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RESEARCH ARTICLE

Harvest quality and postharvest preservation of melon fruits by the effect of agronomic biofortification with iodine compounds and complexes

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Abstract

Agronomic biofortification, particularly with iodine, enriches crops with essential nutrients, addressing nutritional deficiencies. This enhances plant resilience, increasing disease resistance and yield. Consuming iodine-biofortified foods helps prevent diseases such as thyroid disorders and developmental issues. In this study, we evaluated freshly harvested and postharvest fruit quality to determine the effect of biofortification with chitosan, iodine salts (KI and KIO_3) and chitosan-iodine complexes (CS KI and CS KIO_3) at concentrations of 5 and 25 mg (iodine ion) on Syngenta 'Sweet Sunrise' hybrid melon (*Cucumis melo* L.) cultivars. Physicochemical parameters, such as weight, equatorial diameter and flesh firmness, were assessed in freshly harvested fruit. During postharvest storage at 25 °C for 5, 10 and 15 days, weight loss, flesh firmness, peel and flesh color (L, *a*, b**, chroma, °hue), pH, total soluble solids (°Brix), titratable acidity and TSS/TA ratio were measured. Chitosan and iodine salts did not significantly affect weight loss or equatorial diameter. However, KIO_3 had a notable effect on melon properties, enhancing peel and flesh coloration, increasing pH and improving total soluble solids. These findings suggest that chitosan and iodine salts act as natural preservatives, maintaining postharvest quality and enhancing the sweetness and flavor of fruits, making them promising alternatives for extending shelf life and improving melon quality. Among the treatments, CS + KIO_3 at 25 mg was the most effective in preserving postharvest quality and is recommended as the optimal strategy for biofortification in melon.

Keywords: *Cucumis melo*; fertilizer; iodine salts; physicochemical quality; postharvest quality

Introduction

Agricultural practices are crucial for preserving the quality of horticultural products, where the lack of balanced availability of mineral nutrients affects yield, causes physiological disorders and reduces postharvest quality (1). Agronomic biofortification emerges as a concrete solution to increase the mineral content in vegetable foods, such as iodine and address health problems associated with its deficiency in the human population (1-3). Iodine, though not abundant on the Earth's surface, is an essential trace element vital for human health. It plays a crucial role in the biosynthesis of thyroid hormones, i.e., thyroxine (T4) and triiodothyronine (T3), which regulate a wide range of physiological and biochemical processes. It is estimated that between 30 and 38 % of the world's population has inadequate iodine intake (4-8). Therefore, biofortifying vegetables, leafy greens and fruits with iodine presents an excellent opportunity to increase iodine intake in humans and reduce diseases affecting the global population (4, 9).

Plants can absorb iodine through their roots, stomata and leaf cuticular waxes, where it is typically stored (6). The source of iodine in food is the soil, primarily taken up by plant roots, with only the water-soluble and exchangeable fractions being accessible for plant uptake (10). Research suggests that foliar spraying is the most effective method for iodine absorption in plants (11). Moreover, iodized salts have been applied to various crops, including lettuce, tomato, sweet pepper seedlings and spinach (12-15). However, fertilizing plants with iodine, especially at high doses, can disrupt their physiological and biochemical processes, resulting in alterations to their chemical composition. High foliar concentrations of iodine have been shown to induce phytotoxicity, manifested as chlorosis, necrosis, reduced growth and metabolic alterations; however, the severity of these effects depends on the plant species and the form of iodine applied. For instance, it has been reported that basil plants (*Ocimum basilicum* L.) exhibit toxic effects when exposed to potassium iodide (KI) concentrations greater than 1.0 mM and potassium iodate (KIO_3) levels exceeding 10 mM (16). Similarly, it was found that in lettuce, iodide (I^-) at a concentration of 80 µM is toxic, leading to a significant reduction in shoot biomass and triggering the accumulation of free radicals and lipid peroxidation. In contrast, iodate (IO_3^-) at the same concentration did not cause any adverse effects on the plant (17). This is consistent with findings reported in recent reviews, which emphasize that excessive iodine can inhibit plant growth and accelerate tissue senescence (18). Moreover, iodine has even been registered as an herbicide in some agricultural contexts, due to its phytotoxic potential at high concentrations (19). Due to iodine toxicity, modifications in the content of compounds responsible for organoleptic and nutritional properties (sugars and acidity) can be observed, as well as in the nutraceutical compounds of horticultural products and crop yield (5). Despite iodine proving to be a good biofortificant, further research is required regarding compounds or complexes that can enhance its application. Recently, the use of additives such as salicylic acid, humic acid and fulvic acid has been reported to enhance iodine uptake in plants, thereby enriching their edible tissues with iodine (20).

Chitosan is a biopolymer with attractive properties such as biocompatibility, non-toxicity, biodegradability and low allergenicity; these properties make it a valuable material with applications in different fields, one of which is agriculture (21). The use of chitosan as a vehicle for iodine biofortification in agricultural products seems promising due to its inherent stability and preservative properties, which enhance the stability of iodine and its content in the resulting fruit (22). Thus, foliar application of iodine salts (KI and KIO_3) and iodinated chitosan complexes (CS-KI and CS-KIO_3) has been reported to have positive effects on lettuce crops (23). However, information regarding its impact on other crops is lacking. Melon cultivation emerges as an attractive alternative for iodine enrichment, given its increased economic importance and rising production (3, 24).

Melon (*Cucumis melo* L.) is a fruit that belongs to the Cucurbitaceae family and is an important source of antioxidants, vitamin C, β-carotenes and minerals (25). The fruit, seeds and peel are known to offer various health benefits, including anti-ulcer, anti-diabetic, cardiovascular and anti-inflammatory properties (26). Melon fruits are widely consumed, typically fresh, with a high global output of up to 42 million tons in 2020 (27). This study assessed the impact of iodine sources (KI and KIO_3) and iodinated chitosan complexes (CS-KI and CS-KIO_3) on the physical, chemical and quality attributes of the crop at harvest and during postharvest storage.

Materials and Methods

Soil preparation and planting

A 1/4 ha area was prepared for melon cultivation by forming beds measuring 60 cm in width and 15 cm in height. Drip irrigation tape and plastic mulch were installed using a Kenko machine. Melon seeds (*C. melo* L.) var. 'Sweet Sunrise' from Syngenta Mexico (FarMore®FI400 Cucurbits) was used for planting. These seeds had been previously treated for diseases and were planted on day 37 (June 17, 2021) at a spacing of 50 cm between plants and 2 m between rows. The bed length was 120 m, with a total of 12 beds and 2,880 plants in the experimental area. Seed germination exceeded 90 % within 12 days, a typical rate for melon seeds. Netafilm drip irrigation tape was installed at a rate of one liter per hour per square meter. The plastic used for soil mulching was an 80-gauge co-extruded plastic (silver-black) measuring 1.4 m long in width and 1,300 m in length. Perforations were made at the center, with a spacing of 50 cm between plants and the black side was placed facing outward to prevent high temperatures in the soil.

Fertilization

The Steiner solution was used for fertilization at a 25 % concentration, with an injection rate of 100 L m^{-3} of water. Additionally, a chitosan biopolymer solution was applied to the soil as a nematicide. Fertilization began on June 28, 2021 and was applied every three days throughout the entire crop cycle. The experiment was conducted using a completely randomized block design.

Iodinated chitosan complexes (CS-I) and treatments

The chitosan-iodine (CS-I) complexes (CS-KI and CS-KIO_3) were formulated based on the procedure outlined by, utilizing chitosan with a viscometric molecular weight of 420,000 g mol^{-1} and a deacetylation degree of 82 % (Golden Shell, China) (23). Foliar treatments began 37 days after July 17, 2021 and were repeated every 2 weeks. The different treatment utilized in present study are as follows: absolute control (T0), chitosan control (Tc CS at 0.05 %), KI 5 mg (T1), KI 25 mg (T2), KIO_3 5 mg (T3), KIO_3 25 mg (T4), CS KI 5 mg (T5), CS KI 25 mg (T6), CS KIO_3 5 mg (T7) and CS KIO_3 25 mg (T8).

