Enhancing Postharvest Quality and Storability of Sweet Lime Using Methyl Jasmonate and Salicylic Acid Treatments

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Summary

Sweet lime (*Citrus limettioides* Tan.) is a widely cultivated horticultural crop both globally and in Iran; however, it experiences substantial postharvest losses, with estimates reaching 26% in Iran. This study investigated the effects of methyl jasmonate (MeJA) and salicylic acid (SA), two safe and efficient compounds, on the postharvest quality and shelf life of sweet lime. Fruits were treated with MeJA (10 and 20 µM), SA (2 and 4 mM), or distilled water (control) and stored at 9 °C for 120 days. The study evaluated fruit weight loss, total soluble solids (TSS), titratable acidity (TA), taste index (TSS/TA ratio), pH, ascorbic acid (vitamin C) content, total phenol content and antioxidant activity in the juice. All treatments reduced weight loss compared to the control. The 10 µM MeJA treatment was particularly effective, leading to the highest ascorbic acid content, TA retention, greater phenol content and antioxidant activity. Additionally, 20 µM MeJA maintained the highest TSS levels and a stable pH. Initial fruit disinfection with sodium hypochlorite, combined with wrapping the fruits in polyethylene plastic, effectively prevented fungal contamination, even in the control fruits. Overall, 10 µM MeJA was the most effective treatment for preserving sweet lime quality and extending its shelf life.

Key words

antioxidant activity, *Citrus limettioides* Tan, shelf life, taste index, total phenolics

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Introduction

Sweet lime (*Citrus limettioides* Tan.), also known as Palestine or Indian sweet lime, is widely consumed in India, the Middle East, and Latin America, and has medicinal uses in these regions. The fruit is medium-sized, round to slightly oblong, with a greenish-yellow to orange-yellow rind at maturity. Its yellowish flesh and mildly medicinal aroma contribute to its distinctive character. Notably low in acidity, the juice is often perceived as bland. Despite its consumption, commercial processing of sweet lime is limited, with most juicing and bottling occurring at a small scale (Caballero et al., 2003).

The southern regions of Iran, particularly the southern part of Fars Province, including the counties of Jahrom, Firuzabad, and Darab, are primarily home to the commercial cultivation of sweet lime due to specific climatic requirements. Researchers have recorded production potential of up to 1500 kg per tree in these areas (Gheysari Beigi et al., 2016). Additionally, limited cultivation occurs in certain northern regions of Iran's. Household juicing has used a substantial portion of Iran's sweet lime harvest in recent years, leading to a notable increase in citrus juice consumption (Hashempour et al., 2013). Fars Province, with its 13120 hectares of fertile land, high average yields and total production exceeding 554000 tons, is a leading producer of sweet lime in Iran (Ahmadi et al., 2020). Jahrom County, in particular, is a primary production hub, exporting sweet lime to Gulf countries and European markets, including the Netherlands, Germany, and the United Kingdom.

High production volumes and low harvest prices necessitate the storage and gradual release of a significant portion of the sweet lime crop to the market postharvest. According to national data, 20 crops account for about 90% of postharvest losses in Iran, with sweet lime ranking 20th in terms of postharvest losses, estimated at 26% (Mirmajidi Hashtjin et al., 2016). Effective postharvest handling is essential for maintaining fruit quality and minimizing rejection rates, with indicators such as weight loss, decay rate, total soluble solids (TSS), titratable acidity (TA) and the TSS/TA ratio (taste index) critical for quality assessment (Khan et al., 2022). Challenges during storage include microbial spoilage, physiological disorders and fungal pathogens producing mycotoxins, impacting both quality and safety (Nishant et al., 2023). Implementing postharvest technologies like ozone treatment, controlled atmosphere storage and antimicrobial coatings can help address these issues and improve economic returns (Ejaz et al., 2022).

The optimal storage conditions for limes are 9-10 °C with 85-90% relative humidity, providing a storage life of 6-8 weeks (Welby and McGregor 2004). However, the majority of guidelines focus on acidic limes, while there is limited specific information available for sweet lime. This highlights a research gap in understanding the physiological changes in sweet lime during storage and developing effective quality preservation strategies.

