PHILIPP AGRIC SCIENTIST
Vol. 99 No. 1, 34–41
March 2016

ISSN 0031-7454

Quality, Antioxidant Capacity, Antioxidant Compounds and Enzyme Activities of 'El-Bayadi' Table Grapes as Affected by Postharvest UV-C Radiation

Adel D. Al-Qurashi[1] and Mohamed A. Awad[1, 2,*]

[1]Department of Arid Land Agriculture, Faculty of Meteorology, Environment and Arid Land Agriculture, King Abdulaziz University, P. O. Box. 80208, Jeddah, Saudi Arabia
[2]Department of Pomology, Faculty of Agriculture, Mansoura University, El-Mansoura/Egypt
[*]Author for correspondence; e-mail: mawad@mans.edu.eg; Phone: +966-566123090; Fax: +966-26952364

The study evaluated the effect of postharvest UV-C radiation at 0.9, 2.8 and 4.9 kJ m^{-2} on quality, antioxidant capacity, antioxidant compounds and enzyme activities of 'El-Bayadi' table grapes after 30 d of storage at 0 °C ± 1 and 90–95% relative humidity (RH) plus 2 d of shelf life at 20 °C ± 2 and 60–70% RH. UV-C radiation decreased decay and increased total soluble solids (TSS) concentration, while acidity, pH and firmness were not affected compared with the control treatment. UV-C treated grapes retained higher total phenols, total flavonoids and vitamin C concentration. Peroxidase and polyphenoloxidase activities were higher in response to UV-C radiation, especially at 4.9 kJ m^{-2}. However, polygalacturonase and xylanase activities were lower, especially at 2.8 and 4.9 kJ m^{-2} of UV-C radiation, compared with the control. Antioxidant capacity measured by both 1,1-diphenyl-2-picrylhydrazyl (DPPH) and 2,2'-azino-bis(3-ethylbenzo-thiazoline-6-sulfonic acid) (ABTS) methods was not affected by UV-C radiation. UV-C radiation treatment (0.9–4.9 kJ m^{-2}) decreased decay and retained quality of 'El-Bayadi' table grapes after storage and during shelf life.

Key Words: 'El-Bayadi' table grapes, storage, decay, phenols, flavonoids, vitamin C, antioxidant, enzymes, UV-C radiation

Abbreviations: ABTS – 2,2'-azino-bis(3-ethylbenzo-thiazoline-6-sulfonic acid), DPPH – 1,1-diphenyl-2-picrylhydrazyl, PG – polygalacturonase, POD – peroxidase, PPO – polyphenoloxidase, TSS – total soluble solids, UV-C – ultraviolet light radiation

INTRODUCTION

The nutritional and medicinal values of grapes (*Vitis vinifera* L.) make them important for human use and consumption (Zhou and Raffoul 2012). Epidemiological studies showed that fruit and vegetable intake is largely correlated with a lower risk of degenerative diseases caused by oxidative stress such as cardiovascular disease, cancer and stroke mainly due to natural antioxidants such as phenolics, vitamins and carotenoids found in fruits and vegetables (Zhou and Raffoul 2012; Fahmi et al. 2013).

'El-Bayadi', the major white table grape cultivar in the Taif region of the Kingdom of Saudi Arabia (KSA), is characterized by high production and excellent quality. However, the berries possess thin skin and relatively low firmness that limit their storage life and marketing (Al-Qurashi and Awad 2013). Synthetic fungicide application and/or postharvest sulfur dioxide (SO_2) fumigation (Luvisi et al. 1992; Droby and Lichter 2004) are highly restricted due to human health and environmental concerns (Taylor 1993; Zahavi et al. 2000). Accordingly, alternative tools which reduce decay and maintain the quality of grapes without negative impact on both consumers and the environment are critically required. Currently, consumer demand for healthier fruit and vegetables is increasing with special interest in the level of health-promoting phytochemicals (Crupi et al. 2013).

