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Postharvest UV-C Treatment, Followed by Storage in a Continuous Low-Level Ethylene Atmosphere, Maintains the Quality of 'Kensington Pride' Mango Fruit Stored at 20 °C

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Abstract: Mature green 'Kensington Pride' mangoes (*Mangifera indica* L.) were treated with a short-term UV-C light at four different intensities (0, 4.0, 8.3 and 11.7 kJ m^{-2}). After treatment, mangoes were stored for 12 d in air (<0.005 μL L^{-1} ethylene) or 0.1 μL L^{-1} ethylene at 20 °C and 100% relative humidity (RH). Weight loss, peel colour, firmness, ethylene production, respiration rate, total soluble solids (TSS), titratable acidity (TA), total chlorophyll content, total phenolic content (TPC) and total antioxidant activity were assessed at 3-d intervals. The results showed that UV-C treatment delayed skin degreening, reduced endogenous ethylene production, suppressed respiration rate and lowered chlorophyll content compared to untreated control fruit. Fruit treated with UV-C had significantly higher TPC and total antioxidant activity at the end of the storage period than untreated fruits for both storage atmospheres. In addition, UV-C treated fruits remained significantly firmer than untreated fruits. UV-C treatment significantly affected TSS and TA levels in different ways. Storage of fruits in 0.1 μL L^{-1} ethylene significantly affected fruit firmness, respiration rate and ethylene production, while other fruit quality parameters were similar to fruit stored in air. These results indicated that UV-C irradiation could be used as an effective and rapid method to extend the postharvest life of mature green mangoes without adversely affecting certain quality attributes in the presence of low-level ethylene during storage.

Keywords: storage; peel degreening; colour; firmness; total antioxidants; total phenolic content

1. Introduction

Mango (*Mangifera indica* L.) is a tropical, climacteric fruit that is very popular world-wide [1]. However, mangoes are a highly perishable fruit that experience rapid ripening after harvest as a consequence of intense metabolic activity that includes a respiratory peak that occurs between 3 and 4 d after harvest [2]. This short postharvest window results in a need to develop more effective handling practices to reduce fruit losses in the supply chain.

'Kensington Pride' mangoes are the most widely grown in Australia and are harvested just prior to full maturity (green skin and light cream flesh). Fruit are harvested at a minimum 14% dry matter, treated with a postharvest fungicide and stored at 12 °C. The fruit completes its ripening through the supply chain, with full colour development (yellow-red flesh) upon arrival at market. Delaying the natural postharvest ripening is considered the best strategy for increasing storage and shelf life [3].

In addition, delaying fruit ripening also reduces fruit susceptibility to postharvest pathogens and, therefore, many previous research studies have focused on delaying the rate of fruit ripening. A range

of physical and chemical methods have been successfully employed to delay ripening and senescence, and include controlled atmosphere storage [4], low and high temperature treatments [5,6] and simple chemical treatments including carbonate and bicarbonate solutions [7].

Over the past two decades, UV-C treatment (180–280 nm) has been evaluated as a postharvest treatment for fresh fruits and vegetables [8] including to reduce pathogen growth [9]. UV-C treatment has been reported to delay the ripening and senescence of apples [10], tomato [11,12], oranges [13], table grapes [14], mango [15], peaches [16] and limes [17]. Therefore, postharvest UV-C treatment has the potential to become a low cost, low technology treatment for reducing fruit and vegetable loss in the supply chain.

A common factor affecting the postharvest life of fruit (including mangoes) is exposure to endogenous or exogenous ethylene [18]. Ethylene is ubiquitous in the storage environment, where the ethylene levels in supermarkets have been shown to be 0.017–0.035 μL L^{-1} and greater than 0.06 μL L^{-1} in wholesale markets and distribution centres [19]. Limited studies have been conducted to assess the effectiveness of UV-C treatment followed by storage in low levels of ethylene on the postharvest storage and ripening of mangoes. The significance of postharvest handling and transport issues that characterise many supply chains make the investigation of novel, low-cost postharvest treatments for high value, perishable produce an issue of interest for industry. In this study, we examined the effect of a short pre-storage UV-C treatment on the quality of 'Kensington Pride' mango fruit stored in continuous air (containing <0.005 1 μL L^{-1} ethylene) or 0.1 μL L^{-1} ethylene at 20 °C and with 100% relative humidity (RH) for up to 12 d.

