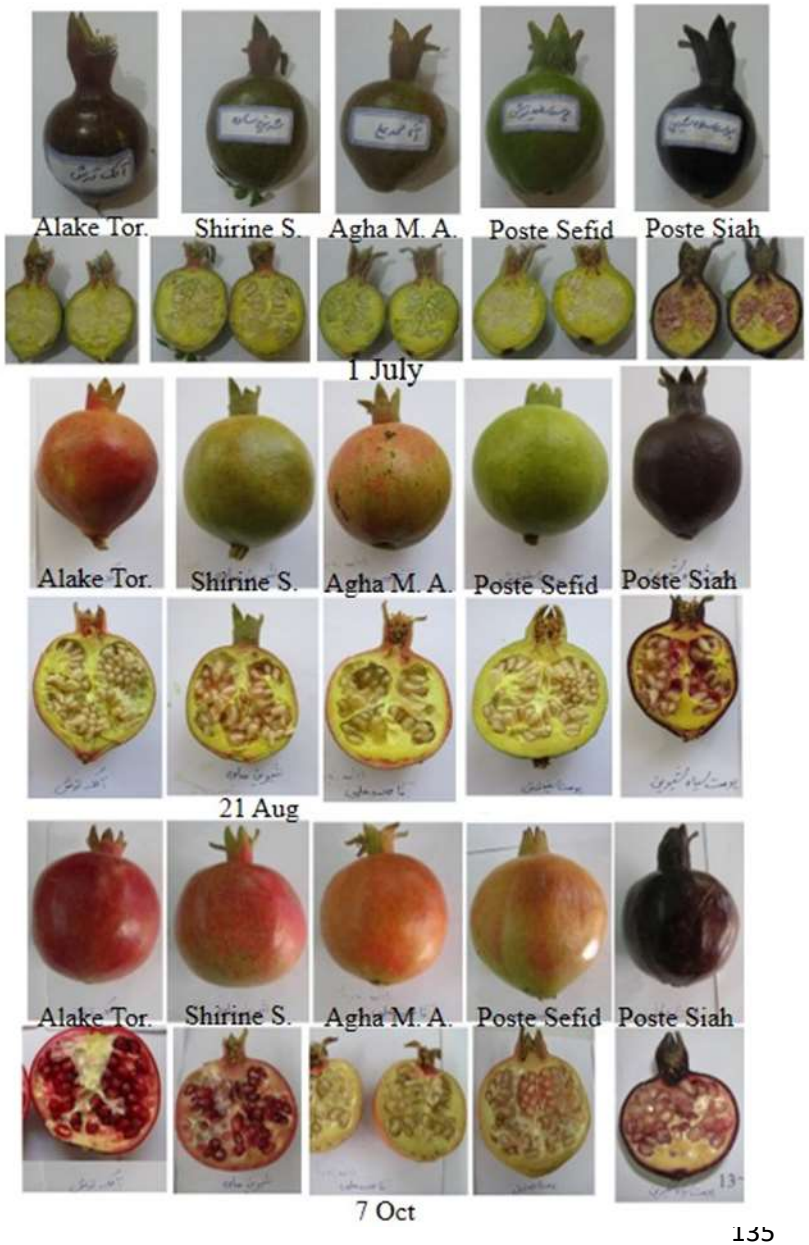


Figure 3. Changes in color characteristics (L*, a*, hue°) of aril and peel of five pomegranate cultivars during growth period in Karaj climatic conditions



