Hindawi Publishing Corporation
Journal of Food Quality
Volume 2017, Article ID 4278795, 10 pages
https://doi.org/10.1155/2017/4278795

Research Article

Improvement of the Antioxidant Properties and Postharvest Life of Three Exotic Andean Fruits by UV-C Treatment

María J. Andrade-Cuvi,[1] Carlota Moreno,[1] María J. Zaro,[2,3] Ariel R. Vicente,[2,4] and Analía Concellón[2]

[1]*Facultad de Ciencias de la Ingeniería, Universidad Tecnológica Equinoccial, Campus Occidental, Av. Occidental y Mariana de Jesús, 170129 Quito, Ecuador*
[2]*Centro de Investigación y Desarrollo en Criotecnología de Alimentos (CIDCA), CCT La Plata CONICET-UNLP, 47 Esq. 116, 1900 La Plata, Argentina*
[3]*Facultad de Ciencias Agrarias y Forestales, Universidad Nacional de La Plata (UNLP), Calle 60 y 119, 1900 La Plata, Argentina*
[4]*Laboratorio de Investigación en Productos Agroindustriales (LIPA), Facultad de Ciencias Agrarias y Forestales, Universidad Nacional de La Plata, Calle 60 y 119, 1900 La Plata, Argentina*

Correspondence should be addressed to María J. Zaro; mariajosezaro16@hotmail.com

Received 27 July 2016; Accepted 19 October 2016; Published 12 January 2017

Academic Editor: Alejandro Hernández

Three Andean fruits naranjilla (*Solanum quitoense* Lam.), uvilla (*Physalis peruviana* L.), and mortiño (*Vaccinium floribundum* Kunth) were subjected to prestorage UV-C treatments (0, 8, or 12.5 kJ m^{-2}) and evaluated weekly to select the most suitable dose for fruit quality maintenance during storage (21 days at 6°C). The highest dose retains quality through lower deterioration index for all three fruits and was selected to further analyze the effects on physicochemical and antioxidant properties during storage. UV-C exposure delayed softening in naranjilla and increased soluble solid content in uvilla. UV-C also improved the maintenance of antioxidant capacity (AC) in mortiño and uvilla. Overall, results indicate that short prestorage UV-C exposure may be an effective nonchemical approach to supplement low temperature storage, maintain quality, and extend the postharvest life of Andean naranjilla, uvilla, and mortiño fruit.

1. Introduction

Despite the large diversity of fleshy fruit-bearing species, world fruit production focuses on a narrow group of temperate and tropical species [1]. However, a variety of novel and exotic fruits recognized for their sensorial and nutritional properties are currently produced and have a great potential to gain international markets [2]. Among these, some native fruits of the Andean Region of South America, such as naranjilla (*Solanum quitoense* Lam.), uvilla (*Physalis peruviana* L.), and mortiño (*Vaccinium floribundum* Kunth), may be included. Naranjilla is a round delicate and acidic berry (ca. 6 cm diameter) produced in Ecuador and Colombia mainly for juice and pulp processing [3]. Uvilla is a sweet, juicy, and bright yellow berry (1.2–2.5 cm diameter) characterized by a calyx which protects the whole fruit [4]. Uvilla is appreciated locally as well as in some European countries for consumption in both fresh and processed forms [5]. Finally, mortiño is a small wild berry (0.5–0.8 cm diameter) resembling traditional blueberries, consumed in traditional desserts and juices [6]. Unfortunately, the information available regarding these fruits' physical, chemical, and antioxidant properties and response to storage is very limited [3, 5, 7]. Although proper low temperature storage management is accepted to reduce fruit deterioration, finding supplemental postharvest treatments would be of great value to improve the postharvest shelf-life.

UV-C irradiation is an alternative as nonchemical technology that has been shown to increase the storability of several fruits through different mechanisms [8], act as a germicidal agent altering microorganism's DNA and affecting cell division [9], modulate fruit ripening [10, 11], and induce

array responses including the accumulation of phytoalexins, the reinforcement of the cell walls, and the induction of defensive enzymes and compounds [9, 12]. UV-C irradiation has been also reported to improve the shelf-life by reduction of fruit respiration [13], softening, and chilling injury [14] and to delay senescence [15, 16]. In addition, there is growing interest on in the effect of UV-C radiation on fruit antioxidants [17]. Previous works found that UV-C exposure elicited antioxidant accumulation in several fruits, such as table grape [18], strawberry [19], blueberry [20, 21], and tomato [22]. However, the relevance and extent of these responses are highly variable depending on the species considered and UV-C dose applied [17].

While promising results as prestorage treatment to retain quality and enhance the nutritional properties have been reported for UV-C treatment in traditional fruits [8, 12, 23], no studies have been conducted to date in uvilla, naranjilla, or mortiño. The potential effect of UV-C treatments to preserve or increase their antioxidant capacity also remains to be determined. Thus, in this work we first selected a suitable UV-C dose for the three Andean fruit and then evaluated the influence of UV-C treatment on antioxidant and physicochemical properties during refrigerated storage to determine the potential of this strategy to supplement proper postharvest temperature management.

2. Materials and Methods

2.1. Plant Material. Fruits of naranjilla (*Solanum quitoense* Lam.), uvilla (*Physalis peruviana* L.), and mortiño (*Vaccinium floribundum* Kunth) produced in Ecuador (cities of Puerto Quito, Machachi, and Cotacachi, resp.) were harvested at commercial maturity. The harvest time was determined based on surface color for naranjilla (75% orange) and mortiño (75% purple) and on calyx color for uvilla (color change from green to yellow). Fruits were rapidly brought to the laboratory after harvest and selected for uniformity and lack of physical damage or decay symptoms. For uvilla, the calyx was previously removed. Fruits were then washed with chlorinated water (100 mg L^{-1} NaClO, pH 7.0 for 3 min) and dried at room temperature.

2.2. UV-C Treatment Selection. Fruits were placed under a bank of 4 UV-C lamps (Philips, TUV G30T8, 30W, USA; emission peak 254 nm) and irradiated at a distance of 30 cm for 10 or 15 min to reach 8 or 12.5 kJ m^{-2}, respectively (UVP, UVX Radiometer, USA). To achieve uniform treatments throughout the surface, the uvillas and naranjillas were manually rotated while the mortiños were placed on a shaker (VWR International, VWR Microplate Shaker, USA). Similarly, mortiños without UV-C treatment (control) were shook. About 200 g of treated fruits was then packed in (a) plastic trays covered with perforated PVC film for uvilla and naranjilla; (b) PET perforated clamshell boxes for mortiño. Samples were stored at 6°C and evaluated weekly for 21 days (d). For each fruit, six trays were prepared per storage time (0, 7, 14, and 21 d) and treatment (UV-C and control). At each sampling date, fruit weight loss and deterioration index were calculated as indicated below to select the most suitable UV-C dose. Untreated fruit packed and stored as previously described was used as control. The whole experiment was repeated twice using fruit from different harvests.

