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Research Article

Using Gum Arabic as an Eco-Friendly Treatment to Improve Shelf Life and Physicochemical Quality of "Wonderful" Pomegranate Fruits

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Abstract:

Pomegranate (*Punica granatum* L.) is a nutrient-rich fruit known for its vibrant red seeds, sweet-tart flavor, and numerous health benefits, making it a popular choice in diets worldwide. Several postharvest treatments have been applied to maintain the quality and extend the shelf life of pomegranate arils. Pomegranate quality problems persist in the majority of producing regions despite the growing demand for fruit worldwide, resulting in significant postharvest losses and waste. In both experimental seasons (2023 and 2024), "Wonderful" pomegranate fruits were picked at the complete maturity stage according to quality indices. Thus, this experiment aimed to verify the efficiency of post-harvest applications of Gum Arabic (GA) at 10% on quality attributes and bioactive compound content of "Wonderful" pomegranates quality during ambient room conditions (25 ± 2 °C and 85% RH). The results revealed that GA at 10% was significantly effective in decreasing loss in fruit weight, juice percentage, SSC, PH values, total phenolic contents, anthocyanin peel and juice content as well as increased tannins, ascorbic acid, and total antioxidant activity comparing with the control treatment. In addition, GA maintained greater titratable acidity content. In general, the obtained data demonstrated that GA treatment had a beneficial impact that extended shelf life and time storage of Wonderful pomegranate fruits by reducing senescence/decomposition of fruits, delaying ripening, and maintaining quality parameters.

1. Introduction

Pomegranate (*Punica granatum* L.) is a valuable fruit crop that has recently become one of Egypt's most promising export fruits (Khedr, 2018). The Wonderful pomegranate is a medium to large-sized cultivar known for its high yield, light-colored arils, abundant juice, and outstanding taste (Holland et al., 2009). "Wonderful" cultivar is now among the most widely cultivated pomegranate cultivars in Egypt due to its ideal combination of productivity and quality. The annual world production of pomegranate exceeds 8.1 million tons (FAO, 2021). India and China are the leading producers of pomegranates, followed by Iran, Turkey, Afghanistan, the United States, Iraq, Pakistan, Syria, and Spain (UNECE, 2021). The growing demand for pomegranate-based products, including pomegranate powder, juice, functional beverages, and other derivatives, is expected to be a key driver of global market growth in the coming years.

The annual demand for pomegranate fruit is fulfilled through post-harvest storage (Kahramanoğlu and Usanmaz, 2016). The short post-harvest shelf life of pomegranate fruit poses a significant challenge to its consumption, as storage under ambient conditions is restricted to just a few weeks (Fawole and Opara, 2013). Despite the growing global demand for pomegranates, quality concerns remain in many producing regions, resulting in significant postharvest losses and waste. This is due to the highly perishable nature of pomegranates, as they are highly susceptible to physiological disorders and decay after harvest. As a result, the overall fruit quality declines, including the loss of its functional properties (Ali et al., 2010). The deterioration of pomegranate's physical, chemical, and sensory characteristics was found to be less severe under cold storage compared to room temperature (Patil et al., 2022).

Gum Arabic (GA) is a dried, adhesive exudate obtained from the stems or branches of Acacia species (Maqbool et al., 2011). It is characterized by its small gelatinous particles and high solubility, making it widely utilized in the industrial sector for emulsification, film formation, and encapsulation (Motlagh., et al 2006). GA has been shown to significantly enhance fruit quality preservation (Re et al., 1999).

GA is a polysaccharide-based coating widely utilized for its excellent film-forming properties, exceptional emulsification, and encapsulation abilities. It is also classified as "Generally Recognized as Safe" (GRAS) by the Joint FAO/WHO Expert Committee on Food Additives. Multiple monographs have highlighted the beneficial effects of GA as an edible coating (Motlagh et al., 2006). Maqbool et al. (2010) demonstrated the potential of using GA combined with chitosan (CH) as a biofungicide to control postharvest anthracnose in bananas. Ali et al. (2010) suggested that GA, when used as an edible coating, effectively delayed the ripening process. Furthermore, Valiathan and Athmaselvi (2018) demonstrated that a composite edible coating of GA and thyme oil, applied through a 3-minute dipping process, effectively preserved the physicochemical and organoleptic properties of green chilies for up to 12 days. In contrast, uncoated chilies had a shelf life of only 6 days at room temperature.

Hence, the primary objective of this experiment was to evaluate the effectiveness of post-harvest GA treatment on physiochemical attributes and preserving the quality of "Wonderful" pomegranates under ambient conditions (25 ± 2°C and 85% RH).

2. Materials and Methods

2.1. Plant materials

The present study was carried out during two successive seasons (2023 and 2024) on "Wonderful" pomegranates. The fruits were picked from trees that were grown in a private orchard at El-Behera governorate, Egypt (latitude, 30º 70` N; longitude, 30º 27`E). Trees were about 7 years old, planted in sandy soil at a 4×5 m distance; irrigated by a drip water system, and subjected to ideal cultural practices adopted in the orchard.

2.2. Source of the used chemicals

The GA used in the experiment was imported from Sigma Aldrich, St. Louis, MO, USA.

2.3. Experimental design and procedures

In October of both experimental seasons (2023-2024), "Wonderful" pomegranate fruits were picked at the complete maturity stage according to quality indices published by Kader (2006) and transferred to the Research Laboratory of Horticulture Department, Faculty of Agriculture, Tanta University. Upon arrival, the fruits were cleaned, sorted, and graded, while any defective ones, including those with wounds or other abnormalities, were removed. The fruits at the same maturity stage were washed with 0.01% sodium hypochlorite solution for 2 min then air dried through a dryer instrument (45 º C) for two minutes until visible moisture on fruit surfaces completely disappeared. Seventy-two cleaned healthy fruits were selected randomly, and divided into 2 groups (36 fruits per group) and every group was divided into 4 subgroups (for the four self-life periods). Each subgroup consisted of three replications (three fruits per replication) and was assigned to one of the following treatments:

1. Control (Water).
2. Gum Arabic (GA) at 10% (W/V).

The treatments were carried out by dipping the fruits in 10% Gum Arabic for 5 min, then the fruits were taken from the soaking of each treatment and left for 30 minutes to dry at room temperature and by an electric fan, then sprayed with 10% GA.