2. Materials and Methods

2.1. Produce

Mature hard (green skin and light cream pulp) mango fruit (*Mangifera indica* L. cv. 'Kensington Pride') were harvested from a mango farm in Queensland and transported by refrigerated truck to Sydney wholesale market for collection. Fruit of uniform size, free from visual blemishes and diseases, were sorted into experimental units. Initial fruit quality was tested on 15 fruits and the results were as follows: the fruit were firm (39 ± 3 N), had low ethylene production (0.013 ± 0.001 μL C_2H_4 kg^{-1} h^{-1}) and respiration rate of 26.7 ± 2.0 mL CO_2 kg^{-1} h^{-1}, with total soluble solids (TSS) of 14.0 ± 0.2 °Brix, titratable acidity (TA) of 0.62 ± 0.07% citric acid, chlorophyll content of 0.61 ± 0.03 (mg/L), total phenolic content of 0.512 ± 0.02 TPC (mg gallic acid equiv/g FW (fresh weight)) and total antioxidant activity of 18.9 ± 1.1 (% DPPH scavenging activity).

2.2. UV-C Treatment and Storage Conditions

The UV-C treatment was conducted using a custom made fully enclosed semi-commercial roller fitted with six germicidal lamps (Sankyo Denki Co., Ltd., G20T10 20 Watt, low pressure mercury, Kanagawa, Japan). A SED008/W detector (International Light Technologies, Inc., Peabody, MA, USA) with Precision Infrared Radiometer (PIR) Irradiance Calibration at 254 nm was used to monitor UV-C intensity. This was connected to an International Light Technologies 1700 series research radiometer that outputs cumulative exposure over time. The positioning of lights inside the chamber was adjusted manually to ensure maximum and uniform exposure of the treated fruit. Treatment units of twelve mangoes were placed inside the unit on the rollers. The number of lights switched on during treatment was controlled manually, with the roller speed being adjusted to deliver the desired UV-C exposures and intensities. For each UV-C treatment, mango fruit were placed approximately 17 cm from the UV-C lights and exposed at the required intensity (0, 4.0, 8.3 and 11.7 kJ m^{-2} UV-C), with an intensity of 0 kJ m^{-2} UV-C as a control treatment. All treatments were conducted at room temperature (20 ± 1 °C) and relative humidity at 80%, unless otherwise stated. Each treatment unit consisted of twelve fruits and the experiment was replicated three times with the same batch of fruit. Post-treatment, the fruit

were stored in either air (containing <0.005 μL L^{-1}) or 0.1 μL L^{-1} ethylene at a storage temperature of 20 °C and 100% RH up to 12 d, with destructive assessment every three d.

2.3. Determination of Fruit Quality Attributes

2.3.1. Weight Loss

Fruit weight was recorded gravimetrically using a standard top loaded balance (Kern PLS 2100-2, Kern & Sohn, Balingen, Germany) and weight loss percentage was calculated according to Equation (1):

$$\text{Weight loss } (\%) = \left(\frac{\text{Initial fruit weight} - \text{final fruit weight}}{\text{Initial fruit weight}} \right) \times 100. \quad (1)$$

2.3.2. Colour

Peel colour was measured using a Minolta colorimeter (Minolta CR-400, Osaka, Japan) with the hue angle value determined and recorded. Before measuring, the colorimeter was calibrated with a white standard calibration plate. For each fruit, the hue value of the peel was measured as the average of three points from the blossom-end area and expressed as hue angle (°Hue) as shown in Equation (2).

$$\text{Hue} = \text{arctangent}\left(\frac{b^*}{a^*} \right) \quad (2)$$

2.3.3. Firmness

A texture analyser (Lloyd Instrument LTD, Fareham, UK) was used to determine firmness of fruit. Mango firmness was determined as the maximum force, required to push a 7 mm probe into the fruit flesh to a depth of 2 mm. The average of two reading points from two equidistant regions on opposite sides of the equatorial region of the fruits [20] was recorded. The readings were expressed in Newton (N).

2.3.4. Ethylene Production

The ethylene production was measured according to Pristijono et al. [11], where mangoes were transferred to a sealed 1500 mL hermetic glass jar with a septum in the lid at 20 °C, and after one hour, a gas sample (1 mL) was collected in a syringe and the ethylene content was analysed. Ethylene was measured by injecting a gas sample into a flame ionization gas chromatograph (Gow-Mac 580, Bridgewater, NJ, USA) fitted with a stainless steel column (2 m × 3.2 mm outer diameter (OD) × 2.2 mm internal diameter (ID)) packed with Porapak Q (80–100 mesh) (Altech, Sydney, Australia), with 110, 90 and 70 °C as the operating temperature of the detector, column and the injector, respectively. Nitrogen, hydrogen and air were used as carrier and combustion gases at flow rates of 60, 30 and 300 mL min^{-1}, respectively. The ethylene concentration was calculated with reference to the concentration of an ethylene standard. The ethylene production rate was calculated by Equation (3) and expressed as μL C_2H_4 kg^{-1} h^{-1}.

