Effect of Kaolin Particle Film on the Fruit Yield and Quality of Three Pomegranate Cultivars

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Summary

A two-year field experiment (2021–2022) was conducted in Birjand, Iran, using a randomized block design with three pomegranate cultivars ('Shisheh-Kab', 'Malas Saveh', and 'Malas Yazdi') and three kaolin concentrations (0, 3, and 5%). Foliar application of kaolin particle film (KPF) significantly influenced fruit yield and quality traits. While kaolin increased fruit weight in 'Shisheh--Kab' and 'Malas Saveh' in the first year, a reduction was observed in the second year, reflecting cultivar × treatment interactions rather than a uniform main effect. The anthocyanin content improved under the kaolin treatments, with 5% KPF increasing the total anthocyanin concentration by approximately 25% compared with that of the control. The highest anthocyanin values were recorded in Malas Yazdi (228.6 mg L^{-1}) and Malas Saveh (208.9 mg L^{-1}), whereas Shisheh-Kab presented the lowest value (97 mg L^{-1}) and a relatively high degree of aril paleness. Kaolin treatment also reduced peel weight and enhanced taste attributes, with titratable acidity (TA) being lowest in 'Shisheh-Kab' and highest in 'Malas Yazdi'. Overall, kaolin particle film application improved fruit quality characteristics, although cultivar-specific responses were evident.

Key words

kaolin, *Punica granatum*, anthocyanin, fruit quality

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Introduction

Pomegranates are cultivated in tropical and subtropical regions of the world as important horticultural products. Iran is one of the main producers of pomegranate worldwide (Sarkhosh et al., 2020). Pomegranates are edible medicinal fruits in the food industry and traditional medicine (Valero-Mendoza et al., 2023; Shricharan et al., 2025). Pomegranate roots, peels, juices and arils contain bioactive compounds with antimicrobial and antioxidant properties (El Hosry et al., 2023). Pomegranate fruits are rich in anthocyanins and phenolic compounds, but their stability is strongly affected by environmental stresses such as temperature and radiation (Verma et al., 2023). In addition, strong hot winds, differences between day and night temperatures, and high temperatures decrease antioxidant levels (Qaderi et al., 2023).

Sunburn is influenced by high temperatures and radiation, especially ultraviolet (UV) radiation (Munné-Bosch and Vincent, 2019). In sunburn, the peel color changes from brown to black, and the water content of arils and phenolic compounds decreases (Shivashankara and Geetha, 2021). Therefore, fruits are waterless and white, which reduces their fresh food and processing value. Another important cause of sunburn is the long interval between irrigations, which results in water loss, browning and cracking of peels exposed to light (Fischer et al., 2022). The paleness of the aril reduces the internal quality of the fruit without external symptoms, and it causes dryness and an unpleasant taste of the aril and leads to a decrease in the processing value. Aril paleness causes significant changes in anthocyanin content, phenolic compounds, ascorbic acid, sugars and extract percentage (Moradi et al., 2022). Researchers have reported that genetics, pruning, fruit size, cultivar and harvest time are effective in determining the incidence of aril paleness (Shivashankara and Geetha, 2021).

The use of light-reflecting compounds is suitable for reducing sunburn (Aliabad et al., 2022). Kaolin is recommended for organic agricultural products (Moradinezhad and Ranjbar, 2024). Kaolin protects plants against insects, pathogens, heat stress and sunburn and increases fruit growth under stress (Mphande et al., 2023). Kaolin foliar application reduces leaf temperature and transpiration and prevents water loss in apple trees (Glenn, 2010). Similarly, kaolin reduces the leaf temperature of apple, citrus, coffee, grapefruit, almond and cotton trees (Pace et al., 2006). Kaolin foliar application increases yield by increasing photosynthesis (Steiman et al., 2007). Kaolin also improves red color and reduces sunburn by reducing fruit temperature (Glenn, 2012).

Kaolin application to pomegranate trees has been extensively studied. Foliar application of kaolin reduces sunburn in the cultivar Hicaznar (Shivashankara and Geetha, 2021). In Australia, pomegranate fruit cv. Wonderful sprayed with kaolin presented less sunburn (Weerakkody et al., 2010). The application of kaolin at specific concentrations and timings has been found to increase fruit yield; decrease sunburn and fruit cracking percentages; and improve fruit weight, firmness, and essential nutrient contents, such as potassium, calcium, and anthocyanin contents (Khayyat and Samadzadeh, 2023). Overall, this research suggests that kaolin application to pomegranate trees, especially under hot climate conditions, is a valuable practice for enhancing fruit marketability and overall quality. Four batches of kaolin at a concentration of 5% were sprayed on pomegranate fruit cv. Mollar de Elche from late June to early August, which led to a reduction in sunburn (Melgarejo et al., 2004). Additionally, kaolin at a concentration of 6% resulted in the lowest percentage of sunburn and the highest percentage of juice in the pomegranate 'Wonderful' cultivar (Harhash et al., 2019). Kaolin, when sprayed on pomegranate trees, significantly improves fruit quality by increasing leaf nutrient content, fruit weight, size, and total soluble solids and reducing fruit cracking and sunburn, particularly at concentrations of 4% and 6% during the growing season (Al-Saif et al., 2022). Previous studies have shown that the use of kaolin can significantly improve fruit quality and reduce disorders such as aril paleness, sunburn, and fruit cracking (Khayyat and Samadzadeh, 2023; Al-Saif et al., 2022; Harhash et al., 2019). However, the literature shows that little information is available about the effects of kaolin on different pomegranate cultivars in Iran. Previous work by Khayyat and Samadzadeh (2023) examined kaolin application to a single cultivar. However, little is known about cultivar-specific responses to kaolin in Iranian orchards. Therefore, the purpose of this study was to test whether kaolin can differentially improve fruit quality and mitigate aril paleness across multiple cultivars.

Materials and Methods

This two-year field experiment (2021–2022) was conducted in a commercial pomegranate orchard in Birjand, South Khorasan, Iran (coordinates: 32.8663° N, 59.2211° E; elevation: 1460 m). The soil type was sandy loam, and trees of the cultivars 'Shisheh-Kab', 'Malas Saveh', and 'Malas Yazdi' were approximately 12 years old and were planted at a spacing of 4 × 5 m. Routine cultivation practices included drip irrigation every 7–10 days, annual fertilization with NPK, and winter pruning.

Kaolin particle film (trade name: Surround WP, Engelhard Corp., USA; particle size distribution < 2 μm) was applied as a single foliar spray each year in early July at three concentrations: 0 (control), 3, and 5%. Approximately 2 L of spray solution was applied per tree until runoff, and no surfactant was used.

The experiment followed a randomized block design with three replicates; each replicate consisted of a plot of five trees (n = 5 trees per treatment × 3 replicates = 15 trees per treatment). Border trees were excluded from sampling. From each tree, 10 fruits were randomly collected at commercial maturity in early November and transported to the Horticultural Laboratory of the University of Birjand for physicochemical and quality assessments.

Physicochemical Assessments

Fruit Fresh Weight, Peel and Arils

The fresh weights of the whole fruit, peel and arils were measured via a digital balance with an accuracy of 0.01 g.

Total Phenol Content (TPC)

The amount of total phenol was determined via the Folin-Ciocalteu method (Singleton and Rossi, 1965).

Total Anthocyanin Content (TAC)

Using the Giusti and Wrolstad (2001) method, the anthocyanin concentration was computed via equation (1):

$$A = (A_{510} - A_{700})pH_{1.0} - (A_{510} - A_{700})pH_{4.5} \quad \text{Eq (1)}$$

Equation (2) was used to calculate the TAC on the basis of the concentration of cyanidin-3-glucoside.

$$TAC\ (mgL^{-1}) = A \times MW \times DF \times 100/f \times d \quad \text{Eq (2)}$$

where f is the molar absorption coefficient of cyanidin-3-glucoside (26,900), DF is the dilution factor (10) and A is the absorbance. MW is the molecular weight of cyanidin-3-glucoside (433.3).