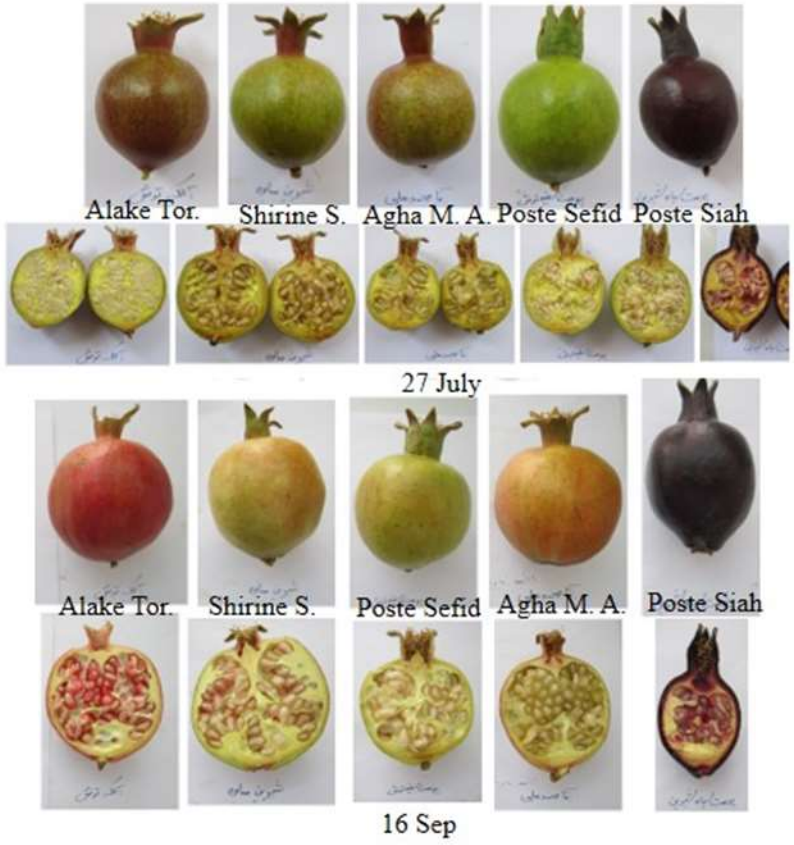


Figure 4. Changes in aril and peel color of five pomegranate cultivars during growth period in Karaj climatic conditions

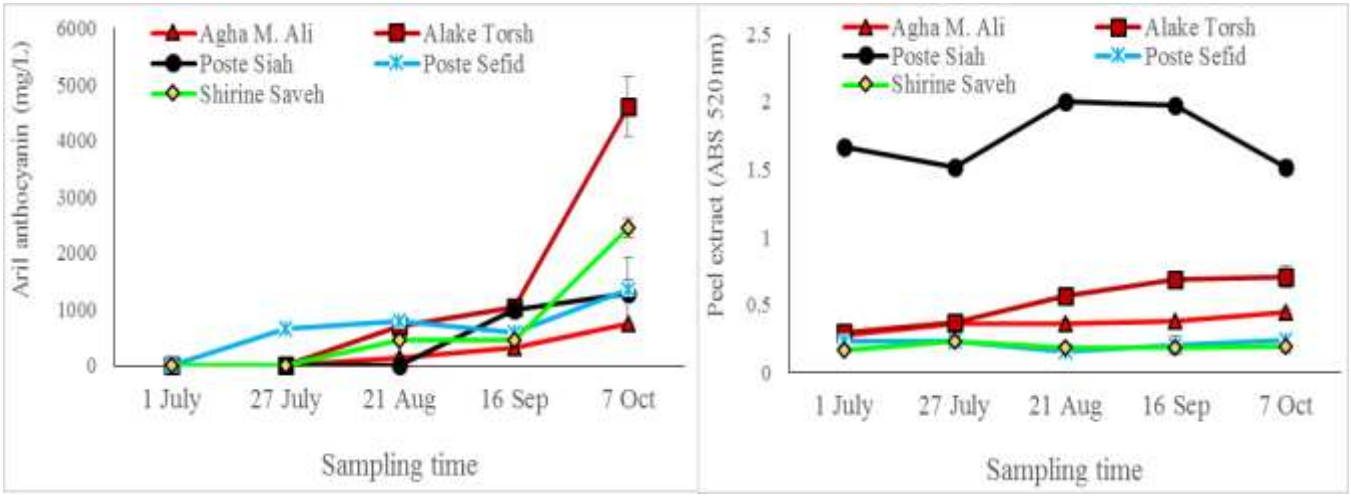


Figure 5. Changes in aril anthocyanin content and peel extract color intensity of five pomegranate cultivars during the growth period under Karaj climatic conditions.

3.4. Total phenolic content and antioxidant capacity of pomegranate aril extract

With the progression of sampling time, antioxidant capacity showed a significant increase in all cultivars. Among them, the highest value of this trait was recorded in the aril extract of AT. Although PSF exhibited higher antioxidant capacity compared with the other cultivars, contrary to the general increasing trend, it showed a marked reduction in this index at the end of the growth period. AMA and SS demonstrated higher antioxidant capacity than PS throughout the season; however, at the end of the growing period, no significant differences were observed among these three cultivars (Figure 6).

The pattern of changes in total phenolic content of aril extracts across cultivars was similar to that of antioxidant capacity. Accordingly, in all cultivars except PSF, total phenolic content increased over time, with the highest value recorded in AT during the experimental period. In PSF, total phenolic content showed an increasing trend throughout the season; however, it decreased markedly at the end of the season. AMA and SS exhibited higher total phenolic content compared with PS during the growing season; however, at the end of the season, PS showed higher total phenolic content (Figure 6).