2.2.1. Deterioration Index (DI). Fruit deterioration was determined by visual inspection using a four-point hedonic scale (1 = no damage, 2 = mild damage, 3 = moderate damage, and 4 = severe damage). The main symptoms assessed were pitting, dehydration, firmness loss, browning, and decay. The deterioration index (DI) was calculated according to the following equation:

$$\mathrm{DI} = \sum \frac{(\text{Damage level}) \times (\text{No. of trays per level})}{(\text{Total No. of trays evaluated})}. \quad (1)$$

For each fruit, six trays were evaluated per storage time and treatment.

2.2.2. Weight Loss. Each fruit tray was individually weighed during storage and weight loss relative to the initial value was calculated and expressed in percentage. Six trays were evaluated per storage time and treatment.

2.3. Optimal UV-C Treatment. Fruits harvested and conditioned as described in Section 2.2 were treated with 12.5 kJ m^{-2} of UV-C radiation, packed, and stored as previously described. For each fruit, six trays containing ca. 200 g of fruit were prepared per storage time (0, 7, 14, and 21 d) and treatment (UV-C and control). At each sampling date fruit was immediately analyzed for physicochemical properties or frozen in liquid N_2 and stored at −80°C until antioxidants analysis. The whole experiment was repeated twice using fruit from different harvests.

2.4. Effect of UV-C Treatment on Physicochemical Properties

2.4.1. Firmness. Firmness was assessed with a penetrometer (TR Turoni, Digital fruit firmness tester 53205, Italy). Tests were performed in the equatorial region of fruit employing a 5 mm diameter probe. Results were expressed as Newton (N). Five fruits per tray were randomly selected and evaluated for each storage time and treatment.

2.4.2. Soluble Solids Content (SSC). Groups of five fruits for naranjilla or fifteen fruits for mortiño and uvilla were randomly selected per tray. Pulp was homogenized and juice was obtained using a blender (Philips, Mixer HR1363 Turbo, Brazil). Soluble solids content was determined with a hand refractometer (Boeco, B&C Hand refractometer 30103, Germany). Results were expressed in percentage (% w/w). For each fruit, four trays were evaluated per storage time and treatment.

2.4.3. Titratable Acidity and pH. Five fruits for naranjilla or fifteen fruits for mortiño and uvilla were randomly selected per tray. Whole mortiños and uvillas and pulp tissue of naranjillas were frozen in liquid N_2 and processed in a

blender. About 15 g of the resulting powder was weighed and 100 mL of water was added. The pH of the solution was measured with a pHmeter (Oakton, PC 510, USA). Acidity was determined by titration with 0.1 N NaOH until pH 8.2. Results were expressed as H^+ meq. per kg fresh weight. For each fruit, four trays were evaluated per storage time and treatment.

2.5. Effect of UV-C Treatment on Antioxidant Properties

2.5.1. Antioxidant Capacity. Groups of five naranjillas and fifteen mortiños and uvillas were randomly selected per tray. Whole mortiños and uvillas and pulp tissue of naranjillas were frozen in liquid N_2 and processed in a blender. A portion of resulting powder was weighed (0.2, 2, and 3 g for mortiño, uvilla, and naranjilla, resp.) and then homogenized with 6 mL ethanol. The suspension was stirred for 30 min at 4°C and centrifuged at 6,000 ×g for 10 min in a refrigerated centrifuge (Hermle, Z323R, Germany). The supernatant was collected and used for antioxidants assays.

The antioxidant capacity (AC) was determined by the ABTS assay [24]. Briefly, 10 μL of ethanolic extract was added to 1 mL $ABTS^{\bullet+}$ working solution (absorbance of 0.700 ± 0.02 at 734 nm), incubated for 6 min at room temperature and the absorbance at 734 nm was measured in a spectrophotometer (Thermo Scientific, Evolution 60S, USA). Trolox® was used as a standard and results were expressed as Trolox Equivalent Antioxidant Capacity (TEAC) in mg per kg fresh weight. Measures were done in triplicate and four extracts were evaluated per storage time and treatment.

2.5.2. Total Phenolics. Total phenolics were evaluated with the Folin-Ciocalteu reagent [25]. An aliquot of 100 μL of ethanolic extract prepared as described in Section 2.5.1 was transferred to a test tube containing 500 μL distilled water. Two hundred microlitres of 1 eq L^{-1} Folin-Ciocalteu reagent was added and allowed to react for 3 min at 20°C. After that 400 μL 20% (m/v) Na_2CO_3 in NaOH 0.1 N was pipetted into each test tube and water was added to a final volume of 3 mL. After 90 min at 20°C, the absorbance at 760 nm was measured in a spectrophotometer. Catechin was used as standard and results were expressed in mg per kg fresh weight. Measurement was done in triplicate and four extracts were evaluated per storage time and treatment.

2.5.3. Flavonoids. Flavonoids were tested according to Shin et al. [26] with minor modifications. An aliquot of 300 μL of ethanolic extract prepared as described in Section 2.5.1 was transferred to test tubes containing 400 μL distilled water and 50 μL 5% (w/v) $NaNO_2$. After 5 min, 50 μL 10% (w/v) $AlCl_3$ was added and samples were incubated at 20°C for 10 min. Finally, 250 μL NaOH 1 N was pipetted into each tube and samples were taken to a final volume of 1.25 mL with distilled water. The absorbance was measured immediately at 510 nm in a spectrophotometer. Catechin was used as standard and results were expressed in mg per kg fresh weight. Measurements were done in triplicate and four extracts were evaluated per storage time and treatment

2.5.4. Anthocyanins. Groups of fifteen mortiños were randomly selected, frozen in liquid N_2, and processed in a blender. Approximately 0.1 g of the resulting powder was added to a test tube containing 10 mL methanol : HCl (99 : 1 v/v), stirred for 10 min and centrifuged at 6,000 ×g for 10 min at 4°C. The supernatant was collected and the pellet was reextracted twice in the same conditions. The supernatants were pooled and brought to a final volume of 30 mL. The absorbance of the extract was measured at 540 nm in a spectrophotometer and results were expressed as mg equivalents of cyanidin-3-glucoside per kg fresh weight. Measurements were done in triplicate and four extracts were evaluated per storage time and treatment.

2.5.5. Carotenoids. Five naranjillas or fifteen uvillas were randomly selected. Whole uvillas and pulp tissue of naranjillas were frozen in liquid N_2 and processed in a blender. Approximately 5 g of the resulting powder was transferred to a glass tube and homogenized with 5 mL petroleum ether and 5 mL acetone. The suspension was stirred for 30 min at 4°C and centrifuged at 6,000 ×g for 10 min at 4°C. The supernatant was collected and the pellet was reextracted as indicated above. The supernatants were pooled and 10 mL of water was added. The absorbance of the upper phase (petroleum ether) was measured at 450 nm in a spectrophotometer. Carotenoid content was expressed in mg β-carotene per kg fresh weight. Four extracts were evaluated per storage time and treatment.

2.5.6. Ascorbic Acid. Ascorbic acid content was determined according to Georgé et al. [27]. Whole uvillas and mortiños and pulp tissue of naranjillas were frozen in liquid N_2 and processed. Approximately 3.5 g of the resulting powder for uvilla and naranjilla and 1 g for mortiño were added to a test tube containing 10 mL acetone : water (70 : 30, v/v). The suspension was first stirred for 10 min and the supernatants were recovered by filtration (raw extracts, RE). Next a solid-phase extraction (Oasis HLB, Waters, USA) of RE was carried out obtaining the washing extract (WE). Finally, the ascorbic acid present in WE was destroyed by heating at 85°C for 2 h and colorimetrically deduced by subtracting the Folin-Ciocalteu response of the heated washing extract (HWE) from that of the WE. The Folin-Ciocalteu reaction was performed as described in Section 2.5.2. Results were expressed in mg ascorbic acid per kg fresh weight. Measurements were done in triplicate and four extracts were evaluated per storage time and treatment.