Ultraviolet light radiation (UV-C) has long been reported to affect several aspects in plants (Levitt 1980). UV-C radiation at optimum wavelengths (254 nm) and doses can induce stress responses often connected with the induction of pathogen resistance system (Nigro et al. 1998; Cantos et al. 2001; Romanazzi et al. 2006 and 2012; Crupi et al. 2013). UV-C has been effective on several crops such as tomatoes (Jagadeesh et al. 2011; Charles et al. 2008; Maharaj et al. 1999), peaches and apples (Liu et al. 1991), carrot (Mercier et al. 1993), citrus (Ben-Yehoshua et al. 2005) and several others (Shama and Alderson 2005; Charles and Arul 2007).

Postharvest UV-C (190-280 nm) radiation has been considered as a physical elicitor for controlling pathogens such as gray mold in several grape cultivars (Nigro et al. 1998; Cantos et al. 2001; Romanazzi et al. 2006; Crupi et al. 2013). This treatment increased the biosynthesis of phytochemicals such as stilbenes (trans-resveratrol) and catechin, phytoalexins connected with the defense resistance system of fruit to pathogens (Nigro et al. 1998; Romanazzi et al. 2006 and 2012). Crupi et al. (2013) found that both cold storage and UV-C radiation for 3 min (2.4 kJ m^{-2}) enhanced the content of cis-resveratrol

and trans-piceid in 'Redglobe' table grapes stored for more than 48 h. UV-C treatment enhanced resistance to pathogens in berries wounded before and after radiation in 'Italia' grape (Nigro et al. 1998). Wine processed from 'Syrah' grapes previously treated with a combination of methyl jasmonate and UV-C radiation contained higher (2.5-fold) trans-resveratrol and piceatannol levels compared with the control (Fernandez-Marin et al. 2014).

Similar to other phenolics, resveratrol concentration in grape varies with grape cultivar, environmental conditions and harvest season (Awad et al. 2000; Bavaresco et al. 2012). Elicitors such as salicylic acid, chitosan, methyl jasmonate, jasmonic acid, benzothiodiazole, aluminum chloride, β-aminobutyric acid, ozone, UV-C light, and *Botrytis cinerea* have been tested to improve nutraceutical properties of grape (Cisneros-Zevallos 2003; Fernandez-Marin et al. 2014).

A synergistic effect on the biosynthesis of phytoalexins has been found between methyl jasmonate and ethephon (Faurie et al. 2009), UV-C and chitosan (Romanazzi et al. 2006 and 2012), UV-C and methyl jasmonate (Larronde et al. 2003), methyl jasmonate and cyclodextrins (Lijavetzky et al. 2008), UV-C and $CaCl_2$ (Wang et al. 2013), and among others (Cisneros-Zevallos 2003). In UV-treated 'Superior' white table grapes, trans-resveratrol concentration was about 10-fold higher than that of untreated grapes after 3 d of storage at 22 °C (Gonzalez-Barrio et al. 2005). However, UV-treated grapes developed some surface browning on the third day of storage at 22 °C. Wang et al. (2013) reported that the combination of $CaCl_2$ and UV-C increased the resveratrol concentration in both leaves and grapes. After harvest, resveratrol concentration reached a maximum level at 13 d, and then slightly declined.

Berry firmness and total soluble solids (TSS) slightly changed during storage with no differences among the treatments. In other fruit, Yang et al. (2014) reported that UV-C radiation of peaches (3.0 kJ m^{-2}) maintained firmness and inhibited respiration rate during 8 d of storage at 20 °C. Also, UV-C radiation activated the antioxidant enzymes and lowered the levels of free radicals. Strawberries treated with three UV-C radiation dosages (0.43, 2.15 and 4.30 kJ m^{-2}, respectively) enhanced the antioxidant capacity and reduced decay during storage at 10 °C compared with the control (Erkan et al. 2008). Likewise, UV-C treatment (3.7 kJ m^{-2}) delayed the ripening of tomatoes (Maharaj et al. 1999).

This study evaluated the effectiveness of postharvest UV-C radiation at different doses on quality characteristics, antioxidant capacity, antioxidant compounds and enzyme activities of 'El-Bayadi' table grapes in an attempt to maintain their quality and improve their nutraceutical value during storage.

MATERIALS AND METHODS

UV-C Irradiance Treatments

A commercial drip-irrigated vineyard of 'El-Bayadi' table grapes was selected in the Taif region (21.4333° N, 40.3500° E) of Saudi Arabia during the 2014 growing season. Uniform samples of bunches were picked at commercial maturation (13–14 Brix% and 0.6–0.7% acidity) and directly transferred to the horticulture laboratory at King Abdulaziz University, Jeddah, Saudi Arabia. A completely randomized experimental design with four replicates was established.