Experimental methods (harvest and postharvest)

The fruits were harvested on September 9, 2021, then transported to the laboratory, washed with running water and commercial detergent and dried at room temperature on paper. Fruit sampling was performed on the day of harvest (day 0) to determine the effect of treatments on fruit development and quality, as well as at 5, 10 and 15 days of storage in a climate chamber (Equitec, EICS 351 HR, Spain) at 25 ± 2 °C and 60 % RH to assess the effect of biofortification treatments on postharvest quality and preservation.

Physicochemical properties

The freshly harvested melon fruits and those stored at 25 °C were weighed using a scale (Ohaus Corp., USA). The diameter of each melon fruit was measured postharvest using a digital vernier caliper (Caliper Accuracy, China). Flesh firmness was measured in Newtons (N) using an automated digital texture analyzer (TA. TX express model 2000, UK) with a 2 mm diameter probe at a penetration speed of 1 mm s^{-1} over 10 mm, both in freshly harvested and stored melon fruits (28). Weight loss percentage during fruit storage at 25 °C was calculated based on the obtained weights. Peel color was evaluated and the peel was removed from the fruit in 3 equidistant regions to measure flesh color using a handheld colorimeter (Hunterlab miniscan, MSEZ-4500L, USA) employing the CIELab scale, with data converted to chroma (C) and hue angle (°h) (28). For pH measurements in the juice, a pH meter (Thermo Scientific Orion Star A211) was used. At the same time, total soluble solids (TSS, °Brix) were measured using a digital refractometer (Atago PAL-1, Atago Co., Ltd., Bellevue, WA, USA) (29). Titration with NaOH (0.5 N) employing phenolphthalein as an indicator

(NMX-F-102-S-1978) was used to determine titratable acidity (TA). The maturity index (TSS/TA ratio) was used to determine fruit ripeness during storage, correlated with its flavor (30).

Statistical analysis

The experimental sample consisted of 1 melon fruit, with 3 fruits per treatment per sampling day and measurements were taken in triplicate. Analysis of variance (ANOVA) followed by Tukey's test at a significance level of α = 0.05 was conducted using INFOSTAT software version 2020 (31). Data visualization was performed using Sigma Plot software version 14.0.

Results and Discussion

Harvest

The growth in demand for sweet melon has spurred the development and introduction of new varieties into the market (32). In this study, the new variety 'Sweet Sunrise' was used, characterized by its intense orange flesh color and increased sweetness, considered a higher-quality fruit with a longer postharvest shelf life. The results of harvested melon fruits showed no significant differences ($p > 0.05$) in fruit weight among treatments; however, a slight decreasing trend in fruit weight was observed in response to the treatments. However, the weight range remained between 1.20 -1.65 kg (Fig. 1a). A range of 0.74 -1.12 kg in melon fruit weight was observed with the foliar application of iodine at concentrations of 5, 10, 15 and 20 µM L^{-1} (3). These values are lower than those obtained in the present study, which may be attributed to differences in experimental conditions, particularly the cultivar used. The slight reduction in fruit weight observed in iodine-treated plants, particularly in treatments T5 CS KI 5 mg to T7 CS KIO_3 5 mg, may be linked to mild phytotoxic effects, as high concentrations of iodine have been reported to disrupt physiological processes and reduce biomass accumulation. Nonetheless, all fruits maintained commercially acceptable sizes, suggesting that the applied doses did not compromise market quality. Potassium iodide (KI) applied to the substrate and through foliar spray at concentrations of 0.5 and 1 mM under greenhouse conditions resulted in melon fruit weights ranging from 0.85 - 1.22 kg (33). Therefore, the melon fruits in this study had a higher weight compared to what has been reported by other authors, which may be due to the variety of melon used. On the other hand, a hydroponic experiment with spinach was conducted to examine the effects of different iodine species-iodide (I^-), iodate (IO_3-) and organic iodine (CH_2ICOO^-)-at varying concentrations (34). The results showed that low levels of iodine in the nutrient solution can effectively stimulate spinach biomass growth, potentially leading to increased weight gain.

The equatorial diameter of the fruits was not significantly affected by the application of different treatments ($p>0.05$). However, a non-significant increasing trend was observed in fruits treated with iodine compared to the absolute control (T0), with diameters ranging from 12.2 -14.3 cm (Fig. 1b). These values exceed those previously reported, where iodine-treated melon fruits showed equatorial diameters ranging from 9.11 - 11.40 cm and polar diameters from 13.00 - 15.75 cm (3). The larger size of fruits in the present study aligns with the observed increase in fruit weight, suggesting that the biofortification treatments, particularly those involving iodine, may have promoted fruit growth despite the lack of statistical significance. This tendency was more noticeable in treatments T4 KIO_3 5 mg and T8 CS + KIO_3 25 mg, which showed the largest average diameters, possibly indicating a synergistic effect between iodine and chitosan on fruit expansion. This could be associated with the role of iodine in modulating plant physiological processes, though its function in plant nutrition is not yet fully understood (4). Therefore, our results contribute to the understanding of the agronomic effects of iodine applications in melon cultivation. In line with this, it has been emphasized that appropriate fertilization strategies are crucial not only for increasing yield but also for improving fruit quality attributes, including size and weight (35).

Flesh firmness also did not show significant differences between treatments, with values ranging from 2.53 -3.37 N (Fig. 1c). This indicates that the addition of iodine salts or iodized chitosan complexes did not affect the physical characteristics of melon fruits. High concentrations of iodine can affect the quality of melon fruits (3). However, in this study, no significant differences, or negative impacts on the quality of melon fruits, were observed due to the application of iodine compounds and complexes. Although not statistically significant, slightly higher firmness values were recorded in treatments T2 KI 25 mg and T3 KIO_3 5 mg, which may suggest a mild structural reinforcement effect on cell walls at harvest. These treatments could therefore be considered promising for maintaining fruit firmness, an important postharvest quality attribute.

Color of flesh and juice intensity are important properties for better visual appearance, directly related to β-carotene content and fruit flavor (25). Results of color parameters (L, a^* and b^*) of melon peel and flesh are shown in Tables 1 and 2. Peel color differed between treatments, with smaller or negative a^* values indicating a green coloration, primarily observed in control fruits (Table 1). Chroma in the peel also varied, where lower chroma values refer to opaquer colors and higher values to more intense colors. Thus, fruits treated with T8 CS KIO_3 25 mg showed a more intense peel color, while T5 CS KI 5 mg treatment resulted in the opaquer peel color in melon fruits (Table 1). The hue angle (°h) indicates the color tone, with control group fruits exhibiting different coloration compared to fruits treated with varying salts of iodine and iodinated complexes, indicating treatment effects on melon fruit peel color, related to fruit ripening, which will be discussed later. These variations in peel color parameters suggest that iodine treatments, particularly T8 CS + KIO_3 25 mg, may enhance external visual appeal of the fruit, which is a key quality attribute in consumer acceptance. This treatment also promoted higher lightness (L), color intensity (C) and b values in the flesh (Table 2), supporting its potential for improving both internal and external fruit color quality.