2.6. Statistical Analysis.

Results were analyzed by ANOVA, the factors being storage time and treatment. Both main factors and their interaction were analyzed. The means were compared on a Fisher test at a level of significance of $P < 0.05$.

3. Results and Discussion

3.1. UV-C Dose Selection. Peel pitting was the most prominent visual symptom of quality loss in uvilla (Figure 1(a1)), whereas softening and peel browning were the main causes of deterioration in naranjilla (Figure 1(a2)). Weight loss and

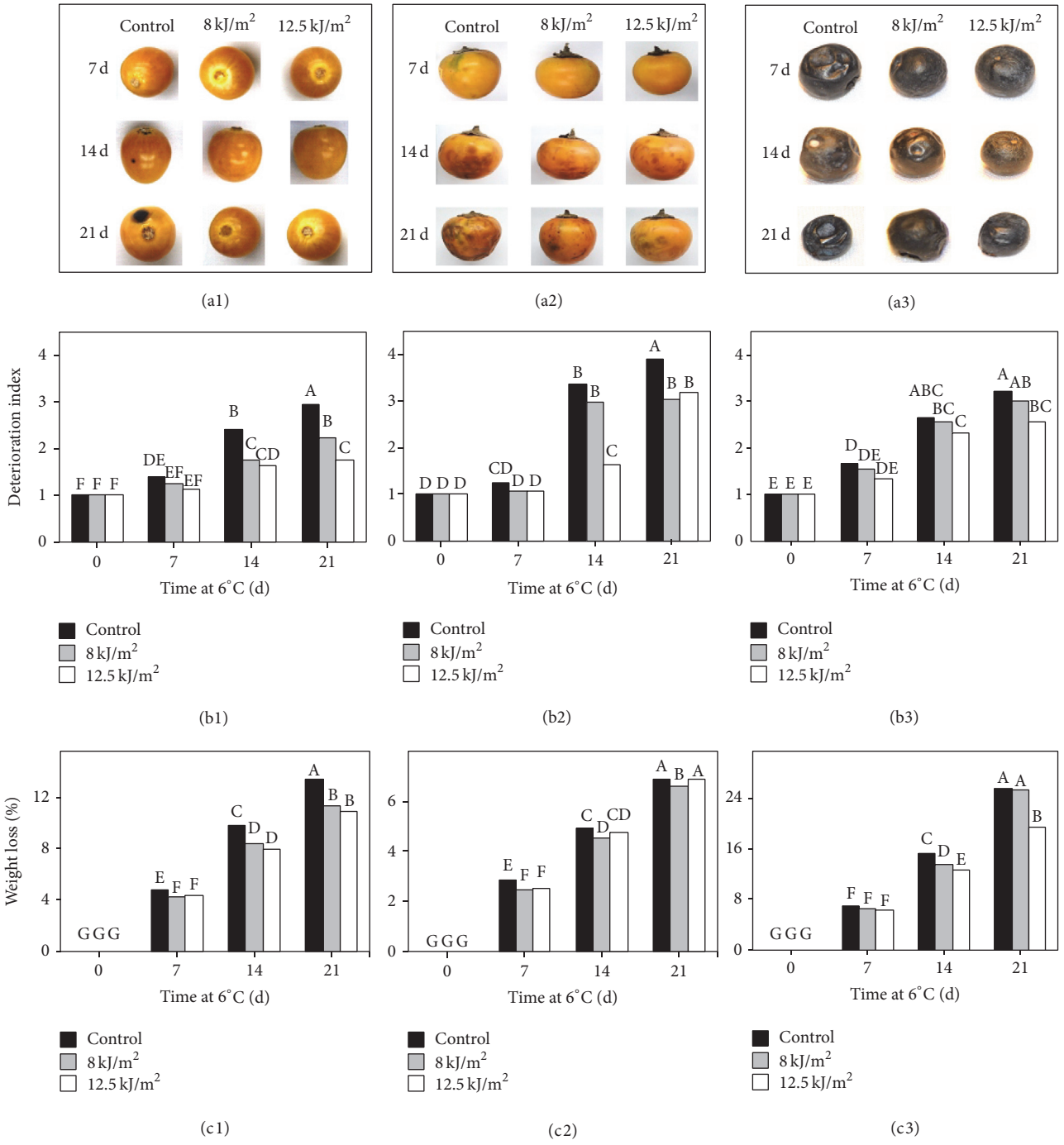

Figure 1: Appearance (a), deterioration index (b), and weight loss (%) (c) in control and UV-C treated (8 and 12.5 kJ m^{-2}) uvilla (left panels) (1), naranjilla (central panels) (2), and mortiño (right panels) (3), stored at 6°C for 0, 7, 14, or 21 d. For each fruit, different letters between treatments show differences according to a Fisher test ($P < 0.05$).

dehydration symptoms were the limiting quality factors in stored mortiño in relation to the high surface/volume ratio of the berries (Figure 1(a3)). Despite this, UV-C treatment improved quality retention in the three fruit studied, especially during the last two weeks of storage (Figures 1(b) and 1(c)). After 14 d, the benefits of UV-C treatment were highest ($P < 0.05$) in naranjilla irradiated with 12.5 kJ m^{-2} (Figure 1(b2)), followed by uvilla which showed similar effects regardless of the UV-C dose applied (Figure 1(b1)). Milder effects were found in treated mortiño, since no significant differences in DI were observed between control and treated fruit (Figure 1(b3)). At the end of storage period, the outcome on DI of treated naranjilla and mortiño with 8 and 12.5 kJ m^{-2} was similar (Figures 1(b2) and 1(b3)), but uvilla treated with the highest dose showed improved quality maintenance (Figure 1(b1)). UV-C treatments also reduced

Table 1: Firmness, soluble solids content (SSC), titratable acidity, and pH in control and UV-C treated (12.5 kJ m^{-2}) uvilla, naranjilla, and mortiño during storage at 6°C for 0, 7, 14, or 21 d. For each fruit, different letters between treatments show differences according to a Fisher test ($P < 0.05$). The mean ± standard error is shown.

