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Postharvest physiological and antioxidant responses of three distinct rose cultivars

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Abstract

This study investigated the postharvest physiological and biochemical responses of three commercial hybrid tea rose cultivars 'Jumilia' (white-pink), 'ID Plus' (red), and 'Penny Lane' (yellow) during cold storage at 4°C over a nine-day period. Key parameters, including relative water content (RWC), electrolyte leakage (EL), total protein concentration, pigment profiles (anthocyanins and carotenoids), and peroxidase (POD) activity, were evaluated. Results showed significant ($p<0.01$) cultivar-dependent variations and time-related declines in most physiological traits. RWC and total protein decreased progressively, while EL significantly increased, signaling membrane destabilization and advancing senescence. Pigment analysis revealed strong cultivar specificity; 'ID Plus' maintained the highest anthocyanin levels, whereas 'Penny Lane' exhibited the greatest initial carotenoid content, which underwent a marked reduction during storage. POD activity patterns differed significantly, with 'Penny Lane' showing higher initial activity followed by a sharp decline, reflecting diverse antioxidant capacities among cultivars. These findings underscore that while storage duration exacerbates physiological degradation, the inherent genetic background primarily governs pigment stability and enzymatic defense mechanisms. This research provides critical insights into cultivar-specific postharvest behavior, aiding in the selection of roses with enhanced longevity and visual quality.

Keywords: Antioxidant enzymes, Cultivar variability, Pigment composition, *Rosa hybrida*, Senescence

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1. Introduction

Cut roses (*Rosa hybrida* L.) represent one of the most important ornamentals in the global floriculture industry due to their aesthetic value and wide commercial demand (Pourghorban et al., 2020). However, the primary challenge in the floriculture supply chain is the rapid senescence that occurs following harvest. Once severed from the mother plant, cut flowers undergo a series of complex physiological and biochemical changes, including the loss of turgor pressure, degradation of cellular components driven by nutrient depletion, water stress, and the accumulation of reactive oxygen species (ROS) (Pourghorban et al., 2020).

The physiological integrity of rose petals during postharvest life is closely linked to their hydration status and membrane stability. The Relative Water Content (RWC) serves as a vital indicator of the plant's ability to maintain turgidity, which is essential for petal expansion and structural stability (Sardari et al., 2022). Concurrently, the stability of the cellular membrane is a primary determinant of floral longevity. Membrane damage, often quantified through ion leakage, serves as a direct measure of electrolyte loss resulting from lipid peroxidation. Furthermore, the degradation of total protein content is a hallmark of senescence, reflecting the breakdown of enzymatic and structural proteins necessary for maintaining cellular homeostasis (Vatankhah et al., 2022). The postharvest life of roses is strictly regulated by the balance between oxidative damage and the plant's antioxidant defense mechanisms. During senescence, the imbalance between ROS production and antioxidant scavenging leads to lipid peroxidation, membrane degradation, and the breakdown of essential pigments, ultimately resulting in petal wilting and color loss. Among the various physiological indicators, enzyme activities such as peroxidase (POD), superoxide dismutase (SOD), and catalase (CAT) play a crucial role in mitigating oxidative stress and prolonging floral longevity (Abri et al., 2014).

Despite the importance of understanding cultivar-specific responses, comprehensive comparative studies integrating physiological, proteomic, and antioxidant indices for these specific commercial roses are scarce. Therefore, this study was designed to investigate the postharvest physiological and antioxidant dynamics of *Rosa* cv. ‘Jumilia’, *Rosa* cv. ‘ID Plus’, *Rosa* cv. ‘Penny Lane’. By analyzing parameters such as RWC, protein content, ion leakage, and antioxidant enzyme activities, this research aims to elucidate the physiological mechanisms underlying senescence and provide a scientific basis for selecting cultivars with superior postharvest stability.

2. Material and methods

2.1. Plant Materials and Experimental Design

Freshly cut flowers of three commercial hybrid tea rose cultivars ‘Jumilia’ (white with pink margins), ‘ID Plus’ (red), and ‘Penny Lane’ (yellow), were prepared from the Nafis Agro-Industrial Complex in Isfahan, Iran. The images of the flowers are visible in Figure 1.

Figure 1.
The studied cultivars

Upon arrival, the flowers were immediately transferred to a controlled environment and maintained at 4˚C to simulate optimal postharvest storage conditions. The experiment was conducted over a period of 9 days, with sampling performed at regular intervals (1, 3, 6, and 9 days after harvest).