Flesh color showed higher luminosity due to the Tc CS treatment, while the lowest luminosity value was observed in fruits treated with T3 KIO_3 5 mg (Table 2). Higher a^* and b^* values indicate more orange hues, which are mainly observed in fruits treated with T2 KI 25 mg and also showed the highest chroma value, indicating a more intense color (Table 2). This suggests that T2 KI 25 mg may enhance the visual appeal of melon flesh by intensifying orange coloration, which is typically

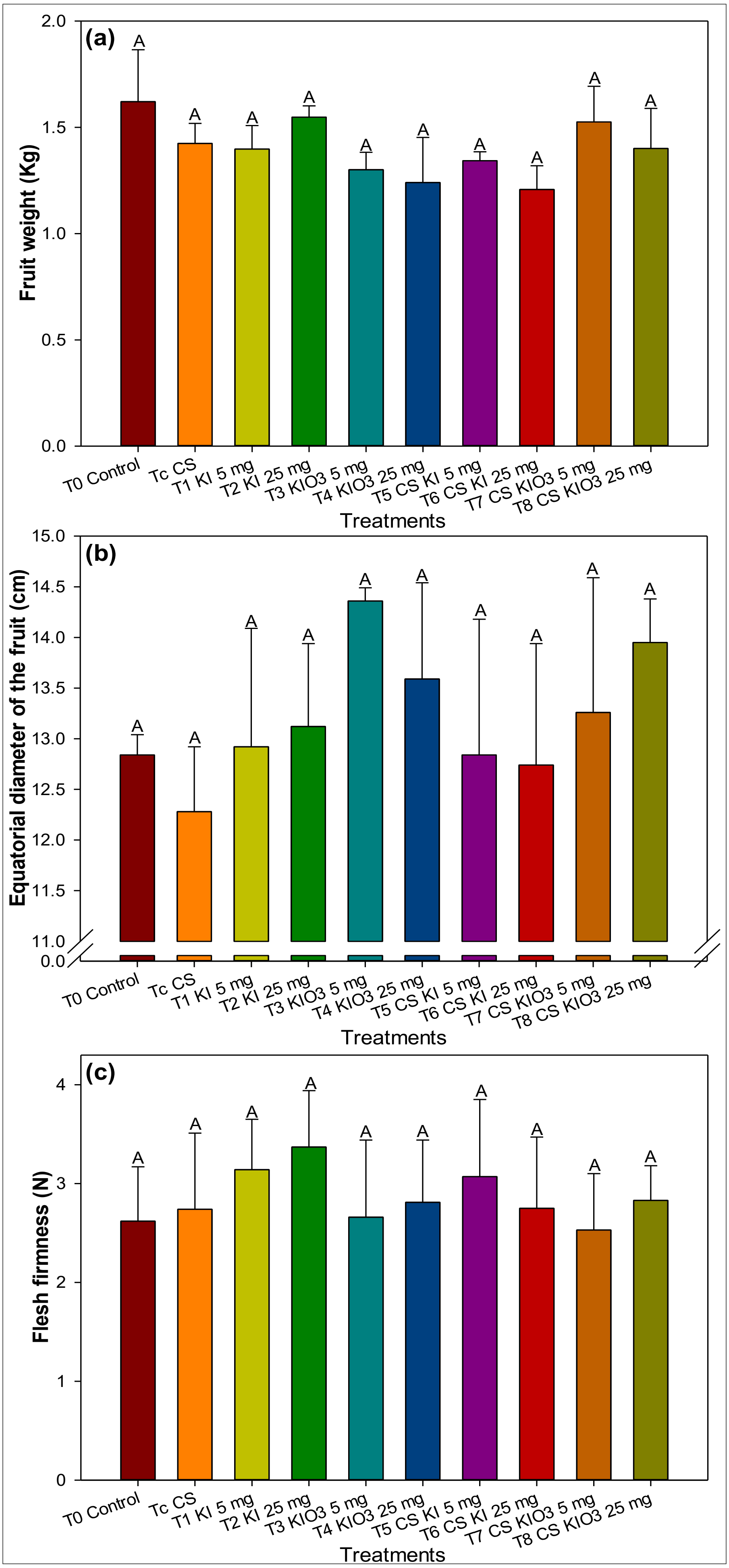

Fig. 1. Fruit weight (Kg) (a), fruit diameter (cm) (b) and flesh firmness (N) (c) of freshly harvested melons subjected to field-applied iodinated treatments.

associated with higher β-carotene content and nutritional value. Finally, there was no treatment effect on hue angle (° hue) (Table 2). Flesh color and carotene content depend on the cultivar, determined by the pigments present in melon fruits (32).

The pH values showed significant differences between treatments, with the highest pH obtained in fruits treated with T3 KIO_3 5 mg. In contrast, the lowest pH value was obtained in control fruits (Fig. 2a). This could indicate that treatments with iodine salts and iodinated complex modify the content of organic acids present in melon fruits. However, no reports were found indicating the effect of iodine-based treatments on fruit pH. Higher pH values may indicate a reduction in acidity, which could be associated with more mature fruits or lower concentrations of organic acids. In contrast, lower pH values, such as those in the control (T0), are associated with greater acidity and potentially sharper flavor perception. Therefore, iodine treatments such as T3 KIO3 5 mg may contribute to reduced acidity and a milder flavor profile.

The sugar content (SST) showed significant differences between treatments, with a higher value of 11.53 ± 0.2 for treatment T3 KIO_3 5 mg. The lowest SST content in fruits treated with Tc CS (6.8 ± 1.5) (Fig. 2b). The biofortification of tomato fruits was achieved using KI, KIO_3 (as sources of iodine) and salicylic acid at a concentration of 1 mg dm^{-3}, corresponding to 7.88 µM iodine and 7.24 µM salicylic acid, respectively (5). Total soluble solids (°Brix) increased from 4.56 ± 0.08 (control) to 4.66 ± 0.10. Applications of KI, KIO_3 and IO_3- were applied both to the substrate and foliarly in melon cultivation at varying concentrations of 0, 0.5 and 1 mM (33). Greater iodine uptake was observed at the lower concentration (0.5 mM), without inducing phytotoxic effects and this was accompanied by an increase in total soluble solids (7.47-8.55). Similarly, in the present study, a lower dose of KIO_3 was found to be the most effective in enhancing sugar content in melon fruits. It was also observed that the soluble solids content (SST) is influenced by iodine concentration, with lower concentrations applied foliarly resulting in increased SST levels in melon, which aligns with the findings of the present study (3). Considering that sweetness is a key attribute for consumer preference, T3 KIO_3 5 mg stands out as the most promising treatment for improving fruit flavor and marketability.

The acidity in flesh juice is related to the number of free protons and is due to the content of various organic acids: acetic, citric, ascorbic, among others (36, 37). The highest content of citric acid was obtained in melon fruits treated with T2 KI 25 mg and the lowest value in fruits treated with T4 KIO_3 25 mg (Fig. 2c). This variation suggests that iodide and iodate forms of iodine may have opposite effects on organic acid metabolism in melon, possibly due to their different uptake and assimilation pathways. The maturity index was higher in fruits treated mainly with T3 KIO_3 5 mg, followed by T4 KIO_3 25 mg, T6 CS KI 25 mg, T7 CS KIO_3 5 mg and T8 CS KIO_3 25 mg, indicating an effect or action of iodine treatments; these treatments could be used to advance harvests (Fig. 2d). The content of citric acid in tomato fruits was found to decrease from 376.9 ± 0.01 - 329.8 ± 0.02 as a result of iodine treatments (5). The application of I^- was found to increase citric acid content, whereas CH_2ICOO^- and OI^{3-} reduced it in hydroponically grown spinach (34). Therefore, the effect of iodine on titratable acidity depends on the crop. In this study, the combination of high SST, low acidity and high maturity index observed in T3 KIO3 5 mg reinforces its suitability as the most effective treatment for enhancing sensory quality and possibly shortening the time to harvest.