Quality index	Storage time (d)	Uvilla		Naranjilla		Mortiño	
		Control	12.5 kJ m^{-2}	Control	12.5 kJ m^{-2}	Control	12.5 kJ m^{-2}
Firmness (N)	0	7.9 ± 0.17^{A}	8.0 ± 0.10^{A}	18.1 ± 0.37^{AB}	19.0 ± 0.55^{A}	—	—
	7	7.3 ± 0.11^{B}	6.7 ± 0.10^{D}	15.8 ± 0.59^{C}	18.5 ± 0.75^{A}	—	—
	14	6.8 ± 0.16^{CD}	7.2 ± 0.21^{BC}	13.3 ± 0.49^{D}	16.5 ± 0.62^{BC}	—	—
	21	7.2 ± 0.16^{BC}	7.1 ± 0.19^{BC}	11.4 ± 0.83^{E}	15.5 ± 0.61^{C}	—	—
SSC (% w w^{-1})	0	13.9 ± 0.13^{D}	14.1 ± 0.07^{D}	7.2 ± 0.44^{C}	7.3 ± 0.27^{C}	10.0 ± 0.0^{A}	9.8 ± 0.0^{B}
	7	15.2 ± 0.06^{C}	15.1 ± 0.05^{C}	7.8 ± 0.12^{ABC}	7.6 ± 0.24^{BC}	9.0 ± 0.0^{C}	9.0 ± 0.0^{C}
	14	15.2 ± 0.09^{C}	16.4 ± 0.1^{B}	7.6 ± 0.24^{C}	7.9 ± 0.13^{ABC}	8.8 ± 0.02^{D}	9.0 ± 0.0^{C}
	21	16.6 ± 0.3^{B}	18.4 ± 0.85^{A}	8.5 ± 0.29^{A}	8.4 ± 0.36^{AB}	9.0 ± 0.0^{C}	9.0 ± 0.0^{C}
Acidity (meq kg^{-1})	0	328.1 ± 8.8^{CD}	327.5 ± 9.0^{CD}	365.0 ± 4.2^{C}	383.7 ± 4.2^{ABC}	197.5 ± 0.7^{C}	182.9 ± 0.0^{E}
	7	337.0 ± 10.5^{BC}	327.5 ± 4.6^{CD}	380.6 ± 2.9^{ABC}	383.7 ± 4.0^{ABC}	192.9 ± 0.6^{D}	195.0 ± 1.7^{CD}
	14	338.4 ± 4.6^{B}	325.4 ± 7.7^{D}	375.6 ± 6.8^{BC}	397.5 ± 7.8^{A}	192.9 ± 0.6^{D}	210.4 ± 1.1^{B}
	21	362.3 ± 19.3^{A}	355.5 ± 9.3^{A}	396.9 ± 12.0^{A}	391.3 ± 6.6^{AB}	214.3 ± 0.0^{A}	214.3 ± 1.5^{A}
pH	0	3.73 ± 0.01^{CD}	3.74 ± 0.01^{C}	3.19 ± 0.01^{A}	3.31 ± 0.10^{A}	2.85 ± 0.01^{B}	2.89 ± 0.01^{A}
	7	3.73 ± 0.02^{CD}	3.70 ± 0.02^{D}	3.21 ± 0.04^{A}	3.20 ± 0.07^{A}	2.90 ± 0.01^{A}	2.85 ± 0.01^{B}
	14	3.79 ± 0.03^{B}	3.86 ± 0.04^{A}	3.27 ± 0.02^{A}	3.31 ± 0.02^{A}	2.85 ± 0.01^{B}	2.72 ± 0.01^{C}
	21	3.74 ± 0.01^{C}	3.74 ± 0.01^{C}	3.28 ± 0.08^{A}	3.29 ± 0.04^{A}	2.72 ± 0.01^{C}	2.73 ± 0.01^{C}

weight loss ($P < 0.05$) in uvilla and naranjilla during storage (Figures 1(c1) and 1(c2)), while for mortiño the treatment with 12.5 kJ m^{-2} was especially effective to delay weight loss ($P < 0.05$) in berries stored for over 2 weeks (Figure 1(c3)). The lower rate of dehydration in treated fruit was related with the prevention of the loss of fruit turgor and firmness, by maintaining integrity of the tissue and cellular membrane [28].

Positive treatment results on quality retention were also observed in other treated fruits. UV-C exposure has been shown to slow-down ripening and fungal development in strawberry [29] and extended the shelf-life of mango by reducing the symptoms of visual damage and decay [30]. Similarly, UV-C retained the quality of tomato [22, 31] and blueberry [21] through the control of weight loss, ripening, and microbial growth. Overall, our results show that the UV-C treatments are effective to reduce deterioration in uvilla and naranjilla and to control the weight loss in mortiño, especially at the higher dose assayed. Thus, the UV-C treatment with a 12.5 kJ m^{-2} dose was selected to further evaluate the effects of UV-C radiation on fruit physicochemical and antioxidant properties of the Andean fruit evaluated here.

3.2. Effect of UV-C Treatment on Physicochemical Properties

3.2.1. Firmness. No firmness determinations were conducted in mortiño given the limited size of this berry and that the limiting factor for postharvest storage was surface dehydration. For the remaining fruit, in contrast to uvilla in which UV-C treatment had no effects on firmness loss, a marked delay in naranjilla softening was observed (Table 1). It is worth noting that at the last sampling date UV-C treated naranjilla showed a similar firmness values than control fruit stored just for 7 days (Table 1). Improved firmness retention has been also reported in other UV-C treated products such as peaches [13], tomato [15, 31, 32], and strawberry [29]. The delay of softening by UV-C radiation has been widely related to the inhibition of an array of degrading enzymes involved in cell wall disassembly [33]. For other climacteric fruit such as cherry tomato, Bu et al. [15] proposed that the inhibition of ethylene production by UV-C treatment may be responsible for maintaining lower expression levels of genes coding for cell wall degrading enzymes which are known to be activated by this hormone, such as pectin methylesterase, polygalacturonase, and endoglucanase.

3.2.2. Soluble Solids Content, Acidity, and pH. At harvest, uvilla presented the highest level of SSC (ca. 13.9–14.1%), followed by mortiño (9.8–10%) and naranjilla (7.2–7.3%) (Table 1). During storage, SSC showed moderate changes in naranjilla and mortiño, whereas it increased markedly in uvilla. Gutierrez et al. [34] also found an increase in SSC during uvilla storage and related this with the climacteric behavior and ripening of fruit. Likewise, Valdenegro et al. [35] reported a constant increase in SSC during uvilla ripening through 14 days of shelf-life period. Interestingly, UV-C treated uvilla showed higher SSC after 14 and 21 days than nonirradiated fruit. However, the nature of this increase is uncertain since the presence of starch in this fruit has not been determined and further studies will be necessary.

Titratable acidity was near 328, 379, and 190 meq Kg^{-1} in uvilla, naranjilla, and mortiño, respectively. No major changes were observed due to UV-C treatment for both acidity and pH (Table 1). Similarly, no changes in these