A photoreactor (model LZC-4V, Luzchem Research Inc, Ottawa, Canada) was used in conducting the UV-C radiation treatments. The UV-C light intensity was kept constant (16 W) and the applied doses (0.9, 2.8 and 4.9 kJ m^{-2}, respectively) were varied by altering the exposure time (1, 3 and 5 min) at a fixed distance of 20 cm above the bunches of grapes. The UV-C lamps were turned on for about 15 min before applying the irradiance treatments. The bunches of grapes were irradiated on both sides. The used UV-C source was OSRAM Puritec (Italy), G8T5/OF germicidal lamp MNS, 8W, G5 with peak emission at 254 nm. Non-UV-C irradiated bunches of grapes were considered as the control treatment. All treatments were stored in perforated plastic bags inside cardboard cartons with air holes for 30 d at 0 °C ±1 and 90–95% relative humidity (RH) plus 2 d of shelf life at 20 °C ±2 and 60–70% RH.

Before applying the UV-C treatments, four samples (30 berries each) were randomly collected from several bunches for initial quality measurements. After 30 d of cold storage plus 2 d of shelf life, samples (30 berries each) were randomly collected from each replicate/ treatment for quality measurements. Additional samples of berries were also collected before UV-C treatments and after storage plus 2 d of shelf life and kept at –80 °C for later biochemical determinations.

Decay Incidence and Weight Loss Determination

The incidence of decay was recorded and expressed in percentage. The total loss in weight was calculated on an initial weight basis and also expressed in percentage.

Firmness, TSS, Acidity and Vitamin C Measurements

Berry firmness was recorded independently in each of the 30 berries per replicate by a digital basic force gauge, model BFG 50N (Mecmesin, Sterling, Virginia, USA) supplemented with a probe of 11 mm diameter that measured the compression force required just to break the berry. The results were expressed in Newton. A homogeneous sample was prepared from these berries per replicate for measuring total soluble solids (TSS), acidity, vitamin C, total phenol, and soluble tannins. TSS was measured as Brix % in fruit juice with a digital refractometer (Pocket Refractometer PAL-3, ATAGO, Japan). Titratable acidity was determined in berry juice diluted with distilled water (1:2) by titration with 0.1 N sodium hydroxide up to pH 8.2, using an automatic titrator (HI 902, HANNA Instrument, USA). The results were expressed as percentage of tartaric acid (g of tartaric acid per 100 mL of grape juice). Ascorbic acid (vitamin C) was measured by the oxidation of ascorbic acid with 2,6-dichlorophenolendophenol dye. The results were expressed in mg per 100 mL of grape juice (Ranganna 1979).

Preparation of the Methanol Extract
Two grams of skin tissue (randomly collected from 30 berries per replicate) were extracted by shaking at 150 rpm for 12 h with 20 mL methanol (80%) and filtered through filter paper No. 1. The filtrate designated as methanol extract was used for estimation of total phenol, total flavonoid and antioxidant activity.

Estimation of Total Phenol
Total phenol concentration was measured according to the method used by Hoff and Singleton (1977). Fifty microliters (50 µL) of the methanol extract was mixed with 100 µL of Folin-Ciocalteu reagent, 850 µL of methanol and allowed to stand for 5 min at ambient temperature. A 500 µL of 20% sodium carbonate was added and allowed to react for 30 min. Absorbance was measured at 750 nm. Total phenol was quantified from a calibration curve obtained by measuring the absorbance of known concentrations of gallic acid; the results were expressed in mg gallic acid equivalent/g.

Estimation of Total Flavonoid
Total flavonoid concentration was determined using a modified colorimetric method described previously by Zhishen et al. (1999). Methanol extract or standard solution (250 µL) was mixed with distilled water (1.25 mL) and 5% $NaNO_2$ solution (75 µL). After standing for 6 min, the mixture was combined with 10% $AlCl_3$ solution (150 µL); 1 M NaOH (0.5 mL) and distilled water (275 µL) were added to the mixture 5 min later. The absorbance of the solutions at 510 nm was then measured. Total flavonoid content was quantified from a calibration curve obtained by measuring the absorbance of known concentrations of catechin and the results were expressed in mg catechin equivalent/g.

