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"Hurdley technologies" utilized to improve postharvest life of asparagus spears (*Asparagus officinalis* L.)

M.E. Tiznado-Hernández [1], A.A. Gardea-Bejar [2], A. Sánchez-Estrada [1] (*), J.A. Orozco-Avitia [1], A.J. Ojeda-Contreras [1], R. Troncoso-Rojas [1], R. Melendrez-Amavizca [3]

[1] *Coordinación de Tecnología de Alimentos de Origen Vegetal, Gustavo Enrique Astiazarán Rosas 46, Hermosillo, 83304 Sonora, México.*

[2] *Coordinación Guaymas, Centro de Investigación en Alimentación y Desarrollo, A.C. (CIAD, A.C.), Gustavo Enrique Astiazarán Rosas 46, Hermosillo, 83304 Sonora, México.*

[3] *Departamento de Investigación en Física, Universidad de Sonora, Hermosillo, CP 83190, Sonora, México.*

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(*) **Corresponding author:**
aestrada@ciad.mx

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Abstract: Asparagus (*Asparagus officinalis* L.) has short shelf-life due to the high metabolic activity of the apical meristems. Storage at low temperature and high relative humidity is used commercially to keep fresh asparagus spears. Techniques denominated "Hurdley technologies" (UV-C or gamma irradiation) have been tested in fruits and vegetables to extend postharvest life. These technologies were used to extend postharvest shelf life of asparagus spears by inhibition of meristematic activity. Spears were irradiated with UV-C at dosages of 2.46, and 4.93 kJ m^{-2} and gamma irradiation at 1 and 1.5 kGy, before storage at 2°C and 90% relative humidity (RH) for 20 days. Metabolic heat (R_q) was measured in apical meristems, as well as whole spear respiration, sugars content, water potential components and color descriptors. Metabolic heat and whole spears respiration rate did not show differences due to effect of UV-C treatments, while spears treated with gamma radiation showed a metabolic activity inhibition of 10 and 15% for 1 and 1.5 kGy, respectively, while whole spear respiration rate was not affected. Changes in color variables showed a slight reduction in gloss. Sugars content in UV-C remained unchanged, while gamma radiation induced a reduction in glucose. An increase in fresh weight loss was noticeable on those treated with gamma irradiation. No changes in water potential components were observed. It was concluded the treatments used did not reported positive benefits in extending asparagus spears shelf life.

1. Introduction

Green asparagus is a high value vegetable, and its consumption dates back to ancient times (Anido and Cointry, 2008). Worldwide demand is increasing because its gourmet features (Pegiou *et al.,* 2020) and

nutraceutical properties (Fan *et al*., 2015).

This produce is harvested while actively growing and continues to grow even after harvest, keeping a high metabolic activity characteristic of apical meristems (Aegerter *et al.,* 2011). Spears are exposed to different stresses after harvest, such as wounding, dehydration and limited nutrient supply. As a result, they cannot maintain metabolic homeostasis because of their high levels of metabolic activity, respiration rate, and carbohydrate consumption. Consequently, spears metabolites are rapidly consumed, affecting their quality and accelerating senescence during storage, transport, and retailing (Anastasiadi *et al.,* 2020).

Quality loss is mainly noticed by color changes, such as the loss of a bright green color, besides tipping, bending and feathering, which together decreases postharvest quality (Anastasiadi *et al.,* 2020). Concomitantly, dehydration adversely affects fresh weight and turgor loss (Gardea *et al.,* 2023). Low temperatures and high humidity are the conditions commonly utilized in many horticultural products to control senescence and increase shelf life (Singh *et al.*, 2014). However, other methods for fresh produce preservation known as "Hurdley technologies" are available now (Arvanitoyannis *et al.*, 2009), including cold plasma (Jia *et al.*, 2022), UV-C irradiation (Haro-Maza and Guerrero-Beltrán, 2013) and gamma ray irradiation (Prakash and Ornelas-Paz, 2019).

Irradiation based technologies take advantage of plants natural defense capabilities by stimulating plant defense mechanism, including biosynthesis of secondary plant metabolites, as well as defense-related enzymes activation (Ghaouth *et al.,* 2003; Arvanitoyannis *et al.,* 2009; Chipurura and Muchuweti, 2010; Bisht *et al.,* 2021).

Furthermore, it has been demonstrated that UV-C irradiation, both in pre- and post-harvest can inhibit the growth and sprouting of vegetables (Duarte-Sierra *et al.,* 2020; Sinha and Häder, 2002; Verdes-Teodor *et al.,* 2019). The same effect has been observed in some gamma-irradiated vegetables as like potato (Blessington *et al.,* 2015; Mani and Hannachi, 2015), seeds and sprouts (Rajkowski and Latiful, 2012).

UV-C irradiation could induce photomorphogenic responses that encourage growth and development in a distinct way, reaching photoreceptors that utilize signals to activate similar gene expression, and thus, inducing phenotypic changes, such as flowering and stem branching (Darras *et al.,* 2012).