The fruits of each treatment were filled in plastic boxes and stored at ambient conditions (25 ± 2 º C and 85% RH) for 28 days as storage intervals. The fruit's physical and chemical properties were recorded before shelf life (zero time) and after 7, 14, 21, and 28 days of storage, respectively.

2.4. Quality Assessments

2.4.1. Fruit physical attributes

2.4.1.1. Fruit weight loss percentage

Fruit weight loss was measured during shelf life using a bench-top digital scale (Model PC-500, Doran Scales, Batavia, IL, USA) and was determined using the following equation:

$$\text{Weight loss (\%)} = \frac{\text{Fruit weight before shelf life - fruit weight after each period of shelf}}{\text{Fruit weight before shelf life}} \times 100$$

2.4.1.2. Juice percentage

Juice percentage was determined according to the following formula:

$$\text{Juice (\%)} = 100 \times \frac{\text{Juice volume per fruit (ml)}}{\text{Fruit weight (g)}}$$

2.4.1.3. Marketable fruit percentage

Marketable fruits percentage was calculated by the following formula:

$$\text{Marketable fruit (\%)} = \frac{\text{Weight of sound fruits at specified shelf life period}}{\text{Initial weight of fruits}} \times 100$$

2.4.2. Chemical properties of fruit

2.4.2.1. Soluble solids content (SSC)

The soluble solids content (SSC) of the juice sample was determined using a hand refractometer (ERMA, Japan, Brix 0–32%), and the results expressed in °Brix, following the AOAC (2005) guidelines.

2.4.2.2. Titratable acidity (TA)

Titratable acidity was quantified as a percentage of citric acid through titration with 0.1 N sodium hydroxide, using phenolphthalein as an indicator, following the AOAC (1990) method. The volume of NaOH used during titration was recorded, and titratable acidity (TA) was expressed as grams of citric acid per 100 mL of fruit juice. TA was then calculated using the following equation:

$$\text{Titratable acidity} = \frac{\text{Volume of NaOH x N x 0.064}}{\text{Volume of juice (ml)}} \text{ X100}$$

Where (N =Normality of NaOH, 0.064 = Equivalent weight of citric acid)

2.4.2.3. SSC/TA ratio

The SSC/TA ratio was determined by dividing the recorded values of SSC and TA in the fruit juice.

2.4.2.4. pH Value

PH measurements were conducted using a digital pH meter (Metrohm Model 601) at 21°C.

2.4.2.5. Total anthocyanin content

A 0.1-gram sample of either juice or peel was finely chopped and placed in brown glass containers with 20 mL of a cold methanol/HCl/water solution (90:1:1, v:v:v). The absorbance of the resulting filtrate was measured at 529 and 650 nm to determine anthocyanin content (Sims and Gamon, 2002). Anthocyanin concentration was calculated using the corrected absorbance formula [AA=A529 - (0.288 A650)] and a molar absorptivity coefficient of 30,000 L mol^{-1} cm^{-1} at 529 nm

(Murray and Hackett, 1991) with slight modification. The results were expressed as mg/100g fresh weight and mg/100 ml juice in the peel and juice, respectively.

2.4.2.6. Total phenolic content

The total phenolic content was measured spectrophotometrically using the Folin-Ciocalteu colorimetric method (Singleton and Rossi, 1965) at a wavelength of 765 nm. Then, the percentage of total phenolic was determined based on a gallic acid calibration curve.

2.4.2.7. Fruit tannins content (%)

The tannin content in fruit juice was analyzed following methods outlined in The International Pharmacopoeia (2003) and AOAC (1965), after modifications. In brief, a 25 ml infusion was measured into a 1 L conical flask, and then mixed with 25 ml of indigo solution and 750 ml of distilled deionized water (dd H_2O). Titration was carried out using 0.1 N aqueous $KMnO_4$ until the blue solution turned green, then gradually with drops until it became golden yellow. A standard solution of Indigo carmine was prepared by dissolving 6 g in 500 ml of dd H_2O, adding 50 ml of 95-97% H_2SO_4 after heating, diluting to 1 L, and filtering. Blank tests were conducted by titrating a mixture of 25 ml Indigo carmine solution and 750 ml dd H_2O.

$$\text{Tannins \%} = \frac{(V - V_0) \times 0.004157 \times 250 \times 100}{g \times 25}$$

Where:
V is the volume (ml) of 0.1 N $KMnO_4$ solution used for titrating the sample.
V_0 is the volume (ml) of 0.1 N $KMnO_4$ solution used for titrating the blank sample.
0.004157 represents the tannin equivalent per ml of 0.1 N KMnO solution.
g is the mass (g) of the sample analyzed.
250 is the total volume (ml) of the volumetric flask.

2.4.2.8. Vitamin C content (V.C)

Vitamin C content was determined following the AOAC (2005) method. In brief, fruit juice samples were mixed with an oxalic acid solution and titrated with a 2,6-dichlorophenol-indophenol dye solution. The results were expressed in milligrams of L- ascorbic acid per 100 mL of juice.

2.4.2.9. Total antioxidant activity (TAA)

Total antioxidant activity was assessed through ferric reducing power evaluations (Oyaizu, 1986).

The ferric-reducing power assay evaluates a sample's antioxidant capacity by measuring its ability to reduce ferric (Fe^{3+}) to ferrous (Fe^{2+}) ions. In this essay, varying concentrations (10 to 100 µg/ml) of the sample or standard (ascorbic acid) are mixed with phosphate buffer (pH 6.6) and potassium ferricyanide solution and then incubated at 50°C for 20 minutes. After cooling, trichloroacetic acid is added, and the mixture is centrifuged. The supernatant is combined with distilled water and ferric chloride solution, and the absorbance is measured at 700 nm using a UV spectrometer. An increase in absorbance indicates higher reducing power, reflecting greater antioxidant activity.