Postharvest

The effect of iodine and chitosan complexes on tomato plants (*Solanum lycopersicum* L.) was investigated, with a focus on iodine accumulation and the uptake of other minerals (38). However, scarcely is known about the effect of crop biofortification on the quality of freshly harvested fruits and/or during postharvest storage. Regarding the results of melon fruits stored at 25 °C, weight loss (WL) did not show statistically significant differences between treatments ($p > 0.05$, Fig. 3a); however, a clear trend was observed. Fruits treated with Tc CS showed the highest WL during storage, with an average of 8.40 % and most of this loss occurred within the first 5 days of storage. In contrast, treatment T8 CS KIO_3 25 mg resulted in the lowest WL, averaging 5.98 %. This indicates that the presence of chitosan combined with KIO_3 reduces water loss through transpiration. Although not statistically significant, the 2.42 % difference in WL between these treatments is noteworthy from a commercial perspective, as fresh produce is marketed by weight. Therefore, minimizing postharvest WL is essential to reduce potential economic losses. As previously noted, WL is primarily associated with water loss, which directly affects fruit freshness, texture and market value.

The flesh of melon fruits softens as they ripen, so measuring their firmness during storage can provide important information about fruit preservation. In Fig. 2b, it is shown that fruits treated with T1 KI 5 mg (2.61 N), followed by T5 CS KI 5 mg (2.41 N) and T3 $KIO_3$5 mg (2.29 N), had the highest flesh firmness throughout the storage period ($p < 0.05$). Meanwhile, fruits treated with T2 KI 25 mg (1.67 N), Tc CS (1.80 N) and T0 control (1.88 N) showed the lowest firmness ($p < 0.05$, Fig. 3b). A reduction in melon fruit firmness of up to 50 % due to storage has been reported; however, such a decline was not observed in the melon fruits of this study during 15 days of storage at room temperature (39). This suggests that iodine treatments at lower concentrations may contribute to delaying softening by helping preserve cell wall integrity. In contrast, the loss of firmness in Tc CS and T2 KI 25 mg indicates that not all iodine forms or concentrations are equally effective.

The luminosity of the peel color did not show significant differences between treatments ($p > 0.05$, Table 3). The values of a^* were higher in the peel of fruits treated with T3 $KIO_3$5 mg, while the lowest values of a^* were obtained in fruits treated with T0 control, T1 KI 5 mg, T8 CS $KIO_3$25 mg and Tc CS. Lower values of a^* indicate a darker gray color. The values of b^* were also modified by the treatments, with the highest value of b^* in the peel of fruits treated with T2 KI 25 mg and lower in fruits treated with T8 CS $KIO_3$25 mg (Table 3). Higher values of b^* would indicate more yellowish tones. The chroma was not affected by the treatments, while the hue value (°h) was higher in the peel of fruits treated with T0 control, T1 KI 5 mg, Tc CS and T8 CS $KIO_3$25 mg. The lowest values of °hue were obtained with T3 $KIO_3$5 mg (Table 3). Lower values of °hue would indicate greener tones. The greatest color change during

Table 1. Peel color of ‘Sweet Sunrise’ melon fruits at harvest under iodinated treatments

Treatments	Peel color				
	L	*a**	*b**	C	°h
T0 Control	63.26 ± 3.49 a	-1.13 ± 0.71 b	23.35 ± 3.61 ab	23.39 ± 3.58 ab	1.62 ± 0.03 a
Tc CS	62.74 ± 2.93 a	1.97 ± 1.96 a	24.59 ± 5.29 ab	24.72 ± 5.38 ab	1.50 ± 0.07 b
T1 KI 5 mg	62.71 ± 4.81 a	1.42 ± 1.35 a	23.41 ± 2.51 ab	23.48 ± 2.53 ab	1.51 ± 0.06 b
T2 KI 25 mg	64.81 ± 4.75 a	1.11 ± 1.36 a	24.88 ± 3.15 ab	24.94 ± 3.21 ab	1.53 ± 0.05 b
T3 KIO_3 5 mg	61.61 ± 4.14 a	0.99 ± 1.85 a	23.88 ± 2.29 ab	23.96 ± 2.32 ab	1.53 ± 0.08 b
T4 KIO_3 25 mg	64.88 ± 3.98 a	1.47 ± 1.14 a	25.25 ± 3.77 ab	25.31 ± 3.80 ab	1.51 ± 0.04 b
T5 CS KI 5 mg	62.46 ± 4.06 a	1.07 ± 1.59 a	22.91 ± 2.72 b	22.99 ± 2.71 b	1.53 ± 0.07 b
T6 CS KI 25 mg	63.89 ± 4.39 a	1.58 ± 1.55 a	24.48 ± 1.13 ab	24.58 ± 1.19 ab	1.51 ± 0.06 b
T7 CS KIO_3 5 mg	61.55 ± 4.53 a	1.08 ± 0.94 a	23.20 ± 1.71 ab	23.24 ± 1.74 ab	1.53 ± 0.04 b
T8 CS KIO_3 25 mg	67.41 ± 3.63 a	2.62 ± 1.35 a	28.17 ± 4.48 a	28.31 ± 4.55 a	1.48 ± 0.04 b

Different letters in the same column and for the same color indicator indicate significant differences with Tukey's test at $P<0.05$.

Table 2. Flesh color of 'Sweet Sunrise' melon fruits at harvest

Treatments	Flesh color				
	L	*a**	*b**	C	°h
T0 Control	65.78 ± 5.86 ab	27.63 ± 5.43 b	53.70 ± 4.57 b	60.47 ± 6.32 b	1.10 ± 0.06 a
Tc CS	68.45 ± 4.24 ab	29.52 ± 3.46 ab	58.15 ± 3.66 ab	65.24 ± 4.64 ab	1.10 ± 0.03 a
T1 KI 5 mg	67.59 ± 4.38 ab	30.34 ± 2.72 ab	58.04 ± 2.59 ab	65.50 ± 3.44 ab	1.09 ± 0.02 a
T2 KI 25 mg	63.91 ± 1.96 ab	32.72 ± 2.51 a	59.19 ± 3.06 a	67.65 ± 3.56 a	1.07 ± 0.03 a
T3 KIO_3 5 mg	62.79 ± 2.04 ab	31.61 ± 1.64 ab	56.77 ± 2.72 ab	64.98 ± 3.04 ab	1.06 ± 0.01 a
T4 KIO_3 25 mg	66.33 ± 2.38 ab	29.93 ± 3.89 ab	58.30 ± 3.75 ab	65.59 ± 4.58 ab	1.10 ± 0.04 a
T5 CS KI 5 mg	67.40 ± 1.80 ab	30.46 ± 3.80 ab	57.90 ± 2.99 ab	65.46 ± 4.27 ab	1.09 ± 0.04 a
T6 CS KI 25 mg	65.41 ± 2.38 ab	31.62 ± 2.29 ab	58.08 ± 2.57 ab	66.14 ± 3.08 ab	1.07 ± 0.02 a
T7 CS KIO_3 5 mg	65.92 ± 2.64 ab	31.81 ± 3.10 ab	59.62 ± 4.33 ab	67.60 ± 5.07 ab	1.08 ± 0.02 a
T8 CS KIO_3 25 mg	66.11 ± 1.43 ab	31.06 ± 2.47 ab	59.90 ± 2.04 a	67.50 ± 2.64 a	1.09 ± 0.03 a

Different letters in the same column and for the same color indicator indicate significant differences with Tukey's test at $P<0.05$.