Titratable Acidity (TA), Total Soluble Solids (TSS), and the TSS/TA Index

To measure *TA*, 1 mL of fruit juice was mixed with phenolphthalein as an indicator, and the mixture was titrated with 0.1 N NaOH to produce a light pink color (Ranganna, 1977). Equation (3) was used to calculate and express TA as a percentage.

$$TA\% = (N \times V_1 \times Eq_{wt} / V_2 \times 1000) \times 100 \quad \text{Eq (3)}$$

Assuming that the predominant acid weight (citric acid) is 60 g, V_1 and V_2 represent the volume of NaOH used and the sample volume, respectively.

A portable refractometer (RF10, 0–32 °Brix, Extech Co., USA) was used to calculate the TSS at room temperature, and the results are expressed in degrees Brix. The TSS-to-TA ratio was also calculated.

Statistical Analysis

Data from the two years were analyzed separately via ANOVA. The cultivar and kaolin concentration were considered fixed factors, and the year was treated as a random factor. Interactions between cultivar × kaolin were tested. Assumptions of normality and homogeneity of variance were checked prior to analysis. Mean comparisons were performed via LSD at the 5% probability level in GenStat (Discovery Edition, Version 9.2, VSN International Ltd., UK).

Results and Discussion

Fruit Fresh Weight in Kaolin-Treated Pomegranate

Kaolin application did not significantly affect fruit fresh weight in the first year, whereas cultivar differences were evident. The effects of kaolin and the interaction effects of kaolin × cultivar were not significant for fruit weight in the first year; however, the effect of cultivar was significant ($P < 0.05$). The maximum weight of fruits was obtained from the cultivars Malas Yazdi (538 g) and Malas Saveh (515.5 g), which was significantly different ($P < 0.05$) from that of the cultivar Shisheh-Kab (417.8 g) (Fig. 1a, b and c).

Kaolin and cultivar had significant effects on fruit weight in the second year ($P < 0.05$). The maximum weight of fruits was obtained in the control group (407.7 g), which was significantly different ($P < 0.05$) from that of the 3% kaolin (370.3 g) and 5% kaolin (365.7 g) groups. The maximum weight of fruits was obtained from the cultivars Malas Saveh (417.5 g) and Malas Yazdi (400.7 g), which was significantly different ($P < 0.05$) from that of the cultivar Shisheh-Kab (325.5 g) (Fig. 1d, e, f).

Fruit weight decreased in the second year, likely due to higher temperatures and the earlier harvest in 2022. Inadequate fruit development and slower ripening may also have contributed. Furthermore, a single kaolin spray might not have been sufficient, indicating that multiple applications could be required. The fresh weight data of different pomegranate cultivars in the present study were consistent with the numerical range presented by other researchers (Rahemi and Atahosseini, 2003; Varasteh et al., 2006). Temperature has been shown to have a positive and direct effect on fruit weight (Boari et al., 2016). However, higher temperatures, even if they increase fruit growth and weight, accelerate the ripening process, resulting in lower fruit weight (Abou, 2015). On the other hand, fruits may suffer from sunburn and reduce their quality when exposed to high temperatures (Xu et al., 2022). In the present study, 3% and 5% kaolin reduced the fresh weight of pomegranate fruits, which was probably due to the effects of kaolin on reducing the temperature of the product. However, conflicting results have been reported regarding the effects of kaolin on fruit weight. For example, in orange (Zaghloul et al., 2017), apple (Faghih et al., 2021), and mango fruits (Chamchaiyaporn et al., 2013), the application of kaolin increased fruit weight. These conflicting reports can be attributed to the different responses of the products to temperature and sunlight. Similarly, in the present study, even in different varieties of the same product, kaolin can have different effects. Our results were consistent with those of Colavita et al. (2010) on pear fruit.

Peel and Aril Weights in KaolinTtreated Fruit

Kaolin application did not significantly affect peel fresh weight in the first year, whereas cultivar differences were evident. The results of the variance analysis revealed that the effects of kaolin and the interaction effects of kaolin × cultivar did not significantly affect the fresh weight of the peel in the first year; however, the effect of cultivar was significant ($P < 0.05$). The maximum weight of the peel was obtained from cv. Shisheh-Kab (209 g), which was significantly different ($P < 0.05$) from that of cv. Malas Saveh (110.8 g) and cv. Malas Yazdi (100.4 g) (Fig. 2a, b and c).

The effects of kaolin, cultivar and their interaction effects were significant on the fresh weight of the peel in the second year ($P < 0.05$). Kaolin reduced the weight of the peel, so the maximum weight of the peel was obtained in the control (148.5 g), which was significantly different ($P < 0.05$) from the values obtained with 3% kaolin (133.1 g) and 5% kaolin (123.6 g). The maximum weight of the peel was obtained from cv. Shisheh-Kab (156.1 g), which was significantly different ($P < 0.05$) from that of cv. Malas Yazdi (128.5 g) and cv. Malas Saveh (120.7 g). The interaction effects of kaolin × cultivar revealed that the minimum weight of the peel was obtained for cv. Shisheh--Kab with 5% kaolin (97.8 g), which differed significantly ($P < 0.05$) from those of the other treatments (Fig. 2d, e and f). Consistent with our findings, foliar spraying of kaolin minimized the thickness of the fruit peel and nonedible parts (Hegazi et al., 2014).

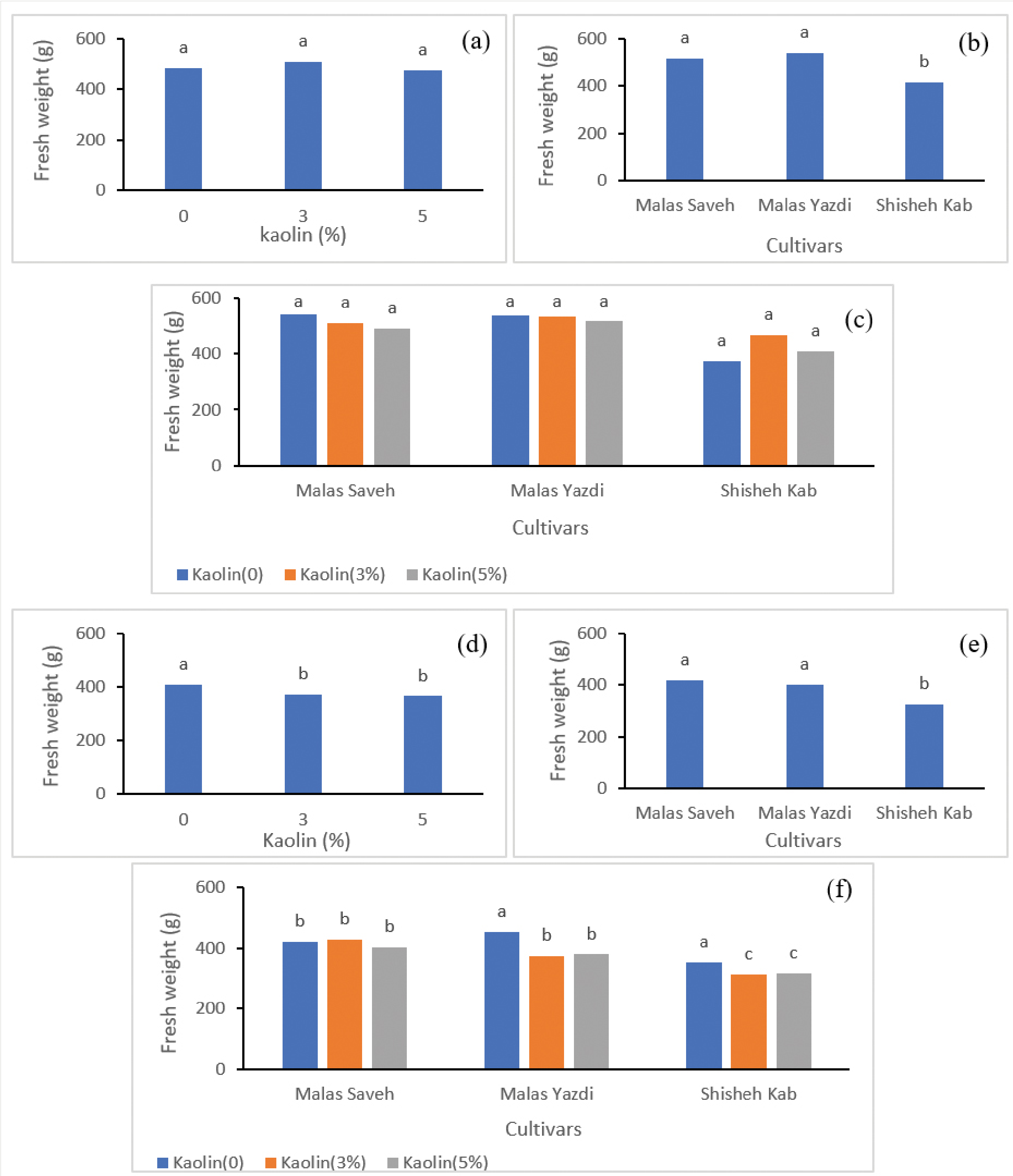

Figure 1. Effect of kaolin and kaolin × cultivar interaction on fruit fresh weight (g) of pomegranate cultivars in 2021 (a–c) and 2022 (d–f). Different letters above columns indicate significant differences at the $P < 0.05$ level according to LSD test