2.5. Statistical analysis

The experiment followed a factorial design with three replicates. The effects of post-harvest treatments and shelf life durations on various attributes were statistically analyzed using analysis of variance (ANOVA) with the COStat program 6.4 (Costat, 2008). Mean values between shelf life periods were compared using the least significant difference (LSD) test at a 0.05 significance level. A two-way hierarchical cluster analysis (HCA) was conducted using the Ward minimum variance method. Additionally, a heat map was generated to visualize multivariate similarities among treatments (Ward, 1963). Principal component analysis (PCA) was employed to reduce the dataset's dimensionality and reveal underlying treatment patterns. JMP Data Analysis Software Version 9 (SAS Institute Inc., 270 Cary, NC, USA) was utilized for performing ANOVA, Tukey's tests, HCA, heatmap creation, and PCA.

3. Results

3.1. Weight loss (%)

Concerning the effect of shelf life periods under ambient conditions (25 ± 2 ° C and 85% RH) for 28 days, the results showed a gradual and significant increase in the weight loss percentage with the extension of the shelf life period in the 2023 and 2024 seasons (Table 1). The highest weight loss percentages, 19.22, and 19.21%, were recorded after 28 days in the first and second seasons, respectively.

Table 1. Effect of post-harvest application of GA on fruit quality attributes of "Wonderful" pomegranates under ambient conditions (25 ± 2 ° C and 85% RH) for 28 days.

	Weight Loss (%)		Marketable fruits (%)		Juice content (%)		Soluble solids content (SSC) (%)		Titratable acidity (TA) (%)		SSC/TA	
	2023	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Treatment (T)												
Control	10.66a*	10.58a	89.34b	89.41b	43.22b	45.21b	14.59a	14.33a	0.91b	0.94b	16.47a	15.63a
Gum Arabic (10%)	8.52b	8.86b	91.48a	91.14a	47.27a	49.25a	14.30b	14.04b	1.00a	1.09a	14.35b	12.96b
Shelf life periods **(Days)**												
0	0.00e	0.00e	100a	100a	37.36e	39.36e	15.56a	15.3a	1.22a	1.23a	12.75d	12.41d
7	5.16d	5.42d	94.84b	94.58b	44.69d	46.67d	15.01b	14.75b	1.02b	1.12b	14.87c	13.28c
14	9.22c	9.02c	90.78c	90.97c	46.02c	48.00c	14.46c	14.2c	0.91c	1.01c	15.96b	14.11b
21	14.36b	14.97b	85.63d	85.02d	48.13b	50.11b	13.9d	13.64d	0.85d	0.88d	16.37ab	15.66a
28	19.22a	19.21a	80.78e	80. 79e	50.02a	52.00a	13.31e	13.05e	0.78e	0.83e	17.1a	16.03a
T*S Sign.	***	***	***	***	***	***	**ns**	**ns**	***	***	***	***

Values followed by the same letter (s) within pre-harvest treatments and shelf life durations in each season show no significant difference at $P \leq 0.05$, as determined by Tukey's HSD test.

As shown in Table 1, the application of 10% GA significantly reduced weight loss compared to the control in both seasons. The highest weight loss percentages under control treatment were 10.66 and 10.58%. Whereas, the lowest weight loss percentages (8.52 and 8.86%) were observed under the GA treatment in the first and second seasons, respectively.

3.2. Marketable fruit percentage

Over the storage period, a gradual and significant decline in the marketable percentage of "Wonderful" pomegranates was observed in both seasons. The lowest marketable percentages (80.79 and 80.78%) were recorded after 28 days in the first and second seasons, respectively. Moreover, the marketable percentage of "Wonderful" pomegranates treated with 10% GA was consistently higher than that of the control in both seasons. The highest marketable percentages (91.48 and 91.14%) were observed in fruits treated with 10% GA during the first and second seasons, respectively. By contrast, the lowest marketable percentages (89.34 and 89.41%) were recorded in the control fruits after 28 days of shelf life in the first and second seasons, respectively.

3.3. Juice percentage

The results showed a gradual and significant increase in the juice percentage of "Wonderful" pomegranates as the shelf life period progressed and the highest juice percentages (50.02% and 52%) were recorded after 28 days in the first and second seasons, respectively. The juice percentages of "Wonderful" pomegranates treated with 10% GA (47.27% and 49.25%) were consistently higher than that of the control treatment in both seasons (Table 1).

3.4. Soluble solids contents (SSC)(%)

The results revealed a gradual and significant decrease in SSC% as the shelf life period progressed in both seasons, regardless the treatment applied (Table 1). The highest SSC contents (13.31 and 13.05%) were recorded after 28 days in the first and second seasons, respectively. GA treatment (10%) resulted in lower SSC contents (14.3 and 14.04%) in the first and second seasons, respectively. On the other side, the highest SSC contents (14.59 and 14.33%) were observed in the control fruits.

3.5. Titratable acidity (TA) content

In the 2023 and 2024 seasons, regardless of treatment effect, there was a notable and gradual decrease in TA content as shelf life period progressed under conditions of 25 ± 2°C and 85% RH. At the end of shelf life periods (28 days), the TA contents for "Wonderful" pomegranates were high (0.78 and 0.83%) in the first and second seasons, respectively. Comparatively, GA 10% treatment consistently showed higher TA percentages than the control in both seasons.

3.6. SSC:titratable acidity ratio (SSC/TA)

During 2023 and 2024 seasons, irrespective of treatments effect, there was a notable and gradual increase in the SSC/TA ratio as the shelf life period extended under conditions of 25 ± 2°C and 85% RH. After 28 days of shelf life, SSC/TA ratios of "Wonderful" pomegranates were higher (17.1 and 16.03) in the first and second seasons, respectively. In contrast, GA at 10% treatment consistently showed lower SSC/TA ratios than the control in both seasons.

3.7. pH value

Data in Table 2 showed a gradual and significant increase in pH values as the shelf life period progressed under conditions of 25 ± 2°C and 85% RH for 28 days. By the end of the storage period, the highest pH values

were recorded in the first and second seasons, respectively. The pomegranates treated with GA at 10% consistently had lower pH values compared to that of the control in both seasons. The GA treatment at 10% resulted in pH values of 3.67 and 3.83, whereas the control treatment recorded slightly higher pH values of 3.75 and 3.92 in the first and second seasons, respectively.