$$\text{Ethylene production } \left(\mu\text{L } C_2H_4 \text{kg}^{-1}\text{h}^{-1} \right) = \frac{C_2H_4\left(\frac{\mu\text{L}}{\text{L}} \right) \times \text{volume of container (L)}}{\text{Initial produce weight (kg)} \times \text{time (h)}} \quad (3)$$

2.3.5. Respiration Rate

A gas sample (5 mL) was taken for analysis 1 h after sealing the glass jars as previously described for ethylene production, and carbon dioxide concentration was measured to within 0.1% using an

ICA40 series low-volume gas analysis system (International Controlled Atmosphere Ltd., Kent, UK). Respiration rate was calculated by Equation (4) and expressed as mL CO_2 kg^{-1} h^{-1}.

$$\text{Respiration}\left(\text{mL } CO_2 \text{ kg}^{-1}\text{h}^{-1}\right) = \frac{\%\ CO_2 \times \text{Volume of container (mL)}}{\text{Initial produce weight (kg)} \times 100 \times \text{time (h)}} \quad (4)$$

2.3.6. Total Soluble Solids (TSS) and Titratable Acidity (TA)

Total soluble solids (TSS), expressed as °Brix, were measured from the pressed juice of fruit with a digital refractometer (ATAGO Inc., Bellevue, WA, USA). Titratable acidity (TA), expressed as % citric acid, was determined on the juice sample by titrating 5 mL juice to pH 8.2 with a 0.1 N NaOH solution using an automatic titrator (Mettler Toledo T50, Switzerland).

2.4. Chemical Analysis and Antioxidant Activity Evaluation

Three mangoes were randomly selected from each treatment unit, after 3, 6, 9 and 12 d. After sampling, mangoes were peeled and the mango flesh was sliced into small pieces, discarding the top and bottom sections, and immediately stored at −20 °C until further analysis. The frozen samples were later analysed for total chlorophyll content, total phenolic content and total antioxidant activity.

2.4.1. Total Chlorophyll

Total chlorophyll content was estimated according to the method of Lichtenthaler and Wellburn [21]. Specifically, 1 g of blended sample was mixed with 10 mL 100% acetone in test tubes and held at −20 °C for 48 h. The samples were then vortexed, centrifuged at 10,000 × rpm for 10 min at 20 °C and then the supernatants were filtered through Whatman No 1 filter in volumetric flasks of 25 mL. Subsequently, 10 mL 100% acetone was added to the precipitate and the samples were shaken at 150 × rpm for 10 min. The samples were again filtered and added to the previous volumetric flasks, which were completed with 100% acetone and the absorption was determined spectrophotometrically at 652 nm. The following formula was used for the calculation of total chlorophyll based on the study by Arnon [22]: Total chlorophyll (mg L^{-1}) = D652 × 1000/34.5, where D652 is the absorbance at 652 nm and 34.5 is the value of the specific absorption coefficient at 652 nm.

2.4.2. Total Phenolic Content

The total phenolic content was measured by the Folin–Ciocalteu method as described by Singleton and Rossi [23], and the results were expressed as mg gallic acid equivalents (GAE) per 100 g of fresh weight (mg GAE 100^{-1} g FW).

2.4.3. Total Antioxidant Activity

DPPH radical scavenging activity was determined according to Brand-Williams et al. [24], with slight modifications. Specifically, 200 µL of the extracted sample were added to 2800 µL 100 µm 2,2-diphenyl-1-picrylhydrazyl (DPPH) methanolic solution, which was then vortexed and maintained in darkness at 20 °C for 1 h. Absorbance was measured at 517 nm. The percentage of DPPH scavenging was calculated according to the equation: % DPPH scavenging = 100 × (control absorbance − sample absorbance/control absorbance).

2.5. Statistical Analysis

The experiment was performed with a completely randomised design, with three replications. The two-way ANOVA and the least significance difference (LSD) were conducted using SAS statistical software version 9.4. Data are reported as means, and differences between the means were considered statistically significant different at $p < 0.05$.

3. Results and Discussion

3.1. Weight Loss

Weight loss is related to transpiration and the respiration rate of the fruit and is the major determinant of mango fruit quality [20]. In this experiment, UV-C treatment did not significantly affect the weight loss during storage in both ethylene storage conditions, as shown in Table 1. This result was expected as all fruits were stored in air containing <0.005 μL L^{-1} or 0.1 μL L^{-1} ethylene at 20 °C, at 100% RH. However, there was a significant difference in weight loss between the two ethylene storage conditions, where fruits stored at 0.1 μL L^{-1} ethylene (20 °C and 100% RH) had significantly greater weight loss compared to those fruits stored in air. This result is contradictory to those previously reported by Pristijono et al. [17] who observed that there was no significant difference in weight loss when lime fruit were stored at both air and 0.1 μL L^{-1} ethylene following UV-C treatments. In this study, the differences in fruit weight loss between air and 0.1 μL L^{-1} ethylene storage atmospheres may be due to the higher respiration rate of fruits stored at 0.1 μL L^{-1} ethylene (as discussed in Section 3.6).