2.2. Physiological and Biochemical Analyses

Relative Water Content (RWC) of the petals was determined using the formula (Bohlouli et al., 2019):

$RWC\ (\%) = ((W_f - W_d) / (W_t - W_d)) \times 100\%$.

Where W_f is fresh weight, W_d is dry weight, and

W_t is turgid weight (obtained by immersing samples in distilled water for 24 h).

Electrolyte leakage (EL): To assess membrane stability, EL was measured by immersing petal samples in deionized water. The initial electrical conductivity EC_1 was recorded, the samples were then autoclaved at 121°C for 20 min to release total electrolytes. After cooling, the final electrical conductivity was measured as EC2and after 24 h, measured. The leakage percentage was calculated as (Dehestani-Ardakani et al., 2019):

$EL\ (\%) = (EC_1/EC_2) \times 100$

Total Protein Content: The total protein concentration was quantified using the Bradford method (Bradford, 1976).

Peroxidase Enzyme Activity (POD) was determined spectrophotometrically by measuring the oxidation of guaiacol in a 100 mM phosphate buffer (pH 7.0). The increase in absorbance was recorded at 470 nm over a specific time interval. The enzyme activity was calculated using the extinction coefficient of tetraguaiacol (26.6 $mM^{-1}.cm^{-1}$) and the results were expressed as µmol. min^{-1}. g^{-1}FW (Putter, 1974).

Total anthocyanins were extracted using acidified methanol and quantified by measuring absorbance at 520nm and 700nm according to the pH differential method. This following formula was used to calculate the anthocyanin concentration (Giusti and Wrolstad, 2001):

Total anthocyanines (mg. g^{-1} FW) = $A \times MW \times DF \times 10^3 / \epsilon \times L$

$A = (A_{520nm} - A_{700nm})\ pH\ _{1.0} - (A_{520nm} - A_{700nm})\ pH\ _{4.5}$

Where MW: is the molecular weight of Cyanidin-3-glucoside (449.2 $g.mol^{-1}$), DF: is the dilution factor (the ratio by which the original extract was diluted), ϵ: is the molar extinction coefficient for Cyanidin-3-glucoside (26,900 $L.mol^{-1} \cdot cm^{-1}$), L: is the cuvette path length (1 cm).

Total carotenoids were extracted in acetone and determined spectrophotometrically at 450 nm. The total carotenoid content was calculated using a standard spectrophotometric formula (Davies, 1976):

Total carotenoids (mg. g^{-1} FW) = $(4 \times A \times V) / W$

Where A: is the absorbance (Optical Density) at 450 nm, V: is the total volume of the extract (mL), W: is the weight of the sample used (g), 4: is the constant derived from the absorption coefficient of β\betaβ-carotene.

2.3. Statistical Analysis

This study was conducted under laboratory conditions using a completely randomized design with three replications, each replication consisting of three stems placed in a vase containing 500 mL of distilled water. The data were analyzed using SPSS version 22. Analysis of variance (ANOVA) was performed, and mean comparisons were conducted using Duncan's multiple range test at $P<0.05$ when the assumption of homogeneity of variances was met. In cases where Levene's test indicated significant heterogeneity of variances, Welch's ANOVA was applied and group means were compared using the Games–Howell test. Graphs were prepared using Excel 2013.

3. Results and Discussion

3.1. Petal relative water content

According to Table 1, the analysis of variance revealed a significant effect of cultivar ($p<0.05$) and a highly significant effect of days ($p<0.01$) on *Rose* RWC. Furthermore, the interaction between cultivar and days was also found to be highly significant ($p<0.01$).

Table 1.
ANOVA for physiological and antioxidant traits of *Rose* cultivars

S. V	df	RWC	EL	Total protein	POD	Total anthocyanins	Total carotenoids
Cultivar	2	84.62^{*}	4.89^{**}	0.17^{ns}	1.92^{**}	2.82^{**}	1.27^{**}
Day	3	539.20^{**}	822.99^{**}	40.29^{**}	0.70^{**}	0.78^{**}	0.06^{**}
Cultivar× Day	6	31.11^{**}	33.52^{**}	3.97^{**}	0.72^{**}	0.18^{**}	0.03^{**}
Error	24	18.41	0.13	0.59	0.003	0.01	0.001
CV		0.09	0.53	0.23	0.54	1.02	1.09

*, ** and ^{ns} significant at p<0.05, p<0.01 and not significant, respectively. For carotenoids Welch's ANOVA and Games–Howell test were used due to unequal variances (Levene's test, p<0.05)

The RWC was significant for cultivar (p<0.05), storage time and their interaction (p<0.01). Mean comparison of RWC showed no significant difference among the cultivars on one and third days. However, after three days, a significant decreasing trend in RWC was observed over the subsequent days. Among the cultivars, 'Jumilia' and 'ID Plus' exhibited the highest RWC values throughout the experimental period (Figure 2).