3.8. Anthocyanin contents in peel (mg/100g fresh fruit)

There was a notable initial decrease in anthocyanin peel content up to day 21, followed by an increase by day 28 in both seasons, regardless of treatments effect. The highest anthocyanin peel contents (4.59 mg/100 g FW in the first season and 4.74 mg/100 g FW in the second season) were detected after 28 days. Comparatively, the anthocyanin content of "Wonderful" pomegranates treated with 10% GA was lower than the control during both seasons. The control group exhibited higher anthocyanin levels (3.87 and 4.19 mg/100 g FW), whereas GA 10% resulted in lower levels (3.15 and 3.44 mg/100 g FW) in the two seasons, respectively.

Table 2. Effect of post-harvest application of GA on bioactive compound content of "Wonderful" pomegranate fruits under ambient conditions (25 ± 2 ° C & 85% RH) for 28 days.

	pH		Anthocyanin peel content (mg/ 100 gfw fruit)		Anthocyanin juice content (mg/ 100 ml juice)		Phenolic content (%)		Vitamin C content (mg/100 ml)		Tannins (%)		Antioxidant activity	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
Treatment														
Control	3.75a*	3.92a	3.87a	4.19a	3.68a	4.02a	12.92b	13.17b	4.36b	4.66b	0.17b	0.19b	12.69b	13.53b
Gum Arabic (10%)	3.67b	3.83b	3.15b	3.44b	3.04b	3.22b	13.37a	13.72a	4.72a	5.04a	0.18a	0.19a	13.98a	14.82a
Shelf life periods (Days)														
0	3.33c	3.37c	4.08b	4.41b	3.89b	4.18b	13.31ab	14.13ab	6.53a	7a	0.24a	0.25a	15.3a	16.3a
7	3.72b	3.91b	3.45c	3.78c	3.3c	3.51c	12.64abc	13.44bc	5.73b	6.14b	0.17b	0.19b	13.05b	13.85b
14	3.79ab	3.99ab	3.06d	3.39d	2.91d	3.12d	12.12bc	12.92cd	4.3c	4.59c	0.16bc	0.18bc	12.19bc	12.99bc
21	3.82ab	4.02ab	2.37e	2.72e	2.23e	2.46e	11.51c	12.31d	3.4d	3.62d	0.15cd	0.17d	11.81c	12.61c
28	3.87a	4.07ab	4.59a	4.74a	4.49a	4.84a	13.63a	14.43a	2.74e	2.91e	0.14d	0.16d	14.32a	15.12a
T*S Sign	*	*	*	*	*	*	ns	ns	***	***	ns	ns	ns	ns

Values followed by the same letter (s) within postharvest treatments and shelf life durations in each season show no significant difference at $P \leq 0.05$, as determined by Tukey's HSD test.

3.9. Anthocyanin juice content

Anthocyanin juice content of "Wonderful" pomegranates decreased significantly after the first 21 days of shelf life but then increased after 28 days in both seasons, regardless the effect of treatments. The highest juice anthocyanin levels were recorded at 28 days (4.49 and 4.84 mg/100 ml) in the two seasons, respectively (Table 2). The juice anthocyanin content of pomegranates treated with 10% GA was consistently lower than the control group. The control group recorded the highest anthocyanin levels, (3.68 and 4.02 mg/100 ml) in the two seasons, respectively. In contrast, 10% GA treatment resulted in lower levels (3.04 and 3.22 mg/100 ml) in the two seasons, respectively (Table 2).

3.10. Total phenolic content

Total phenolic content decreased significantly during the first 21 days of shelf life but increased again by day 28 in both seasons, regardless of the treatments effect. The highest total phenolic contents were recorded at 28 days (13.63 mg Gal/100 ml and 14.3mg Gal/100 ml in the two seasons, respectively (Table 2). The pomegranates treated with 10% GA exhibited higher total phenolic contents (13.37 mg Gal/100 ml and 13.72 mg Gal/100 ml) compared to the control (12.92 mg Gal/100 ml and 13.17 mg Gal/100 ml) in the two seasons, respectively.

3.11. Vitamin C content (V.C)

The results in Table 2 showed a gradual and significant decrease in ascorbic acid content as the shelf life periods progressed in both the 2023 and 2024 seasons, regardless the effect of treatments.

The pomegranates treated with 10% GA retained higher ascorbic acid content compared to the control group. The GA-treated fruits recorded higher values (4.72 and 5.04 mg/100 ml), while the control group showed slightly lower levels (4.36 and 4.66 mg/100 ml) in the two seasons, respectively (Table 2).

3.12. Tannins (%)

The results showed a gradual and significant decrease in the tannins content of "Wonderful" pomegranates with the extension of shelf life periods in the two season seasons, regardless of the treatments effect (Table 2). In the first and second seasons, the "Wonderful" pomegranates had the lowest tannins content (0.14 and 0.16%) after 28 days, respectively. The highest tannins

contents (0.18 and 0.19%) of "Wonderful" pomegranates juice were obtained by 10% GA, while the lower contents (0.17 and 0.19%) were detected under the control treatment, in both seasons.

3.13. Antioxidant activity

The antioxidant activity progressively decreased during the first 21 days of shelf life, followed by a significant increase by day 28 in both Seasons, regardless the treatments effect. The antioxidant activity of pomegranates treated with 10% GA was consistently higher than that of the control group throughout the 28-day of shelf life. The control group had the lowest antioxidant activity levels (Table 2).

3.14. Principal component analysis (PCA) illustrated the impact of post-harvest application of GA on "Wonderful" pomegranate fruits during shelf life period

PCA biplot (Figure 1 A and C) and loading plot (Figure 1 B and D) together offer a detailed insight into the effects of post-harvest applications of Gum Arabic on "Wonderful" pomegranate fruits stored at 25 ± 2 ° C and 85% RH for 28 days during 2023 and 2024 seasons.

Combined, PC1 and PC2 explained 21.9 and 58.2 % of the total variance in the data, with PC1 accounting for 58.2 and 56.3%, and PC2 contributing 21.9% and 22.6 over the two experimental seasons, consecutively. The PCA biplot displayed the distribution of treatments according to their principal component scores, showing clusters of treatments that are closely situated and overlapping, indicating similar responses. Furthermore, the analysis revealed a significant impact of GA on the parameters, based on a distinct cluster separate from the control was detected. Additionally, GA showed a noticeable impact compared to the control in both seasons (Figure 1 A and C). Overall, the use of Gum Arabic seemed to have an impact, but both treated and untreated samples showed a general trend of transformation over time.