Evaluation of Antioxidant Activity
DPPH radical scavenging assay. Free radical scavenging activity of the methanol extract was determined using the 1,1-diphenyl-2-picrylhydrazyl (DPPH) method (Ao et al. 2008). A methanol extract (0.1 m) was added to 0.9 mL of freshly prepared DPPH methanol solution (0.1 mM). An equal amount of methanol was used as control. After incubation for 30 min at room temperature in the dark, the absorbance (Abs) was measured at 517 nm using a spectrophotometer. Activity of scavenging (%) was calculated using the formula

DPPH radical scavenging % = [(Abs control – Abs sample)/Abs control] x 100

The inhibition concentration (IC_{50}) was defined as µg phenolics of the test sample that decreases 50% of the initial radical. The IC_{50} values were calculated from the dose response curves.

ABTS radical cation decolorization assay. ABTS (2,2'-azino-bis (3-ethylbenzo-thiazoline-6-sulfonic acid) also forms a relatively stable free radical, which decolorizes in its non-radical form. The spectrophotometric analysis of $ABTS^{\bullet+}$ scavenging activity was determined according to the method of Re et al. (1999). In this method, an antioxidant was added to a pre-formed ABTS radical solution and after a fixed time period, the remaining $ABTS^{\bullet+}$ is quantified spectrophotometrically at 734 nm. $ABTS^{\bullet+}$ was produced by a reaction of 7 mM ABTS in H_2O with 2.45 mM potassium persulfate ($K_2S_2O_8$), stored in the dark at room temperature for 16 h. The $ABTS^{\bullet+}$ solution was diluted to give an absorbance of 0.750 ± 0.025 at 734 nm in 0.1 M sodium phosphate buffer, pH 7.4 (25 µL $ABTS^{\bullet+}$ solution was increased to 900 µL buffer). This solution was then added to 100 µL of the crude methanol extract. The absorbance was recorded 1 min after mixing and the percentage of radical scavenging was calculated relative to a blank containing no scavenger. The extent of decolorization was calculated as percentage reduction of absorbance. The scavenging capability of test compounds was calculated using the equation

$$ABTS^{\bullet+} \text{ scavenging } (\%) = (1 - AS/AC) \times 100$$

where AC is the absorbance of a control (blank) lacking any radical scavenger and AS is the absorbance of the remaining $ABTS^{\bullet+}$ in the presence of scavenger. The results were plotted as the percentage of scavenging activity against the concentration of the phenolic contents. The inhibition concentration (IC_{50}) was defined as µg phenolics of the test sample that decreases 50% of the initial radical. The IC_{50} values were calculated from the dose response curves.

Enzyme Assay
Crude extract. One gram of berry skin (randomly collected from 30 berries per replicate) was homogenized with 20 mM Tris-HCl buffer (pH 7.2). The homogenate was centrifuged at 10,000 rpm for 10 min at 4 ºC. The supernatant was designed as crude extract and stored at −20 ºC for peroxidase, polyphenoloxidase, polygalacturonase and xylanase assay.

Peroxidase assay. Peroxidase (EC 1.11.1.7) activity (POD) was assayed according to the method used by Miranda et al. (1995). The reaction mixture contained in 1 mL: 0.008 mL of 0.97 M H_2O_2, 0.08 mL of 0.5 M guaiacol, 0.25 mL of 0.2 M sodium acetate buffer (pH 5.5) and the least amount of enzyme preparation. The change in absorbance at 470 nm due to guaiacol oxidation was followed for 1 min using a spectrophotometer. One unit of enzyme activity was defined as the amount of enzyme which increases the O.D. 1.0 per h under standard assay conditions.

Polyphenoloxidase assay. Polyphenoloxidase (EC 1.14.18.1) (PPO) activity was assayed with catechol as a substrate according to the spectrophotometric procedure of Jiang et al. (2002). The extract (0.2 mL) was rapidly added to 2.8 mL of 20 mM catechol solution prepared in 0.01 M sodium phosphate buffer (pH 6.8). The increase in absorbance at 400 nm was recorded for 3 min using a spectrophotometer. One unit of enzyme activity was defined as the amount of the enzyme that causes a change of 0.1 in absorbance per min.