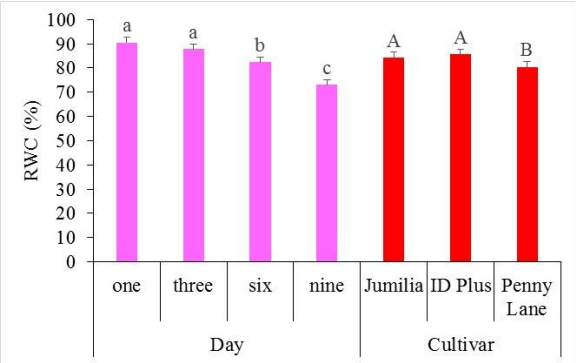

Figure 2.
Main effects of storage time (day) and cultivar on RWC in rose flowers during postharvest storage. Uppercase letters show differences between cultivars and lowercase letters show differences between storage time (Duncan, p<0.05). means + SE (n=3)

The interaction between the 'ID Plus' cultivar and the observed reduction in RWC suggests that this specific cultivar may be more susceptible to water loss over time compared to others, or it may have a different physiological response to the conditions that led to water deficit. While the overall trend across all cultivars showed a decrease in RWC, the specific pattern for 'ID Plus' warrants attention (Figure 3).

This could imply differences in root water uptake efficiency pre-harvesting, and transpiration rates, or the ability to maintain tissue hydration under the prevailing environmental conditions during the study.

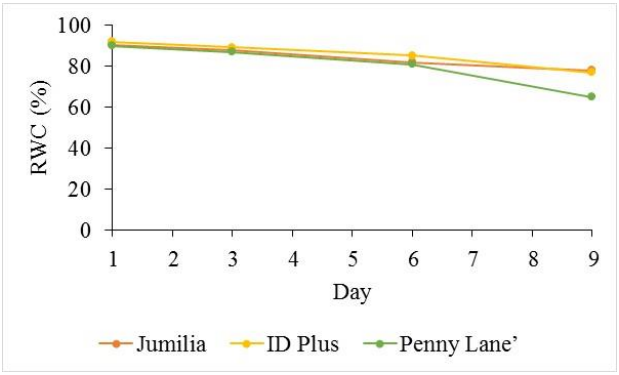

Figure 3.
Interaction effects of cultivar and storage time (day) on RWC in rose petals.

The higher leaf RWC observed in the cultivars 'Jumilia' and 'ID Plus' may be attributed to their genetic background, which likely confers superior capacity for water uptake, retention, and osmotic adjustment. These cultivars may possess genetically determined traits such as more efficient root systems, lower stomatal density or conductance, thicker cuticular layers, and enhanced cellular water conservation mechanisms. Such inherited characteristics can improve their ability to maintain cell turgor and leaf hydration under changing postharvest environmental conditions, resulting in higher RWC compared with the other cultivar (Alboghobeish et al., 2021).

3.2. Electrolyte leakage

Based on Table 1, the EL was significantly influenced by the cultivar, storage duration, and their

interaction ($p<0.01$). A progressive increase in EL was observed across all cultivars throughout the 9-day storage period, rising from a mean of 7.33% on day 1 to 29.14% on day 9, indicating a cumulative loss of cellular membrane integrity. Regarding cultivar differences, 'Penny Lane' exhibited the highest average EL (17.06%), followed by 'ID Plus', and 'Jumelia' 16.49%, and 15.79%, respectively (Figure 4).

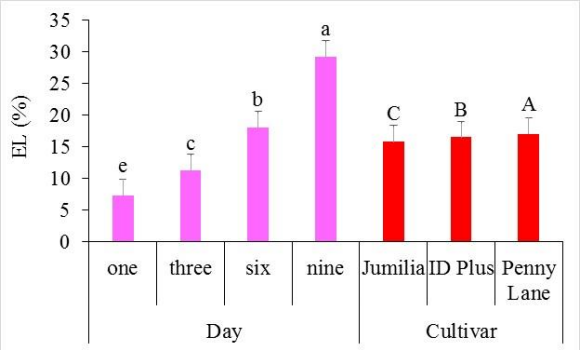

Figure 3.
Main effects of storage time (day) and cultivar on EL in rose flowers during postharvest storage. Uppercase letters show differences between cultivars and lowercase letters show differences between storage time (Duncan, $p<0.05$). means + SE (n=3)