Similarly, the loading plot's direction and length obtained each parameter's contribution to the two principal components. Antioxidant-related parameters including total phenolic content, antioxidant activity, peel and juice anthocyanin contents are closely clustered (Figure 1 B and D), suggesting that these variables were positively correlated. This implies that samples with high anthocyanin contents either in the peel or in the juice tended to have higher antioxidant activity and total phenolic content. These properties were typically linked to the quality, freshness, and health benefits of the fruit.

Additionally, physicochemical parameters (Tannins, SSC, titratable acidity, and Vitamin C) were strongly associated with PC1 in the positive direction (Figure 1 B and D), meaning they defined a particular category of samples. This suggested that samples rich in sugars, acids, and vitamin C form a separate cluster, independent of antioxidant compounds. Otherwise, weight loss and SSC/TA ratio were negatively associated with PC1 (Figure 1 B and D), meaning they showed an inverse relationship with the parameters in the right quadrants. This suggested that samples experiencing higher weight loss may also exhibit lower sugar content and acidity balance, possibly due to degradation over time. It also implied that prolonged storage or environmental stress may lead to reduce antioxidant properties.

Generally, samples rich in anthocyanins, phenolics, and antioxidants contents are distinct from those rich in sugars, acids, and vitamin C, meaning different storage conditions or treatments could enhance one property over the other. Over time, weight loss increases, and antioxidant activity decreases, suggesting that fresh samples tend to retain more beneficial compounds.

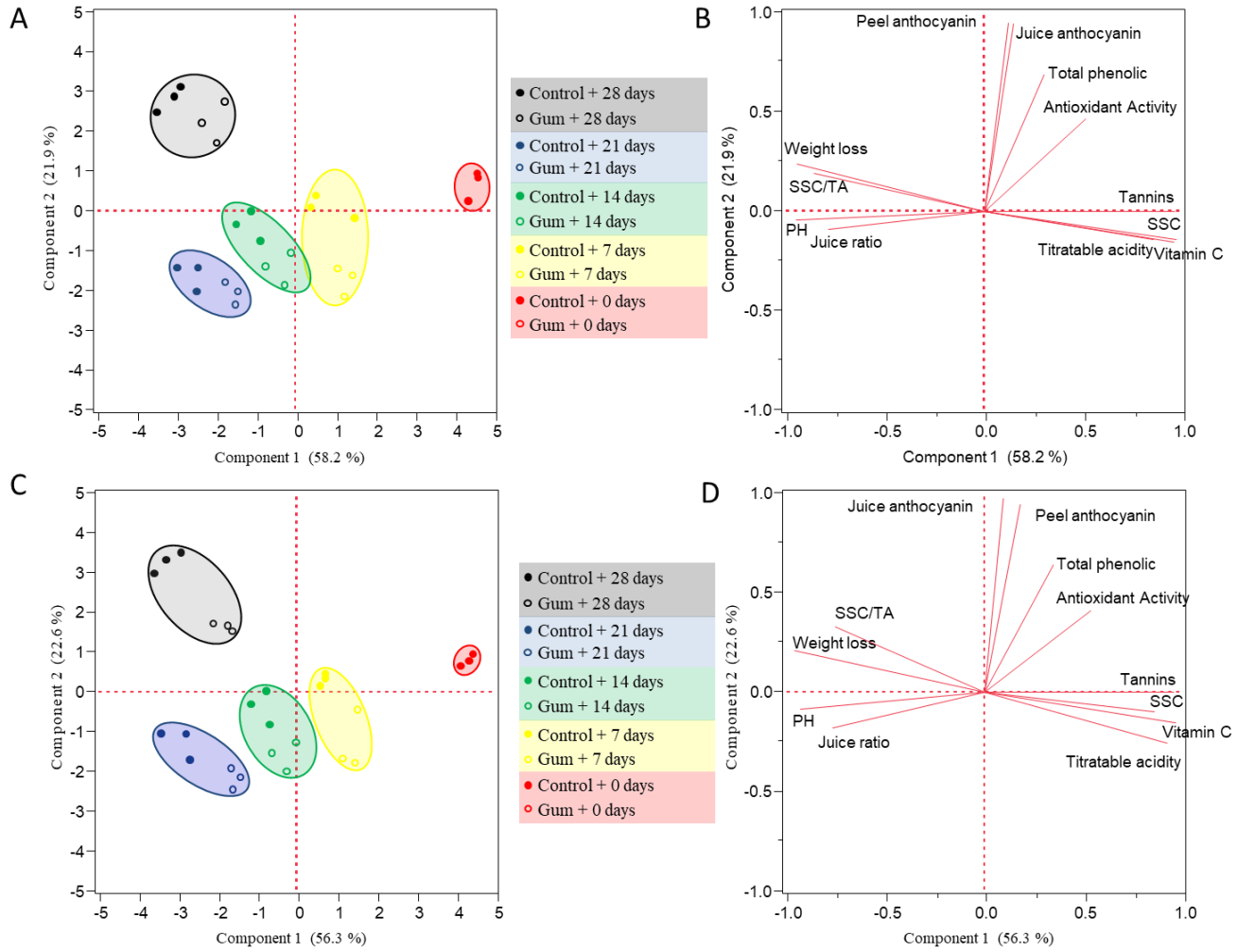

Figure 1. Principal component analysis (PCA) shows the multivariate variation among juice ratio, weight loss, PH, soluble solids content, titratable acidity, soluble solids content /titratable acidity, total phenolic, antioxidant activity, peel and juice anthocyanin contents, tannins as well as vitamin C after Gum Arabic treatment compared to the control for 28 days under shelf life conditions (25 ± 2 ° C and 85% RH) on "Wonderful" pomegranate fruits during 2023 and 2024 seasons. (A) PCA-scatter blots. Colored symbols correspond to all previous parameters after the different treatments. (B) PCA-loading plot. The vectors shown in the figure indicate the direction and strength of each parameter. The two principal axes explain the variance. The cells represent the average of each parameter level (n=3).