Polygalacturonase and xylanase assay. Polygalacturonase (EC 3.2.1.15) (PG) and xylanase (EC 3.2.1.8) activities were assayed by determining the liberated reducing end products using galacturonic acid and xylose, respectively (Miller 1959). The reaction mixture (0.5 mL) contained 5 mg of substrate, 0.25 mL of 0.2 M sodium acetate buffer (pH 5.5) and a suitable amount of crude extract. Assays were carried out at 37 °C for 1 h. Dinitrosalicylic acid reagent (0.5 mL) was then added to each tube and heated in a boiling water bath for 10 min. After cooling to room temperature, the absorbance was measured at 560 nm. The substrates used were polygalacturonic acid and xylene for polygalacturonase and xylanase, respectively. One unit of enzyme activity was defined as the amount of enzyme which liberated 1 μM of reducing sugar per h under standard assay conditions.

Statistical Analysis

The data were analyzed as a completely randomized design with four replicates by analysis of variance (ANOVA) using the statistical package software SAS (SAS Institute Inc., 2000, Cary, NC., USA). Comparisons between means were made by *F*-test and the least significant difference (LSD) at P≤5%.

RESULTS

Postharvest UV-C radiation at all the applied doses significantly decreased the percentage decay in grape berries after storage from 3.93 to 7.04% compared with the control (15.75%) (Table 1). There were no significant differences among the different UV-C doses. However, the lowest decay percentage was observed at a UV-C dose of 4.9 kJ m^{-2}. Weight loss ranged from 4.37 to 4.83% and was not significantly affected by the UV-C radiation treatments (Table 1). TSS concentration of berries slightly changed after storage in the control compared with the initial, but was higher at UV-C radiation doses of 0.9 and 2.8 kJ m^{-2} compared with the other treatments (Table 2). However, the other quality characteristics (acidity, pH and firmness of berries) showed slight changes after storage, except for firmness that showed much lower values than the initial, and were not significantly affected by the UV-C radiation treatments (Table 2).

Total phenol concentration was lower in all treatments after storage than the initial value (Table 3). Nevertheless, UV-C radiation at the different doses maintained significantly higher total phenol concentration than the control. In this respect, total phenol concentration significantly increased as the UV-C radiation dose increased (Table 3). Total flavonoid concentration in all treatments showed higher values after storage compared with the initial, except for UV-C irradiance at 0.9 kJ m^{-2}. UV-C radiation at 4.9 kJ m^{-2} showed significantly higher total flavonoid concentration than all the other treatments. Total flavonoid concentration significantly increased as the UV-C radiation dose was increased (Table 3).

Vitamin C concentration decreased after storage only in the control compared with the initial. It was significantly higher at 0.9 and 2.8 kJ m^{-2} UV-C radiation compared with the control (Table 3). POD showed higher activity after storage in all treatments compared with the initial (Table 4). UV-C radiation at 4.9 kJ m^{-2} significantly increased the POD activity compared with

Table 1. Decay and weight loss percentage in 'El-Bayadi' table grapes after storage and shelf life as affected by postharvest UV-C irradiance.

Treatment	Decay (%)	Weight Loss (%)
Initial	*0.0*	0.0
Control	15.75a	4.37
UV-C irradiance		
0.9 kJ m^{-2}	6.12b	4.43
2.8 kJ m^{-2}	7.04b	4.45
4.9 kJ m^{-2}	3.93b	4.83
F-test	*	NS
LSD (0.05)	*8.32*	-

Measurements were done after 30 d of cold storage plus 2 d at 20 °C. Means within each column followed by the same letter are not significantly different at *P*≤0.05.
*Significant at *P*≤0.05; NS, not significant; -, not calculated

Table 2. Quality characteristics of 'El-Bayadi' table grapes after storage and shelf life as affected by postharvest UV-C irradiance.