Additionally, gamma irradiation has the potential to destroy DNA, stopping plant meristematic activity (Arvanitoyannis *et al*., 2009), and therefore, they can inhibit potato sprouting (Cools *et al.,* 2014) or reduce growth rate in *Fressia hybrid* L. (Darras *et al.,* 2019).

In summary, reduction in spear tip meristematic activity will reduce respiratory and sugar consumption rates, which in turn will cause a reduction in deterioration rate (Verlinden, 2014). To our knowledge, the effects of ionizing and non-ionizing irradiations on asparagus spear shelf life has not been explored.

Microcalorimetry capacity to measure the heat product of metabolism such as changes in respiratory variables can contribute to our understanding of plants metabolic activity in response to external stimulus (Wadsó and Hansen, 2015). Microcalorimetry is an excellent nondestructive tool for detecting small metabolic changes in intact vegetable tissues. Gardea *et al.* (2023) have suggested that calorimetry is a practical tool to detect changes in tip metabolic activity related to physiological and quality changes that determine spear shelf-life.

Based on the above mentioned, our objective was to evaluate the potential to increase green spears shelf-life by using "Hurdley technologies", such as UV-C and Gamma irradiations.

2. Materials and Methods

Plant material and stored treatments

Asparagus (*Asparagus officinalis* L.) cv. Brock was harvested from a commercial asparagus orchard near Caborca, Sonora, Mexico, 30°47'22.32"N, 112°45'51.98"O. Spears were of standard quality with dimensions of 18 cm in length and 1.0-1.5 cm in diameter. Asparagus were grouped for experiments with non-ionizing and ionizing irradiation. In each, there were 6 groups of 25 spears each and packaged upright into a commercial plastic box (30 cm height x 35 cm length x 30 cm depth) including moisture pads at the bottom.

In the first experiment (experiment 1), asparagus spears were exposed to UV-C irradiation, removed from the top cover of the boxes, and placed inside a laminar hood. The UV-C irradiation was carried out using two lamps (unfiltered General Electric 15 W G15T8 lamps), 15 cm above the box. Time exposure was equivalent to 2.46 and 4.96 kJ m^2 of energy level.

During the second experiment (experiment 2), gamma radiation was applied at absorbed doses of 1 and 1.5 kGy using a Gammacell 2200 Excel irradiator (MDS Nordion, March Road, Ottawa, Notary, Canada) equipped with a ^{60}Co source of activity of 14.4 KCi, and a chamber for irradiating samples with a maximum volume of 3.7 L, located at the University of Sonora, Hermosillo, Sonora, Mexico.

After treatments exposure, spears were stored in a controlled temperature chamber kept at 2°C and 90-95% RH. In each experiment, a non-irradiated group was included as control. Every 4 days (d) tip metabolic activity (R_q), and the respiration rate of whole spear were assessed; also fresh weight loss, water potential turgor pressure and osmotic potential, sugar content (sucrose, glucose, fructose), color lightness (L*), hue angle (H°), chroma (C), and change color ($^{\Delta}E$).

Metabolic heat [R_q, ($\mu W mg^{-1}$)] of asparagus spears apical sections

Microcalorimetry ability to measure changes in metabolic heat can contribute to our understanding of plants metabolic activity in response to external stimulus. Six asparagus spears were sampled for treatment and kept protected in a cooler with moist absorbent paper and ice pack gels to prevent dehydration and transferred immediately to the lab.

Metabolic heat production [R_q, W mg^{-1} of dry weight (dw)] was determined by isothermal microcalorimetry at 25°C, according to Millan-Soto *et al.* (2019). We used a multi-cell differential scanning microcalorimeter CSC 4100 (Calorimetry Science Corporation, Pleasent Grove, Utah, USA), equipped with four sealed metal cells of 1 mL. The fourth cell was used as reference and kept empty during measurements. With the aim to prevent condensation inside the instrument, we kept a steady flow of 1.75 $mLmin^{-1}$ with N_2. The temperature in the instrument chamber was kept constant at 15°C using a circulating-cooling bath (PolyScience, Niles, Illiinois, USA). Three samples were measured simultaneously. In total, six asparagus spears tissues with an average fresh weight of 90 mg were used. To prevent sample dehydration during data acquisition, 50 µL of sterile water were added on each cell and one apical meristem was used per cell, with cut side (basal) in contact with water. After placing the samples, the instrument was allowed to stabilize for about 2500 s to achieve a steady-state metabolic heat rate, which usually happened during the last quarter of this protocol period.

$$CO_2\ (g) + 2OH\text{-}(aq) = CO_3^{2-}(aq) + H_2O\ (aq)\ \Delta H = -108.5\ kJ\ mol^{-1}$$ (Orozco *et al.,* 2022)

Samples were dried in a vacuum oven precision (model 19, Thermo Electron Corp. USA) at 65°C for 48 h. Further, the data were baseline adjusted and calculated based on dry weight.