3.15. Heat map analysis to illustrate the impact of post-harvest application of GA on "Wonderful" pomegranate fruits during shelf life period

The heat map in Figure 2 represented the changes in various physicochemical properties of a fruit sample over time (0 to 28 days) under two different treatments: Control and Gum Arabic treatment during 2023 and 2024 seasons. The measured parameters included juice ratio, weight loss, pH, soluble solids content/titratable acidity, titratable acidity, tannins, vitamin C, soluble solids content, peel and juice anthocyanin contents, , total phenolic content, and antioxidant activity.

The control group showed an increase in weight loss over time, whereas the Gum Arabic-treated sample appeared to retain more weight in both seasons, suggesting that Gum Arabic coating helped to reduce moisture loss. In addition, the pH changes over time, with a possible decline, indicating increased acidity as the fruit ripens or degrades (Figure 2). Furthermore, vitamin C and antioxidant activity were decreased over time with the control group experiencing a more rapid decline, suggesting that Gum Arabic treatment helped in preserving antioxidant properties. Furthermore, soluble solids content and titratable acidity were varied, which could be due to sugar accumulation or acid degradation. On the other hand, peel and juice anthocyanin contents, along with total phenolic content were degraded over time, with Gum Arabic treatment possibly slowing the reduction (Figure 2).

Overall, the Gum Arabic -treated samples generally showed a slower rate of degradation in terms of weight loss, vitamin C content, and antioxidant activity compared to the control group. In addition, applying Gum Arabic coating helped on preserving fruit quality by reducing oxidation, weight loss, and maintaining biochemical components over a longer storage period (Figure 2).

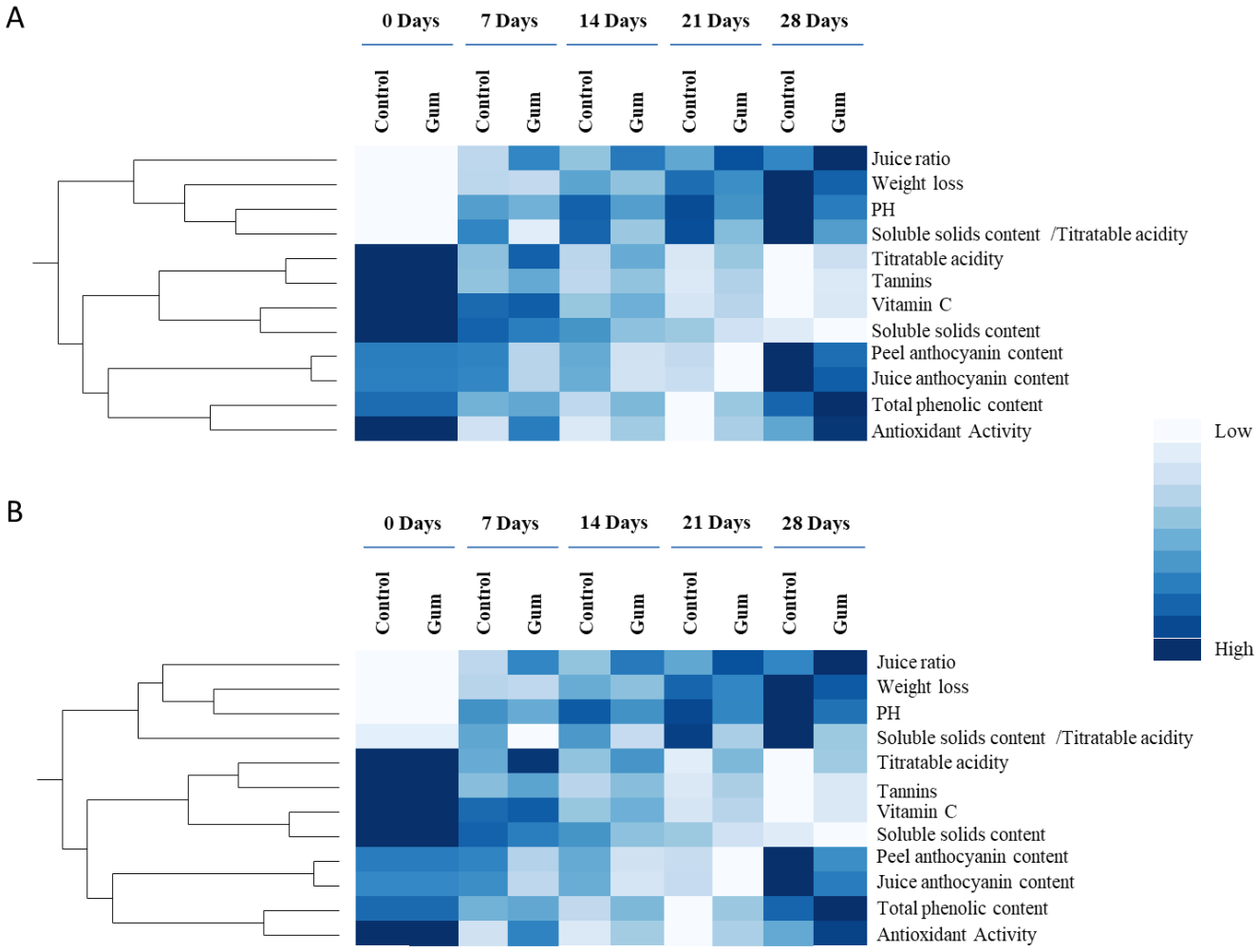

Figure 2. A two-way hierarchical cluster analysis and heat map demonstrating the effects of Gum Arabic treatment compared to the control for 28 days shelf life under ambient room conditions (25 ± 2 ° C and 85% RH) on various parameters of "Wonderful" pomegranate fruits including juice content, weight loss, PH, soluble solids content , titratable acidity, soluble solids content /titratable acidity, total phenolic, antioxidant activity, peel and juice anthocyanine contents, tannins and vitamin C during the (A) 2023 and (B) 2024 seasons. The cells represent average of each parameter level (n=3).

4. Discussion

In general, the weight loss percentage of pomegranate fruits increased throughout the shelf life. This increase might be explained by the loss of water as a result of physiological processes such as respiration, transpiration, and metabolic activities (Srivastava and Dwivedi, 2000).