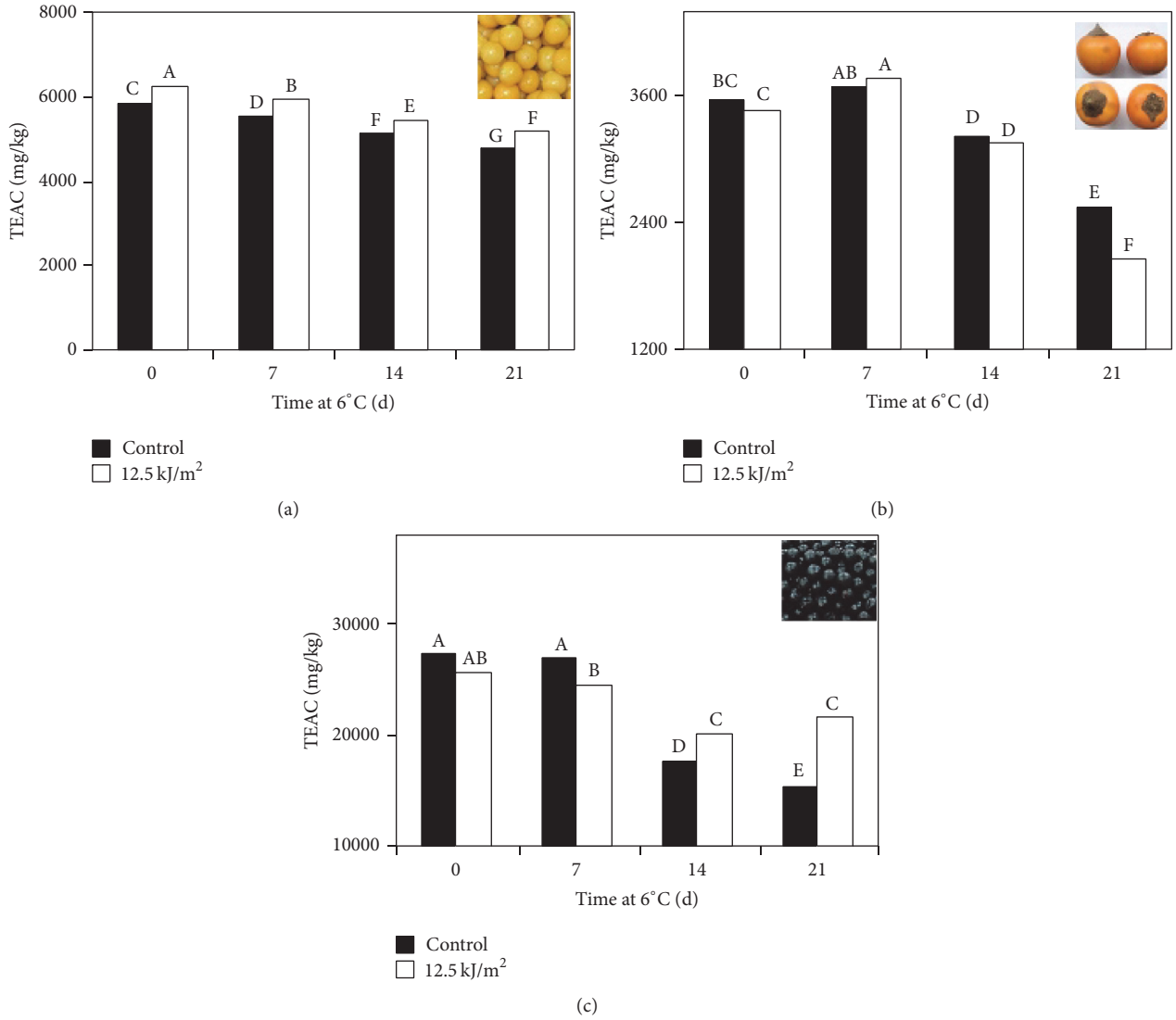

Figure 2: Antioxidant capacity (TEAC, Trolox Equivalent Antioxidant Capacity) in control and UV-C treated (12.5 kJ m^{-2}) uvilla (a), naranjilla (b), and mortiño (c), stored at 6°C for 0, 7, 14, or 21 d. For each fruit, different letters between treatments show differences according to a Fisher test ($P < 0.05$).

attributes were found in UV-C treated strawberry [36], grapefruit [37], and blueberry [38]. Overall, results show that UV-C treatment caused no negative changes in fruit taste-related attributes and indeed favored the SSC accumulation in uvilla.

3.3. Effect of UV-C Treatment on Antioxidant Properties

3.3.1. Antioxidant Capacity (AC). The TEAC value at harvest was around 5- and 7-fold higher in mortiño (6,800 mg kg^{-1}) than in uvilla (1,500 mg kg^{-1}) and naranjilla (870 mg kg^{-1}), respectively (Figure 2). Mortiño showed a very high AC, which was even higher than that reported for other *Vaccinium* species [6, 39]. Though lower than in mortiño, the AC of uvilla and naranjilla are comparable with those found in tree tomato [40] and higher than those of common subtropical fruit, such as citrus [41].

Significant losses of AC were found in the three fruits studied during storage (Figure 2); however, the effect of the UV-C treatment varied markedly depending on the species considered. Treated uvilla showed higher AC than the control fruit ($P < 0.05$) immediately after treatment and during storage (Figure 2(a)). The nature of the response suggests that UV-C radiation elicited antioxidant accumulation. In accordance, an increase of the antioxidant activity after UV-C radiation was found in other fruit such as strawberry [42], table grape [18], and blueberry [20]. Genes coding for key regulatory steps of the phenylpropanoid pathway, such as phenylalanine ammonia-lyase (PAL), have been shown to be upregulated in response to UV-C radiation in some but not all fruit [33, 43, 44]. Downstream enzymes involved in flavonoid synthesis, such as chalcone synthase, chalcone isomerase, and dihydroflavonol reductase, were also induced in response to UV-C elicitation [45, 46].

Table 2: Ascorbic acid, total phenolics, flavonoids, anthocyanins, and carotenoids in control and UV-C treated (12.5 kJ m^{-2}) uvilla, naranjilla, and mortiño stored at 6°C for 0, 7, 14, or 21 d. For each fruit, different letters between treatments show differences according to a Fisher test ($P < 0.05$). The mean ± standard error is shown.