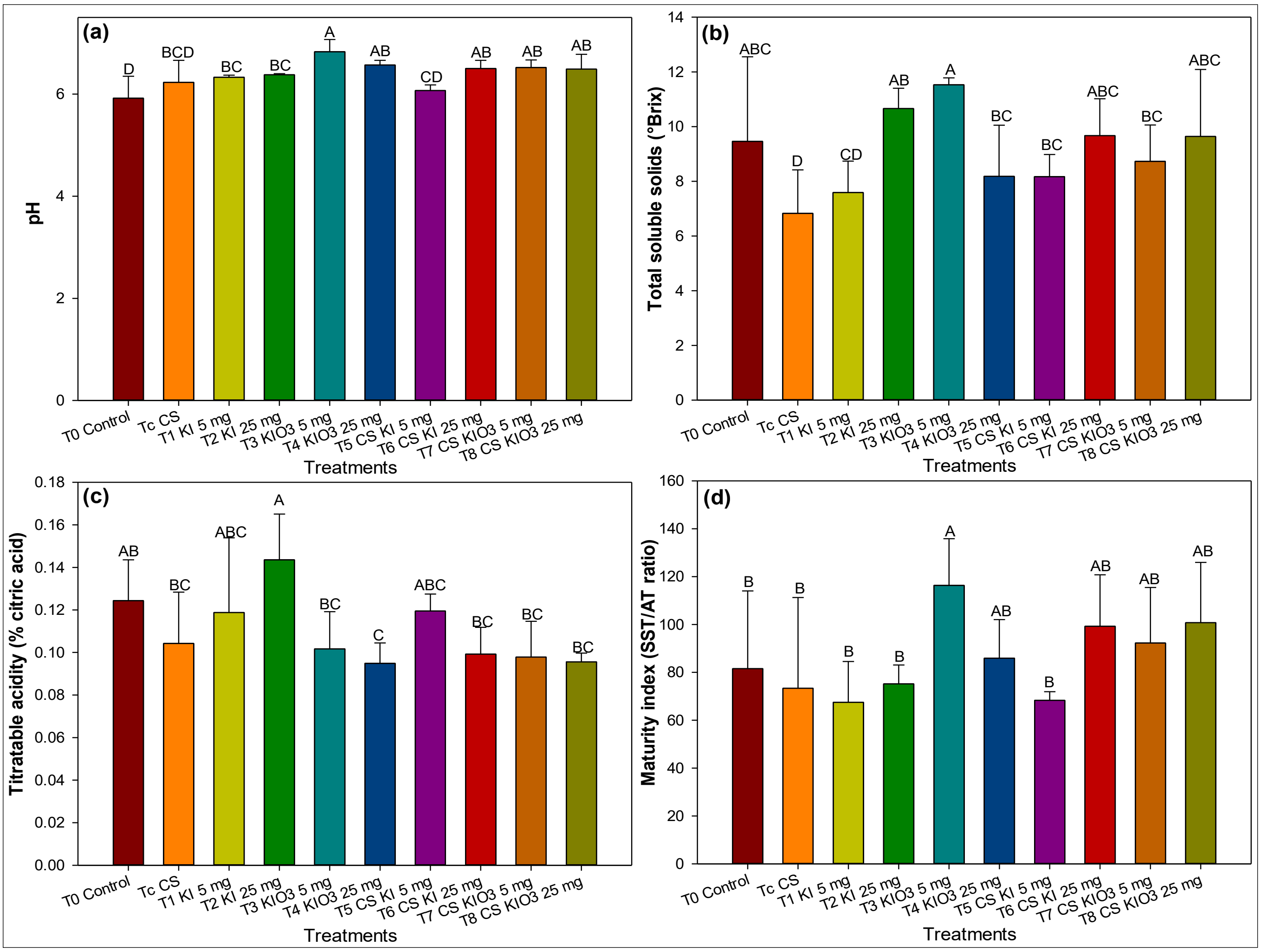

Fig. 2. pH (a), total soluble solids (°Brix) (b), titratable acidity (% citric acid) (c) and maturity index (TSS/AT ratio) (d) of freshly harvested melons under iodinated treatments.

storage was observed in fruits treated with T8 CS $KIO_3$25 mg, while the smallest variations in peel color were in fruits treated with T0 control, T1 KI 5 mg and Tc CS; therefore, the treatments appear to influence the peel coloration of melon fruits.

The luminosity of the flesh color was higher in fruits treated with T8 CS $KIO_3$25 mg (67.19) and lower in the flesh of T0 control fruits (62.82) ($p < 0.05$, Table 4). The values of a^* were higher in fruits treated with T5 CS KI 5 mg (32.56) and T2 KI 25 mg (31.76), while the lowest values were obtained with the controls T0 control (28.06) and Tc CS (28.75) ($p < 0.05$, Table 4). Higher values of a^* and b^* would indicate more orange flesh colors. The highest b^* values were obtained with treatments T4 $KIO_3$25 mg (57.14) and the lowest with control Tc CS (53.37) ($p < 0.05$, Table 4). Higher values of a^* and b^* would indicate more orange flesh colors. Chroma values remained unaffected by the treatments. However, significant differences in °hue were observed, with the highest value recorded in the flesh of T0 control fruits (1.091) and the lowest in fruits treated with T5 CS KI 5 mg (1.052) ($p < 0.05$, Table 4). Higher °hue values correspond to a shift toward more yellowish flesh tones. Finally, the color change of the flesh during storage was greater in the fruits of the controls Tc CS (11.362) and T0 control (9.354), while the lowest changes in flesh color occurred with treatments T6 CS KI 25 mg (4.8) and T2 KI 25 mg (4.962) ($p < 0.05$, Table 4). A greater color change can indicate greater ripening during storage or loss of color, suggesting that iodine salt-based treatments have a positive effect on fruit color preservation during storage. Generally, the results show that iodine-based treatments influence both peel and flesh color during storage. These findings suggest that iodine biofortification, particularly when optimized doses and in combination with chitosan, helps preserve visual quality during postharvest storage, an important factor for consumer preference and market value.