Coating fruits with Gum Arabic (GA) has been shown to create significant differences and enhance fruit shelf life (Maqbool, et al 2011 and Ali et al 2010). The exchange of water between the internal and external atmospheres is considered the main factor contributing to fruit weight loss and decay, leading to a reduced marketable percentage during cold storage. With the progression of cold storage, there was an increase in the transpiration rate and ethylene production (Emam et al., 2021). These findings align with those of Anjum et al. (2020), who reported that guava fruits coated with 10% GA exhibited a significant reduction in weight loss (%) and a delayed change in firmness. Similarly, Khaliq et al. (2016) found that 'Choke Anan' mangoes treated with edible GA coatings experienced significantly lower weight loss (%) compared to uncoated fruits during cold storage.

El-Gioushy et al. (2022) reported that natural edible coatings helped on maintaining the marketability of guava at a higher level compared to uncoated fruits. Additionally, fruit samples coated with GA (10%) and GA (10%) + moringa (10%) retained a higher marketability percentage, despite significant differences among treatments.

The juice content is a crucial factor, as was already established. According to our findings, the amount of juice increased during storage, most likely as a result of the arils' tissues "softening" and making it easier to extract the juice. Ferrara et al. (2014) revealed a small change in pomological and juice content features in the fruit of pomegranate at harvest. Low molecular weight coating improved Juice percentage and the water content for citrus stored at 15˚C for 56 days, (Chien et al., 2007). These findings are in line with those of Anjum et al.

(2020), who observed that guava fruits coated with 10% GA exhibited a significant reduction in weight loss (%) and a delayed change in juice percentage during storage at room temperature, compared to uncoated fruits of banana and papaya. Emam et al., (2024) reported that treating pomegranate fruits with either oils or edible coatings positively influenced both juice weight and volume.

The high increase in SSC of control fruits could be explained by increased hydrolytic degradation of complex starch polymer into simple sugars by hydrolytic enzymes during the ripening process and this indicates the deterioration of fruit quality (Emam et al., 2024). The application of GA coating treatments has been shown to slow changes in soluble solids content by inhibiting respiration processes, which in turn reduces the conversion of starch to sugar during storage (Soyer et al., 2003). El-Ramady et al. (2015) reported that coating treatments had a significant impact on SSC, despite some noticeable variations. However, fruits treated with GA coatings exhibited lower SSC values compared to uncoated fruits.

Previous studies have highlighted the significance of SSC content in fruit during storage (Zhou et al., 2007). Edible coatings create semipermeable barriers that restrict gas exchange, thereby slowing respiratory and metabolic processes and minimizing the loss of essential nutrients such as organic acids (Porta, 2015). Consequently, Kawhena et al., (2022) found that applying GA coatings often led to a reduction in SSC content during storage, with coated fruits exhibiting lower SSC levels than uncoated ones.

The organic acids stored mainly in the cell vacuoles are the source of acidity in fruits, these acids act as respiratory substrates, and therefore, their contents decrease with the extension of the storage periods (Scott, 1980; Ball, 1997). In addition, TA as an important quality parameter of maturity and ripening fruits influences fruit taste and aroma. The decline in TA content during the storage study was due to the metabolic changes in fruit resulting from the use of organic acid during the respiratory process (Kaur et al., 2013).

However, the edible coating acts as a barrier to water and gas exchange in the fruit. Thus, controlling metabolic changes whilst maintaining organic acid by lowering the respiratory process. Similar effects on titratable acidity were observed during storage of strawberry fruit coating by Aloe vera and ascorbic acid (Sogvar et al., 2016), as well as in 'Yali' pears (Lin et al., 2008). Additionally, Kawhena et al. (2022) reported that the application of GA coatings often reduces the loss of TA content during cold storage. In our current research, GA coating treatments resulted in higher TA content compared to fruit that was not coated.

SSC/TA is an important parameter for assessing the ripening of fruits and it is a good indicator of fruit flavor, as a lower ratio of SSC/Acid makes fruits more desirable (Petriccione et al., 2015). The SSC/TA ratio is a reliable indicator of fruit maturity, as it is closely associated with consumers' organoleptic perception of sweetness and acidity (Hasnaoui et al., 2011). The lower TA content in coated fruit may have significantly contributed to maintaining a higher SSC/TA ratio compared to uncoated fruit. The preservation of higher TA content can be attributed to reduce cellular activity, as organic acids act as substrates in the Krebs cycle, providing energy for repairing aging cells and membranes (Soyer et al., 2003). Moreover, Kawhena et al. (2022) observed that the SSC/TA ratio increased with prolonged storage, with GA-coated treatments exhibiting lower values compared to the control.

Organic acids, such as citric and malic acids, serve as primary substrates for respiration. Therefore, a decline in acidity is expected in highly respiring fruits, as observed in the control samples (El-Anany et al., 2009). The higher pH value in the control samples may be attributed to the reduced hydrolysis and deposition of organic acids, which were gradually oxidized due to a slower respiration process (Senturk Parreidt et al., 2018).

The effect of GA treatment on pH values showed that the control samples experienced an increase in pH throughout the storage period; with significantly higher pH readings compared to the GA treated samples. In contrast, the treatments exhibited insignificant changes in pH ($P > 0.05$) up to the 15th day (Lelgut, 2020). The Gum Arabic coating modified the atmosphere around the fruit by forming a semipermeable film that restricted moisture and gas exchange. This barrier effectively slowed acid degradation, resulting in mangoes with lower pH values (higher titratable acidity) compared to the control samples (Yaman and Bayoindirli, 2002).

Anthocyanins are responsible for the desirable red color of many red-colored fruits (Li et al., 2010). The formation and intensity of anthocyanin are major criteria for the ripening and maturity stages. The increase in the total anthocyanin during storage period can be clarified by the appearance of anthocyanin bound to membranes due to the degradation of chlorophyll. After that, the anthocyanin content may decrease especially in cases of prolonged storage because of their breakdown in plant tissues by enzyme such as glycosidases (anthocyaninases), polyphenoloxidases, and peroxidases that are enhanced by cold conditions (Leong and Oey, 2011). Various authors have reported a continuous accumulation of anthocyanins induced by cold temperatures (5–10 °C), followed by a sharp decline with prolonged storage duration (Fawole and Opara, 2013).