Antioxidant content	Storage time (d)	Uvilla		Naranjilla		Mortiño	
		Control	12.5 kJ m^{-2}	Control	12.5 kJ m^{-2}	Control	12.5 kJ m^{-2}
Ascorbic acid (mg kg^{-1})	0	523.0 ± 0.8^{B}	573.1 ± 1.5^{A}	472.1 ± 5.3^{A}	451.5 ± 7.1^{ABCD}	153.9 ± 0.0^{B}	163.4 ± 2.4^{A}
	7	449.5 ± 0.9^{D}	489.4 ± 0.9^{C}	465.2 ± 8.2^{AB}	456.5 ± 3.7^{ABC}	73.9 ± 0.2^{D}	83.2 ± 0.5^{C}
	14	395.4 ± 1.5^{E}	357.4 ± 5.8^{F}	431.9 ± 4.1^{D}	456.1 ± 14.6^{ABC}	47.1 ± 1.2^{F}	54.6 ± 0.4^{E}
	21	259.8 ± 1.8^{G}	243.5 ± 4.7^{H}	446.0 ± 6.1^{BCD}	439.7 ± 2.6^{CD}	24.7 ± 1.0^{H}	32.8 ± 2.0^{G}
Phenolics (mg kg^{-1})	0	388.7 ± 1.3^{C}	490.1 ± 0.8^{A}	378.9 ± 1.1^{B}	374.5 ± 1.1^{CD}	5185.4 ± 32.6^{B}	5530.0 ± 11.1^{A}
	7	369.3 ± 0.5^{E}	440.3 ± 0.7^{B}	376.2 ± 1.4^{A}	361.7 ± 0.7^{E}	4911.6 ± 33.8^{C}	4914.5 ± 25.2^{C}
	14	330.8 ± 1.2^{F}	380.3 ± 3.9^{D}	382.6 ± 0.9^{A}	364.1 ± 0.4^{E}	4347.0 ± 26.4^{D}	4194.9 ± 13.4^{E}
	21	292.3 ± 0.8^{H}	325.9 ± 1.9^{G}	373.3 ± 0.4^{D}	341.7 ± 0.6^{F}	3727.2 ± 6.7^{F}	3566.1 ± 10.7^{G}
Flavonoids (mg kg^{-1})	0	103.4 ± 0.3^{A}	102.6 ± 0.2^{AB}	363.3 ± 1.3^{B}	328.4 ± 0.7^{E}	2572.2 ± 15.5^{C}	2755.8 ± 6.4^{A}
	7	101.2 ± 0.2^{C}	101.3 ± 0.3^{BC}	352.6 ± 0.4^{C}	313.8 ± 0.7^{F}	2286.7 ± 20.9^{F}	2113.2 ± 2.2^{G}
	14	95.1 ± 0.2^{D}	90.7 ± 1.0^{E}	344.5 ± 0.3^{D}	311.3 ± 0.8^{G}	2367.9 ± 17.8^{E}	2485.5 ± 12.0^{D}
	21	89.5 ± 0.4^{E}	81.4 ± 0.3^{F}	368.8 ± 0.6^{A}	300.2 ± 0.7^{H}	2515.7 ± 17.8^{D}	2643.5 ± 9.9^{B}
Anthocyanin (mg kg^{-1})	0	—	—	—	—	4776.3 ± 264.3^{A}	4905.7 ± 65.4^{A}
	7	—	—	—	—	4383.6 ± 627.4^{AB}	4523.8 ± 236.4^{AB}
	14	—	—	—	—	4065.54 ± 226.1^{BC}	4525.9 ± 69.8^{AB}
	21	—	—	—	—	3670.8 ± 424.7^{C}	4391.6 ± 207.8^{AB}
Carotenoids (mg kg^{-1})	0	16.9 ± 0.08^{C}	19.7 ± 0.06^{A}	16.77 ± 0.05^{A}	16.37 ± 0.01^{B}	—	—
	7	15.6 ± 0.07^{E}	17.3 ± 0.10^{B}	14.52 ± 0.05^{E}	13.77 ± 0.18^{G}	—	—
	14	14.6 ± 0.07^{G}	16.4 ± 0.02^{D}	$16.31 \pm 0.0.09^{B}$	15.62 ± 0.07^{C}	—	—
	21	13.1 ± 0.11^{H}	14.9 ± 0.04^{F}	15.08 ± 0.05^{D}	14.03 ± 0.02^{F}	—	—

UV-C treatment did not trigger the accumulation of antioxidants in mortiño but was effective to slow-down the loss of AC during storage ($P < 0.05$). Consequently, after both 14 and 21 days, UV-C treated mortiño maintained higher AC than control fruit (Figure 2(c)). Losses of antioxidants have been shown to increase due to loss of cell compartmentation. This has been particularly important in phenolic-rich fruit in which tissue disruption may facilitate the access of polyphenol oxidases and peroxidases to their substrates [13]. The increased stability on fruit AC in this case may have been due to improved maintenance of tissue integrity as reflected in a lower DI and weight loss (Figure 1(c)).

Finally, UV-C treatment did not exert appreciable benefits ($P < 0.05$) on the AC of naranjilla (Figure 2(b)). Instead, at long storage times slightly lower AC was recorded in treated fruit. These results point to a very diverse response to UV-C irradiation among the fruit studied. No benefits in AC are observed in treated naranjilla, while UV-C exposure may be exploited as a prestorage treatment to prevent degradation or to induce antioxidant accumulation in mortiño and uvilla, respectively, contributing to a good quality and high human nutrition.

3.3.2. Main Antioxidants Compounds. The main antioxidant groups prevailing on the three fruits studied were markedly different (Table 2). Ascorbic acid was present at high level in uvilla and naranjilla (523 and 472 mg kg^{-1}, resp.) as opposed to mortiño where it was 3-4-fold lower (Table 2). Carotenoid content was comparable in naranjilla and uvilla (ca. 16 mg kg^{-1}) mainly due to the contribution of β-carotene which has been identified as the major compound within this antioxidant group in both fruits [3, 4]. Naranjilla and uvilla also had similar contents of total phenolics; however, the major class of compounds differed. Flavonoids were the most abundant subgroup of phenolics in naranjilla, as opposed to uvilla where they were just 30% of this group (Table 2). As expected, total phenolics in mortiño were 10-fold higher than in uvilla and naranjilla, mainly due to contribution of anthocyanins (Table 2). In accordance, Vasco et al. [6] found that anthocyanins accounted for about 67% of mortiño phenolics.

To characterize the responses to UV-C radiation, we also analyzed the changes in each antioxidant group during storage. UV-C treatment induced ascorbic acid accumulation in uvilla just after the treatment. However, the differences with the control lasted until day 7. Flavonoids were not elicited in this fruit by UV-C and decreased with slight variations between control and treated uvilla during storage (Table 2). Interestingly, higher levels of phenolic compounds and carotenoids were found in UV-C treated uvilla just after the photochemical treatment. Alothman et al. [10] also found a rapid increase of total phenolics and flavonoid compounds just after UV-C exposure in banana and guava. Carotenoids were induced by UV-C exposure in yellow bell pepper [28]

and carrot [47]. Results show that uvilla antioxidants are particularly responsive to elicitation by UV-C radiation.

In mortiño ascorbic acid, total phenolic compounds or flavonoids were slightly enhanced immediately after UV-C exposure (Table 2). Moreover, the UV-C treated berries retained a slight but higher content than control fruit during storage. Flavonoids, particularly anthocyanins, showed higher stability in UV-C treated mortiño after long-term storage. These results are in line with the report for blueberry by Nguyen et al. [21] who described an increase of phenolic and anthocyanin compounds after UV-C treatment and a reduced degradation rate during refrigerated storage.

4. Conclusions

UV-C radiation improved quality retention of uvilla and naranjilla and to a lesser extent in mortiño. Treatment with 8 and 12.5 kJ m^{-2} resulted in similar effects in naranjilla and mortiño. In contrast, the highest UV-C dose was more beneficial in uvilla and also effectively reduced the weight loss in mortiño. Consequently, this dose was selected to further evaluate the physicochemical and antioxidant properties during storage. UV-C treatment was highly effective to delay softening in naranjilla and increased the SSC in uvilla. At long storage times, UV-C treated uvilla and mortiño maintained higher AC than untreated fruit. The increase of AC found in uvilla could result from the activation of the biosynthesis pathway of phenolic compounds in response to UV radiation. Instead, in mortiño the treatment markedly improved anthocyanin stability at long storage times presumably by maintaining of the tissue integrity. Overall, results indicate that short prestorage UV-C exposure may be an effective non-chemical approach to supplement low temperature storage, maintain quality, and extend the postharvest life of Andean naranjilla, uvilla, and mortiño fruit.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This work was supported by the Dirección de Investigación y Transferencia de Tecnología, Universidad Tecnológica Equinoccial, Quito-Ecuador (Research Projects III.UIO.ING.04A and III.UIO.ING.04B). María J. Andrade Cuvi and Carlota Moreno are research members of the Equinoctial and Technological University from Ecuador. Maria J. Zaro is a Graduate Fellow of the National University of La Plata, Argentina. Ariel R. Vicente and Analía Concellón are research members of the CONICET, Argentina.