Table 1. Weight loss and firmness of mangoes after treatment with different intensities of UV-C, followed by storage for 3, 6, 9, and 12 d in continuous air containing <0.005 μL L^{-1} or 0.1 μL L^{-1} ethylene at 20 °C.

Storage/UV-C (kJ m^{-2})	Weight Loss (%)				Firmness (N)			
	3 d	6 d	9 d	12 d	3 d	6 d	9 d	12 d
<0.005 μL L^{-1} Ethylene								
0	0.9 ^{a}	1.2 ^{a}	1.2 ^{a}	1.4 ^{a}	27.4 ^{a}	24.4 ^{a}	23.4 ^{a}	20.7 ^{a}
4	1.0 ^{a}	1.2 ^{a}	1.3 ^{a}	1.5 ^{a}	26.1 ^{a}	25.7 ^{a}	25.5 ^{a}	22.6 ^{a}
8.3	1.1 ^{a}	1.3 ^{a}	1.4 ^{a}	1.5 ^{a}	29.0 ^{a}	27.0 ^{a}	26.4 ^{ab}	25.6 ^{b}
11.7	1.1 ^{a}	1.3 ^{a}	1.4 ^{a}	1.6 ^{a}	32.6 ^{b}	30.8 ^{b}	30.3 ^{c}	28.8 ^{c}
0.1 μL L^{-1} Ethylene								
0	1.1 ^{a}	1.3 ^{a}	1.4 ^{a}	1.6 ^{a}	22.9 ^{a}	22.0 ^{a}	21.6 ^{a}	21.0 ^{a}
4	0.9 ^{a}	1.2 ^{a}	1.4 ^{a}	1.6 ^{a}	24.4 ^{a}	23.4 ^{b}	23.1 ^{a}	22.5 ^{a}
8.3	1.0 ^{a}	1.4 ^{a}	1.5 ^{a}	1.7 ^{a}	25.0 ^{a}	24.5 ^{b}	24.3 ^{ab}	23.9 ^{b}
11.7	1.2 ^{a}	1.5 ^{a}	1.6 ^{a}	1.7 ^{a}	30.7 ^{b}	28.3 ^{b}	27.6 ^{b}	26.0 ^{b}

Values are the mean of 3 replicates. Letters indicate mean values at the same columns, treatments, storage atmosphere and storage time that are statistically different ($p < 0.05$).

3.2. Firmness

Ripening of mango fruit is closely linked to textural softening, mainly due to changes in cell wall structure and composition [3]. In this study, mangoes treated with 11.7 kJ m^{-2} UV-C light and stored in air (less than 0.005 μL L^{-1} ethylene) resulted in significantly firmer fruit than other treatments, as shown in Table 1. However, fruit stored at 0.1 μL L^{-1} ethylene showed differential responses, where the UV-C intensities of 8.3 and 11.7 kJ m^{-2} UV-C produced significantly firmer fruits than untreated fruits after 6 d of storage. These observations are consistent with the previous report by González-Aguilar et al. [15] who found that the firmness of 'Tommy Atkins' mangoes was maintained with 10 min exposure to UV-C light. Liu et al. [25] also reported that UV-C treatment at an intensity of 4 kJ m^{-2} delayed the rate of softening of tomato fruit. In this study, UV-C treatment resulted in firmer fruit and may be associated with the defence mechanism of plant tissue. Ultraviolet light has been shown to induce biological stresses in plants and defence mechanisms of plant tissues with the consequent production of phytoalexin compounds, where the accumulation of phytoalexin could be accompanied by other inducible defences such as cell wall modifications [26].