Methyl jasmonate (MeJA) and salicylic acid (SA) are two critical phytohormones that enhance postharvest quality and disease resistance in horticultural crops (Asghari and Soleimani Aghdam, 2010; Wang et al., 2021). MeJA, a volatile phytohormone, regulates hormone biosynthesis and plant defenses against different stresses. Its application improves antioxidant capacity and phenol content, extending shelf life, enhancing fruit quality and reducing chilling injury, with notable long-lasting effects during storage (Wang et al., 2021). Similarly, SA, an endogenous signal molecule, regulates stress responses and photosynthesis, delays fruit ripening by inhibiting ethylene biosynthesis and extends shelf life. SA also boosts pathogen resistance, prevents oxidative stress by reducing lipid peroxidation, and induces heat shock proteins to protect against chilling injury (Asghari and Soleimani Aghdam, 2010).

Given the significant impact these treatments have on preserving quality and extending storage life, the present study aimed to investigate the effects of exogenous MeJA and SA on sweet lime characteristics. This study evaluated the impact of various concentrations of these compounds on quantitative and qualitative indicators of sweet lime fruit, with the goal of ensuring practical applicability for future use.

Material and Methods

Plant Materials

Sweet lime (*Citrus limettioides* Tan.) fruits were picked greenish-yellow from a commercial orchard in Jahrom County (53°57'37"E and 28°50'47"N) and taken to the postharvest physiology lab. Fruits that were uniform in size and had no signs of infection or damage were chosen and treated with 2% sodium hypochlorite for 2 minutes. Following a rinse with distilled water, the fruits were left to dry naturally at room temperature.

Experimental Design and Treatments

The chemicals used were purchased from Sigma-Aldrich (Madrid, Spain). The experiment followed a completely randomized factorial design, consisting of 10 treatments, each replicated four times (with 15 fruits per replicate). The experimental factors included fruit immersion in five solutions: MeJA (10 and 20 µM), SA (2 and 4 mM), and distilled water as a control; sampling time was conducted at two intervals (2 and 4 months of storage). Following a 10-minute fruit immersion and natural drying at room temperature, each fruit was individually wrapped in polyethylene plastic and stored at 9 °C with 85 ± 5% relative humidity for four months. The treated fruits were evaluated for their physicochemical and antioxidant properties after 2 and 4 months of storage.

Fruit Weight Loss

The mass variation method, as described by Taghipour and Assar (2022), was applied, with weight loss calculated as a percentage using Formula 1:

$$Weight\ loss\ (\%) = ((W_0 - W_1) / W_0) \times 100 \qquad (1)$$

where W_0 represents the initial mass and W_1 represents the final mass.

Juice TSS Content

Measuring TSS content was performed using a Milwaukee MA871 (Hungary) instrument at room temperature (Taghipour and Assar, 2022) and reported as a percentage (%).

Juice TA Content

The index was determined by titrating with a 0.1 M NaOH solution until the soloution's pH reached 8.2 (Taghipour and Assar, 2022) and was reported as a percentage of citric acid.

Juice TSS/TA Ratio

Taste index was calculated by dividing the TSS value by the TA value (Taghipour and Assar, 2022).

Juice pH

The juice pH was measured using a pH meter (PHAC, Paat Ariya Sanat, Iran) as described by Taghipour and Assar (2022).

Ascorbic Acid Content

The ascorbic acid content in the fruit juice was quantified using the 2,6-dichlorophenolindophenol titration method, as outlined by Taghipour and Assar (2022), and presented as milligrams per 100 grams of juice (mg·100 g^{-1}).

Total Phenol Content

The total phenol content was measured using the Folin-Ciocalteu method (Taghipour and Assar, 2022). Briefly, the methanolic extract was mixed with Folin reagent, followed by the addition of sodium carbonate. After a 5-hour incubation at room temperature, absorbance was measured at 760 nm. The phenol content was calculated using a gallic acid standard curve and expressed as micromoles per gram of fresh weight (μM g^{-1}·FW).

Antioxidant Activity

The total antioxidant activity of the fruit extract was assessed using the DPPH free radical inhibition method (Taghipour and Assar, 2022). In brief, diluted samples were mixed with DPPH and incubated in the dark at room temperature for 20 minutes. Absorbance was measured at 517 nm, with a control lacking the fruit extract. Antioxidant activity was calculated as a percentage using this standard formula:

DPPH Scavenging Activity (%) = [(Absorbance of Control–Absorbance of Sample) /Absorbance of Control] × 100 (2)

Statistical Analysis

To compare the mean values, the least significant difference (LSD) test was applied at a significance level of $P \leq 0.05$. Data analysis was conducted using SAS/STAT® 9.4 (2013) software.