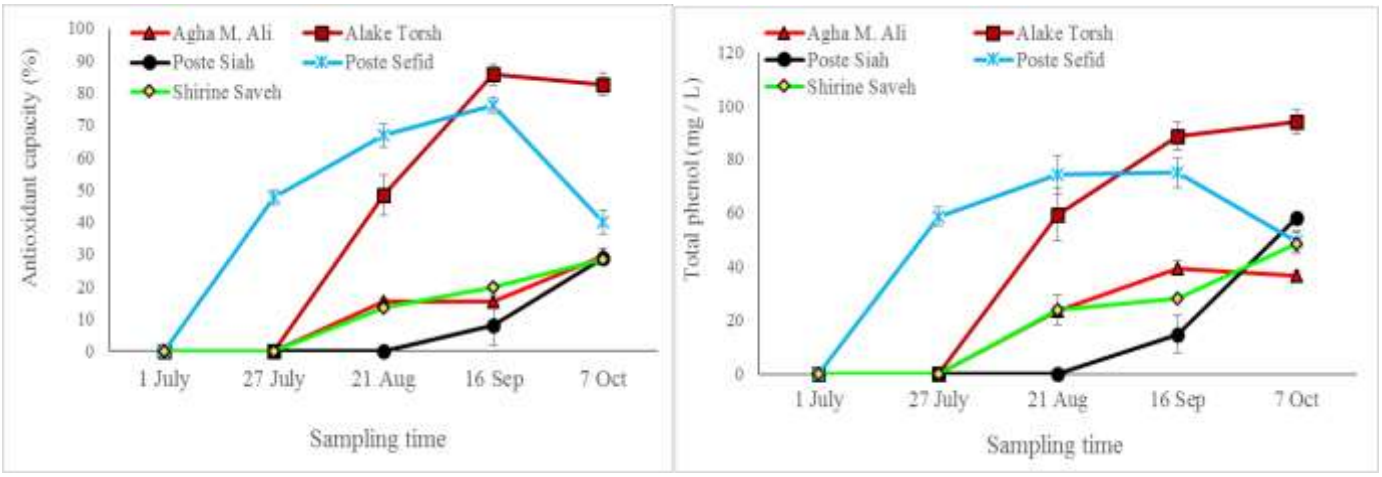


Figure 6. Changes in total phenols and antioxidant capacity of aril extracts of five pomegranate cultivars during growth period in Karaj climatic conditions

3.5. Correlation among traits

The results of Pearson correlation analysis among traits are presented in Table 1. Pearson correlation analysis between peel and aril color traits of pomegranate revealed significant relationships among the different color components. In fruit peel, a significant negative correlation was observed between a* and hue angle ($r \approx -0.63$), indicating that with an increase in peel a* (higher redness), hue angle decreased. In addition, L* showed a significant positive correlation with hue angle ($r \approx 0.69$), indicating that hue angle decreased with decreasing L*.

In arils, stronger correlations were observed among color indices. A significant negative correlation was found between a* and hue angle ($r \approx -0.95$). Moreover, L* showed a significant positive correlation with hue angle ($r \approx 0.80$). In addition, L* exhibited a significant negative correlation with a* ($r \approx -0.80$).

The evaluation of relationships between peel and aril color indices showed that peel a* had a significant negative correlation with aril L* ($r \approx -0.61$) and aril hue angle ($r \approx -0.60$), while it showed a significant positive correlation with aril a* ($r \approx 0.65$). In contrast, peel hue angle showed a significant negative correlation with aril a* ($r \approx -0.55$), but a significant positive correlation with aril L* ($r \approx 0.64$) and aril hue angle ($r \approx 0.70$).

Color indices of peel and aril showed significant relationships with biochemical compounds of the fruit. Anthocyanin content showed a significant positive correlation with aril a* ($r \approx 0.75$) and peel a* ($r \approx 0.61$), while it showed a significant negative correlation with aril L* ($r \approx -0.61$) and aril hue angle ($r \approx -0.60$). No significant relationships were observed for other parameters. Antioxidant capacity showed a significant positive correlation only with peel L* ($r \approx 0.43$) and no clear relationship with other color traits.