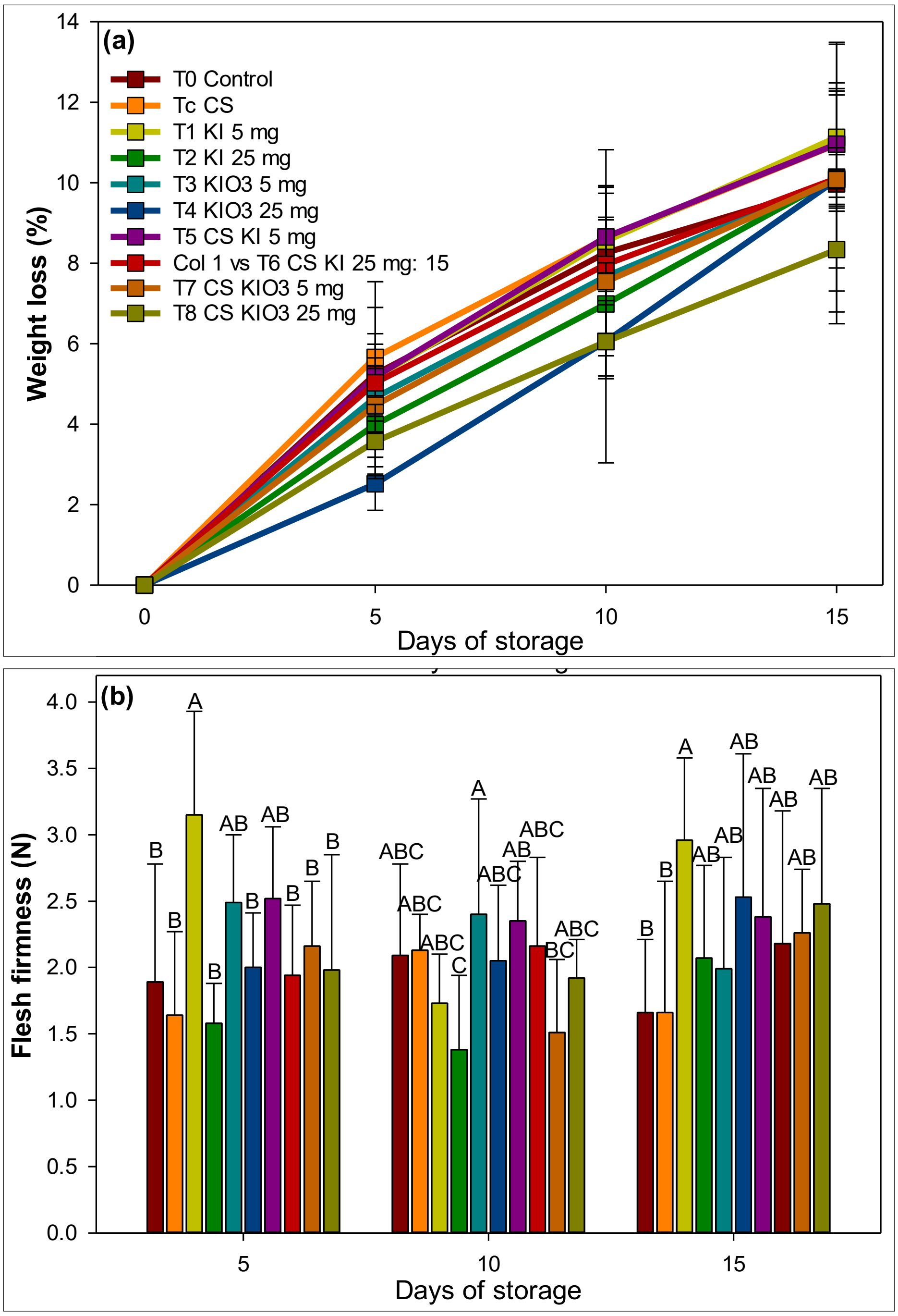

Fig. 3. Weight loss (%) (a) and flesh firmness (N) (b) of melons during postharvest storage at 25 °C under field-applied iodinated treatments.

Table 3. Peel color of 'Sweet Sunrise' melon fruits during storage at 25 °C (measured every 5 days)

Treatments	Day	Peel color					
		L	*a**	*b**	C	°h	DE
T0 Control	5	63.25 ± 4.27 a	0.69 ± 0.85 a	24.09 ± 1.49 ab	24.11 ± 1.49 ab	1.54 ± 0.03 a	4.44 ± 1.82 ab
	10	62.46 ± 4.56 a	0.69 ± 1.06 a	23.29 ± 1.41 a	23.32 ± 1.42 a	1.54 ± 0.05 a	4.68 ± 1.92 ab
	15	63.01 ± 4.87 a	0.29 ± 1.00 ab	24.74 ± 1.55 ab	24.76 ± 1.54 ab	1.56 ± 0.04 ab	4.63 ± 2.74 a
Tc CS	5	62.18 ± 3.92 a	0.28 ± 0.52 a	22.44 ± 1.53 b	22.45 ± 1.53 b	1.56 ± 0.02 a	4.40 ± 2.23 ab
	10	64.86 ± 2.00 a	0.42 ± 2.07 a	25.85 ± 5.15 a	25.92 ± 5.19 a	1.56 ± 0.08 a	5.43 ± 3.36 ab
	15	63.57 ± 4.18 a	2.35 ± 1.62 b	25.92 ± 2.84 ab	26.06 ± 2.93 ab	1.48 ± 0.05 a	4.51 ± 2.86 a
T1 KI 5 mg	5	63.83 ± 3.92 a	0.47 ± 1.48 a	23.18 ± 2.59 ab	23.22 ± 2.63 ab	1.55 ± 0.06 a	4.71 ± 1.32 ab
	10	65.31 ± 3.85 a	0.91 ± 1.21 a	24.37 ± 1.62 a	24.41 ± 1.68 a	1.53 ± 0.04 a	4.84 ± 1.25 ab
	15	65.44 ± 4.01 a	0.90 ± 1.10 b	24.54 ± 1.66 ab	24.58 ± 1.65 ab	1.53 ± 0.05 a	4.71 ± 2.29 a
T2 KI 25 mg	5	63.59 ± 3.84 a	0.26 ± 1.21 a	25.50 ± 1.05 a	25.53 ± 1.05 a	1.56 ± 0.05 a	3.63 ± 2.32 b
	10	64.75 ± 4.45 a	1.71 ± 1.26 a	25.26 ± 1.44 a	25.35 ± 1.48 a	1.50 ± 0.05 a	4.00 ± 2.44 b
	15	65.78 ± 3.45 a	4.40 ± 3.85 ab	28.39 ± 4.77 ab	28.87 ± 5.34 ab	1.43 ± 0.10 ab	6.77 ± 5.01 a
T3 KIO_3 5 mg	5	62.43 ± 3.54 a	0.75 ± 0.73 a	23.04 ± 1.36 b	23.06 ± 1.37 b	1.54 ± 0.03 a	3.22 ± 2.22 b
	10	64.34 ± 3.12 a	1.01 ± 1.18 a	24.81 ± 3.04 a	24.85 ± 3.08 a	1.53 ± 0.04 a	4.19 ± 3.17 b
	15	66.79 ± 3.96 a	7.95 ± 8.94 a	29.72 ± 5.78 a	31.39 ± 8.34 a	1.35 ± 0.19 b	11.25 ± 10.47 a
T4 KIO_3 25 mg	5	63.61 ± 4.22 a	-0.25 ± 1.09 a	22.40 ± 1.59 b	22.42 ± 1.59 b	1.58 ± 0.05 a	5.14 ± 2.48 ab
	10	62.87 ± 2.39 a	0.95 ± 1.36 a	24.11 ± 1.88 a	24.17 ± 1.90 a	1.53 ± 0.06 a	3.37 ± 2.15 b
	15	65.30 ± 5.08 a	3.95 ± 2.00 ab	28.18 ± 4.04 ab	28.49 ± 4.23 ab	1.44 ± 0.06 ab	6.71 ± 3.49 a
T5 CS KI 5 mg	5	64.22 ± 3.53 a	-0.04 ± 0.98 a	22.22 ± 1.34 b	22.24 ± 1.35 b	1.57 ± 0.04 a	4.13 ± 1.19 ab
	10	63.87 ± 2.91 a	1.33 ± 0.66 a	26.28 ± 4.06 a	26.32 ± 4.05 a	1.52 ± 0.03 a	4.80 ± 3.81 ab
	15	65.64 ± 6.28 a	3.53 ± 4.28 ab	28.48 ± 7.53 ab	28.87 ± 8.01 ab	1.47 ± 0.11 ab	8.67 ± 9.12 a
T6 CS KI 25 mg	5	62.77 ± 5.12 a	1.12 ± 0.74 a	23.28 ± 0.94 ab	23.32 ± 0.96 ab	1.52 ± 0.03 a	4.43 ± 2.99 ab
	10	63.77 ± 5.10 a	1.28 ± 1.32 a	25.46 ± 2.99 a	25.51 ± 3.04 a	1.52 ± 0.05 a	5.23 ± 2.65 ab
	15	64.18 ± 4.40 a	3.41 ± 1.94 ab	26.30 ± 1.39 ab	26.58 ± 1.54 ab	1.44 ± 0.07 ab	5.19 ± 1.49 a
T7 CS KIO_3 5 mg	5	65.35 ± 2.50 a	0.76 ± 0.42 a	23.78 ± 1.61 ab	23.80 ± 1.62 ab	1.54 ± 0.02 a	4.33 ± 2.17 ab
	10	64.97 ± 3.67 a	1.28 ± 0.78 a	25.31 ± 0.67 a	25.35 ± 0.69 a	1.52 ± 0.03 a	5.09 ± 1.90 ab
	15	64.47 ± 2.53 a	2.41 ± 2.36 ab	27.05 ± 3.11 ab	27.23 ± 3.24 ab	1.49 ± 0.08 ab	6.03 ± 3.00 a
T8 CS KIO_3 25 mg	5	62.92 ± 3.72 a	0.87 ± 1.15 a	24.03 ± 1.67 ab	24.07 ± 1.74 ab	1.54 ± 0.04 a	7.25 ± 2.03 a
	10	60.86 ± 4.87 a	0.43 ± 1.05 a	24.43 ± 1.39 a	24.45 ± 1.42 a	1.56 ± 0.04 a	8.71 ± 3.30 a
	15	61.61 ± 4.85 a	1.33 ± 1.70 b	22.91 ± 2.26 b	23.01 ± 2.17 b	1.51 ± 0.08 a	8.92 ± 3.57 a

Different letters for the same color indicator indicate significant differences between treatments by day of sampling with Tukey's test at $P<0.05$.