Results

Fruit Weight Loss

The analysis of variance (ANOVA) results indicated that both the immersion treatment and storage duration, as well as their interaction, had a significant effect on the weight loss of sweet lime fruits (data not shown). At both sampling points, the control fruits exhibited a significantly higher weight loss compared to those treated with SA and MeJA, with no significant difference observed between the treated fruits (Fig. 1).

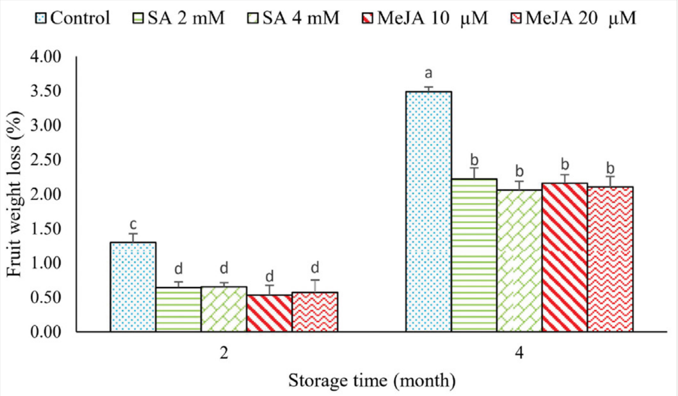

Figure 1. Fruit weight loss in control and treated fruits (with salicylic acid (SA) and methyl jasmonate (MeJA) via dip method for 10 minutes) during storage at 9 °C and 85 ± 5% relative humidity (RH). Means with the same letter are not significantly different according to the LSD test at $P \leq 0.05$.

Juice TSS

Based on the analysis of variance (ANOVA), both experimental factors and their interaction had a significant effect on the TSS content of the fruit juice (data not shown). The trend in this index showed a significant decrease during the storage period in both the control and treated fruit groups. However, at both sampling points, the TSS levels in the treated fruit juice were higher than those in the control, with all differences statistically significant except for one instance. After two months of storage, the TSS content of the fruit treated with 2 mM SA was statistically similar to that of the control. After four months of storage, the highest TSS content, significantly greater than that of the fruit treated with other treatments or the control, was observed in the fruit treated with the highest concentration (20 μM) of MeJa (Fig. 2).

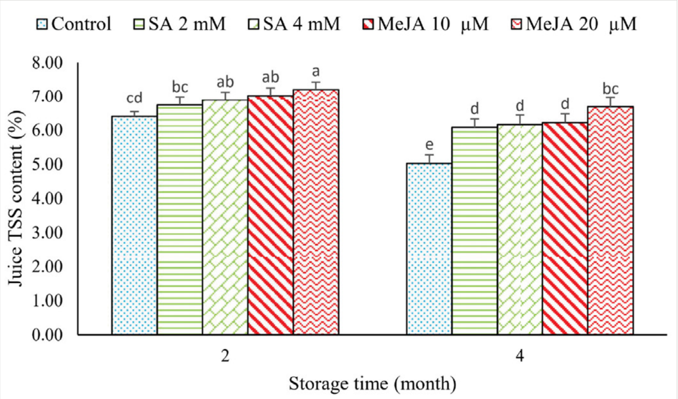

Figure 2. Juice total soluble solids (TSS) content in control and treated fruits (with salicylic acid (SA) and methyl jasmonate (MeJA) via dip method for 10 minutes) during storage at 9 °C and 85 ± 5% relative humidity (RH). Means with the same letter are not significantly different according to the LSD test at $P \leq 0.05$.

Juice TA

The analysis of variance (ANOVA) demonstrated that the experimental factors and their interaction had a significant effect on the TA content of sweet lime juice (data not shown). After two months of storage, this index was significantly higher in all treated fruits compared to the control, with the highest level observed in those treated with 20 μM MeJA. Following this, fruits treated with 10 µM MeJA and 4 mM SA had the next highest TA levels, and finally, fruits treated with 2 mM SA, still had a higher TA than the control. At the end of the storage period, fruits treated with MeJA had the highest TA content in the juice. At this point, fruits treated with 10 µM MeJA showed significantly higher TA levels compared to those treated with SA and the control, with no change in their TA content since the previous sampling. Although fruits treated with 20 µM MeJA experienced a significant decline in TA during the final 20 days of storage, their TA levels at the end of the experiment were similar to those of fruits treated with 10 µM MeJA, with no statistical difference observed (Fig. 3).