Table 1. The Pearson correlation among the different Pomegranate cultivars traits

	Peel Color	Hue Peel	a* Peel	L* Peel	Hue* Aril	a* Aril	L* Aril	Total Phenol	Antioxidant	Anthocyanin	Fruit Weight
Fruit Weight	-0.309	0.126	0.232	0.665**	-0.436*	0.567**	-0.47*	0.702**	0.644**	0.513**	1
Anthocyanin	0.006	-0.272	0.612**	0.247	-0.577**	0.743**	-0.604**	0.695**	0.636**	1	
Antioxidant	-0.193	0.01	0.372	0.433*	-0.26	0.387	-0.278	0.968**	1		
Total Phenol	-0.171	-0.026	0.402*	0.451*	-0.324	0.447*	-0.352	1			
L* Aril	-0.485*	0.639**	-0.609**	0.098	0.790**	-0.788**	1				
a* Aril	0.306	-0.544**	0.644**	0.059	-0.95**	1					
Hue Aril	-0.522**	0.690**	-0.599**	0.162	1						
L* Peel	-0.846**	0.685**	-0.072	1							
a* Peel	0.248	-0.627**	1								
Hue Peel	-0.87**	1									
Peel Color	1										

ns, * and **: not significant, significant at 5% and 1% levels of probability, respectively

Total phenolic content showed a significant positive correlation with peel a* ($r \approx 0.40$), peel L* ($r \approx 0.45$), and aril a* ($r \approx 0.48$). Peel extract color intensity showed a significant negative correlation with aril L* ($r \approx -0.49$), peel L* ($r \approx -0.85$), aril hue angle ($r \approx -0.52$), and peel hue angle ($r \approx -0.87$), while no clear relationship was observed with other color traits.

Significant positive correlations were also observed among antioxidant capacity, total phenolic content, anthocyanin content, and fruit weight. Fruit weight showed a significant positive correlation with peel L* ($r \approx 0.67$) and aril a* ($r \approx 0.57$), whereas it showed a significant negative correlation with aril L* ($r \approx -0.47$) and aril hue angle ($r \approx -0.44$).

4-Discussion

Most commercial pomegranate cultivars in Iran exhibit red coloration, which is recognized as a quality indicator among consumers [17]. In the present study, except for PS, the remaining cultivars were characterized by red color indices. The a* color index in the positive range indicates red coloration. On the other hand, an increase in red coloration in fruits is generally associated with a decrease in hue angle and a reduction in L* value [18]. Based on the results of this study, AT showed the highest color intensity among the evaluated cultivars, and SS also exhibited desirable color development. In contrast, AMA did not show appropriate color development under the climatic conditions of Karaj. Meanwhile, PSF ultimately produced arils with red coloration.

The results clearly demonstrated that the pattern of color development in peel and aril of PS differed from that of the other cultivars. In this cultivar, color development in both peel and aril was more pronounced at early growth stages; however, no considerable changes were observed during the later stages of the growing season. In contrast, in the other cultivars, peel and aril coloration increased with progression of the growing season, with marked changes particularly observed at the final stages of development. Moreover, peel coloration generally started earlier than aril coloration, and aril coloration intensified at later developmental stages coinciding with cooler temperatures, highlighting the importance of low temperature in pomegranate color development [19].

The observed differences in coloration patterns may be attributed to two factors: first, differences in the types of anthocyanins present in PS compared with the other cultivars; and second, differences in anthocyanin composition between peel and aril of red-colored cultivars. In a similar study, Hernández et al. [19] investigated color development patterns in five pomegranate clones in Spain and reported that all cultivars showed similar trends in anthocyanin accumulation during growth and development, although they differed significantly in total anthocyanin content. They also found that fruits located in the northern part of the tree contained higher anthocyanin levels than those in the southern part, which was attributed to lower temperatures and the positive effect of cooler conditions on anthocyanin accumulation.

Zhao et al. [12] investigated the expression of genes involved in the anthocyanin biosynthetic pathway in the peel of white and red pomegranate cultivars and reported that the main difference in white cultivars was the lack of activity of anthocyanidin synthase, leading to the absence of pigment accumulation in the peel. In another study, Ben-Simhon et al. [9] compared arils of red and white pomegranate cultivars and demonstrated that the lack of expression of a key gene involved in anthocyanidin synthase was the main reason for white aril coloration in white cultivars. Therefore, differences in color development patterns among cultivars or between peel and aril within a single cultivar may be attributed to variation in the expression levels of genes involved in the

anthocyanin biosynthetic pathway, which requires further detailed investigation.