3.3. Colour

Colour is one of the major visual attributes of many fruits and it is the most visible symptom of 'Kensington Pride' mango fruit ripening which shows a characteristic change in skin colour from

green to yellow during ripening. The results presented in Figure 1 shows that the peel of untreated fruit had a significantly lower hue angle compared to all treated fruit after 3 d storage at 20 °C for both storage atmospheres, where the low hue angle value indicated less green (yellow) skin. Exposure to UV-C irradiation of up to 11.7 kJ m^{-2} significantly delayed skin colour change during storage. The increased UV-C intensities of UV-C from 0 to 4.0, 8.3 and 11.7 kJ m^{-2} resulted in progressively slower skin degreening and indicate that the UV-C treatment on skin colour was dose dependent. Similar results have also been observed after exposure of green tomato fruit to UV-C light, where UV-C treatment delayed the ripening of tomatoes by maintaining their green colour [11,27,28]. Artés-Hernández et al. [29] also reported that UV-C treatment preserved the green colour of spinach and Pristijono et al. [17] found that UV-C treatments improved lime fruit quality by preserving the peel's green colour during storage.

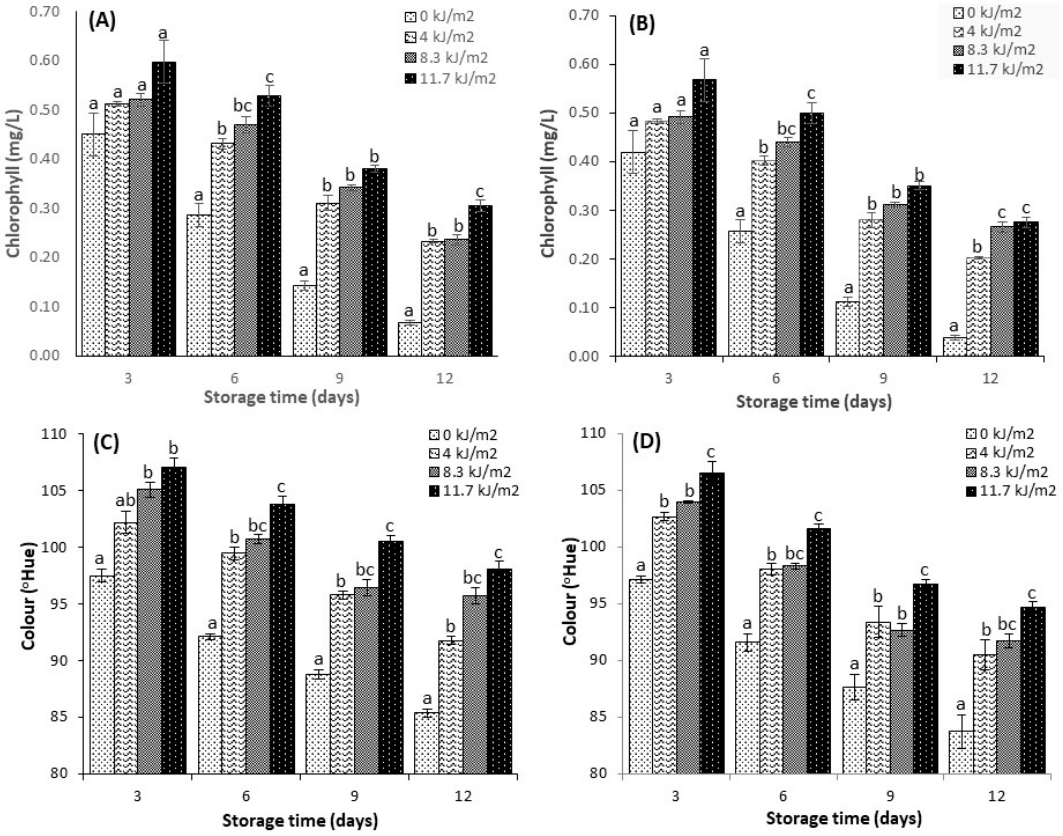

Figure 1. Total chlorophyll content (**A**,**B**) and colour (**C**,**D**) of mangoes after treatment with UV-C, followed by storage for 12 d in continuous air containing <0.005 µL L^{-1} (**A**,**C**) and 0.1 µL L^{-1} ethylene (**B**,**D**) at 20 °C. Different letters above bars indicate values are statistically different within storage day ($p < 0.05$).

3.4. Total Chlorophyll

Total chlorophyll content of the fruit was not statistically different between treated and untreated fruits after 3 d storage, in both storage conditions, as shown in Figure 1. However, after 6 d storage, the untreated mangoes showed significantly lower chlorophyll content than all UV-C treated fruits, in both storage conditions. This result is in agreement with a previous report by Costa et al. [30] who observed that UV-C treatment delays chlorophyll degradation in broccoli florets, and Pongprasert et al. [31] who reported similar results in banana fruit. However, Imaizumi et al. [32] reported that cucumbers treated with UV-C showed a decrease in chlorophyll level during storage. The difference may be associated with the difference in skin fruit structure and type of produce, where mango is a climacteric fruit and chlorophyll degradation relates to the natural ripening process of

fruit, whilst cucumber is non-climacteric produce and a decreasing chlorophyll level is associated with fruit senescence.