Table 4. Flesh color of 'Sweet Sunrise' melon fruits during storage at 25 °C (measured every 5 days)

Treatments	Day	Flesh color					
		L	*a**	*b**	C	°h	DE
T0 Control	5	63.32 ± 4.03 a	32.06 ± 4.84 ab	56.84 ± 5.47 ab	65.29 ± 7.01 ab	1.06 ± 0.03 ab	9.20 ± 3.79 a
	10	65.23 ± 2.90 ab	29.25 ± 3.80 a	51.91 ± 8.55 a	59.76 ± 7.97 ab	1.05 ± 0.09 b	7.71 ± 5.99 b
	15	59.93 ± 6.41 c	22.90 ± 8.20 b	52.09 ± 2.27 a	57.28 ± 4.87 ab	1.16 ± 0.12 a	11.15 ± 6.36 a
Tc CS	5	63.40 ± 2.33 a	34.06 ± 2.93 a	60.28 ± 1.98 a	69.26 ± 3.07 a	1.06 ± 0.03 ab	7.35 ± 3.77 a
	10	70.33 ± 7.50 a	22.63 ± 6.66 b	46.29 ± 10.21 b	51.58 ± 11.91 b	1.12 ± 0.05 a	17.17 ± 9.44 a
	15	62.10 ± 2.03 bc	29.57 ± 4.51 ab	53.54 ± 4.09 a	61.22 ± 5.48 b	1.07 ± 0.05 b	9.58 ± 2.71 a
T1 KI 5 mg	5	64.32 ± 1.51 a	28.56 ± 5.16 ab	55.38 ± 5.75 ab	62.37 ± 7.10 ab	1.10 ± 0.05 ab	7.16 ± 5.28 a
	10	64.33 ± 1.56 ab	29.77 ± 2.49 a	54.47 ± 2.67 a	62.09 ± 3.29 a	1.07 ± 0.03 ab	5.99 ± 1.41 b
	15	63.60 ± 1.54 bc	31.79 ± 2.33 b	56.71 ± 2.66 a	65.02 ± 3.38 ab	1.06 ± 0.02 b	5.63 ± 1.26 a
T2 KI 25 mg	5	65.54 ± 1.31 a	31.36 ± 2.57 ab	56.86 ± 3.35 ab	64.94 ± 4.13 ab	1.07 ± 0.01 ab	4.59 ± 2.64 a
	10	62.50 ± 3.35 ab	31.68 ± 2.44 a	55.15 ± 1.98 a	63.61 ± 2.81 a	1.05 ± 0.02 b	5.73 ± 2.44 b
	15	64.32 ± 2.60 abc	32.26 ± 2.13 b	56.12 ± 2.18 a	64.74 ± 2.81 ab	1.05 ± 0.02 b	4.56 ± 1.92 a
T3 KIO_3 5 mg	5	64.89 ± 2.20 a	30.64 ± 3.82 ab	56.92 ± 4.11 ab	64.66 ± 5.34 ab	1.08 ± 0.03 ab	5.25 ± 3.37 a
	10	65.44 ± 0.54 ab	33.62 ± 2.22 a	60.02 ± 3.02 a	68.80 ± 3.65 a	1.06 ± 0.01 ab	5.32 ± 2.62 b
	15	63.80 ± 1.90 bc	28.81 ± 3.43 ab	53.47 ± 3.91 a	60.76 ± 4.87 ab	1.08 ± 0.03 b	6.25 ± 2.98 a
T4 KIO_3 25 mg	5	67.58 ± 5.61 a	26.60 ± 6.22 b	52.17 ± 6.39 b	58.65 ± 8.26 b	1.11 ± 0.06 a	9.26 ± 8.42 a
	10	65.89 ± 2.21 b	32.79 ± 2.89 a	59.51 ± 2.98 a	67.96 ± 3.87 a	1.07 ± 0.02 ab	5.09 ± 2.02 b
	15	67.25 ± 3.67 ab	33.28 ± 4.49 b	59.73 ± 7.30 a	68.41 ± 8.26 a	1.06 ± 0.03 b	7.85 ± 5.78 a
T5 CS KI 5 mg	5	64.52 ± 1.93 a	33.62 ± 7.73 a	56.44 ± 1.36 ab	65.93 ± 5.17 ab	1.04 ± 0.08 b	6.67 ± 6.18 a
	10	64.83 ± 3.06 ab	31.73 ± 4.83 a	55.82 ± 5.22 a	64.24 ± 6.85 a	1.06 ± 0.03 b	7.57 ± 3.09 b
	15	62.71 ± 8.98 abc	32.36 ± 2.65 b	57.97 ± 3.35 a	66.40 ± 4.07 ab	1.06 ± 0.02 b	7.67 ± 7.85 a
T6 CS KI 25 mg	5	65.09 ± 2.22 a	31.56 ± 2.04 ab	56.96 ± 2.01 ab	65.13 ± 2.63 ab	1.07 ± 0.02 ab	3.44 ± 1.16 a
	10	64.42 ± 1.99 ab	32.11 ± 2.86 a	57.85 ± 5.14 a	66.19 ± 5.65 a	1.06 ± 0.02 ab	5.13 ± 3.22 b
	15	66.40 ± 1.99 abc	29.39 ± 1.65 ab	53.72 ± 2.56 a	61.24 ± 2.80 ab	1.07 ± 0.02 b	5.83 ± 1.77 a
T7 CS KIO_3 5 mg	5	67.37 ± 1.26 a	29.01 ± 2.60 ab	54.43 ± 2.59 ab	61.70 ± 3.25 ab	1.08 ± 0.03 ab	6.50 ± 3.02 a
	10	63.18 ± 0.56 ab	33.90 ± 3.10 a	59.05 ± 1.97 a	68.12 ± 3.06 a	1.05 ± 0.03 b	4.76 ± 1.45 b
	15	65.48 ± 2.13 bc	30.61 ± 3.97 b	54.92 ± 3.75 a	62.91 ± 4.91 ab	1.06 ± 0.04 b	6.00 ± 4.54 a
T8 CS KIO_3 25 mg	5	65.24 ± 2.68 a	28.72 ± 3.27 ab	54.24 ± 4.28 ab	61.41 ± 4.95 ab	1.08 ± 0.03 ab	7.78 ± 3.34 a
	10	65.53 ± 1.67 b	33.50 ± 2.33 a	57.28 ± 2.61 a	66.36 ± 3.41 a	1.04 ± 0.01 b	5.10 ± 0.72 b
	15	70.80 ± 5.53 a	30.09 ± 7.18 b	54.99 ± 10.90 a	62.70 ± 12.97 ab	1.07 ± 0.03 b	11.74 ± 9.95 a

Different letters for the same color indicator indicate significant differences between treatments by day of sampling with Tukey's test at $P<0.05$.