Whole spears respiration

Carbon dioxide production was determined according to Badillo and Segura-Ponce (2020). Six asparagus spears were placed in a 1 L container (three containers by treatment). Air samples (1 mL) were taken from each headspace after incubation for 1 h and injected into a Varian 3400cx gas chromatograph equipped with a HayeSep N column (2 m x 3.17 mm inside diameter, Supelco, Inc.) coupled to a thermal conductivity detector. The parameters were: 100°C injection temperature, 170°C thermal conductivity detector, and 120°C flame ionization detector. Nitrogen was used as a carrier gas with a flow rate of 25 mL min^{-1} CO_2 production was calculated using CO_2 standards of known concentration according to the algorithm:

$$mL\ CO_2\ Kg^{-1}\ h^{-1} = (spa * Stc * hs) / (Stpa * w * t)$$

Where spa is the sample peak area, Stc is the concentration of the reference standard (CO_2: 0.05 mL L^{-1}), hs is the headspace volume (L), Stpa is the standard peak area, w is the sample weight (kg), and t is the incubation time in hours. Results were expressed in mL CO_2 kg^{-1} h^{-1}.

Sugars

Glucose, fructose, and sucrose were quantified according to Ma *et al.* (2014) with some modifications. Briefly, 10 g of tissue were mixed with 50 mL of distilled water and homogenized for 2 minutes with a T25 Ultra-Turrax homogenizer (IKA, Staufen, Germany) equipped with a dispersing tool (IKA, Staufen, Germany). The samples were filtered, and 2 mL of filtrate were placed in eppendorf vials and centrifuged at room temperature for 15 minutes at 3700 *g*. The supernatant was purified with GV filters with 0.22 µm pore size. 20 µL of sample filtrate were injected into an HPLC (Varian ProStar 210) equipped with a LC-NH_2 column (Sigma Chemical Co., St. Louis; 250 m length, 4.6 mm of internal diameter, and 5 µm of particle size) with an LC-NH_2 guard column and a refractive index detector (Varian ProStar 350). The

mobile phase used was acetonitrile:water (80:20, v/v) at a flow of 1 ml min^{-1}. Quantification was carried out with a mix of standards curves done by injecting into the HPLC equipment solutions of glucose, fructose, and sucrose with different concentrations. The r^2 for glucose, fructose, and sucrose standard curves were 0.9544 and 0.9634, and 0.9321, respectively. Individual sugars were reported as mg g fw^{-1} of sample.

Water status

A Sartorius balance was used to determine spears fresh weight loss (FWL) every four days. Five bunches per treatment were taken and their initial and final weights (at the end of the storage period) were recorded. The results were averaged and expressed in percentages of FWL.

In the middle segment of the spear, a cylinder 1.5 cm long was cut to evaluate water potential (Ψw). Three asparagus spears were used for treatment every 4 d, according to Muy-Rangel *et al.* (2004). Three spear middle segments were weighed and soaked in sucrose solutions with molalities of 0.1, 0.05, 0.015 and 0.025.

The osmotic potential (Ψs) component was calculated by the equation Ψs = -CiRT; where Ci is sucrose molality, R is the gases ideal constant (0.0083 $Kg{\cdot}MPa{\cdot}mol^{-1}\,K^{-1}$) and T is the temperature at 273 °K (Rodríguez-Burgos *et al.,* 2015). Sucrose solutions pressure potential (Ψp) is zero because the solution is not inside of a container. Pressure potential was calculated from the equation Ψw = Ψp – Ψs, taking into account that pressure potential is zero, we concluded that osmotic potential equals tissue water potential Ψw = -Ψs (Rodríguez-Burgos *et al.,* 2015). Samples were left to rest for 2.25 h (time required to reach equilibrium between samples and solution). Then removed and excess water dried on tissue paper and their weights were recorded. After that, sucrose solution, in which the tissues did not gain or lose weight, corresponds to water potential.

The Ψs was determined in the middle segment of 3 spears with a steam pressure osmometer Wescor model 5520 using the methodology developed by Jia *et al.* (2020). A sap sample obtained from the middle segment was preserved at -20°C until use. After defrosting at room temperature, 10 µL of exudate was placed on a 0.32 cm^2 filter paper disc and placed inside the chamber. The osmometer was calibrated with standards of 100, 290, and 1000 mg kg^{-1} NaCl solution and the results of molality were converted to an osmotic potential with the Van't Hoff equation, where Ψs = CiRT (Jia *et al.,* 2020). Pressure potential (Ψp) was calculated with the difference between osmotic and water potentials according to Jia *et al.* (2020).

Color

The color of spears was measured with a portable colorimeter (Minolta CR200, Konica Minolta, Japan). The L*, a*, and b* color space variables were recorded in the tip, middle and basal segments of 10 asparagus spears, every four days. Differential color parameter ($^{\Delta}E$) was calculated using the following equation: $(^{\Delta}E) = [(L^*-L^{*0})^2+ (a^*-a^{*0})^2+ (b^*-b^{*0})^2]^{1/2}$; where: L^{*0}, a^{*0}, and b^{*0} were the readings of the color space at zero-day; while L*, a*, and b* correspond with the color space variables determined at each sampling day (Kohli *et al.,* 2022). Hue angle (H°) was calculated from a* and b* color space variables using the following equation: [H°=tan-1 (b*/a*) when a*>0 and b*>0 or H°=180+ tan-1 (b*/a*) when a*<0 and b*>0)], and saturation color named chroma using the following equation: $C = (a^{*2}+b^{*2})^{1/2}$ (Kohli *et al.,* 2022).