3.5. Ethylene Production

The ethylene production rates of treated fruit showed that UV-C treatments suppressed ethylene production during storage, and that this effect occurred after 3 and 6 d storage for fruits stored in 0.1 μL L^{-1} ethylene and air, respectively, as shown in Table 2. There was no significant difference in ethylene production between the different UV-C treatments when fruits were stored in air, however different responses were found when fruits were stored in 0.1 μL L^{-1} ethylene. In this case, ethylene production was significantly suppressed by 8.3 and 11.7 kJ m^{-2} UV-C after 6 d storage. These results showed that the UV-C treatment delayed fruit ripening by inhibiting ethylene production during storage, in both storage conditions. These results are consistent with previous findings where a reduction of ethylene production was observed in tomatoes following UV-C treatment [11,12,33]. The different storage conditions resulted in significant differences in ethylene production ($p < 0.05$), with fruit stored in 0.1 μL L^{-1} ethylene having higher ethylene production rates than fruit stored in air. The results showed that stored mango fruit treated with UV-C in absence of low levels of ethylene slowed endogenous ethylene production during storage.

Table 2. Respiration rate and ethylene production of mangoes after treatment with different intensities of UV-C, followed by storage for 3, 6, 9, and 12 d in continuous air containing <0.005 μL L^{-1} or 0.1 μL L^{-1} ethylene at 20 °C.

Storage/UV-C (kJ m^{-2})	Respiration Rate (mL CO_2 kg^{-1} h^{-1})				Ethylene Production (μL C_2H_4 kg^{-1} h^{-1})			
	3 d	6 d	9 d	12 d	3 d	6 d	9 d	12 d
<0.005 μL L^{-1} Ethylene								
0	47.71 ^{a}	51.55 ^{a}	68.47 ^{a}	72.96 ^{a}	0.029 ^{a}	0.022 ^{a}	0.023 ^{a}	0.020 ^{a}
4	48.48 ^{a}	52.04 ^{a}	66.86 ^{a}	72.06 ^{a}	0.024 ^{a}	0.017 ^{b}	0.015 ^{b}	0.013 ^{b}
8.3	38.65 ^{b}	41.54 ^{b}	55.19 ^{b}	66.67 ^{b}	0.025 ^{a}	0.017 ^{b}	0.015 ^{b}	0.011 ^{b}
11.7	39.73 ^{b}	41.83 ^{b}	53.58 ^{b}	67.56 ^{b}	0.026 ^{a}	0.016 ^{b}	0.014 ^{b}	0.010 ^{b}
0.1 μL L^{-1} Ethylene								
0	54.37 ^{a}	61.12 ^{a}	67.74 ^{a}	72.95 ^{a}	0.062 ^{a}	0.052 ^{a}	0.052 ^{a}	0.042 ^{a}
4	59.22 ^{b}	65.60 ^{b}	67.83 ^{a}	68.83 ^{b}	0.047 ^{b}	0.045 ^{a}	0.044 ^{a}	0.038 ^{a}
8.3	61.14 ^{b}	63.59 ^{b}	64.82 ^{b}	67.31 ^{b}	0.040 ^{b}	0.033 ^{b}	0.034 ^{b}	0.027 ^{b}
11.7	50.97 ^{c}	54.71 ^{c}	57.14 ^{c}	60.41 ^{c}	0.029 ^{c}	0.029 ^{b}	0.031 ^{b}	0.031 ^{b}

Values are the mean of 3 replicates. Letters indicate mean values in the same columns, treatments, storage atmosphere and storage time that are statistically different ($p < 0.05$).

3.6. Respiration Rate

The ripening of climacteric fruit such as mangoes are characterised with an increase in fruit respiration rate during ripening [34]. This was also observed in this experiment, where respiration rates across all treatments and storage times ranged from 48 to 73 mL CO_2 kg^{-1} h^{-1}, as shown in Table 2. After 3 d storage, the untreated fruit had significantly higher respiration rates than fruit treated with UV-C, for fruits stored in 0.1 μL L^{-1} ethylene atmosphere. For fruits stored in less than 0.005 μL L^{-1} ethylene, there was no difference in respiration rates between untreated and 4.0 kJ m^{-2} UV-C. These effects remained after 12 d storage, in both storage atmospheres. The suppression of the respiration rate during ripening in UV-C treated fruit has also been reported in pepper [35], avocado [36] and lime fruit [17]. The results in this study showed that respiration was relatively constant in either the absence or presence of endogenous ethylene. These results suggest that UV-C treatment followed by storage in air (less than 0.005 μL L^{-1}) or 0.1 μL L^{-1} ethylene at 20 °C maintained mango fruit quality by reducing the respiration rate during storage as a natural ripening of mango fruit.