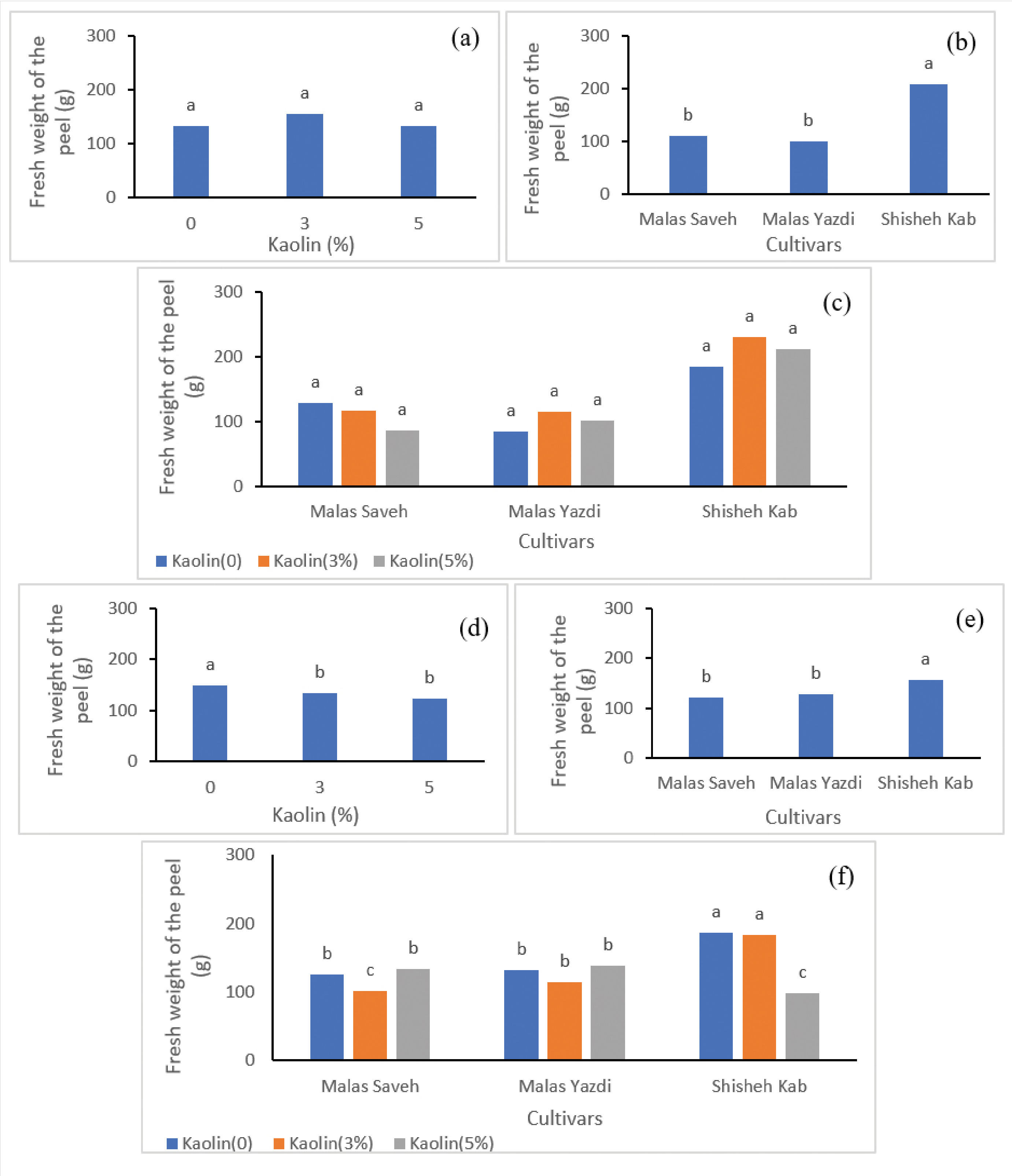

Figure 2. Effect of kaolin and kaolin × cultivar interaction on peel fresh weight (g) of pomegranate cultivars in 2021 (a–c) and 2022 (d–f). Different letters above columns indicate significant differences at the $P < 0.05$ level according to LSD test

In general, peel thickness is an important factor in different types of pomegranate fruit, and the thicker the peel is, the greater the weight of the peel. In the present study, the weights of the peels of the fruits of Malas Saveh and Malas Yazdi were the same, whereas the weights of the peels of the fruits of the Shisheh-Kab variety were greater than those of the other two varieties, which is in accordance with the results of Varasteh et al. (2006). The fruit peel not only protects the fruit from environmental stresses but also plays an important role in resisting internal growth pressures, controlling fruit expansion, and maintaining fruit integrity. Joshi et al. (2021) studied the effects of climate and temperature on the properties of pomegranate fruit peels. They reported that with increasing temperature (more than 40 °C) and decreasing humidity (less than 35%), the fruit peel thickened and became highly plastic to retain water in the pores so that it did not resist turgor pressure. These authors reported that temperature and humidity were two very important and effective factors affecting the mechanical properties of fruit peels. Singh et al. (2020) reported similar results.

Fresh Weight of the Arils in Kaolin-Treated Fruit

The effects of kaolin and the interaction effects of kaolin × cultivar were not significant for the fresh weight of the arils in the first year; however, the effect of cultivar was significant ($P < 0.05$). The maximum weight of arils was obtained from the cultivars Malas Yazdi (437.6 g) and Malas Saveh (404.8 g), which was significantly different ($P < 0.05$) from that of the cultivar Shisheh-Kab (208.8 g) (Fig. 3a, b and c).

The effects of cultivar and the interaction effect of kaolin × cultivar were significant for the fresh weight of the arils in the second year ($P < 0.05$); however, the effects of kaolin were not significant. The maximum weight of the arils was obtained from the cultivars Malas Saveh (296.9 g) and Malas Yazdi (272.1 g), and it was significantly different ($P < 0.05$) from that of the cultivar Shisheh-Kab (169.4 g). The interaction effects of kaolin × cultivar revealed that the maximum weight of the arils was obtained in cv. Malas Saveh with 3% kaolin (326.4 g) and cv. Malas Yazdi without kaolin (318.1 g), which differed significantly ($P < 0.01$) from those of the other treatments (Fig. 3d, e and f).

Varasteh et al. (2006) report that the aril ratio in pomegranate of the Shishe Kab variety is approximately 50%, whereas this ratio is approximately 60% and 75% in the Malas Saveh and Malas Yazdi varieties, respectively, which is in accordance with the results of the present study. The results revealed that the lowest aril weight of the pomegranates was associated with the Shisheh-Kab variety. Hegazi et al. (2014) reported that foliar spraying of Manfaloty and Wonderfull trees with 2.5 or 5% kaolin increased fruit weight and the number and yield of fruit and marketable fruits while reducing sunburn. Gharaghani et al. (2015) also reported that foliar spraying of apple trees with 2, 4 and 6% kaolin increased fruit weight. These authors explained this finding by increasing plant photosynthesis, reducing leaf temperature and reducing the transpiration rate via the addition of kaolin. Additionally, the research has shown that kaolin treatment effectively reduces the water consumption and stomatal conductance of plants under water stress, which in turn reduces the leaf thickness, transpiration rate and water retention in the plant (Segura et al., 2015). In the present study, 5% and 3% kaolin increased pomegranate weight in the Shishe Kab and Malas Saveh cultivars, respectively. This was probably due to a reduced transpiration rate, moisture retention, and reduced temperature. The results of the present study were similar to those of other researchers (Faghih et al., 2021; Khayyat and Samadzadeh, 2023). However, 3% and 5% kaolin in the Malas Yazdi cultivar reduced the aril weight, indicating different responses to foliar spraying with kaolin in different cultivars.