Statistical analysis

Analysis of variance (ANOVA) was performed based on a completely randomized design, with a factorial arrangement of treatments, where two irradiation protocols, plus controls were established and evaluated on six dates (3 x 6). When main effects significant differences (p<0.05) were found, Tukey multiple range tests were carried out. All the analysis were done with the Infostat 2017e version (University of Cordoba, Cordoba, Argentina).

3. Results and Discussion

Metabolic heat of meristematic apical tissue and respiration rate of whole pears.

Statistical analysis did not find a significant interaction between storage period and UV-C dosages. UV-C irradiated spears showed a metabolic heat (*Rq*) significant reduction during storage at 2°C ($p<0.05$) (Table 1). All samples started at 40 µw mg^{-1} dw, then steadily decreased until reaching 22 µW mg^{-1} dw on day 20. It follows the same pattern as that reported by Gardea-Bejar *et al.* (2023) which found a constant decrease in metabolic heat by spears stored at 2 and 5°C. Regarding UV-C dosages, no significant differ-

Table 1 - Effect of the UV-C radiation over physiology and quality parameters in asparagus during storage at 2°C, independent of level energy

Variable	UV-C					
	Storage time (days)					
	0	4	8	12	16	20
Metabolic heat (µW mg^{-1}dw) **	40.3 e	34.2 d	29.2 c	26.5 bc	23.6 ab	22.4 a
Respiration (mL CO_2 Kg^{-1} h^{-1}) **	15.8 d	12.3 c	10.2 a	10.4 ab	9.7 a	11.1 b
Fructose (mg g^{-1} fw)*	14.24 a	10.48 a	9.95 a	8.72 a	7.94 a	7.60 a
Glucose (mg g^{-1} fw)*	16.22 b	10.95 ab	10.76 ab	8.51 a	8.16 a	7.58 a
Chroma (C)	38.6 a	37.8 a	38.2 a	38.3 a	37.5 a	38.1 a
Hue (°)	114.3 ab	115.0 b	114.7 ab	114.3 ab	113.8 ab	112.9 a
L**	47.7 abc	49.0 c	49.0 c	48.04 bc	46.59 ab	45.58 a
ΔE	0.0 a	3.2 b	3.7 b	3.6 b	4.5 b	4.3 b

*Significant interaction, ** Highly significant interaction.
Means followed by same letters within rows are not statistically significant (Tukey, p > 0.05).

ences were found between controls and UV-C treated spears, averaging of 29 µW mg^{-1} dw.

Gamma-exposed spears data did not report significant interactions, but significant main factors. As far as storage period, no differences (P>0.05) were found in the first eight days averaging ca. 39 µW mg^{-1} dw. However, starting on day 12^{th}, significant reductions (P<0.05) took place decreasing to 10.9 on day 20 (Table 2). As far as gamma irradiated treatments a significant effect was found between controls and 1 and 1.5 kGy averaging values of 34.7, 31.5 and 27.0 kGy (Table 3), respectively. Thus, implying a severe injury by gamma radiation to meristematic cells, as reported elsewhere (Dina *et al.,* 2018).

Usually, deterioration rate of harvested commodities is proportional to their respiration rate (Kader, 1992). A significant reduction, although somehow erratic, in respiration of UV-C treated spears was found along the 20 days storage, starting at 15.8 mL CO_2 Kg^{-1} h^{-1} and eventually leveling to 11.1 units (Table 1). Slightly higher respiration rate was observed in UV-C treated tomatoes with 15.8- and 19.8- mL CO_2 Kg^{-1} h^{-1} at 20°C irradiated with at 0.003 y 0.033 KJm^{-2} (Cote *et al.,* 2013). Even though asparagus apical meristem shows the highest respiratory activity (Anastasiadi *et al.,* 2022) and that is why the respiration rate of the upper segment (apical zone) is the one with the highest rates (Verlinden *et al.,* 2014). Further, the normal behavior for whole asparagus spears in postharvest is the reduction in respiration rate after harvested (Wu and Yang, 2016). In cherry (Michailidis *et al.,* 2019), and broccoli florets (Costa *et al.,* 2006), UV-C irradiation affected respiratory metabolism, resulting in a slower respiratory rate than in non-irradiated plants (Yang *et al.,* 2014).