At the beginning of storage (Day 1), 'Jumilia' exhibited the lowest electrolyte leakage (5.43%), while Penny Lane showed the highest initial leakage (9.33%). By Day 9, electrolyte leakage increased significantly in all cultivars, reaching its maximum in Penny Lane (33%), followed by 'Jumilia' (30.2%). In contrast, 'ID Plus' demonstrated the highest membrane stability at the end of the storage period, with its leakage only reaching 24.22%. This indicates that although all cultivars underwent membrane degradation, 'ID Plus' maintained significantly better membrane integrity during long-term storage compared to the other two cultivars (Figure 5).

The progressive increase in LE during storage may be attributed to the deterioration of cell membrane structure and increased membrane permeability caused by senescence and oxidative stress. Lower electrolyte leakage in 'ID Plus' suggests a greater ability to preserve membrane stability and reduce cellular damage under storage conditions. Therefore, this cultivar may possess better postharvest performance and higher tolerance to prolonged storage compared to 'ID Plus' and 'Jumilia'.

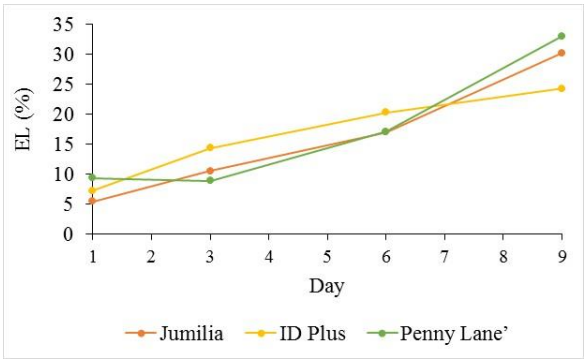

Figure 4.
Interaction effects of cultivar and storage time (day) on EL in rose petals.

The increase in EL over time may be attributed to the progressive disruption of cell membrane integrity and the consequent enhancement of membrane permeability under the experimental stress conditions. As membrane damage intensifies, a greater amount of electrolytes and ions leaks from the cells into the surrounding medium. In addition, with prolonged exposure, the ability of cells to maintain homeostasis and osmotic regulation declines, leading to a greater ion gradient between the intracellular and extracellular environments and, ultimately, increased ionic leakage (Mohammadi et al., 2020). This pattern reflects the cumulative effect of time on cell membrane stability.

The progressive increase in EL during storage indicates a gradual loss of membrane integrity in rose petals. Membrane deterioration is a common physiological response during postharvest senescence, as structural lipids and membrane-associated proteins become damaged, leading to increased membrane permeability and enhanced ion efflux. The observed differences among cultivars suggest variation in membrane stability and tolerance to postharvest stress (Sabokdast et al., 2022). The sharper increase in EL observed in 'Jumilia' indicates a greater susceptibility to membrane damage during storage, whereas the more gradual increase in 'ID Plus' suggests relatively better maintenance of membrane integrity. 'Penny Lane' showed moderate stability during the early storage period but exhibited a marked increase in EL toward the end of storage.

Overall, these results indicate that storage duration plays a critical role in membrane deterioration, while cultivar-dependent differences may influence the rate at which membrane stability declines during postharvest storage.

3.3. Total protein

According to Table 1, total protein content was significantly affected by storage time and the cultivar × day interaction ($P<0.01$). The highest protein contents were observed on the first, with values of 11.29 mg. g^{-1} FW. With increasing storage time, total protein content decreased in all three cultivars (Figure 6).

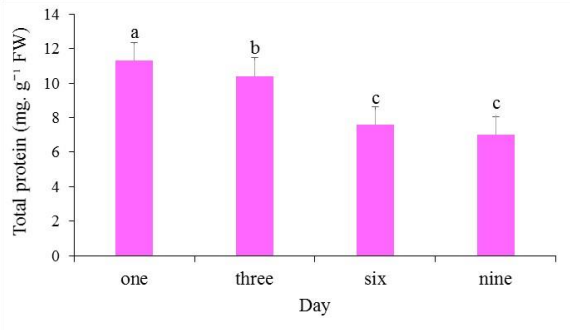

Figure 5.
Main effects of storage time (day) and cultivar on total protein in rose flowers during postharvest storage. Lowercase letters show differences between storage time (Duncan, $p<0.05$). means + SE (n=3)

As illustrated in Figure 7, 'ID Plus' and 'Jumilia' showed no significant changes up to day 3; however, after this time the decline in protein content was more pronounced in 'ID Plus' than in 'Jumilia'. In contrast, 'Penny Lane' exhibited a gradual decrease in protein content from the first day of storage.