Total Phenols in Kaolin-Treated Fruit

Significant increases in total phenolic content were observed with kaolin application, particularly at 5%, while cultivar differences also contributed to the observed variation in phenolic content. The results revealed that the effects of kaolin and cultivar significantly affected the TPC in the first year ($P < 0.05$); however, the interaction effects of kaolin × cultivar were not significant. The highest TPC was obtained with 5% kaolin (11.3 mg·100 g^{-1} fresh weight), which was significantly different ($P < 0.05$) from that with 3% kaolin (9.2 mg·100 g^{-1} fresh weight) and the control (8.4 mg·100 g^{-1} fresh weight). The highest TPC was obtained from cv. Malas Yazdi (mg·100 g^{-1} fresh weight) and cv. Malas Saveh (9.8 mg 100 g^{-1} fresh weight), with a significant difference ($P < 0.05$) compared with that of cv. Shisheh-Kab (8.7 mg 100 g^{-1} fresh weight) (Fig. 4a, b and c).

The effects of cultivar and the interaction effects of kaolin × cultivar were significant for the TPC in the second year ($P < 0.05$); however, the main effects of kaolin were not significant. The highest TPC was obtained from cv. Malas Yazdi (8.7 mg·100 g^{-1} fresh weight) and cv. Malas Saveh (8.4 mg·100 g^{-1} fresh weight), with a significant difference ($P < 0.05$) compared with that of cv. Shisheh-Kab (7.3 mg·100 g^{-1} fresh weight). The interaction effects of kaolin × cultivar showed that the highest TPC was obtained in cv. Malas Yazdi without kaolin (9.3 mg·100 g^{-1} fresh weight), cv. Malas Saveh with 3% and 5% kaolin, and cv. Malas Yazdi with 3% and 5% kaolin, which differed significantly ($P < 0.01$) from the other treatments (Fig. 4d, e and f). Kaolin increases photosynthetically active radiation (PAR), followed by phenylalanine ammonia-lyase enzyme activity, which increases the TPC (Sharma et al., 2018).

Nasrabadi et al. (2024), in a recently published report, reported that in the first year of their experiment, the phenol content of the Malas Yazdi pomegranate cultivar was 19% higher than that of the Shisheh-Kab pomegranate cultivar. The results of the present study were consistent with the results of Nasrabadi et al. (2024), who reported that the phenol content of the Shisheh-Kab pomegranate cultivar was 16% lower than that of the Malas Yazdi and Malas Saveh cultivars. Hamdy et al. (2022) investigated the effects of foliar spraying of kaolin at concentrations of 2, 4 and 6% on the antioxidant properties of mango fruit. These authors reported that with increasing kaolin concentration, the amount of phenol in mango tree leaves decreased. Similarly, in the present study, 5% kaolin reduced the total phenol content in pomegranate fruit compared with the control and 3% kaolin. One of the plant defense mechanisms when exposed to high temperatures (such as stress) is to increase the synthesis of antioxidants such as phenolic compounds, which maintains the stability of the plant against oxidative stress (Naikoo et al., 2019). At high temperatures, enzymes such as phenylalanine ammonia lyase are activated, which increases the synthesis of phenolic compounds.

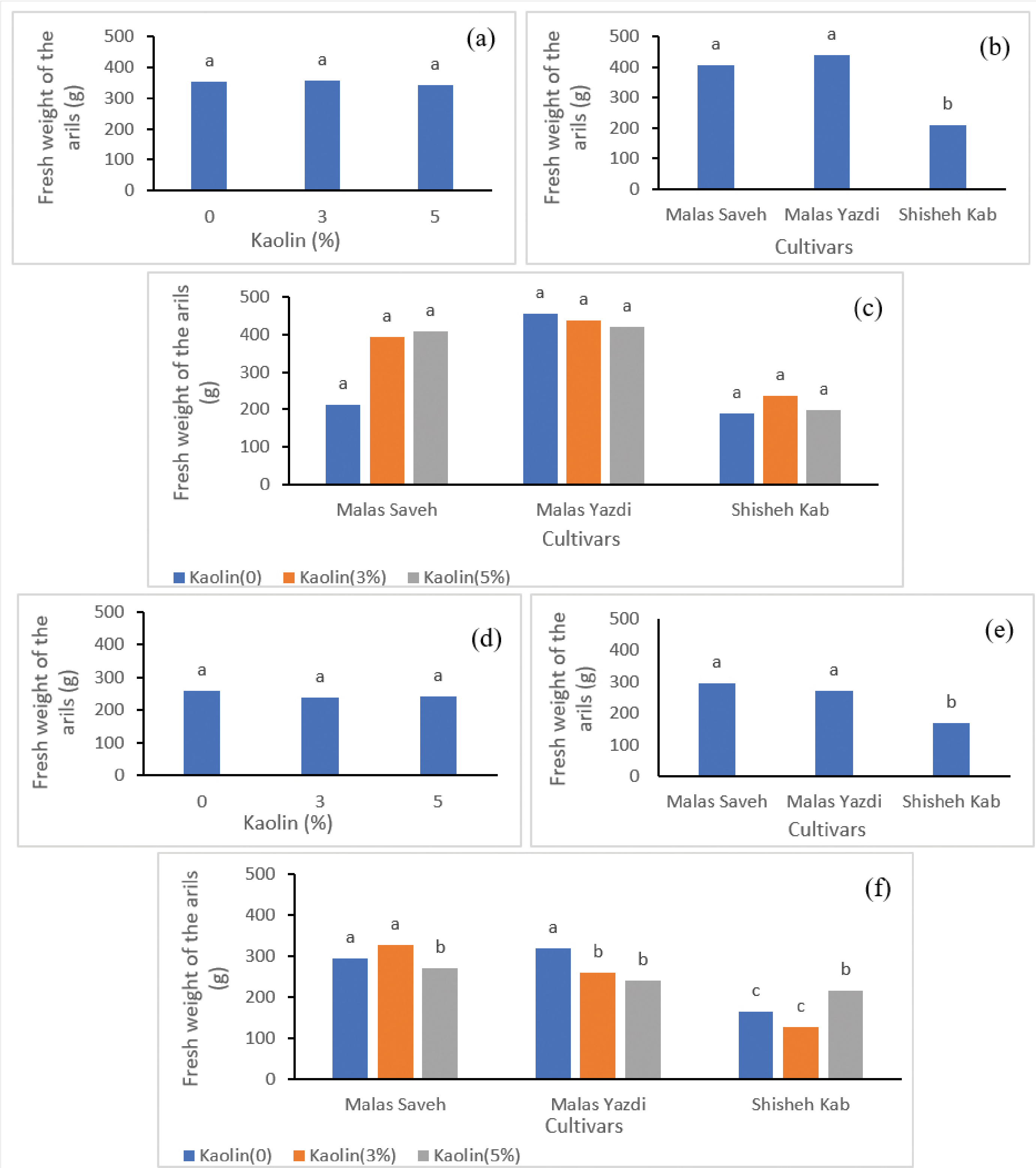

Figure 3. Effect of kaolin and kaolin × cultivar interaction on aril fresh weight (g) of pomegranate cultivars in 2021 (a–c) and 2022 (d–f). Different letters above columns indicate significant differences at the $P < 0.05$ level according to LSD test