As far as UV-C treatments, a slight but significant

Table 2 - Effect of the gamma radiation on physiology and quality parameters in asparagus during storage at 2°C, independently of energy level

Variables	Gamma					
	Storage time (days)					
	0	4	8	12	16	20
Metabolic heat (µW mg^{-1}dw) **	38.7 d	40.4 d	38.0 cd	33.0 c	27.2 b	10.9 a
Respiration (mL CO_2 Kg^{-1} h^{-1}) **	15.8 c	10.3 b	10.3 b	10.7 b	4.38 a	4.5 a
Fructose (mg g^{-1} fw)	10.52 a	8.24 a	8.16 a	-----	-----	-----
Glucose (mg g^{-1} fw)*	6.67 a	5.02 a	6.36 a	-----	-----	-----
Chroma C©	34.5 ab	33.9 a	33.2 a	35.8 b	34.6 ab	34.0 a
Hue (°)	118.2 a	118.3 a	118.9 a	115.1 a	115.6 a	114.4 a
L**	47.7 c	38.7 a	41.5 b	41.8 b	41.7 b	41.3 b
ΔE	0.0 a	15.2 e	12.8 d	9.1 b	12.2 d	11.0 c

*Significant interaction, ** Highly significant interaction.
Means followed by same letters within rows are not statistically significant (Tukey, p > 0.05).

change in response to irradiation was found with values of 11.8, 11.3 and 11.5 for controls, irradiation at 2.4 and 4.96 KJm^2, respectively (Table 3). We hypothesized that low respiration rate may be caused by reducing succinic dehydrogenase and cytochrome C oxidase activities and higher integrity of mitochondrial membrane with the consequence of lower permeability and gas exchange, as was demonstrated in UV-C irradiated peach during postharvest (Yang *et al.,* 2014).

Table 3 shows that gamma-irradiated spears went through a statistically significant reductions in respiratory activity during storage starting at 15.8 mL CO_2 Kg^{-1} h^{-1} on day 0 and ending at 4.5 on day 20^{th}. Gamma irradiation dosages induced a significant reduction ($P<0.05$) with increasing irradiation strength with values of 10.8, 8.7 and 8.4 mL CO_2 Kg^{-1} h^{-1} for the 0, 1 and 1.5 kGy treatments (Table 3). As reported in several crops, low dosages resulted in increasing responses (Lu *et al.,* 2023), while exposures above 0.5 kGy caused decreases, (Ali *et al.,* 2015). A clear impact of gamma irradiation on bamboo shoots irradiated at 0.5 kGy and stored at 2°C and 90% RH decreased respiratory rate at 60 and 5 % at the beginning and end of the experiment (Zeng *et al.,* 2015), Preuss and Britta (2003) stated that a high dose of gamma radiations affects cell cycle arrest during G2/M phase, inhibiting growth during cell division, consequently causing a drop in respiratory rate.

Sugar content in asparagus spear

Sucrose was not detected in asparagus spears, while fructose and glucose were present in both experiments.

Constant declines in fructose and glucose contents were observed along storage, although statistically significant only for glucose, starting at 16 mg g^{-1} fw and ending below 7.6 (Table 1). Such behavior has been reported by Davies *et al.* (1996) in spears of the cultivar Limbras with sugar values falling down 30% in the first three days of storage.

Reductions in sugar content is normal for asparagus during postharvest due to their constant energy needs to maintain their high respiratory activity (Sergio *et al.*, 2019).

Same pattern was found in Gamma irradiation spears (Table 2), although this experiment last only eight days of storage. Since gamma irradiation accelerates spear metabolic activity, glucose is consumed rapidly (King *et al.,* 1990), triggering senescence as a result, in addition to depletion caused by damage to tissue membranes and cell walls (Ali *et al.,* 2015).

Water status

Spears fresh weight losses (FWL) did not differ between UV-C irradiated treatments and controls. At 4th and 8th days of storage, FWL accounted for 2 and 3% respectively, on days 12th and 16th, increased to 5 and 7%, and finally at day 20 reached 13% (Fig. 1A). Wang *et al.* (2019) found results slightly lower in spears wrapped in perforated film, reporting a FWL of only 2 % after 20 days in storage at 2°C at 85% RH. Further, Wang *et al.* (2020) reported FWL within a range of 3.0-5.0% in asparagus under modified atmosphere and stored at 4°C.

Gamma irradiated spears showed significant

Table 3 - Effect of different UV-C and Gamma irradiation over physiology and quality parameters in asparagus during storage at 2°C. Values are the average of six sampling dates

Experiments	UV-C (KJ m^{-2})			Gamma (kGy)		
Variable	0 (control)	2.4	4.96	0 (control)	1.0	1.5
Metabolic heat (μW mg^{-1}dw) **	30 a	29 a	29 a	34.7 c	31.5 b	27.9 a
Respiration (mL CO2 Kg^{-1} h^{-1}) **	11.8 b	11.3 a	11.5 ab	10.8 b	8.7 a	8.4 a
Fructose (mg g^{-1} fw)	9.97 a	9.99 a	9.55 a	9.35 a	8.87 a	8.70 a
Glucose (mg g^{-1} fw)*	10.91 a	10.40 a	9.72 a	10.33 b	3.11 a	4.61 a
Chroma (C)	38.9 b	37 a	38.2 ab	35.1 b	33.9 a	34.0 a
Hue (°)	115.1 b	113.7 a	113.7 a	126.4 a	131.7 a	137.3 a
L**	47.88 a	47.92 a	47.05 a	45.8 b	40.7 a	39.8 a
ΔE	2.4 a	2.9 a	4.5 b	5.1 a	11.9 b	13.2 c

* Significant interaction, ** Highly significant interaction.
Means followed by same letters within rows are not statistically significant (Tukey, $p>0.05$).