The reduction in total protein content during storage can be attributed to the progression of senescence in floral tissues. During senescence, catabolic processes become dominant and proteolytic enzymes such as proteases are activated, leading to the degradation of cellular proteins into peptides and amino acids (Abbasi and sheikhakbari-Mehr, 2025).

The slower decline in protein content observed in 'Jumilia' suggests a greater ability to maintain metabolic activity and delay senescence-related degradation during storage. In contrast, the rapid reduction in 'Penny Lane' and 'ID Plus' may indicate higher sensitivity to storage stress and accelerated protein breakdown in floral tissues.

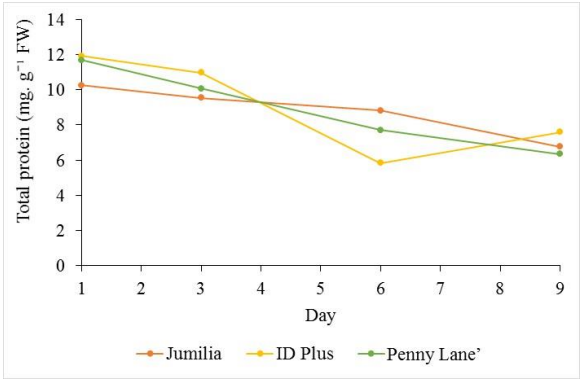

Figure 6.
Interaction effects of cultivar and storage time (day) on total protein in rose petals.

The reduction in total protein content during storage can be attributed to the progression of senescence in floral tissues. During senescence, catabolic processes become dominant and proteolytic enzymes such as proteases are activated, leading to the degradation of cellular proteins into peptides and amino acids. This process contributes to the recycling of nitrogenous compounds and the remobilization of cellular resources (Bagheri Tirtashi et al., 2013). In addition, oxidative stress and metabolic alterations during postharvest storage may further accelerate protein degradation by damaging cellular structures and increasing membrane permeability. The observed differences among cultivars suggest variation in their physiological responses to storage conditions and their ability to maintain protein stability during the postharvest period (Kharrazi et al., 2017; Khatib and Bohlouli, 2025).

3.4. Peroxidase enzyme activity

The results indicate that the pattern of POD activity varied among cultivars during the storage period. suggesting a reduction in the antioxidant enzymatic defense system over time. The significant cultivar × day interaction also shows that the rate of decrease was not identical among cultivars. According to the ANOVA presented in Table1, POD

activity was significantly affected by cultivar, day, and the interaction between cultivar × day interaction ($p<0.01$). POD activity decreased during storage, and it was ranged from 0.63 to 1.27 µmol. min^{-1}. $g^{-1}FW$ (Figure 8).

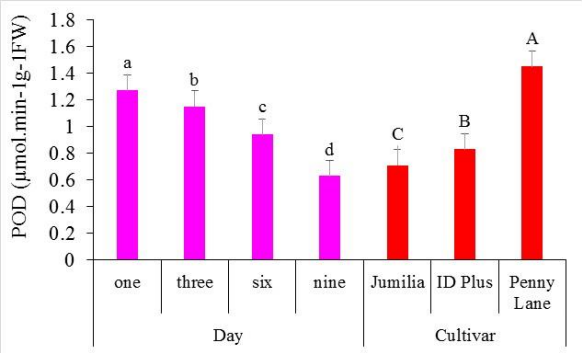

Figure 7.
Main effects of storage time (day) and cultivar on anthocyanins in rose flowers during postharvest storage. Uppercase letters show differences between cultivars and lowercase letters show differences between storage time (Duncan, $p<0.05$). means + SE (n=3)

The highest activity was observed in 'Penny Lane', particularly on day 1 with values of 2.47 µmol. min^{-1}. $g^{-1}FW$. In contrast, the trends in POD activity for the 'ID Plus' and 'Jumilia' were more similar to each other. The lowest level of enzyme activity were observed on day nine, with reported 0.9, 0.53, and 0.46 µmol. min^{-1}. $g^{-1}FW$ 'Penny Lane', 'ID Plus', and 'Jumilia' respectively (Figure 9).