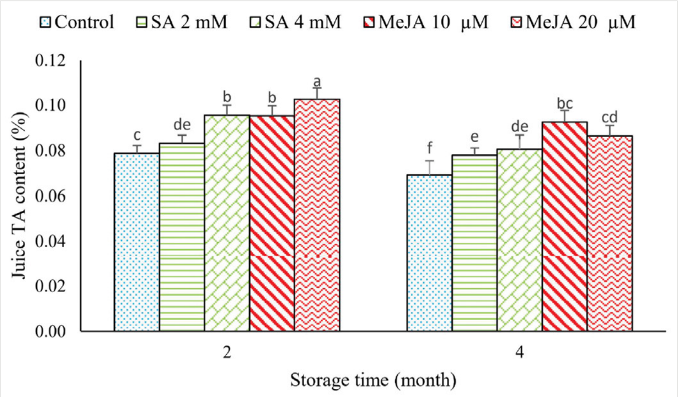

Figure 3. Juice titratable acids (TA) in control and treated fruits (with salicylic acid (SA) and methyl jasmonate (MeJA) via dip method for 10 minutes) during storage at 9 °C and 85 ± 5% relative humidity (RH). Means with the same letter are not significantly different according to the LSD test at $P \leq 0.05$.

Juice TSS/TA Ratio (Taste Index)

The analysis of variance (ANOVA) revealed that only the effect of the immersion treatment and its interaction with storage duration had a significant impact on the TSS/TA ratio (data not shown). After two months of storage, fruits treated with both concentrations of MeJA and the higher concentration of SA had a lower TSS/TA ratio compared to the control fruits and those treated with 2 mM SA. After four months of storage, the TSS/TA ratio was similar across all treatments, with the only statistically significant difference being that fruits treated with 10 µM MeJA had the lowest ratio among all groups. Notably, there was a significant decrease in this ratio in the control fruits during the storage period, whereas the TSS/TA values in the treated fruits remained stable up to the end of the storage period (Fig. 4).

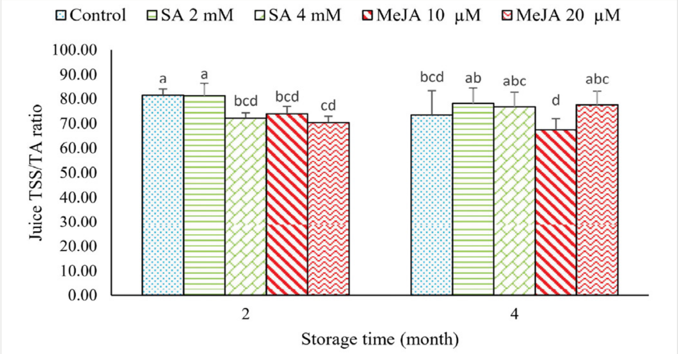

Figure 4. Juice TSS/TA ratio (taste index) in control and treated fruits (with salicylic acid (SA) and methyl jasmonate (MeJA) via dip method for 10 minutes) during storage at 9 °C and 85 ± 5% relative humidity (RH). Means with the same letter are not significantly different according to the LSD test at $P \leq 0.05$.

Juice pH

The analysis of variance (ANOVA) revealed that the experimental factors and their interactions significantly affected the pH of sweet lime juice (data not shown). Statistically, the pH showed an increasing trend in all cases except for the treatment with the higher concentration of MeJA, where no change in pH was observed. At both sampling times, the pH levels of the control and fruits treated with various concentrations of SA and 10 µM MeJA were similar and significantly higher than the pH of the juice from fruits treated with 20 µM MeJA (Fig. 5).

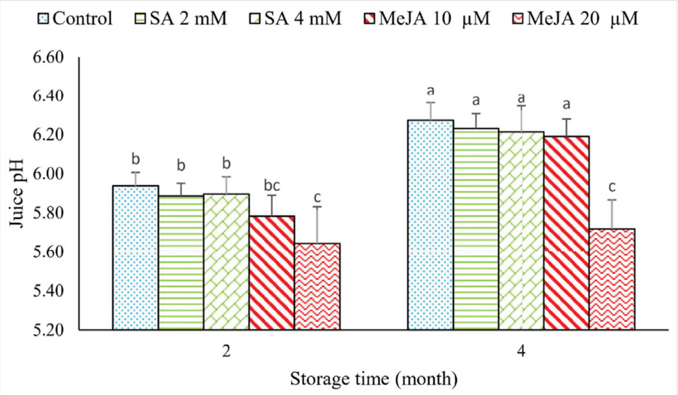

Figure 5. Juice pH in control and treated fruits (with salicylic acid (SA) and methyl jasmonate (MeJA) via dip method for 10 minutes) during storage at 9 °C and 85 ± 5% relative humidity (RH). Means with the same letter are not significantly different according to the LSD test at $P \leq 0.05$.