Treatment	Total Soluble Solids (Brix %)	Acidity (%)	pH	Firmness (N)
Initial	13.90	0.76	3.29	34.9
Control	13.56b	0.69	3.46	16.5
UV-C irradiance				
0.9 kJ m^{-2}	15.53a	0.58	3.55	13.9
2.8 kJ m^{-2}	15.73a	0.65	3.51	15.5
4.9 kJ m^{-2}	13.50b	0.69	3.40	16.6
F-test	***	NS	NS	NS
LSD (0.05)	0.95	-	-	-

Measurements were done after 30 d of cold storage plus 2 d at 20 °C. Means within each column followed by the same letter are not significantly different at *P*≤0.05.
***Significant at *P*≤0.001; (NS), not significant; (-), not calculated

Table 3. Total phenols and flavonoids in peel and vitamin C concentration of 'El-Bayadi' table grapes after storage and during shelf life as affected by postharvest UV-C irradiance.

Treatment	Phenol (mg g^{-1} fw)	Flavonoid (mg g^{-1} fw)	Vitamin C (mg 100 mL^{-1} juice)
Initial	2.07	0.54	1.25
Control	1.19d	0.86b	0.75b
UV-C irradiance			
0.9 kJ m^{-2}	1.43c	0.55c	1.50a
2.8 kJ m^{-2}	1.68b	0.91b	1.75a
4.9 kJ m^{-2}	1.89a	1.01a	1.25ab
F-test	***	***	***
LSD (0.05)	0.088	0.046	0.57

Measurements were done after 30 d of cold storage plus 2 d at 20 °C. Means within each column followed by the same letter are not significantly different at *P*≤0.05.
** and ***Significant at *P*≤0.01 and 0.001, respectively.
fw – fresh weight

Table 4. Antioxidant and hydrolytic enzyme activities of 'El-Bayadi' table grapes peel after storage and shelf life as affected by postharvest UV-C irradiance.

Treatment	Peroxidase (U/min/g fw)	Polyphenoloxidase (U/min/g fw)	Polygalacturonase (U/h/g fw)	Xylanase (U/h/g fw)
Initial	9.68	8.57	45.3	12.97
Control	13.55b	3.72b	46.3a	11.38b
UV-C irradiance				
0.9 kJ m^{-2}	11.49c	7.05a	42.1b	12.31a
2.8 kJ m^{-2}	12.71b	7.45a	39.9c	10.98c
4.9 kJ m^{-2}	15.24a	7.30a	42.1b	10.60d
F-test	***	***	***	***
LSD (0.05)	1.13	1.79	0.80	0.095

Measurements were done after 30 d of cold storage plus 2 d at 20 °C. Means within each column followed by the same letter are not significantly different at $P \leq 0.05$.
***Significant at $P \leq 0.001$.
fw – fresh weight

all other treatments including the control, while UV-C radiation at 0.9 kJ m^{-2} significantly decreased POD activity compared with all treatments including the control. POD activity significantly increased as the UV-C radiation dose increased. PPO showed much lower activity during storage in the control treatment compared with the initial (Table 4), while the UV-C radiation at all doses maintained significantly higher PPO activity than the control. There were no significant differences in the PPO activity among the different UV-C radiation doses.

PG activity slightly changed after storage in most treatments compared with the initial. UV-C radiation at the different doses showed significantly lower PG activity than the control. Xylanase activity slightly changed after storage in the control treatment compared with the initial. UV-C radiation at 0.9 kJ m^{-2} maintained significantly higher xylanase activity than all the other treatments. However, UV-C radiation at 2.8 and 4.9 kJ m^{-2} showed significantly lower xylanase activity than the control. Xylanase activity significantly decreased with an increase in the UV-C radiation dose (Table 4).

The antioxidant capacity of berry extract measured by means of the DPPH method increased after storage (lower IC_{50} value) in all the treatments compared with the initial value (12.36) (Table 5). IC_{50} values obtained by means of the DPPH method ranged from 9.11 to 9.91 µg phenolic concentration among all treatments. There were no significant differences among the UV-C radiation treatments and the control while the antioxidant capacity of berry extract measured by the ABTS method decreased after storage (higher IC_{50} value) in all the treatments compared with the initial value. The IC_{50} value ranged from 2.74 to 4.14 µg phenolic concentration among all treatments. UV-C radiation tended to increase the antioxidant activity (lower IC_{50} values) compared with the control but the differences among the treatments were not significant (Table 5).

Table 5. Antioxidant activates (IC_{50} values) of 'El-Bayadi' table grapes peel after storage and shelf life as affected by postharvest UV-C irradiance.