Fischer et al. (2011) reported that the degradation of anthocyanin content during storage is likely due to the ability of edible coatings to reduce the activity of polyphenol oxidase and peroxidase enzymes by altering the internal atmosphere of coated fruits. Similarly, Yousef et al. (2020) found that anthocyanin degradation in litchi fruit is influenced by polyphenol oxidase and peroxidase activity, while Rajasekar et al. (2012) observed that applying chitosan coating reduced enzyme activity in stored pomegranates. Emam et al. (2024) highlighted that anthocyanin is the primary phenolic compound responsible for the purple-red coloration of pomegranates. Furthermore, pomegranate fruit anthocyanins were found to exhibit higher antioxidant activity than vitamin C, vitamin E, and β-carotene. Moreover, treating pome-

granate fruits with 2% rosemary oil in combination with 10% GA proved to be the most effective coating treatment for enhancing total anthocyanin content, yielding the highest significant values compared to the control. The ”Wonderful” pomegranate variety showed a gradual and significant increase in anthocyanin content as the storage period progressed.

In addition, Phenolic compounds play a crucial role in scavenging free radicals and reducing the development of senescence stress (Fischer et al., 2011). Researchers have associated changes in the synthesis and biosynthesis of phenolic compounds with the activity of phenylalanine ammonia-lyase and polyphenol oxidase enzymes. These processes can be influenced by applying coatings to the fruit surface, which inhibit gas exchange and limit moisture loss (Martínez-Romero et al., 2013).

Besides, Emam et al., (2024) reported that total phenol content gradually decreased as the cold storage period progressed. Meanwhile, significant differences were observed between all coating treatments and the uncoated samples during storage. The treatment with 2% rosemary oil combined with 10% Gum Arabic recorded the lowest total phenol content compared to the control. All coating treatments effectively reduced phenolic compound degradation while extending the storage period. The application of coatings to fresh fruit before cold storage is often associated with increased phenolic compound production, likely as a response to low temperatures and modifications in the internal atmosphere (Wang and Gao, 2013).

The decline in ascorbic acid content during cold storage is typically linked to an accelerated rate of senescence (Yahia et al., 2013). This loss is primarily due to the rapid conversion of L-ascorbic acid into dehydroascorbic acid, facilitated by the enzyme L-ascorbic acid oxidase (Hussein et al., 2015). Emam et al. (2024) reported that ascorbic acid is a crucial quality factor that is highly susceptible to degradation due to oxidation during storage. In pomegranate fruits, vitamin C content gradually declined throughout the storage period, with the highest loss occurring in untreated fruits. Regarding ascorbic acid retention, fruits coated with GA showed a better response, exhibiting less degradation during storage. The retention of ascorbic acid in the coated fruits may be attributed to the decrease in respiration rate and reduction of oxidation, uncoated fruits showed faster loss in ascorbic acid than coated fruits as suggested by Abdel-Salam (2016) in Ruby Seedless Grapevine and Atrash et al. (2018) in Mexican lime fruits.

Fruit juices that include tannins, which are phenolic component groups, have astringency and turbidity. Fruit juices' tannin concentration was influenced by several parameters, including the juices' pH and viscosity, as well as the cultivar, parts, and maturity stages. There have been numerous approaches studied to remove tannins from fruit juices. Numerous fruit juices, including those from apples, grapes, and berries, are high in tannins (Smeriglio, 2017). The juices' turbidity, brown hue, and astringency were all impacted by the high tannin content. Tannins must thus be eliminated from fruit juice to ensure both consumer approval and storage stability. This may be attributed to post-harvest treatments that minimized tannin deterioration by lowering the respiration rate and creating a modified atmosphere within the fruit, which influenced its metabolism as it matured (El-Gioushy et al., 2022).

Meanwhile, GA is believed to enhance taste by influencing acidity, bitterness, and the astringency of tannins (Ribereau-Gayon et al., 2020). Its complex molecular structure allows it to delay or reduce astringent and bitter sensations by temporarily interacting with taste receptors. This effect may be attributed to the inhibition of salivary protein and tannin interactions or precipitation by Arabic gum (Bichescu and Stanciu, 2018).

The presence and production of ascorbic acid and phenolic compounds, including flavonoids, tannins, and phenolic acids, play a crucial role in inducing radical scavenging activity (RSA). Additionally, the antioxidant activity of GA also contributed to maintaining the antioxidant activity of the segment at all stages of the storage study. Similar results were found with Khaliq et al., (2016) on mango fruit. They suggested GA as a novel coating material for the retention of antioxidant activity and extending the shelf-life of fruits.

In general, a positive correlation has been observed between total phenolic content, total flavonoids, and antioxidant capacity (Mphahlele et al., 2016). The delayed increase in antioxidant activity in “Wonderful” pomegranate fruit treated with a 10% GA may be attributed to delay maturation of these fruits compared to the control. This effect was also evident in a previous study, where papaya fruit coated with GA exhibited a slower ripening process by delaying biochemical and physiological changes during cold storage (Kawhena et al., 2022). Additionally, other factors, such as the presence of antioxidants and vitamins, also contribute to the overall effectiveness of antioxidant activity (Addai et al., 2013).

5. Conclusions

The findings of this study highlight on the effectiveness of Gum Arabic 10% (GA) as a postharvest treatment for preserving the quality and extending the storability of “Wonderful” pomegranate fruits under ambient shelf life conditions (25 ± 2 ° C and 85% RH). GA treatment significantly reduced weight loss, maintained higher juice percentage, and preserved essential bioactive compounds, including phenolics, anthocyanins, tannins, and ascorbic acid. Additionally, it helped on retaining titratable acidity (TA) while reducing the decline in soluble solids content (SSC) and pH values. The enhanced antioxidant activity indicated the protective role of GA in slowing down fruit senescence and maintaining overall fruit quality. Therefore, these results recommended that GA coating presents a promising eco-friendly and cost-effective approach to minimizing postharvest losses and enhancing the marketability of “Wonderful” pomegranates.

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