Juice Ascorbic Acid

The analysis of variance (ANOVA) showed that the experimental factors and their interactions significantly affected the ascorbic acid content of sweet lime juice (data not shown). The trend in this index showed a significant decrease in both the control and treated fruits. However, at both sampling times, the highest ascorbic acid content was observed in fruits treated with 10 µM MeJA. There were no significant differences between fruits treated with various concentrations of SA, while the control fruits had the lowest ascorbic acid content (Fig. 6).

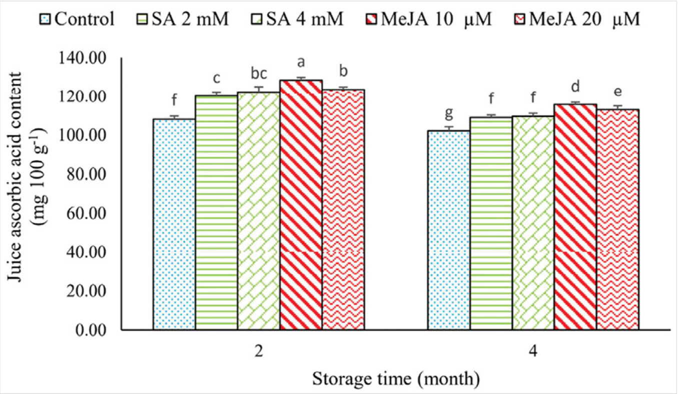

Figure 6. Juice ascorbic acid content in control and treated fruits (with salicylic acid (SA) and methyl jasmonate (MeJA) via dip method for 10 minutes) during storage at 9 °C and 85 ± 5% relative humidity (RH). Means with the same letter are not significantly different according to the LSD test at $P \leq 0.05$.

Juice Total Phenol

The analysis of variance (ANOVA) revealed that both the experimental factors and their interactions significantly affected the total phenol content of sweet lime juice (data not shown). The trend in this index showed a significant decrease in both control and treated fruits. After two and four months of storage, fruits treated with MeJA and higher concentrations of SA had similarly higher levels of total phenol, while control fruits had the lowest levels. After two months, the difference in total phenol content between these treated fruits and those treated with 2 mM SA was significant. However, after four months, the only significant difference was between fruits treated with the lowest concentration of SA and those treated with 10 µM MeJA, with no other significant differences among the treated fruits (Fig. 7).

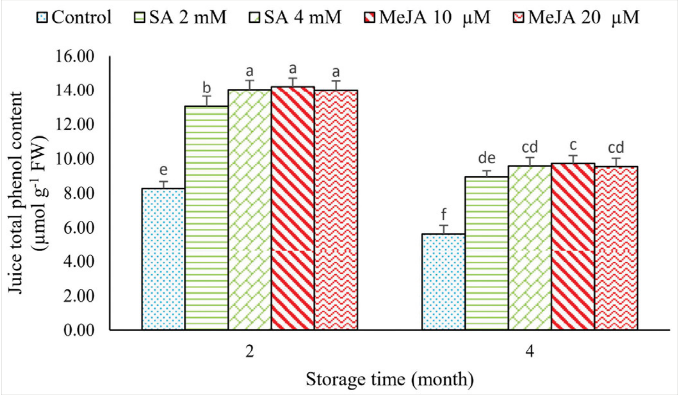

Figure 7. Juice total phenol content in control and treated fruits (with salicylic acid (SA) and methyl jasmonate (MeJA) via dip method for 10 minutes) during storage at 9 °C and 85 ± 5% relative humidity (RH). Means with the same letter are not significantly different according to the LSD test at $P \leq 0.05$.

Juice Antioxidant Activity

Based on the analysis of variance (ANOVA), both the experimental factors and their interactions significantly affected the antioxidant activity of sweet lime juice (data not shown). Over time, the trend showed a significant decrease in both control and treated fruits. At both sampling times, the control fruits exhibited the lowest antioxidant activity. The highest activity was observed in fruits treated with 10 µM MeJA, which differed significantly only from fruits treated with the lowest concentration of SA (Fig. 8).