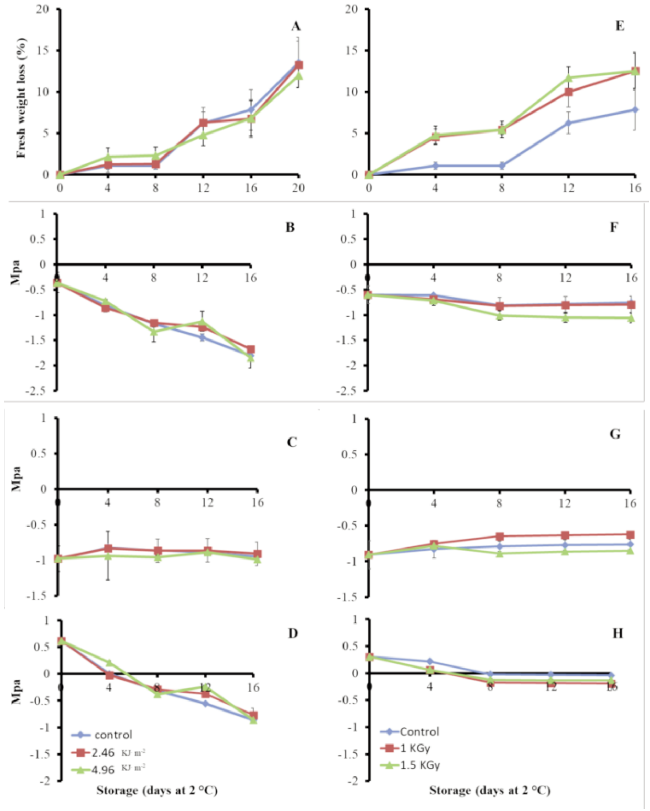

Fig. 1 - Changes in fresh weight loss (A and E), water potential (B and F), osmotic pressure (C and G) and turgor potential (D and H) in asparagus spears cv. Brock treated with UV and Gamma levels as indicated and stored at 2°C and 90% of relative humidity. A, B, C, and D graphics correspond UV-C irradiation experiment; E, F, G and H graphics correspond Gamma irradiation experiment. Differential color parameter (ΔE). Values increased during storage from 0 to 4.3 units at day 20 (Table 1). While the highest UV-C dosage caused almost a double-fold significant ($p<0.05$) increase from 2.4 to 4.5 units (Table 3).

effects on spears FWL. After 16 days of storage, FWL accounted for 12% in the irradiated samples, and only 7.5% in controls (Fig. 1E). By contrast, Lescano *et al.* (1993) found that FWL increased linearly, without significant differences between controls and irradiated samples in white asparagus with doses of 1.0, 1.5 and 2 kGy. These data support the rapid senescence of irradiated spears.

No differences among treatments in water potential for both experiments were found on each sampling day. Ψw decreased gradually, from -0.5 Mpa at 0 days down to -2 Mpa at 16 days in the UV-C experiment (Fig. 1B). Gamma-irradiated asparagus decreased at slightly slow rate down to only -1Mpa (Fig. 1F). Although no significant differences were found within each experiment, UV-C treated spears reached final values around -1.75Mpa, while Gamma irradiation caused a mean decrease between -0.5 and -1.0 Mpa. Therefore, as far as water potential, gamma irradiation caused a less aggressive response. Osmotic pressures (Ψs) remain constant in both experiments without significant changes during the 16 d storage at 2°C (Fig. 1C and G).

Spear turgor potential (Ψp) in UV-C fell below the 0 Mpa threshold at day 4 and kept decreasing down to -4 Mpa on day 16 (Fig. 1D). On the other side, gamma irradiated asparagus remained basically constant at around 0 MPa along the 16 days of storage, subsequently, it was no longer possible to evaluate the water status of the asparagus spears gamma irradiation treated after day 16th (Fig. 1H).

According to Siomos (2003), asparagus spears have between 92 and 94% water content, which reduces drastically once harvested, the loss of commercial quality occurs when the FWL exceeds 8%. Spears in the UV-C treatment reached such threshold only until day 16; although turgor pressure fell below 0 on day 8 without showing any visual dehydration. When samples were Gamma irradiated FWL did exceed 8% on day 12, showing obvious signs of dehydration, a cooked appearance, slippery epidermis, and loss of rigidity because of the effects of gamma irradiation (Jeong and Jeong, 2018).

Color parameters

Table 1 shows the results of C, H°, L* and $^{\Delta}$E in asparagus spears treated with UV-C kept at 2°C for 20 d.

Chroma (C), no significant changes were found during the 20 days storage period. However, UV-C at 2.4 KJ·m^{-2} did cause a small, but significant decrease, as compared to controls and the 4.96 KJ·m^{-2} exposure (Table 3). The C results of both experiments found in this work agree with data published by Costa *et al.* (2006), who found similar tendencies, suggesting the slight presence of a dull color.