Treatment	DPPH (IC_{50})	ABTS (IC_{50})
Initial	12.36	2.74
Control	9.30	4.14
UV-C irradiance		
0.9 kJ m^{-2}	9.31	3.15
2.8 kJ m^{-2}	9.91	3.58
4.9 kJ m^{-2}	9.11	3.70
F-test	NS	NS
LSD (0.05)	-	-

Measurements were done after 30 d of cold storage plus 2 d at 20 °C.
IC_{50} value, the concentration (µg phenolic) of the test sample that decreases 50% of the initial radical
ABTS – 2,2'-azino-bis(3-ethylbenzo-thiazoline-6-sulfonic acid), DPPH – 1,1-diphenyl-2-picrylhydrazyl

DISCUSSION

As a non-climacteric fruit, table grapes have relatively low rate of physiological activity during storage. However, berries are subject to postharvest decay and weight loss due to the occurrence of a number of physiological disorders (cracking, shattering and browning) and diseases mainly caused by fungus (Yahia et al. 1983). The search for alternative tools to synthetic chemicals to control postharvest losses and keep fruit quality is currently attracting greater worldwide attention.

Our study tested the effectiveness of pre-storage UV-C radiation on the quality characteristics, antioxidant capacity, antioxidant compounds and enzyme activities of 'El-Bayadi' table grapes during storage. We found that UV-C radiation treatments, especially at 4.9 kJ m^{-2}, greatly decreased decay after 30 d of cold storage plus 2 d of shelf life compared with the control. These results might be explained by two different mechanisms: a direct inhibition effect of UV-C radiation on the growth of pathogens as reported for minimally processed 'Red Oak Leaf' lettuce by Allende et al. (2006) and/or indirect effect via the induction of genes/enzymes, especially phenylalanine ammonia lyase (PAL) and POD, connected with the natural defense system that lead to more accumulation of anti-pathogen phenols, flavonoids and phytoalexins (resveratrol) in berry peel (Nigro et al. 1998; Cantos et al. 2001; Romanazzi et al. 2006 and 2012; Crupi et al. 2013). In confirmation, our results showed that UV-C treated grapes retained higher total phenol, total flavonoid and vitamin C concentration than the control.

Total phenol and flavonoid concentration increased as the UV-C radiation dose increased. Vitamin C concentration was higher as a result of UV-C radiation, especially 0.9 and 2.8 kJ m^{-2}, compared with the control (Table 3). Jagadeesh et al. (2011) reported that UV-C radiation increased vitamin C concentration in tomatoes. Also, increase in the antioxidant enzyme POD and

decrease in the cell wall-degrading enzyme PG and xylanase activities that were induced by UV-C radiation at 4.9 kJ m^{-2} might also partially explain the observed reduction in decay, possibly by enhancing cell membrane stability of the berries. Such changes in enzyme activities by UV-C radiation did not, however, result in higher berry firmness (Table 2). Moreover, UV-C radiation, especially at 0.9 and 2.8 kJ m^{-2}, increased TSS concentration of berry compared with the control and had no significant effects on acidity and pH.

Wang et al. (2013) reported that UV-C radiation in combination with calcium chloride treatment enhanced the resveratrol level of grapes but had no effects on berry firmness and TSS concentration. Gonzalez-Aguilar et al. (2001) found higher levels of sugars and lower levels of organic acids in ripe 'Tommy Atkins' mangoes treated with UV-C radiation for 20 min while UV-C radiation for 10 min, as recommended treatment, resulted in similar values in the control treatment. However, in peaches, UV-C radiation at 3.0 kJ m^{-2} retarded ripening, maintained firmness and inhibited respiration rate, increased antioxidant enzyme activities and lowered the levels of free radicals compared with the control during 8 d of storage at 20 °C (Yang et al. 2014). Also, UV-C radiation at 3.7 kJ m^{-2} delayed ripening in tomatoes (Maharaj et al. 1999).

In the current study, UV-C radiation treatments had no effect on weight loss (Table 1). A similar result has been reported on 'Tommy Atkins' mangoes treated with UV-C radiation for 10 or 20 min and stored at 5 or 20 C for 14 d (Gonzalez-Aguilar et al. 2001). However, Liu et al. (1991) reported that UV-C irradiation stimulated the activity of lignifying enzymes and suppressed water loss in apples and peaches. Thus, the exact mechanism(s) of UV-C radiation treatments on fruit ripening, physico-chemical quality and biochemical attributes requires further investigation.