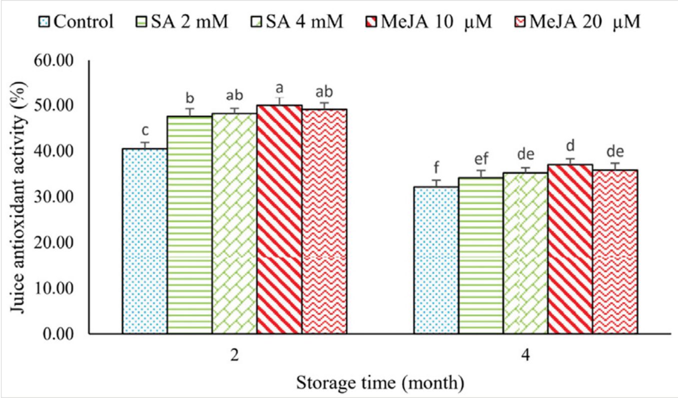

Figure 8. Juice total antioxidant activity in control and treated fruits (with salicylic acid (SA) and methyl jasmonate (MeJA) via dip method for 10 minutes) during storage at 9 °C and 85 ± 5% relative humidity (RH). Means with the same letter are not significantly different according to the LSD test at $P \leq 0.05$..

Discussion

Weight loss is a critical quality indicator during the postharvest period of horticultural products, directly related to the intensity of water loss due to ongoing respiration and transpiration processes (Hanif et al., 2020). Shojah and Mortazavi (2011) find that the extent of weight loss during storage significantly varies among different citrus species and cultivars. This fact demonstrates that this difference is attributed to variations in peel thickness or protective coatings on the peel, such as waxes on the cuticle, which act as natural barriers against water loss from the fruit. Limes, like other citrus fruits such as oranges, lemons and grapefruits, are categorized as having moderate water loss (Welby and McGregor, 2004). Piga et al. (2000) reported that the increase in weight loss in citrus fruits due to water loss during storage was highly dependent on the storage duration and temperature. It has been suggested that sweet lime can be stored acceptably for up to two weeks at room temperature (Iqbal et al., 2019). As mentioned earlier, the optimal storage conditions and duration for different lime varieties are 9 to 10 °C and 85 to 90% relative humidity, and approximately 6 to 8 weeks, respectively (Welby and McGregor, 2004). However, extending the postharvest shelf life along with maintaining an acceptable level of weight loss is now needed and globally preferred, essentially for preserving fruit quality and marketability for a longer period of time.

Previous research (Barsha et al., 2021; Hussain et al., 2019) suggests that keeping weight loss below 10% through various pre- and postharvest treatments is crucial for citrus fruits. For example, Barsha et al. (2021) found that treating mandarins with 75% paraffin wax resulted in minimal weight loss—3.10%, 4.83%, and 10.33% over 7, 14, and 21 days, respectively—while maintaining high marketable fruit percentages and juice content. In this study, weight loss of 1.30% and 3.49% was observed in control fruits after two and four months of storage, respectively. This suggests the effectiveness of the material preparation and storage method used, particularly the initial fruit disinfection with diluted sodium hypochlorite solution followed by packaging in polyethylene plastic. Notably, no signs of pathogen contamination or decay, which could exacerbate weight loss, were observed in either the control or treated fruits. Various reports highlight the significant impact of packaging methods on extending shelf life, maintaining quality, reducing moisture loss and lowering microbial load in horticultural products (Bhatia and Asrey, 2019).

The results of this study demonstrate the positive effect of treatments with MeJA and SA on significantly reducing weight loss of sweet lime during storage. SA and MeJA are particularly noted for their role in reducing weight loss in horticultural products by preventing fungal infections, preserving cell health and reducing metabolic activity (Bhatia and Asrey, 2018; Glowacz and Rees, 2016; Hosseinifarahi et al., 2020; Khademi and Ershadi, 2013; Koyuncu et al., 2019; Wang et al., 2021). Their inhibitory effect on aging-related enzymes, reduced respiration rates and the suppression of ethylene synthesis contribute to delayed aging and extended shelf life of products (Bhatia and Asrey, 2018; Glowacz and Rees, 2016; Hosseinifarahi et al., 2020; Khademi and Ershadi, 2013; Koyuncu et al., 2019; Wang et al., 2021). Consistent with our findings, Zheng and Zhang (2004) reported that SA treatments significantly and positively affected weight loss reduction in Ponkan and Kinnow mandarins. Similarly, Darwish et al. (2021) observed that pre-harvest application of SA to strawberries also mitigated weight loss during refrigerated storage. Additionally, Li et al. (2023) found that the application of MeJA to papaya fruit reduced physiological weight loss, thereby maintaining fruit quality during cold storage.