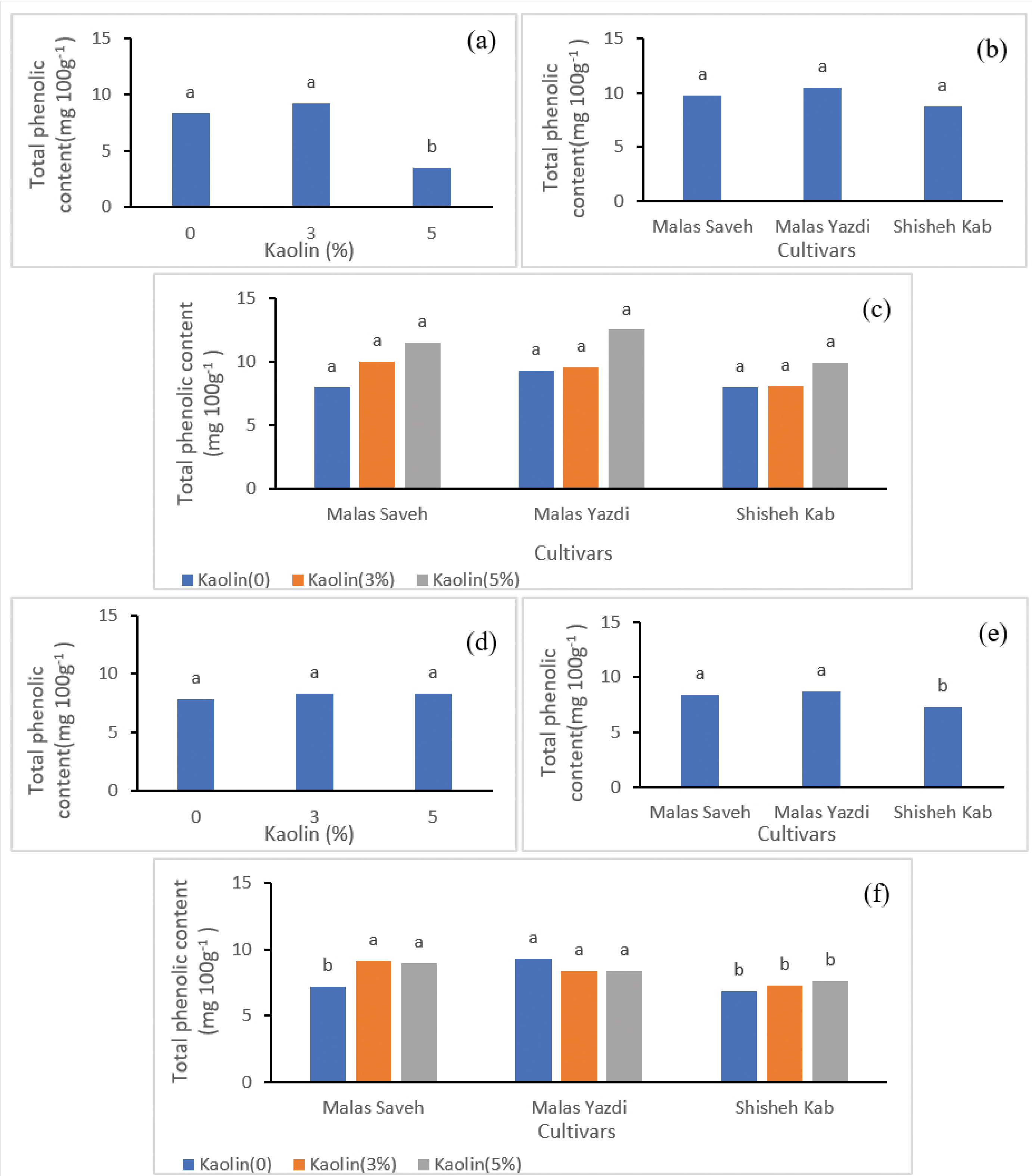

Figure 4. Effect of kaolin and kaolin × cultivar interaction on total phenolic content (mg GAE 100 g^{-1} FW) of pomegranate cultivars in 2021 (a–c) and 2022 (d–f). Different letters above columns indicate significant differences at the $P < 0.05$ level according to LSD test

However, under normal conditions (without stress), the phenylalanine enzyme is used in the protein synthesis process (Barros and Dixon, 2020), which explains the decrease in phenolic content when it is sprayed with 5% kaolin. Kaolin reduces the surface temperature of the fruit and protects the product from heat stress. The results obtained from the present study were in accordance with reports recorded by other researchers (Brito et al., 2019; Brito et al., 2018).

Total Anthocyanin Content in Arils of Kaolin-Treated Fruit

Marked enhancements in total anthocyanin content were detected under kaolin treatments, with cultivar differences further modulating the response. Kaolin and cultivar had significant effects on TAC in the first year ($P < 0.05$); however, the interaction effect of kaolin × cultivar was not significant. The highest TAC was obtained with 5% kaolin (207.7 mg·L^{-1}) and 3% kaolin (189.7 mg·L^{-1}), with a significant difference ($P < 0.05$) compared with the control (114.5 mg·L^{-1}). The highest TAC was obtained in cv. Malas Yazdi (213.2 mg L^{-1}), which was significantly different ($P < 0.05$) from that in cv. Malas Saveh (173.4 mg L^{-1}) and cv. Shisheh-Kab (125.3 mg·L^{-1}) (Fig. 5a, b and c).

In addition, the effects of kaolin and cultivar on TAC were significant in the second year ($P < 0.05$); however, the interaction effect of kaolin × cultivar was not significant. The highest TAC was obtained with 5% kaolin (199.9 mg·L^{-1}) and 3% kaolin (187.1 mg·L^{-1}), with a significant difference ($P < 0.05$) compared with the control (147.4 mg·L^{-1}). The highest TAC was obtained for cv. Malas Yazdi (228.6 mg L^{-1}) and cv. Malas Saveh (208.9 mg·L^{-1}), which was significantly different ($P < 0.05$) from that of cv. Shisheh-Kab (97 mg·L^{-1}) (Fig. 5d, e and f). In line with our results, foliar application of kaolin increased the anthocyanin content (Ahmed and Gaber, 2022). The temperature of the fruit decreases because the application of kaolin increases the anthocyanin content (Tarara et al., 2008).

In the present study, aril paleness was not directly measured through visual scoring or color indices. Instead, paleness was inferred from the anthocyanin concentration, as lower anthocyanin levels are strongly associated with reduced aril pigmentation (Khademi et al., 2025). This indirect approach is consistent with previous reports, where anthocyanin content has been validated as a reliable indicator of aril color intensity and paleness disorders in pomegranates (Karami and Faraji, 2025). Therefore, the observed differences in anthocyanin concentration among cultivars and kaolin treatments provide meaningful insights into the potential occurrence of aril paleness.

The results of the present study revealed that the highest and lowest levels of anthocyanin were found in the Malas Yazdi and Shisheh-Kab pomegranate cultivars. In this way, the Malas Yazdi cultivar had approximately 40% more anthocyanin than the Shisheh-Kab cultivar. Similarly, Varasteh et al. (2006) reported that the level of anthocyanin in the Shisheh-Kab pomegranate cultivar was approximately 35% lower than that in the Malas Yazdi cultivar. Environmental conditions strongly influence the secondary metabolism of plant cells (Teixeira et al., 2013), which causes changes in the quality of products. High temperature reduces the biosynthesis and content of anthocyanins (Carbonell-Bejerano et al., 2013). Genes encoding enzymes involved in the biosynthesis of anthocyanins, such as the enzymatic activity of UFGT (a key enzyme in anthocyanin synthesis), are affected by heat stress and are inactivated at high temperatures (Zhao et al., 2021; Tan et al., 2023). The results of the present study showed that the application of 3% and 5% kaolin increased the accumulation of anthocyanins in pomegranate fruit. In this context, Conde et al. (2016) investigated the effect of foliar spraying with kaolin on the anthocyanin content of red grape fruit. They reported that the application of foliar kaolin reduced harmful solar radiation, including ultraviolet and infrared radiation, and increased the synthesis of anthocyanins with decreasing temperature. However, trees that were not sprayed with kaolin presented minimal anthocyanin contents. Another factor affecting the anthocyanin content is water stress. As Conde et al. (2016) reported, kaolin, by preventing water loss from plant tissues by controlling transpiration, conserved water in fruit tissue, which ultimately increased the accumulation of anthocyanin.