In the variable of Hue, erratic but significant changes were observed, although after 20 days of storage showed 113 units, similar to initial values. UV-C radiation at both exposures caused a small and significant reduction from 115 to 113.7 units (Table 1). These values are slightly lower than reported by Wang *et al.* (2020) in asparagus treated with CO_2 and jept under modified atmospheres at 4°C with values of 120-122, corresponding to slightly yellow.

Significant changes were recorded in L, although somehow erratic, increasing on days 4, 8 and 12, following to a decrease to initial values. As far as the

effects by UV-C on L, no significant changes occurred (Table 1).

These slight color changes observed in green fruits and vegetables treated with UV-C are probably due to chlorophyll degradation induced by irradiation damage to the chloroplast and biosynthesis of some anthocyanins (Siomos *et al.,* 2000; Villanueva *et al.,* 2005; Li *et al.;* 2006). Indeed, in our lab, we investigated the development of yellowish color in cucumbers treated with large UV-C irradiation energy levels and observed a color change from intense green to a paler green (data not shown). However, in the UV-C irradiation experiment, the differences in color observed in this experiment probably are enough to cause a significant change as to induce consumer rejection.

Table 3 shows color-related results of Gamma-irradiated spears at two intensities. A significant, but erratic, response was observed in Chroma during storage ending with values similar to the initial 35.5 units. Gamma irradiation exposures caused a significant, although small, reduction of 1.1 units in C (Table 2).

Gamma irradiation did not cause significant changes in Hue during the 20 days storage with values averaging 114.4 units. (Table 2).

Gamma irradiation did cause a significant and overall reduction in L during storage, ending on 41.3 units as compared to the initial 47.7 (Table 2). Also, significant reductions were found when exposed to two gamma irradiations, with 40.7 and 39.8 units for 1 and 1.5 kGy, respectively (Table 3). Gamma irradiated papayas at 0.75 kGy stored at 11°C and 90 % RH showed similar behavior. Indeed, irradiated papaya (C = 40.89 and L* = 51.50) achieved a slightly more intense color, as compared with non-irradiated controls (C = 41.67 and L* = 52.50). Borzouei *et al.* (2013) determined that chlorophyll content in cv. Roshan increased after exposure to radiations at 100 kGy, which could correlate with stimulated metabolism of pigment biosynthesis, suggesting that yellow color developed slightly more quickly in controls (Pimentel and Walder, 2004).

Peak color differential ($^{\Delta}$**E)** was recorded just after 4 d in storage reaching 15.2 units, followed by significant decreases reaching 11 units at day 20 (Table 2). Exposure to gamma irradiation did cause a significant increase in this variable with controls showing 5.1 units and 11.9 and 13.2 units for exposures at 1 and 1.5 kGy irradiation causing a loss of glossy appearance (Table 3). Such change in the green chlorophyll appearance from bright to dull is associated with decrease of L and slight changes in chroma may result from deformations in thylacoyd structure and damage to chloroplasts (Wi *et al.,* 2007; Choi *et al.,* 2021).

4. Conclusions

"Hurdley technologies" do not extend postharvest shelf life in asparagus spears cv. "Brock", although the UV-C irradiation with energy levels of 2.46 $kJ.m^{-2}$ and 4.92 $kJ.m^{-2}$ did not adversely affect spear postharvest quality. The levels of UV-C radiation applied did not affect metabolic activity significantly. A slight tendency to develop a yellowish coloration was observed when irradiated with UV-C 4.96 KJm^{-2}.

Gamma irradiated spears decayed rapidly, as demonstrated by several variables. Such as a drastic decrease in metabolic heat production and respiration, as well as development of a glossy color, cooked appearance, slippery epidermis, and losses in fresh weight and turgency. At the intensities tested, Hudley technologies do not extend postharvest shelf-life of asparagus spears.

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References

AEGERTER B., CAHN M., KOIKE S., SMITH R., HARTZ T., SUSLOW T., 2011 - *Asparagus Production in California*. - Agriculture and Natural Resources, University of California, Davis, CA, USA, Pub. No. 7234, pp. 1-6.

ALI H., GHORI Z., SHEIKH S., GU A., 2015 - *Effects of gamma radiation on crop production,* pp. 27-78. - In: HAKEEM K. (eds.) *Crop production and global environmental issues*. - Springer, Cham, Switzerland, pp. 592.

ANASTASIADI M., COLLINGS E.R., SHIVEMBE A., QIAN B., TERRY L.A., 2020 - *Seasonal and temporal changes during storage affect quality attributes of green asparagus*. - Postharvest Biol. Technol., 159: 111017.

ANASTASIADI M., COLLINGS E.R., TERRY L.A., 2022 - *Investigating the role of abscisic acid and its catabolites on senescence processes in green asparagus under con-*

trolled atmosphere (CA) storage regimes. - Postharvest Biol. Technol., 188: 111892.

ANIDO F.L., COINTRY E., 2008 - *Asparagus*, pp. 87-119. - In: PROHENS J., and F. NUEZ (eds.) *Vegetables II. Handbook of plant breeding*, *vol. 2*. Springer, New York, NY, pp. 365.

ARVANITOYANNIS I.S., STRATAKOS A.C., TSAROUHAS P., 2009 - *Irradiation applications in vegetables and fruits: a review*. - Crit. Rev. Food Sci. Nutr., 49(5): 427-462.