The majority of TSS in fruit juice is composed of sugars, which, along with organic acids, are the main components determining the flavor of citrus fruits and are consumed as respiratory substrates during the postharvest period (Rasouli et al., 2019). The sugar content in fruit juice during storage is influenced by a balance between consumption, production and concentration processes. An increase in sugar content during storage may result from water loss and the consequent concentration of juice constituents. Higher storage temperatures exacerbate the concentration of soluble solids, primarily due to increased water loss. Moreover, the enhanced solubility of hemicellulose and polyurethanes within the cell wall can also contribute to a rise in soluble solids concentration over the storage period (Taherpour et al., 2020).

In the present study, due to the slow rate of weight loss during storage, which indicates a slow rate of water loss, no significant increase in TSS was observed in the juices of either the control or treated fruits. The notable change was a significant decrease in TSS in both the control and treated fruits, which was likely linked to their respiration rates. This resulted in a lower TSS content in the control fruits compared to the treated ones. However, it appears that respiration rates were not excessively high, as indicated by the weight loss trend in the control fruits, whose final weight loss remained below the 10% threshold (Barsha et al., 2021; Hussain et al., 2019). Moreover, if respiration had been more severe, a significant increase in sugar content due to extensive cell wall degradation would have been expected (Taherpour et al., 2020). These findings further support the hypothesis that initial disinfection, proper washing and the use of polyethylene plastic for packaging can serve as highly effective and efficient techniques for maintaining postharvest fruit quality. This can be attributed to the precise control of green mold, which is one of the most serious threats to the postharvest lifespan and quality of citrus fruits (Kassim et al., 2020). The effectiveness of this control was such that not a single fruit, even among the control groups, exhibited any signs of contamination or mold.

Regarding the acidic taste of fruit juices, two common parameters are TA and pH. TA is the most critical factor influencing the acidic taste of the product, while pH is less significant but still plays a role (Friedrich, 2001). The TA index represents the concentration of total organic and amino acids present and the total amount of hydrogen ions, often referred to as total acidity. In contrast, pH refers to the concentration of free hydronium ions (H_3O^+), which is influenced by the ionization of acids present. In other words, while pH is also affected by the type and concentration of acids, it primarily indicates the degree of ionization of the acids and the amount of free hydrogen ions produced, which, when combined with water, form hydronium ions (Friedrich, 2001). However, since the ability of microorganisms to contaminate food and fruit juices is more related to hydronium ion concentration than TA, pH is also considered an important quality parameter, especially in processing in the food industry (Tyl and Sadler, 2017). As a result, due to the distinct impact of each of these indices on product quality, it is recommended to evaluate both as quality indicators.

In most reports on the storage of horticultural products, it is assumed that pH changes are dependent on the function of changes in the TA of fruit juices. Over time, the reduction in organic acids through respiration is accompanied by an increase in juice pH (Hosseinifarahi et al., 2020). On the other hand, it has been stated that there is not necessarily a direct or predictable relationship between TA and pH. For example, juices with different pH levels can have similar TA values, or vice versa (Friedrich, 2001). This is consistent with the findings of the present study. Fruits treated with lower concentrations of SA and MeJA showed no changes in TA content during storage, despite an increase in juice pH. Conversely, fruits treated with higher concentrations of MeJA exhibited no changes in juice pH, despite a decrease in TA content. Gheysari Beigi et al. (2016) reported that with increased storage time, the pH level of sweet lime juice rises, and they identified the decrease in TA as an indicator of fruit aging and deterioration. There are some reports indicating that the TA of fruit juice does not change during the storage of limes (Castillo et al., 2014). Shafiee et al. (2010) also reported that the pre- or postharvest application of SA was associated with stability in the TA of strawberry juice, which aligns with the results of the present study for fruits treated with lower concentrations of SA and MeJA.

Although TSS and TA are both key qualitative parameters, the TSS/TA ratio, known as the taste index, is the primary factor influencing consumer acceptance (Taghipour and Assar, 2022). After four months of storage, the TSS/TA ratio showed a significant decrease only in the control fruits, with no significant changes in the treated groups.