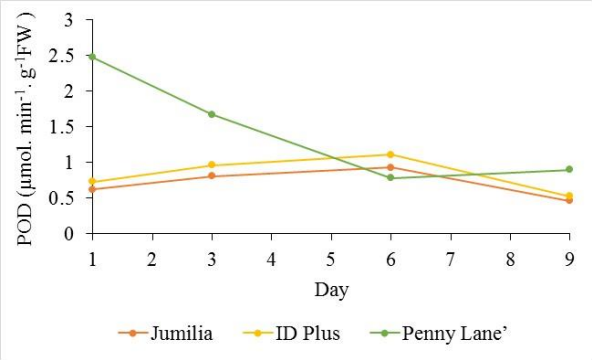

Figure 8.
Interaction effects of cultivar and storage time (day) on POD activity in rose petals.

The observed decrease in POD activity over time is most plausibly attributable to the progression of floral senescence, during which the plant's antioxidant and enzymatic defense capacities gradually decline (Bagheri Tirtashi et al., 2013). Early in the experiment, elevated peroxidase activity particularly in the **'**Penny Lane**'** may reflect an intensified response to redox imbalance and reactive oxygen species (ROS) production.

However, as the flowers age, proteolytic degradation and reduced protein synthesis can diminish the abundance and catalytic efficiency of peroxidase, while the overall reprogramming of metabolism toward senescence associated processes may further limit enzyme functionality. In addition, senescence related hormonal signaling (e.g., ethylene) and changes in cellular substrate availability can contribute to the time dependent attenuation of peroxidase activity (Khavarinajad, 2018). The cultivar dependent pattern suggests that genetic differences influence both the timing of senescence onset and the magnitude of ROS scavenging responses, resulting in more pronounced early activity in **'**Penny Lane**'** and a relatively more synchronized decline in **'**ID Plus**'** and **'**Jumilia**'**.

The temporal reduction in peroxidase activity is likely coupled with a loss of membrane structural integrity, a hallmark of advanced floral senescence. As enzymatic scavenging diminishes, the unchecked accumulation of ROS can lead to the peroxidation of membrane lipids, thereby increasing electrolyte leakage and cellular de-compartmentalization (Bagheri Tirtashi et al., 2013). This structural breakdown not only exacerbates the decline in POD functionality by disrupting the localized environments of cell wall-bound and vacuolar isoforms but also accelerates the leaching of pigments and nutrients. Consequently, the earlier and more dramatic shift in POD activity observed in 'Penny Lane' might indicate a faster transition toward lipid peroxidation and membrane destabilization compared to 'ID Plus' and 'Jumilia', which appear to maintain a more regulated, albeit declining, antioxidant status throughout the storage time.

3.5. Total anthocyanin

The results of the ANOVA (Table 1), indicated that the total anthocyanin content was significantly

influenced by the cultivar, storage duration, and their interaction ($p<0.01$). Among the studied cultivars, 'ID Plus' exhibited the highest anthocyanins with an average of 1.5 mg. g^{-1}FW, followed by 'Penny Lane' (0.28 mg. g^{-1}FW) and 'Jumilia' (0.15 mg. g^{-1}FW).

Regarding the effect of storage time, a significant and progressive decline in anthocyanins was observed across all cultivars. The mean anthocyanin content decreased from 0.84 mg. g^{-1}FW on day 1 to 0.63 mg. g^{-1}FW on day 3, followed by a sharper decline to 0.3 mg. g^{-1}FW on day 6, finally reaching its lowest value of 0.21 mg. g^{-1}FW on day 9 (Figure 10).

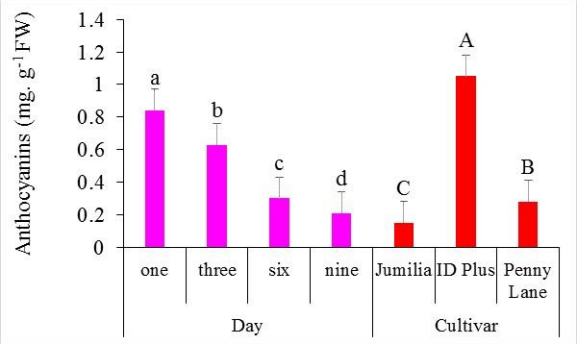

Figure 9.
Main effects of storage time (day) and cultivar on anthocyanins in rose flowers during postharvest storage. Uppercase letters show differences between cultivars and lowercase letters show differences between storage time (Duncan, $p<0.05$). means + SE (n=3)

Figure 11, shows the temporal changes in petal anthocyanin content during cold storage (days 1, 3, 6, and 9) in three rose cultivars. Overall, the interaction effect revealed that while all cultivars followed a downward trend, the rate of anthocyanins degradation was more pronounced in the high anthocyanin cultivar ('ID Plus') compared to the others.