The pH value showed differences among treatments during storage (Fig. 4a), with fruits treated with T5 CS KI 5 mg (6.92) exhibiting the highest pH values and T2 KI 25 mg (6.62) exhibiting the lowest values at 15 days of storage ($p < 0.05$). However, the pH range of the fruits ranged from 5.92 - 7.29. A higher pH (closer to neutrality) could result in a milder flavor profile, while lower pH values are associated with a sharper, more acidic taste. These differences suggest that iodine treatments can modulate acidity during storage, potentially affecting fruit sensory quality and preservation. The sugar content represented as °Brix showed significant differences ($p < 0.05$) among treatments, with the highest SST content in fruits treated with T2 KI 25 mg (9.14), T6 CS KI 25 mg (8.36 °Brix) and T3 KIO_3 5 mg (8.33 °Brix); the lowest values were obtained with T4 KIO_3 25 mg (6.85 °Brix) and Tc CS (6.90 °Brix) (Fig. 4b). The lower sugar content in chitosan control fruits (Tc CS) during storage indicates that iodine-based treatments may be affecting the sweetness and flavor of the fruits, as they exhibit the highest °Brix value. Storage time has been identified as a factor influencing soluble solids content (SST) in melon fruits; however, no changes in SST content were observed during storage when comparing freshly harvested and stored fruits across seven melon varieties (32, 39). The increase in SST observed in this study may reflect enhanced sugar accumulation or slowed sugar degradation during storage due to the effect of iodine compounds on metabolic pathways.

The titratable acidity reported as a percentage of citric acid was modified by the treatments, with fruits treated with T2 KI 25 mg (7.19 TA) showing the highest citric acid content, while control fruits Tc CS (4.71 TA) exhibited the lowest citric acid content ($p < 0.05$, Fig. 4c). This indicates a positive effect of iodine salt-based treatments on the content of organic acids in melon fruits. A reduction in titratable acidity was observed during storage across the seven evaluated melon varieties (39). The maintenance of higher acidity in iodine-treated fruits may contribute to a more balanced flavor profile and improved resistance to microbial spoilage, thus enhancing postharvest shelf life.

The maturity index was higher in control fruits (T0 control) (189.65) throughout storage, indicating greater ripening and, consequently, lower quality in their chemical composition. Meanwhile, fruits treated with T2 KI 25 mg (136.96) showed the lowest maturity index value, suggesting a positive effect on fruit preservation ($p < 0.05$, Fig. 4d). An increase in the maturity index (SST/TA ratio) during melon postharvest was observed regardless of the variety, consistent with the trend shown between Fig. 2d and 4d (39).Iodine can have a complex impact on plant metabolism, with effects varying depending on the plant species, the form of iodine applied and environmental conditions (40). Chitosan iodate treatment has been shown to result in higher iodine retention in residual crops, likely due to the electrostatic interaction between chitosan and iodate that enhances iodine retention (22). Therefore, it is essential to continue investigating the impact of plant biofortification on postharvest fruit quality. In this study, the lower maturity index values suggest a delay in ripening and better preservation of chemical quality during storage. Among the treatments evaluated, T8 CS KIO_3 25 mg was the most effective in preserving the postharvest quality of melon fruits, reducing weight loss, maintaining firmness and color and achieving a balanced sweetness–acidity profile. This treatment is recommended as a promising strategy for iodine biofortification with added postharvest benefits.

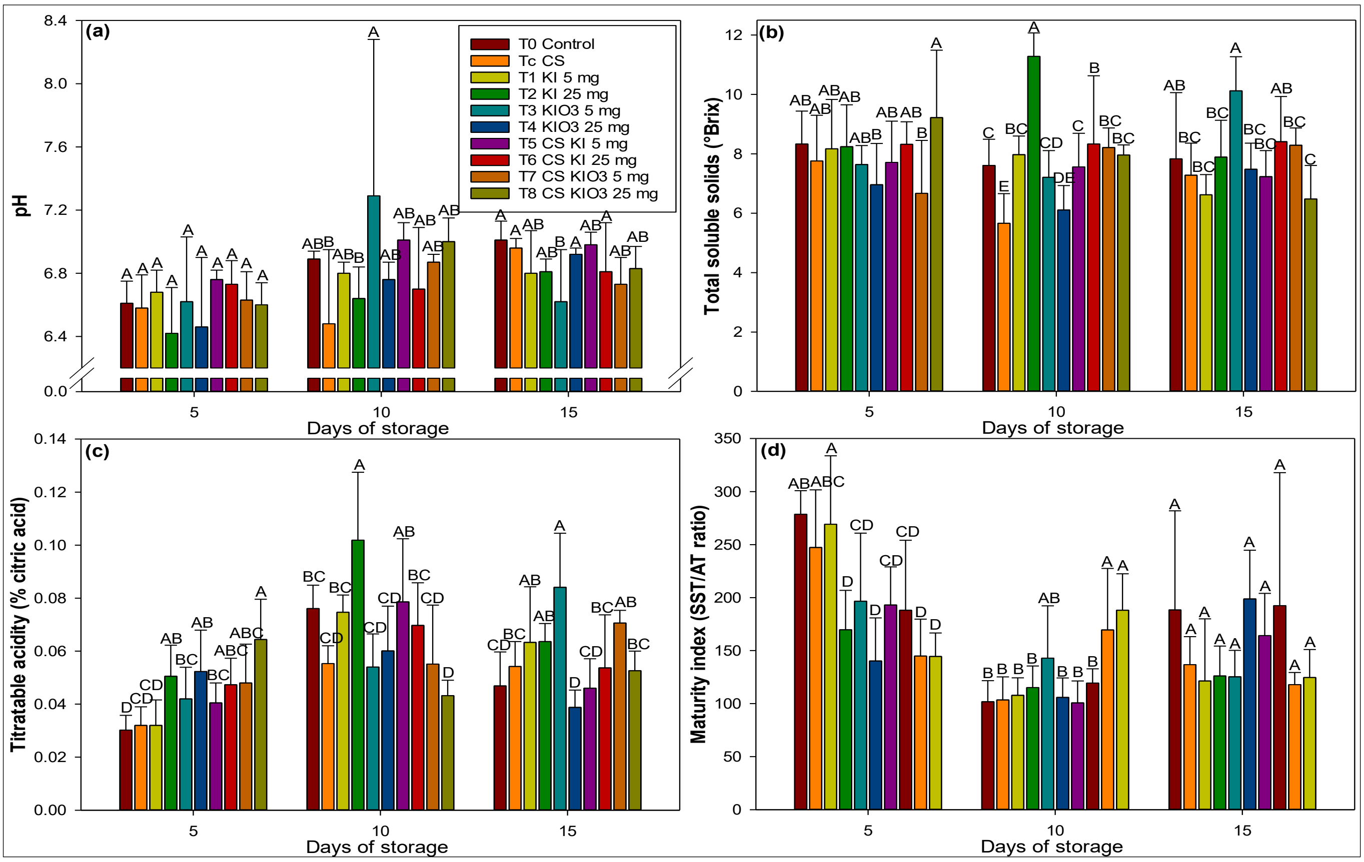

Fig. 4. pH (a), total soluble solids (°Brix) (b), titratable acidity (% citric acid) (c) and maturity index (SST/AT ratio) (d) of melons during storage at 25 °C under iodinated treatments.

Conclusion

The application of iodine compounds and iodized complexes showed favorable effects on color, pH, total soluble solids (TSS), acidity and maturity index in harvested fruits. Weight loss differed by 2.42 % between iodine-treated and untreated fruits during 5, 10 and 15 days of storage, while firmness was better preserved. Significant differences were also observed in color, pH, TSS, acidity and maturity index throughout storage. The use of iodine salts and complexes (CS KI and CS KIO_3) represents an agricultural alternative for biofortifying crops without compromising melon quality during harvest and postharvest. Among the evaluated strategies, the treatment with chitosan and KIO_3 at 25 mg (T8) consistently showed the best performance across multiple quality parameters, highlighting its potential for commercial application in melon production.

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Authors' contributions

LAASM participated in the investigation and writing original draft. HOO participated in the resources, investigation, formal analysis, writing and review and editing. ETL participated in the conceptualization, supervision, writing, review and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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