3.7. TSS and TA

TSS and TA were assessed every 3 d following UV-C treatment. The results presented in Table 3 showed that untreated fruit had the highest TSS levels and the lowest TA, with no significant differences detected in TSS and TA in fruit stored either in air containing <0.005 or 0.1 μL L^{-1} ethylene. Decreases in fruit TSS were observed with increasing UV-C intensity for both storage conditions. The levels of TA followed an opposite pattern to the changes in TSS levels. At the beginning of the experiment, the initial TA level was 0.626% citric acid, but after 3 d storage, the control fruit had the lowest TA levels, indicating rapid ripening. The higher UV-C intensities resulted in the maintenance of higher TA levels, with the highest TA levels found in mango that was treated with 11.7 kJ m^{-2} for all storage conditions. These results suggest that the UV-C effect was dose dependent on TSS and TA levels. However, these results are in contrast to a previous study by González-Aguilar et al. [15] that showed the concentration of sucrose was significantly higher in 'Tommy Atkins' mangoes following treatment with UV-C radiation for 20 min and subsequent storage at 5 °C for 14 d. These differences may be due to differences in maturity of the fruit used in these experiments, treatments and storage conditions, and the assessment of sugar levels.

Table 3. Total soluble solids (TSS) and titratable acidity (TA) of mangoes after treatment with different intensities of UV-C, followed by storage for 3, 6, 9, and 12 d in continuous air containing <0.005 μL L^{-1} or 0.1 μL L^{-1} ethylene at 20 °C.

Storage/UV-C (kJ m^{-2})	TSS (°Brix)				TA (% Citric Acid)			
	3 d	6 d	9 d	12 d	3 d	6 d	9 d	12 d
<0.005 μL L^{-1} Ethylene								
0	14.6 ^{a}	15.0 ^{a}	16.4 ^{a}	17.1 ^{a}	0.273 ^{a}	0.141 ^{a}	0.130 ^{a}	0.109 ^{a}
4	13.0 ^{b}	14.4 ^{a}	14.0 ^{b}	14.7 ^{b}	0.342 ^{b}	0.194 ^{a}	0.178 ^{b}	0.146 ^{b}
8.3	13.0 ^{b}	13.8 ^{ab}	14.0 ^{b}	13.9 ^{c}	0.338 ^{b}	0.179 ^{a}	0.159 ^{bc}	0.119 ^{ab}
11.7	12.5 ^{b}	13.2 ^{c}	13.0 ^{c}	13.1 ^{d}	0.501 ^{c}	0.283 ^{b}	0.244 ^{c}	0.232 ^{c}
0.1 μL L^{-1} Ethylene								
0	14.4 ^{a}	16.6 ^{a}	16.6 ^{a}	17.0 ^{a}	0.165 ^{a}	0.129 ^{a}	0.117 ^{a}	0.093 ^{a}
4	14.1 ^{ab}	14.1 ^{b}	15.3 ^{b}	16.2 ^{a}	0.170 ^{a}	0.142 ^{a}	0.132 ^{b}	0.113 ^{b}
8.3	13.7 ^{ab}	13.7 ^{c}	14.3 ^{c}	14.4 ^{b}	0.229 ^{a}	0.172 ^{a}	0.153 ^{b}	0.115 ^{b}
11.7	13.0 ^{b}	13.3 ^{d}	13.4 ^{d}	14.2 ^{b}	0.551 ^{b}	0.329 ^{b}	0.255 ^{b}	0.207 ^{c}

Values are the mean of 3 replicates. Letters indicate mean values in the same columns, treatments, storage atmosphere and storage time that are statistically different ($p < 0.05$).

3.8. Total Phenolic Content

Many studies have reported the enhancement of phenolic compound content following UV-C irradiation, such as in tomato [11,37], apple [38], mango [39], grape [14] and sweet cherry [40]. In this study, untreated mangoes had significantly lower TPC compared to 8.3 and 11.7 kJ m^{-2} after 9 d storage, as shown in Table 4. The highest TPC was measured in the highest UV-C dosage of 11.7 kJ m^{-2} at the end of experiment for both storage conditions. These observations are consistent with those previously reported by González-Aguilar et al. [39] who found that mangoes exposed to UV-C for 10 min produced higher levels of TPC during storage at 25 °C for 18 d. These observations may be due to the induction of protective pathways of the fruit, with the production and accumulation of UV-light-absorbing flavonoids and other phenolics, or may be due to general abiotic stresses. These stresses have been shown to affect the biosynthesis of the three main groups of secondary metabolites, including terpenes, phenolic and nitrogen-containing compounds [41].