References

[1] M. D. S. M. Rufino, R. E. Alves, E. S. De Brito, J. Pérez-Jiménez, F. Saura-Calixto, and J. Mancini-Filho, "Bioactive compounds and antioxidant capacities of 18 non-traditional tropical fruits from Brazil," *Food Chemistry*, vol. 121, no. 4, pp. 996–1002, 2010.

[2] J. Contreras-Calderón, L. Calderón-Jaimes, E. Guerra-Hernández, and B. García-Villanova, "Antioxidant capacity, phenolic content and vitamin C in pulp, peel and seed from 24 exotic fruits from Colombia," *Food Research International*, vol. 44, no. 7, pp. 2047–2053, 2011.

[3] A.-L. Gancel, P. Alter, C. Dhuique-Mayer, J. Ruales, and F. Vaillant, "Identifying carotenoids and phenolic compounds in naranjilla (*Solanum quitoense* Lam. var. Puyo hybrid), an Andean fruit," *Journal of Agricultural and Food Chemistry*, vol. 56, no. 24, pp. 11892–11899, 2008.

[4] M. F. Ramadan, "Bioactive phytochemicals, nutritional value, and functional properties of cape gooseberry (*Physalis peruviana*): an overview," *Food Research International*, vol. 44, no. 7, pp. 1830–1836, 2011.

[5] L. A. Puente, C. A. Pinto-Muñoz, E. S. Castro, and M. Cortés, "*Physalis peruviana* Linnaeus, the multiple properties of a highly functional fruit: a review," *Food Research International*, vol. 44, no. 7, pp. 1733–1740, 2011.

[6] C. Vasco, K. Riihinen, J. Ruales, and A. Kamal-Eldin, "Chemical composition and phenolic compound profile of mortiño (*vaccinium floribundum* kunth)," *Journal of Agricultural and Food Chemistry*, vol. 57, no. 18, pp. 8274–8281, 2009.

[7] A. Valente, T. G. Albuquerque, A. Sanches-Silva, and H. S. Costa, "Ascorbic acid content in exotic fruits: a contribution to produce quality data for food composition databases," *Food Research International*, vol. 44, no. 7, pp. 2237–2242, 2011.

[8] G. Shama, "Process challenges in applying low doses of ultraviolet light to fresh produce for eliciting beneficial hormetic responses," *Postharvest Biology and Technology*, vol. 44, no. 1, pp. 1–8, 2007.

[9] P. Civello, A. Vicente, and G. Martinez, "UV-C technology to control postharvest diseases of fruit and vegetables," in *Recent Advances in Alternative Postharvest Technologies to Control Fungal Diseases in Fruits and Vegetables*, R. Troncoso-Rojas, M. E. Tiznado-Hernandez, A. Gonzalez-Leon, and R. Troncoso-Rojas, Eds., Transworld Research Network, Kerala, India, 2006.

[10] M. Alothman, R. Bhat, and A. A. Karim, "UV radiation-induced changes of antioxidant capacity of fresh-cut tropical fruits," *Innovative Food Science and Emerging Technologies*, vol. 10, no. 4, pp. 512–516, 2009.

[11] R. Maharaj, J. Arul, and P. Nadeau, "UV-C irradiation effects on levels of enzymic and non-enzymic phytochemicals in tomato," *Innovative Food Science and Emerging Technologies*, vol. 21, pp. 99–106, 2014.

[12] M. Charles and J. Arul, "UV treatment of fresh fruit and vegetables for improved quality: a status report," *Stewart Postharvest Review*, vol. 3, pp. 1–8, 2007.

[13] Z. Yang, S. Cao, X. Su, and Y. Jiang, "Respiratory activity and mitochondrial membrane associated with fruit senescence in postharvest peaches in response to UV-C treatment," *Food Chemistry*, vol. 161, pp. 16–21, 2014.

[14] M. J. Andrade-Cuvi, A. R. Vicente, A. Concellón, and A. R. Chaves, "Changes in red pepper antioxidants as affected by UV-C treatments and storage at chilling temperatures," *LWT—Food Science and Technology*, vol. 44, no. 7, pp. 1666–1671, 2011.

[15] J. Bu, Y. Yu, G. Aisikaer, and T. Ying, "Postharvest UV-C irradiation inhibits the production of ethylene and the activity of cell wall-degrading enzymes during softening of tomato (*Lycopersicon esculentum* L.) fruit," *Postharvest Biology and Technology*, vol. 86, pp. 337–345, 2013.

[16] T. Jiang, M. M. Jahangir, Z. Jiang, X. Lu, and T. Ying, "Influence of UV-C treatment on antioxidant capacity, antioxidant enzyme activity and texture of postharvest shiitake (*Lentinus edodes*) mushrooms during storage," *Postharvest Biology and Technology*, vol. 56, no. 3, pp. 209–215, 2010.

[17] G. A. Gonzalez-Aguilar, J. A. Villa-Rodriguez, J. F. Ayala-Zavala, and E. M. Yahia, "Improvement of the antioxidant status of tropical fruits as a secondary response to some postharvest treatments," *Trends in Food Science and Technology*, vol. 21, no. 10, pp. 475–482, 2010.

[18] P. Crupi, A. Pichierri, T. Basile, and D. Antonacci, "Postharvest stilbenes and flavonoids enrichment of table grape cv Redglobe (*Vitis vinifera* L.) as affected by interactive UV-C exposure and storage conditions," *Food Chemistry*, vol. 141, no. 2, pp. 802–808, 2013.

[19] M. Erkan, S. Y. Wang, and C. Y. Wang, "Effect of UV treatment on antioxidant capacity, antioxidant enzyme activity and decay in strawberry fruit," *Postharvest Biology and Technology*, vol. 48, no. 2, pp. 163–171, 2008.

[20] C. Y. Wang, C.-T. Chen, and S. Y. Wang, "Changes of flavonoid content and antioxidant capacity in blueberries after illumination with UV-C," *Food Chemistry*, vol. 117, no. 3, pp. 426–431, 2009.

[21] C. T. T. Nguyen, J. Kim, K. S. Yoo, S. Lim, and E. J. Lee, "Effect of prestorage UV-A, -B, and -C radiation on fruit quality and anthocyanin of 'Duke' blueberries during cold storage," *Journal of Agricultural and Food Chemistry*, vol. 62, no. 50, pp. 12144–12151, 2014.

[22] L. H. Liu, D. Zabaras, L. E. Bennett, P. Aguas, and B. W. Woonton, "Effects of UV-C, red light and sun light on the carotenoid content and physical qualities of tomatoes during post-harvest storage," *Food Chemistry*, vol. 115, no. 2, pp. 495–500, 2009.

[23] L. A. Terry and D. C. Joyce, "Elicitors of induced disease resistance in postharvest horticultural crops: a brief review," *Postharvest Biology and Technology*, vol. 32, no. 1, pp. 1–13, 2004.