At the beginning of storage (day 1), 'ID Plus' exhibited the highest anthocyanins (1.59 mg. g^{-1}FW), which gradually declined to 0.51 mg. g^{-1}FW by day 9, representing a 68% reduction. In contrast, 'Penny Lane' started with a moderate anthocyanins of 0.71 mg. g^{-1}FW on day 1 but underwent a drastic and sharp decline of approximately 97%, reaching a near depleted level of 0.02 mg. g^{-1}FW on day 9. 'Jumilia' maintained the lowest initial anthocyanins (0.22 mg. g^{-1}FW), which steadily decreased to 0.09 mg. g^{-1}FW at the end of the storage time (59% reduction).

The reduction in anthocyanins content during storage may be associated with pigment degradation and oxidative processes occurring under cold storage conditions. Cultivars with greater anthocyanins retention, such as 'ID Plus', may exhibit better color stability and visual quality during the postharvest period. In contrast, the sharp decline observed in 'Penny Lane' indicates a lower resistance of anthocyanin pigments to storage stress.

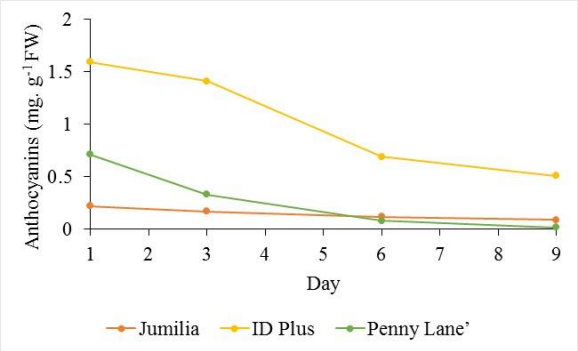

Figure 11.
Interaction effects of cultivar and storage time (day) on anthocyanins activity in rose petals.

The overall decrease in anthocyanins across the 9 day period (from 0.84 on day 1 to 0.21 mg. g^{-1}FW on day 9) is consistent with progressive senescence and postharvest stress, which can promote pigment loss through multiple, concurrent mechanisms. During storage, increased oxidative stress and reduced membrane integrity may enhance anthocyanins degradation and/or oxidation, while shifts in cellular/vacuolar conditions can reduce anthocyanin stability and favor discoloration (Rodov and Friedman, 2006). The particularly sharp reduction observed in 'Penny Lane' implies a higher susceptibility to these postharvest changes, whereas the greater retention in 'ID Plus' suggests comparatively stronger pigment stabilization that slows anthocyanins breakdown over time (Rodov and Friedman, 2006). The marked accumulation of anthocyanins in 'ID Plus' indicates that red petal coloration in this cultivar is closely associated with higher flavonoid pigment biosynthesis.

3.5. Total carotenoids

ANOVA (Table 1), indicated significant effects of cultivar, storage time, and their interaction on total carotenoid content ($p<0.01$). The highest carotenoid levels were recorded in 'Penny Lane' (0.63 mg. g^{-1} FW), while 'ID Plus' (0.08 mg. g^{-1} FW) and 'Jumilia' with values of 0.07 mg. g^{-1} FW) showed substantially lower values. Throughout the 9 day storage, mean carotenoid content significantly declined from 0.37 to 0.16 mg. g^{-1} FW, reflecting a clear time-dependent degradation (Figure 12).

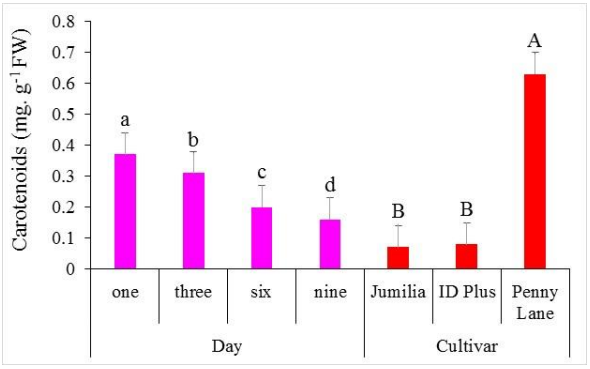

Figure 10.
Main effects of storage time (day) and cultivar on carotenoids in rose flowers during postharvest storage. Uppercase letters show differences between cultivars (Games–Howell, $p<0.05$) and lowercase letters show differences between storage time (Duncan, $p<0.05$). means + SE (n=3).