The increase in total phenolic content and antioxidant capacity during fruit development was generally consistent with the accumulation of anthocyanins and the intensification of red coloration in most cultivars. This correlation indicates that phenolic compounds, particularly anthocyanins, play a major role in determining the antioxidant capacity of the fruit [20]. In AT, which exhibited the highest color intensity and anthocyanin content, total phenolic content and antioxidant activity were also at their highest levels, indicating a positive relationship between pigment biosynthesis pathways and phenolic metabolism. On the other hand, in PSF, despite relatively high antioxidant capacity at early stages, the decline of these indices at the end of the season suggests lower stability of phenolic compounds in this cultivar, likely due to weaker anthocyanin biosynthesis pathways and reduced protection of other antioxidant compounds during the later stages of development [8]. Differences among cultivars in the pattern of phenolic and antioxidant changes may be attributed to genetic variation in the expression of genes involved in the phenylpropanoid and anthocyanin biosynthesis pathways. Moreover, environmental conditions, particularly decreasing temperatures during the final stages of development, appear to stimulate anthocyanin synthesis as well as enhance the activity of enzymes involved in phenolic biosynthesis, thereby increasing antioxidant capacity. Therefore, the pattern of phenolic and antioxidant changes is not only correlated with color development but may also serve as an indicator of fruit metabolic status and its defensive capacity against environmental stresses [8, 20].

5-Conclusion

The experimental findings demonstrated that the pattern of coloration and accumulation of bioactive compounds in different Iranian pomegranate cultivars varies and is influenced by both cultivar type and climatic conditions. AT exhibited the highest anthocyanin content and antioxidant capacity, indicating superior coloration and nutritional value, whereas PS showed a distinct coloration pattern compared with the other cultivars. It was also revealed that peel coloration begins earlier than aril coloration, and low temperatures during the final stages of fruit development enhance red color intensity. Overall, genetic differences in the anthocyanin biosynthetic pathway play a major role in the color diversity of different pomegranate cultivars. Furthermore, based on the results of this study, peel and aril color indices of pomegranate, particularly a*, were shown to be reliable indicators for predicting fruit quality. These relationships provide the possibility of indirect evaluation of certain bioactive compounds in pomegranate (such as anthocyanins) through simple color attributes.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

Not applicable.

Author Contributions

Orang Khademi: Conceptualization, supervision, investigation, data curation, formal analysis, and writing-original draft preparation. Maryam Esmati: Investigation and data collection. Mohammad Ali Askari Sarcheshmeh: Provision of plant materials and writing-review and editing. Erfan Sepahvand: Provision of plant materials, methodology, and writing-review and editing.

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بررسی روند رنگ‌گیری و تغییرات خواص آنتی‌اکسیدانی پنج رقم انار در طی فصل رشد

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چکیده

رنگ قرمز در بیشتر ارقام تجاری انار، شاخص اصلی کیفیت محسوب می‌گردد. مطالعات زیادی نوع و مقدار آنتوسیانین‌ها را در ارقام انار بررسی نموده است، اما تغییرات رنگ‌گیری در ارقام بومی ایران کمتر مورد توجه بوده است. در این پژوهش، تغییرات رنگی و خصوصیات فیزیکوشیمیایی پوست و آریل پنج رقم انار بومی ایران (آقا محمدعلی، آلک ترش، پوست سیاه، پوست سفید و شیرین ساوه) در شرایط اقلیمی کرج مورد ارزیابی قرار گرفت. نتایج نشان داد، با پیشرفت فصل رشد، وزن و قطر میوه در همه ارقام افزایش یافت؛ در این میان؛ رقم پوست سفید بیشترین و رقم پوست سیاه کمترین مقادیر را داشتند. شاخص L* در آریل همه ارقام روند کاهشی، ولی در پوست آنها روند افزایشی نشان داد. شاخص a*در آریل و پوست اغلب ارقام (به‌جز رقم پوست سیاه) روند افزایشی نشان داد و در مراحل پایانی تشدید شد؛ که در نهایت نیز رقم آلک ترش بیشترین a* را داشت. زاویه هیو در اکثر ارقام روند کاهشی داشت، و رقم پوست سیاه کمترین مقدار را دارا بود. آریل‌های رقم آلک ترش بالاترین مقادیر آنتوسیانین، فنل و آنتی‌اکسیدان را دارا بودند، در حالی که پوست، رقم پوست سیاه بیشترین شدت رنگ را نشان داد. روند تغییرات فنل کل و ظرفیت آنتی‌اکسیدانی در اغلب ارقام افزایشی بود، ولی در رقم پوست سفید در انتهای آزمایش کاهش یافت. مقدار آنتوسیانین آریل در همه ارقام روند افزایشی نشان داد. بررسی ضرایب همبستگی نیز روابط معنی‌داری و مشخصی را بین شاخص‌های رنگ پوست و آریل با یکدیگر و با ترکیبات زیست‌فعال نشان داد.