Titratable Acidity of Juice in Kaolin-Treated Fruit

Distinct cultivar-driven differences were evident in titratable acidity, whereas kaolin treatments had no significant effect on titratable acidity in the first year. The results revealed that the effect of kaolin and the interaction effect of kaolin × cultivar were not significant for TA in the first year; however, the effect of cultivar was significant ($P < 0.05$). The maximum TA was obtained in cultivar Malas Yazdi (2.9%), which was significantly different ($P < 0.05$) from that in cultivar Shisheh-Kab (2%) and cultivar Malas Saveh (1.9%) (Fig. 6a, b and c).

The results of the variance analysis revealed that the effects of kaolin, cultivar and their interaction were significant for TA in the second year ($P < 0.05$). The maximum TAs obtained in the 3% kaolin (2.1%) and control (1.9%) groups were significantly different ($P < 0.05$) from that in the 5% kaolin (1.5%) group. The maximum TA was obtained in the cultivar Malas Yazdi (2.1%), which was significantly different ($P < 0.05$) from that in the cultivars Shisheh-Kab (1.7%) and Malas Saveh (1.6%). The interaction effects of kaolin × cultivar showed that the maximum TA was obtained in cv. Malas Yazdi with 3% kaolin (2.6%) and without kaolin (2.3%), which differed significantly ($P < 0.05$) from the other treatments (Fig. 6d, e and f). In line with our results, applying a high concentration of kaolin decreased tannins and acidity in pomegranate fruit (Ahmed and Gaber, 2022).

The range of data presented for TA in different pomegranate cultivars in the present study is in accordance with the results of Varasteh et al. (2006). As shown in the present study, the lowest and highest TA values were for the Shisheh-Kab and Malas Yazdi cultivars, respectively. Varasteh et al. (2006) also reported that pomegranates of the Shisheh-Kab cultivar had a TA of 0.98%, whereas the TA in pomegranate of the Malas Yazdi cultivar was 1.35%.

Among the studied cultivars, Shisheh-Kab consistently presented lower anthocyanin concentrations and titratable acidity, which is associated with a greater incidence of aril paleness. In contrast, Malas Yazdi maintained higher anthocyanin levels even without kaolin application, highlighting its superior genetic potential for color development.

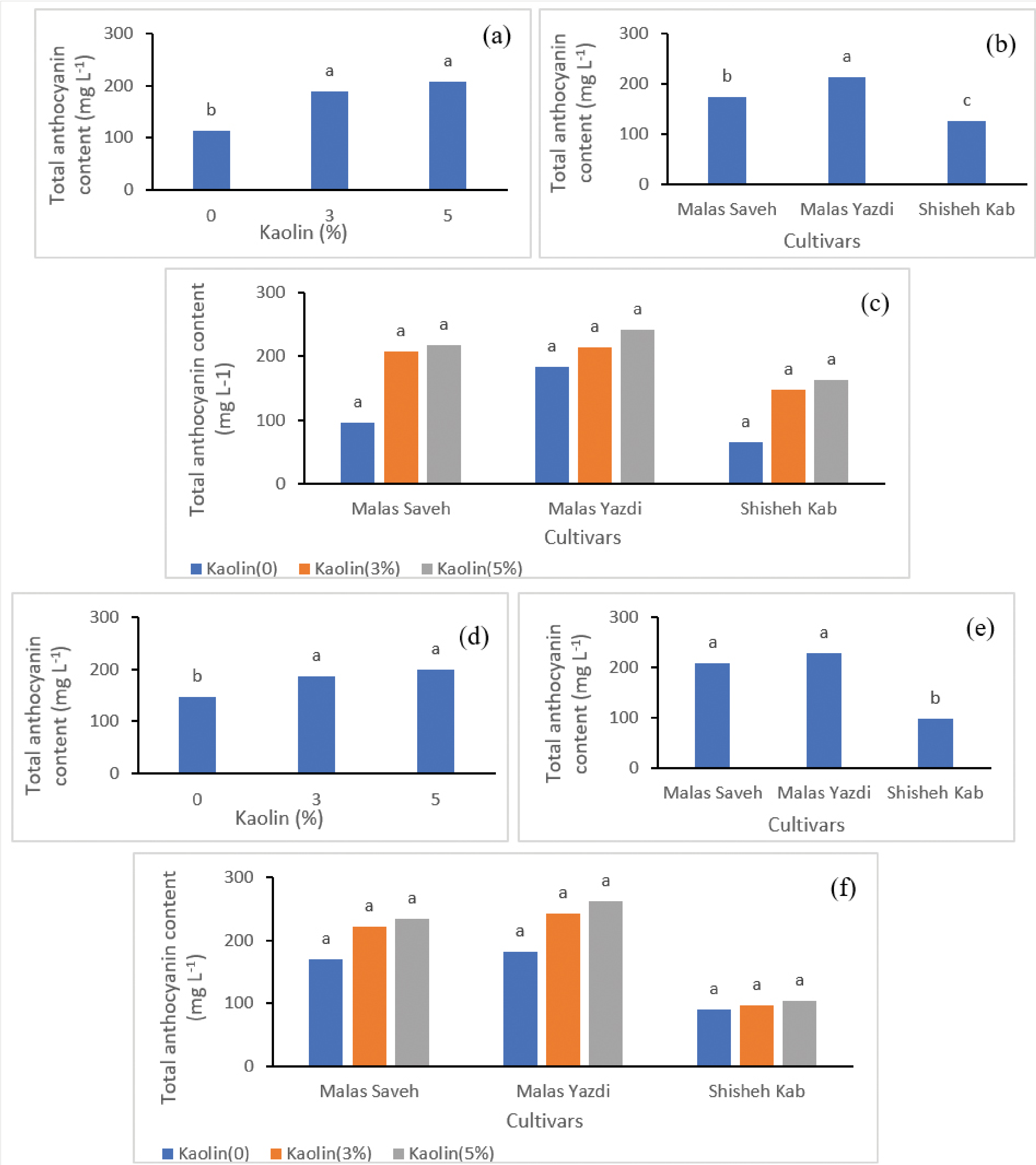

Figure 5. Effect of kaolin and kaolin × cultivar interaction on total anthocyanin content (mg L^{-1}) of pomegranate cultivars in 2021 (a–c) and 2022 (d–f). Different letters above columns indicate significant differences at the $P < 0.05$ level according to LSD test