Table 4. Total phenolic content (TPC) and total antioxidant activity of mangoes after treatment with different intensities of UV-C, followed by storage for 3, 6, 9, and 12 d in continuous air containing <0.005 μL L^{-1} or 0.1 μL L^{-1} ethylene at 20 °C.

Storage/UV-C (kJ m^{-2})	TPC (mg Gallic Acid Equiv/g FW				Total Antioxidant Activity (% DPPH Scavenging Activity)			
	3 d	6 d	9 d	12 d	3 d	6 d	9 d	12 d
<0.005 μL L^{-1} Ethylene								
0	0.533 ^{a}	0.583 ^{a}	0.603 ^{a}	0.656 ^{a}	18.23 ^{a}	19.74 ^{a}	20.88 ^{a}	26.41 ^{a}
4	0.546 ^{a}	0.572 ^{a}	0.681 ^{ab}	0.735 ^{ab}	18.09 ^{a}	19.43 ^{a}	19.36 ^{a}	22.23 ^{a}
8.3	0.608 ^{a}	0.627 ^{a}	0.733 ^{b}	0.735 ^{ab}	19.26 ^{a}	20.60 ^{a}	21.64 ^{a}	28.16 ^{ab}
11.7	0.621 ^{a}	0.676 ^{a}	0.826 ^{c}	0.814 ^{b}	20.17 ^{a}	23.88 ^{a}	25.46 ^{b}	33.88 ^{b}
0.1 μL L^{-1} Ethylene								
0	0.515 ^{a}	0.551 ^{a}	0.583 ^{a}	0.631 ^{a}	19.16 ^{a}	19.57 ^{a}	20.72 ^{a}	21.91 ^{a}
4	0.514 ^{a}	0.547 ^{a}	0.642 ^{ab}	0.698 ^{ab}	20.09 ^{a}	20.23 ^{a}	19.33 ^{a}	26.10 ^{b}
8.3	0.568 ^{a}	0.588 ^{a}	0.694 ^{b}	0.735 ^{ab}	19.86 ^{a}	20.23 ^{a}	21.47 ^{a}	27.74^{bc}
11.7	0.586 ^{a}	0.642 ^{a}	0.778 ^{b}	0.780 ^{b}	21.57 ^{a}	23.55 ^{a}	25.32 ^{a}	32.64 ^{c}

Values are the mean of 3 replicates. Letters indicate mean values in the same columns, treatments, storage atmosphere and storage time that are statistically different ($p < 0.05$).

3.9. Total Antioxidant Activity

The effect of UV-C irradiation on the DPPH antioxidant activity of mangoes is presented in Table 4 and shows that there was no significant difference in DPPH antioxidant activity between treated fruit and the control, after 6 and 9 d storage. However, by 12 d storage, the highest UV-C dose of 11.7 kJ m^{-2} had significantly higher DPPH antioxidant activity than all other treatments, in both storage atmospheres. These results are in agreement with previous studies on UV-C treatments increasing antioxidant capacities in pepper [35], fresh-cut mango [42] and sweet cherry [40]. The main antioxidants in mango are carotenoids, ascorbic acid and phenolic compounds [43]. However, the relationship between total phenolic and antioxidant activity is not always proportional. For example, in this experiment an increase in total phenolic content did not result in increased antioxidant activity, where fruit treated with 8.3 or 11.7 kJ m^{-2} UV-C significantly increased in TPC after 9 d storage (in both storage atmospheres), but antioxidant activity did not significantly increase for fruit that was stored in 0.1 μL L^{-1} ethylene. The assessment of the single antioxidant assay indicated that an increase in phenolic compounds beyond critical levels could reduce scavenging capacity values [44]. However, its interactions with other antioxidants, such as β-carotene, lutein or α-tocopherols could act either additively, synergistically or antagonistically in scavenging free radicals [45].

4. Conclusions

Postharvest UV-C treatments with an intensity of at least 4.0 kJ m^{-2} were an effective non-chemical treatment to delay the ripening of mature stage 'Kensington Pride' mangoes. The delay in ripening was associated with slower skin degreening, reduced fruit firmness, suppressed respiration rate and ethylene production, lower TSS, and higher TA levels. The level of TPC was also significantly affected by UV-C treatment, whereas DPPH antioxidant activity showed higher activities at a high UV-C dosage. The storage conditions (i.e., either in air or ethylene) affected firmness, respiration rate and endogenous ethylene production. Overall, the UV-C treatment in the presence of low levels of ethylene improved mango quality by delaying fruit ripening, maintaining fruit firmness and increasing both TPC and antioxidant activity.

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