There were no visible damages such as browning of berry skin or flesh as a result of the UV-C doses. However, some skin browning occurred in 'Superior' white table grapes due to UV-C radiation on the third day of storage at 22 °C (Gonzalez-Barrio et al. 2005). PPO, as a defense enzyme, showed much lower activity during storage in the control treatment compared with the initial while UV-C radiation at all doses retained higher PPO activity and total phenol and flavonoid concentrations compared with the control (Tables 3 and 4).

Both PPO and POD enzymes were not specifically activated after 3 d of storage at 22 °C following UV-C radiation treatment of 'Superior' white table grapes (Gonzalez-Barrio et al. 2005). PPO is a well-known enzyme involved in the oxidation of phenolics to quinones, especially (+)-catechin, gallic acid, chlorogenic acid, and ellagic acid as the most important PPO substrates. Quinone polymerizations produce brown-colored compounds that are highly toxic to several pathogens and may cause tissue browning (Campos-Vargas and Saltveit 2002). PPO activity was 3-fold higher in ripe mangoes than in unripe ones and was positively correlated with total phenolics during storage (Hossain et al. 2014). Moreover, both PPO and total phenolics were involved in anthracnose resistance in mangoes and their level could be used to evaluate the degree of resistance of cultivars to the incidence of diseases (Gong et al. 2013). The regulation of phenolic metabolism is, however, more likely determined not only by PPO but also by several other phenolic-biosynthetic enzymes such as phenylalanine ammonia lyase (PAL) (Liu et al. 2007).

The antioxidant capacity of berry peel extract measured by both DPPH and ABTS, after 30 d of storage plus 2 d of shelf life, was not affected by the UV-C radiation treatments (Table 5). However, Crupi et al. (2013) found that UV-C radiation of 'Redglobe' table grapes for 1 min (0.8 kJ m^{-2}) and storage for 120 h at 4 °C resulted in an increase in both total phenol concentration and the antioxidant capacity, measured by the oxygen radical absorbance capacity assay (ORAC), by about 2- to 4-fold compared with the control. Also, UV-C radiation for 1, 5 or 10 min in strawberries (0.43, 2.15 and 4.30 kJ m^{-2}, respectively) enhanced the antioxidant capacity and reduced decay incidence during storage at 10 °C compared with the control (Erkan et al. 2008).

The differences among the antioxidant assays may be due to differences in sensitivity/potential among the antioxidant compounds such as phenolics and flavonoids and vitamin C toward a specific assay (Ciz et al. 2010). In our experiment, the correlations between the antioxidant activity (measured by DPPH and ABTS assays) and total phenol, flavonoid and vitamin C were insignificant (data not shown). Also, the literature on the correlations between several phenolic classes and the antioxidant capacity of grapes are greatly variable (Kallithraka et al. 2005; Bozan et al. 2008; Xu et al. 2010; Jordao et al. 2012). Thus, phenolic compounds may not be the exclusive factor contributing to the antioxidant activity of grapes but might work synergistically with vitamins and minerals (Sanchez-Moreno et al. 1999). In conclusion, UV-C radiation treatments (0.9 to 4.9 kJ m^{-2}) of 'El-Bayadi' table grapes effectively decreased decay, retained higher total phenols, flavonoids and vitamin C concentration compared with the control after 30 d of cold storage plus 2 d of shelf life. After evaluating its side effects, if there are any, UV-C radiation treatment may be used as alternative physical elicitor to synthetic chemicals.

ACKNOWLEDGMENTS

This project was funded by the Deanship of Scientific Research (DSR), King Abdulaziz University, Jeddah under Grant no. G-1436-155-375. The authors acknowledge with thanks financial and technical support from the DSR. Also, we would like to thank Dr. Mohamed Ibraheem; Nageeb Al-Masoudi, MSc; Nour Gamal, BSC; and Saied Sabry, BSc. of the Arid Land Agriculture Department, Faculty of Meteorology, Environment and Arid Land Agriculture, King Abdulaziz University, for their valuable technical support.

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