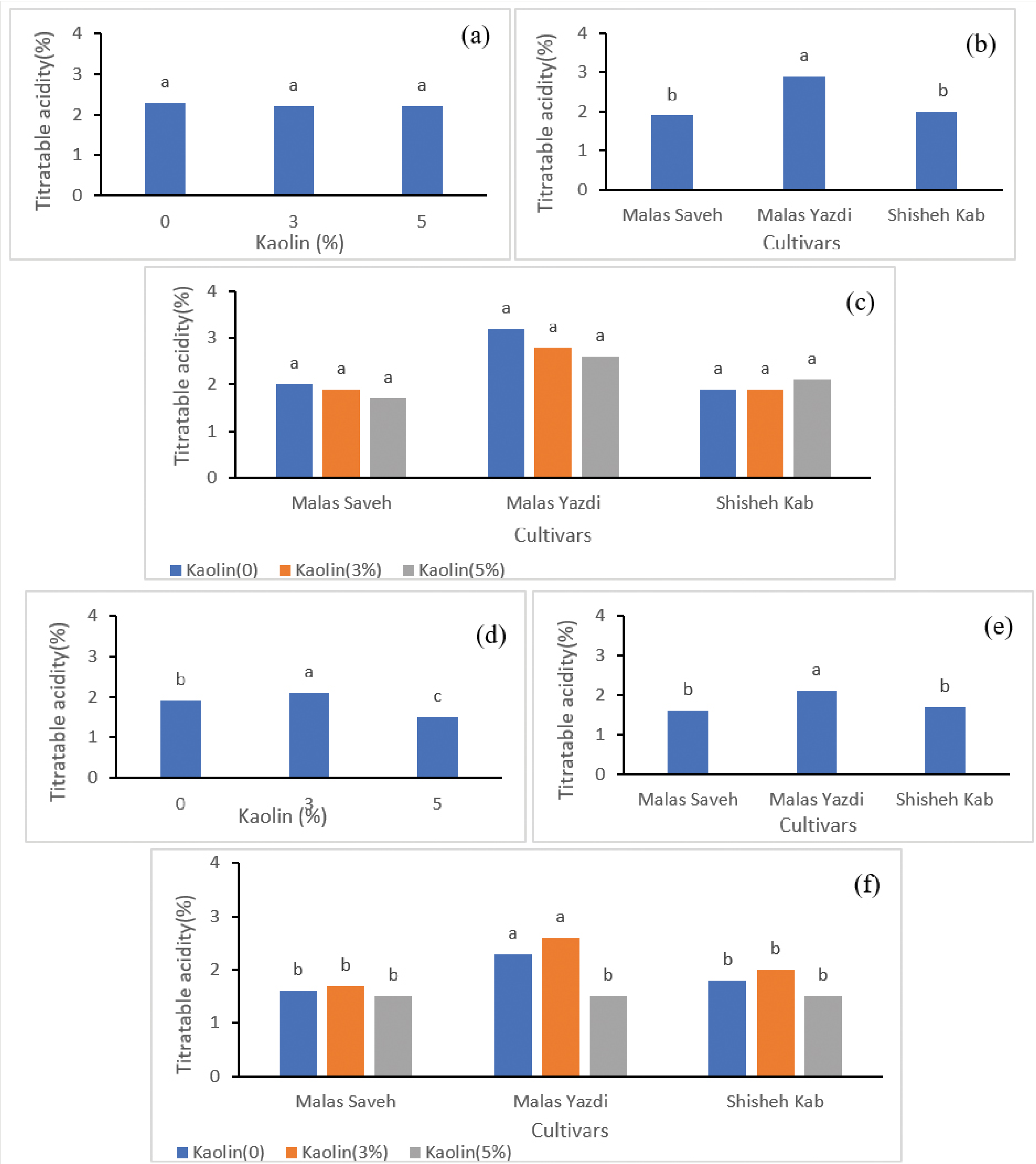

Figure 6. Effect of kaolin and kaolin × cultivar interaction on titratable acidity (% citric acid) of pomegranate cultivars in 2021 (a–c) and 2022 (d–f). Different letters above columns indicate significant differences at the $P < 0.05$ level according to LSD test

These cultivar-specific responses are of practical importance for growers, as they provide guidance in selecting suitable cultivars for warmer regions where aril paleness is more prevalent. Thus, kaolin application may enhance fruit quality traits, but inherent cultivar differences remain a decisive factor in determining the final fruit quality.

Total Soluble Solids in Kaolin-Treated Fruit

The variation in total soluble solids was driven primarily by the kaolin treatment, whereas the cultivar and their interaction had no significant influence on total soluble solids in the first year. The effects of cultivar and the interaction effect of kaolin × cultivar were not significant for the TSS in the first year; however, the effect of kaolin was significant ($P < 0.05$). The maximum TSS content was significantly greater in the 3% kaolin (18.3%) and control (17.6%) groups ($P < 0.05$) than in the 5% kaolin group (16.9%) (Fig. 7 a, b and c).

The results revealed that the effects of kaolin and the interaction effects of kaolin × cultivar were not significant for TSS in the second year; however, the effect of cultivar was significant ($P < 0.05$). The maximum TSS was obtained in the cultivars Malas Saveh (16.8%) and Malas Yazdi (16.3%), which was significantly different ($P < 0.05$) from that of the cultivar Shisheh-Kab (16%) (Fig. 7d, e and f). In line with our results, foliar application of kaolin increased biochemical contents such as the TSS of pomegranate fruits (Hegazi et al., 2014; Ahmed and Gaber, 2022). The reflective effect of kaolin reduces the temperature of the leaf and causes the accumulation of sugars by reducing the respiration rate (Ahmed and Gaber, 2022).

Taste Index (TSS/TA) in Kaolin-Treated Fruit

Cultivar identity played a significant role in influencing the taste index, whereas kaolin treatment and their interaction had no significant influence on the taste index in the first year. The taste index is obtained on the basis of the TSS-to-TA ratio. The effects of kaolin and the interaction effects of kaolin × cultivar were not significant for the taste index in the first year; however, the effect of cultivar was significant ($P < 0.05$). The highest taste indices were obtained for cv. Malas Saveh (16.8%) and cv. Malas Yazdi (16.3%), which were significantly different ($P < 0.05$) from those of cv. Shisheh-Kab (16%) (Fig. 8a, b and c).

In addition, the effects of kaolin and cultivar on the taste index were significant in the second year ($P < 0.05$); however, the interaction effect of kaolin × cultivar was not significant. Compared with the other treatments, the highest taste index was obtained with 5% kaolin (10.8%), which was significantly different ($P < 0.05$). The highest taste indices were obtained for cv. Malas Saveh (10.4) and cv. Shisheh-Kab (9.2), which were significantly different ($P < 0.05$) from those of cv. Malas Yazdi (8.1) (Fig. 8d, e and f).

In line with the results of the present study, previous studies reported that the taste index (TSS/TA) of the fruit of the Malas Yazdi pomegranate cultivar was lower than that of other cultivars (Nasrabadi et al., 2024; Vazifeshenas et al., 2015). Faghih et al. (2021) reported that the application of 1.5% and 3% kaolin led to an increase in soluble solids and ultimately led to an increase in the taste index of apple fruit. In the present study, foliar spraying with 5% kaolin increased the taste index of the fruit. By reducing the temperature of the fruit and reducing the respiration rate, carbohydrates accumulated in the fruit, and ultimately, the fruit had a better taste (Glenn et al., 2003; Menzel, 2022).

In addition to the detailed results presented in Figs. 1–8, a summary table has been provided to facilitate interpretation of the main findings. For clarity, the main effects of kaolin on fruit weight, peel and aril weight, phenolic content, anthocyanin content, titratable acidity, soluble solids, and the taste index are summarized in Table 1. This overview highlights the average responses across cultivars and years, allowing readers to quickly identify the magnitude of changes and the most effective kaolin concentrations.

Table 1. A summary of main effects of Kaolin on evaluated traits of pomegranate cultivars during 2021-2022

Trait	Key cultivar response	Best kaolin concentration
Fruit fresh weight (g)	Malas Yazdi and Malas Saveh highest in 2021 and 2022	3% highest in 2021; 0% highest in 2022
Peel fresh weight (g)	Shisheh-Kab highest in 2021 and 2022	3% highest in 2021; 0% highest in 2022
Aril fresh weight (g)	Malas Yazdi and Malas Saveh highest in 2021 and 2022	0% highest in 2021 and 2022
Total phenolic content (mg GAE 100 g^{-1} FW)	Malas Yazdi highest in 2021 and 2022	3% highest in 2021; 0% highest in 2022
Total anthocyanin (mg L^{-1})	Malas Yazdi highest in 2021 and 2022	3% highest in 2021 and 2022
Titratable acidity (%)	Malas Yazdi highest in 2021 and 2022	0% highest in 2021; 3% highest in 2022
Total soluble solids (%)	Malas Yazdi and Malas Saveh highest in 2021 and 2022	3% highest in 2021; 0% highest in 2022
Taste index	Malas Saveh highest in 2021 and 2022	0% highest in 2021; 5% highest in 2022