Regarding the interaction effect, the highest carotenoid content was observed in 'Penny Lane' on day 1 (0.88 mg. g^{-1} FW), which significantly decreased to 0.41 mg. g^{-1} FW by day 9. In contrast, 'ID Plus' and 'Jumilia' started with much lower baseline levels (0.14 and 0.10 mg. g^{-1} FW on day 1, respectively). By the end of the storage period (day 9), the carotenoid content in these two cultivars reached their minimum values of 0.04 mg. g^{-1} FW for 'ID Plus' and 0.03 mg. g^{-1} FW for 'Jumilia'. The degradation trend followed a similar downward pattern across all cultivars, although the magnitude of change was more pronounced in the yellow colored 'Penny Lane' (Figure 13).

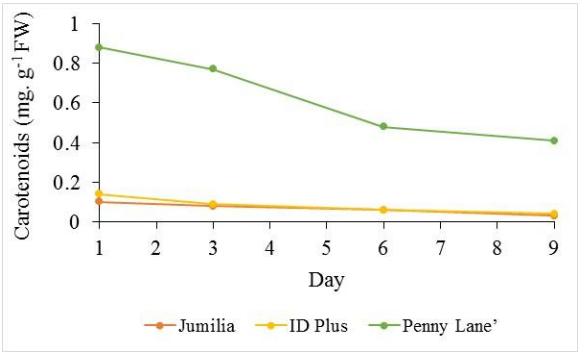

Figure 13.
Interaction effects of cultivar and storage time (day) on carotenoids in rose petals.

The significant variation in initial carotenoids content among the studied cultivars is primarily attributed to their genetic makeup and pigment profile. The yellow cultivar, 'Penny Lane', exhibited substantially higher carotenoids levels compared to 'ID Plus' and 'Jumilia'.

In yellow roses, carotenoids (such as lutein and zeaxanthin) are the predominant pigments, whereas in red and white/pink-edged cultivars, the pigment profile is dominated by anthocyanins or remains at basal levels, respectively (Ma et al., 2015).

Throughout the 9 day postharvest period, a consistent decline in carotenoid concentration was observed across all cultivars. This degradation is a hallmark of floral senescence. As the petals age, the stability of the carotenoid-protein complexes within the chromoplasts decreases, leading to the liberation and subsequent oxidation of these pigments (Ma et al., 2015).

Furthermore, the increased activity of enzymes such as lipoxygenase and carotenoid cleavage dioxygenases (CCDs) during storage likely accelerated the breakdown of carotenoids into colorless apocarotenoids (Sun et al., 2018).

The more pronounced absolute reduction in 'Penny Lane' suggests that cultivars with higher initial pigment concentrations may undergo more rapid visible degradation, although they maintain higher aesthetic value for a longer period compared to the low-carotenoid cultivars. The minimal baseline levels observed in 'ID Plus' and 'Jumilia' by day 9 (0.04 and 0.03 mg. g^{-1} FW) indicate an almost complete exhaustion of the carotenoid pool, coinciding with the advanced stages of petal wilting.

4. Conclusion

In summary, the present study showed that postharvest storage progressively impaired the physiological and biochemical quality of cut rose flowers. The decline in RWC by the ninth day of storage indicated a gradual loss of water status in petal tissues, which is one of the early signs of senescence. This was accompanied by an increase in EL, confirming that membrane integrity was increasingly compromised as storage duration progressed. Compounding this cellular decline, the observed reduction in total protein content by the end of the storage period suggests a transition toward catabolic metabolism and protein degradation. The simultaneous decline in POD activity further underscores a compromised antioxidant defense system, leaving the petal tissues vulnerable to unchecked oxidative damage. These physiological stressors directly impacted the aesthetic and ornamental value of the flowers. The depletion of total anthocyanins and total carotenoids especially in the most sensitive cultivars highlight that pigment degradation is not an isolated event but a consequence of broader metabolic disruption and membrane failure. Collectively, our results demonstrate that the postharvest longevity of roses is determined by a complex interplay between water status, membrane stability, and the robustness of the antioxidant system. Cultivars such as ID Plus, which demonstrated superior maintenance of RWC and membrane integrity, alongside higher pigment retention, offer significant potential for breeding programs aimed at extending the vase life and commercial value of cut flowers. Conversely, the rapid deterioration observed in Penny Lane serves as a model for understanding the accelerated senescence pathways in sensitive rose varieties.

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