[24] R. Re, N. Pellegrini, A. Proteggente, A. Pannala, M. Yang, and C. Rice-Evans, "Antioxidant activity applying an improved ABTS radical cation decolorization assay," *Free Radical Biology and Medicine*, vol. 26, no. 9-10, pp. 1231–1237, 1999.

[25] A. Concellón, M. Zaro, A. Chaves, and A. Vicente, "Changes in quality and phenolic antioxidants in dark purple American eggplant (*Solanum melongena* L. cv. Lucía) as affected by storage at 0°C and 10°C," *Postharvest Biology and Technology*, vol. 66, pp. 35–41, 2012.

[26] Y. Shin, R. H. Liu, J. F. Nock, D. Holliday, and C. B. Watkins, "Temperature and relative humidity effects on quality, total ascorbic acid, phenolics and flavonoid concentrations, and antioxidant activity of strawberry," *Postharvest Biology and Technology*, vol. 45, no. 3, pp. 349–357, 2007.

[27] S. Georgé, P. Brat, P. Alter, and M. J. Amiot, "Rapid determination of polyphenols and vitamin C in plant-derived products," *Journal of Agricultural and Food Chemistry*, vol. 53, no. 5, pp. 1370–1373, 2005.

[28] S. Promyou and S. Supapvanich, "Effect of ultraviolet-C (UV-C) illumination on postharvest quality and bioactive compounds in yellow bell pepper fruit (*Capsicum annuum* L.) during storage," *African Journal of Agricultural Research*, vol. 7, pp. 4084–4096, 2012.

[29] M. Baka, J. Mercier, R. Corcuff, F. Castaigne, and J. Arul, "Photochemical treatment to improve storability of fresh strawberries," *Journal of Food Science*, vol. 64, no. 6, pp. 1068–1072, 1999.

[30] G. A. González-Aguilar, R. Zavaleta-Gatica, and M. E. Tiznado-Hernández, "Improving postharvest quality of mango 'Haden' by UV-C treatment," *Postharvest Biology and Technology*, vol. 45, no. 1, pp. 108–116, 2007.

[31] J. Pinheiro, C. Alegria, M. Abreu, E. M. Gonçalves, and C. L. M. Silva, "Use of UV-C postharvest treatment for extending fresh whole tomato (*Solanum lycopersicum*, cv. Zinac) shelf-life," *Journal of Food Science and Technology*, vol. 52, no. 8, pp. 5066–5074, 2014.

[32] E. A. Barka, S. Kalantari, J. Makhlouf, and J. Arul, "Impact of UV-C irradiation on the cell wall-degrading enzymes during ripening of tomato (*Lycopersicon esculentum* L.) fruit," *Journal of Agricultural and Food Chemistry*, vol. 48, no. 3, pp. 667–671, 2000.

[33] M. A. Pombo, H. G. Rosli, G. A. Martínez, and P. M. Civello, "UV-C treatment affects the expression and activity of defense genes in strawberry fruit (*Fragaria* × *ananassa*, Duch.)," *Postharvest Biology and Technology*, vol. 59, no. 1, pp. 94–102, 2011.

[34] M. S. Gutierrez, G. D. Trinchero, A. M. Cerri, F. Vilella, and G. O. Sozzi, "Different responses of goldenberry fruit treated at four maturity stages with the ethylene antagonist 1-methylcyclopropene," *Postharvest Biology and Technology*, vol. 48, no. 2, pp. 199–205, 2008.

[35] M. Valdenegro, L. Fuentes, R. Herrera, and M. A. Moya-León, "Changes in antioxidant capacity during development and ripening of goldenberry (*Physalis peruviana* L.) fruit and in response to 1-methylcyclopropene treatment," *Postharvest Biology and Technology*, vol. 67, pp. 110–117, 2012.

[36] S. Cote, L. Rodoni, E. Miceli, A. Concellón, P. M. Civello, and A. R. Vicente, "Effect of radiation intensity on the outcome of postharvest UV-C treatments," *Postharvest Biology and Technology*, vol. 83, pp. 83–89, 2013.

[37] G. Dhallewin, M. Schirra, M. Pala, and S. Ben-Yehoshua, "Ultraviolet C irradiation at 0.5 $kJ.m^{-2}$ reduces decay without causing damage or affecting postharvest quality of star ruby grapefruit (*C. paradisi* Macf)," *Journal of Agricultural and Food Chemistry*, vol. 48, no. 10, pp. 4571–4575, 2000.

[38] P. Perkins-Veazie, J. K. Collins, and L. Howard, "Blueberry fruit response to postharvest application of ultraviolet radiation," *Postharvest Biology and Technology*, vol. 47, no. 3, pp. 280–285, 2008.

[39] F. P. Prencipe, R. Bruni, A. Guerrini, D. Rossi, S. Benvenuti, and F. Pellati, "Metabolite profiling of polyphenols in *Vaccinium* berries and determination of their chemopreventive properties," *Journal of Pharmaceutical and Biomedical Analysis*, vol. 89, pp. 257–267, 2014.

[40] C. Mertz, A.-L. Gancel, Z. Gunata et al., "Phenolic compounds, carotenoids and antioxidant activity of three tropical fruits," *Journal of Food Composition and Analysis*, vol. 22, no. 5, pp. 381–387, 2009.

[41] H. Wang, G. Cao, and R. L. Prior, "Total antioxidant capacity of fruits," *Journal of Agricultural and Food Chemistry*, vol. 44, no. 3, pp. 701–705, 1996.

[42] A. Allende, A. Marín, B. Buendía, F. Tomás-Barberán, and M. I. Gil, "Impact of combined postharvest treatments (UV-C light, gaseous O_3, superatmospheric O_2 and high CO_2) on health promoting compounds and shelf-life of strawberries," *Postharvest Biology and Technology*, vol. 46, no. 3, pp. 201–211, 2007.

[43] Y. Dong, D. Mitra, A. Kootstra, C. Lister, and J. Lancaster, "Postharvest stimulation of skin color in Royal Gala apple,"

Journal of the American Society for Horticultural Science, vol. 120, no. 1, pp. 95–100, 1995.

[44] C. Stevens, V. A. Khan, J. Y. Lu et al., "The germicidal and hormetic effects of UV-C light on reducing brown rot disease and yeast microflora of peaches," *Crop Protection*, vol. 17, no. 1, pp. 75–84, 1998.

[45] W. L. Kubasek, B. W. Shirley, A. McKillop, H. M. Goodman, W. Briggs, and F. M. Ausubel, "Regulation of flavonoid biosynthetic genes in germinating Arabidopsis seedlings," *Plant Cell*, vol. 4, no. 10, pp. 1229–1236, 1992.

[46] F. A. Tomás-Barberán and J. C. Espín, "Phenolic compounds and related enzymes as determinants of quality in fruits and vegetables," *Journal of the Science of Food and Agriculture*, vol. 81, no. 9, pp. 853–876, 2001.

[47] C. Alegria, J. Pinheiro, M. Duthoit, E. M. Gonçalves, M. Moldão-Martins, and M. Abreu, "Fresh-cut carrot (cv. Nantes) quality as affected by abiotic stress (heat shock and UV-C irradiation) pre-treatments," *LWT—Food Science and Technology*, vol. 48, no. 2, pp. 197–203, 2012.