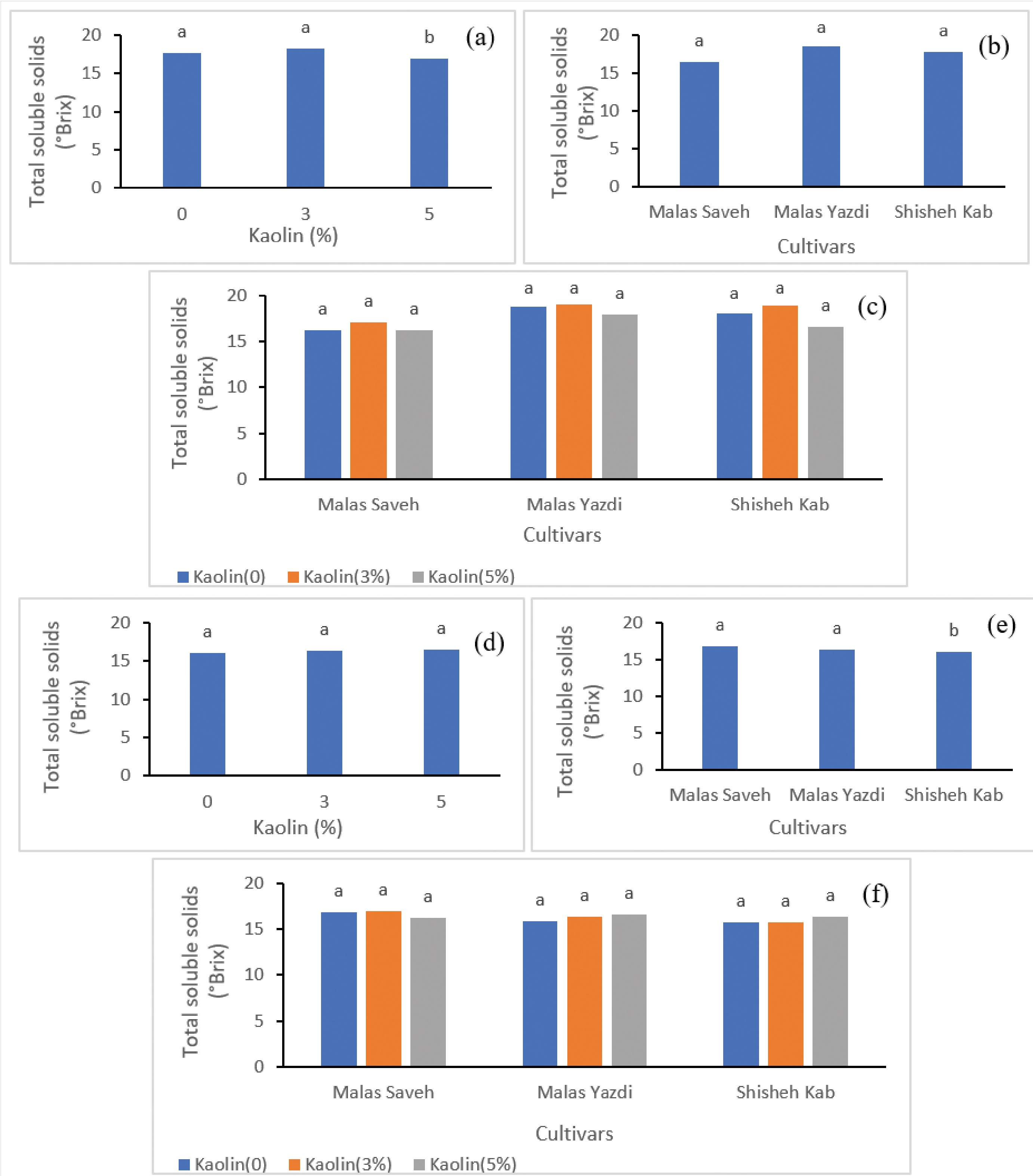

Figure 7. Effect of kaolin and kaolin × cultivar interaction on total soluble solids (%) of pomegranate cultivars in 2021 (a–c) and 2022 (d–f). Different letters above columns indicate significant differences at the $P < 0.05$ level according to LSD test

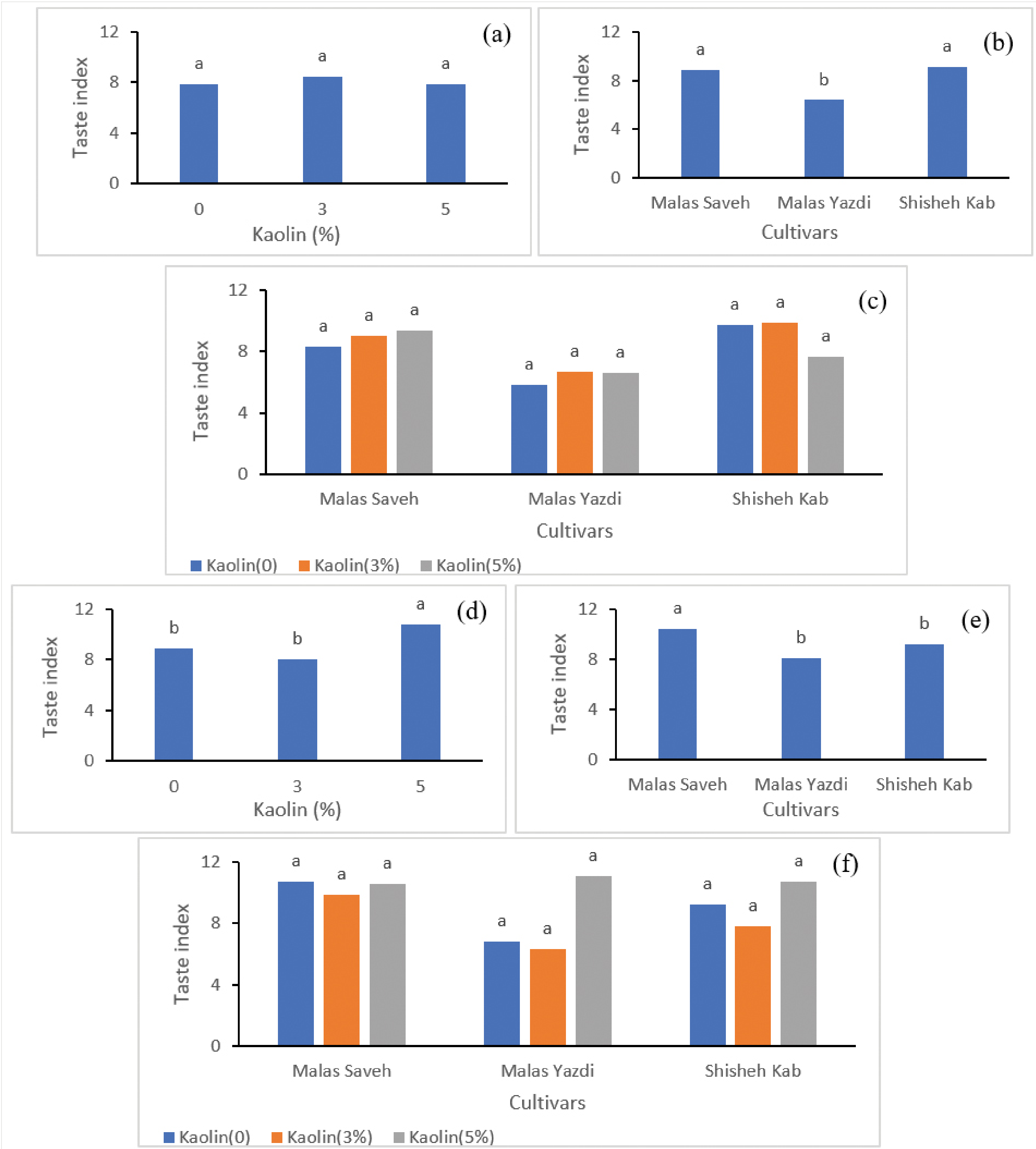

Figure 8. Effect of kaolin and kaolin × cultivar interaction on taste index of pomegranate cultivars in 2021 (a–c) and 2022 (d–f). Different letters above columns indicate significant differences at the $P < 0.05$ level according to LSD test

Conclusion

Foliar application of kaolin particle film improved several fruit quality attributes, including the anthocyanin concentration, phenolic content, and taste index, across all the studied pomegranate cultivars. The highest accumulation of anthocyanin was observed in the cultivar Malas Yazdi, while fruit weight responses varied among cultivars, with the cultivar Malas Yazdi showing the highest fruit weight in the first year and the cultivar Malas Saveh in the second year. However, in the second year, kaolin application reduced fruit weight, indicating a potential trade-off between quality enhancement and yield. These cultivar-specific differences highlight the importance of genetic background in determining fruit responses to kaolin. Overall, kaolin particle film improved fruit quality characteristics, but the magnitude of the physicochemical response differed among cultivars. Therefore, further studies are needed to optimize the kaolin concentration, application timing, and cultivar selection to maximize fruit quality while minimizing yield losses.

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CRediT Autorship Declaration

Mehdi Jahani: Methodology, writing, reviewing and editing. **Mohammadhassan Sayyari Zohan:** Methodology, formal analysis. **Farid Moradinezhad:** Investigation, writing. **Mehdi Khayyat:** Investigation, formal analysis, writing. **Mohammad Reza Mirzaee:** Methodology, writing.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

Availability of Data and Material

All the data are presented in the manuscript.

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