Ascorbic acid (Vitamin C) is a vital nutrient and antioxidant in fruits (Li et al., 2023). Total phenol content and antioxidant activity are the other crucials for the health benefits and shelf life of fruits (Li et al., 2023). Shojah and Mortazavi (2011), in their study on different citrus cultivars, indicate that in addition to the influence of species and cultivar, the storage duration and temperature also affect the changes in ascorbic acid, total phenol content, and the antioxidant capacity of citrus fruit juices. They reported that the antioxidant capacity of the juices decreased over time, attributing this to changes in total phenol content and ascorbic acid levels influenced by factors such as fruit aging, which aligns with the findings of the present study. Consistent with these results, Tavarini et al. (2008) also reported a decline in the antioxidant capacity of kiwifruit juice with prolonged storage.

The results of the present study indicate that ascorbic acid content, total phenol content and antioxidant capacity were better preserved in the treated fruit juices compared to the control. MeJA treatment has been shown to enhance the ascorbic acid content in papaya, thereby improving its nutritional value and enhancing the DPPH radical scavenging activity, indicating improved antioxidant properties (Li et al., 2023). The application of 0.1 mM MeJA and 0.5 mM SA on lemons significantly enhanced the antioxidant systems and maintained fruit quality and overall sensory characteristics during cold storage (Serna-Escolano et al., 2021). Similarly, SA treatment in strawberries helped to preserve the ascorbic acid content during storage (Darwish et al., 2021). SA treatment in strawberries also conserved the total phenol content and maintained the antioxidant activity during storage (Darwish et al., 2021).

The phenylpropanoid pathway is the primary route for producing many natural phenol compounds such as hydroxycinnamic acids, flavonoids, isoflavonoids, lignin, coumarins and stilbenes (Samadi et al., 2015). Phenylalanine ammonia-lyase (PAL) is the primary enzyme that plays a crucial role in regulating the products of the phenylpropanoid pathway. It facilitates the conversion of phenylalanine into trans-cinnamic acid, which continues the cycle and leads to the production of phenol compounds (Bagal et al., 2012). MeJA and SA influence the PAL enzyme activity, thereby activating the phenylpropanoid pathway and increasing the production of phenol compounds (Wang et al., 2009; Wen et al., 2005).

SA and MeJA, as natural elicitors, effectively enhance secondary metabolite production by mimicking artificial stress, which triggers internal signals that lead to the accumulation of these compounds and increased stress resistance in plants (Ahmadi Moghadam et al., 2013; Popova et al., 2003; Wang et al., 2009). Exogenous application of these elicitors interacts with membrane receptors, producing reactive oxygen species, nitric oxide and protein kinases, thereby activating protective metabolic pathways (Andi et al., 2001; Raman et al., 2011). Increased activity of antioxidant enzymes like catalase (CAT) and ascorbate peroxidase (APX), which help mitigate oxidative stress during postharvest storage, could lead to enhanced levels and better preservation of antioxidants such as ascorbic acid in MeJA-treated fruits (Zuñiga et al., 2020). The upregulation of genes involved in JA signaling, such as AcLOX, AcAOS, AcAOC, AcOPR3, AcJAR1, AcCOI1, and AcMYC2, also plays a role in enhancing the fruit's antioxidant response (Li et al., 2022). Moreover, SA enhances the fruit's antioxidative defense by increasing the activity of enzymes like peroxidase (POD) and polyphenol oxidase (PPO). These enzymes play a crucial role in scavenging reactive oxygen species (ROS), thereby protecting the fruit from oxidative damage during storage (Li et al., 2022).

Conclusion

The findings of this study highlight the effectiveness of MeJA and SA treatments in preserving the postharvest quality and extending the shelf life of sweet lime. Both treatments effectively reduced weight loss and preserved key quality parameters, including TSS, TA, ascorbic acid, total phenol, and antioxidant activity. The 10 µM MeJA treatment exhibited the most pronounced benefits in maintaining the fruit's nutritional and antioxidant qualities during storage. These results suggest that MeJA and SA are promising tools for improving postharvest management, potentially enhancing the economic viability and marketability of sweet lime. Future research should focus on understanding the underlying physiological mechanisms and assessing the practical application of these treatments in commercial settings to further minimize postharvest losses and improve food security.

CRediT Authorship Contribution Statement

Pedram Assar, Leila Taghipour: Project design, execution, statistical analysis, and manuscript writing and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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