BADILLO G.M., SEGURA-PONCE L.A., 2020 - *Classic and reaction-diffusion models used in modified atmosphere packaging (MAP) of fruit and vegetables*. - Food Eng. Rev., 12: 209-228.

BISHT B., BHATNAGAR P., GURURANI P., KUMAR V., TOMAR M.S., SINHMAR R., RATHI N., KUMAR S., 2021 - *Food irradiation: Effect of ionizing and non-ionizing radiations on preservation of fruits and vegetables - a review*. - Trends Food Sci. Technol., 114: 372-385.

BLESSINGTON T., SCHEURING D.C., NZARAMBA M.N., HALE A.L., REDDIVARI L., VESTAL T.A., MAXIM J.E., MILLER J.C., 2015 - *The use of low-dose electron-beam irradiation and storage conditions for sprout control and their effects on Xanthophylls, antioxidant capacity, and phenolics in the potato cultivar Atlantic*. - Am. J. Potato Res., 92: 609-618.

BORZOUEI A., KAFI M., SAYAHI R., RABIEI E., AMIN P.S., 2013 - *Biochemical response of two wheat cultivars (*Triticum aestivum *L.) to gamma radiation*. - Pak. J. Bot., 45(2): 473-477.

CHIPURURA B., MUCHUWETI M., 2010 - *Effect of irradiation and high pressure processing technologies on the bioactive compounds and antioxidant capacities of vegetables*. - Asian J. Clinic. Nutr., 2(4): 190-199.

CHOI H.I., HAN S.M., JO Y.D., HONG M.J., KIM S.H., KIM J.B., 2021 - *Effects of acute and chronic gamma irradiation on the cell biology and physiology of rice plants*. - Plants, 10(3): 439.

COOLS K., DEL CARMEN ALAMAR M., TERRY L.A., 2014 - *Controlling sprouting in potato tubers using ultraviolet-C irradiance.* - Postharvest Biol. Technol., 98: 106-114.

COSTA L., VICENTE A.R., CIVELLO P.M., CHAVES A.R., MARTÍNEZ G.A., 2006 - *UV-C treatment delays postharvest senescence in broccoli florets*. - Postharvest Biol. Technol., 39: 204-210.

COTE S., RODONI L., MICELI E., CONCELLÓN A., CIVELLO P.M., VICENTE A.R., 2013 - *Effect of radiation intensity on the outcome of postharvest UV-C treatments.* - Postharvest Biol. and Technol., 83: 83-89.

DARRAS A.I., DEMOPOULOS V., BALI I., TINIAKOU C., 2012 - *Photomorphogenic reactions in geranium (*Pelargonium x hortotum*) plants stimulated by brief exposures of ultraviolet-C irradiation.* - Plant Growth Regul., 68: 343-350.

DARRAS A.I., VLACHODIMITROPOULOU A., DIMITRIADIS C., 2019 - *Regulation of corm sprouting, growth and flowering of pot* Freesia hybrida *L. plants by cold and UV-C irradiation forcing*. - Sci. Hortic., 252(27): 110-112.

DAVIES K.M., SEELYE J.F., IRVING D.E., BORST W.M., HURST P.L. KING G.A., 1996 - *Sugar regulation of harvest-related genes in asparagus.* - Plant Physiol., 111(3): 877-883.

DINA Y., ELHETAWY M., REFAAT M.H., ABD M.S., SALEM T.M.S., 2018 - In vitro*, induction of salt tolerant potato (*Solanum tuberosum *l.) Plants with gamma irradiation and characterization of genetic variations through sds-page and issr-pcr analysis.* - Plant Biotechnol., 56: 167-176.

DUARTE-SIERRA A., TIZNADO-HERNÁNDEZ M.E., KUMAR JHA D., JANMEJA N., ARUL J., 2020 - Abiotic *stress at hormesis Level: An approach to maintain quality, delay decay and enhance phytochemical composition in commodities during postharvest*. - Compr. Rev. Food Sci. and Food Saf., 19(6): 3659-3682.

FAN R., YUAN F., WANG N., GAO Y., HUANG Y., 2015 - *Extraction and analysis of antioxidant compounds from the residues of* Asparagus officinalis *L*. - J. Food Sci. Technol., 52(5): 2690-2700.

GARDEA-BEJAR A.A., SÁNCHEZ-ESTRADA A., OROZCO-AVITIA J.A., TIZNADO-HERNÁNDEZ M.T., TRONCOSO-ROJAS R. MERCADO-RUIZ J.N., OJEDA-CONTRERAS A.J., FORTIZ-HERNÁNDEZ J., ROBLES-SARDÍN A.E., 2023 - *Microcalorimetry as a tool to measure shelf-life at postharvest of green asparagus*. - N. Z. J. Crop Hortic. Sci., 51(1): 1-8.

GHAOUTH A.E., WILSON C.L., CALLAHAN A.M., 2003 - *Induction of chitinase, β-1, 3-glucanase, and phenylalanine ammonia lyase in peach fruit by UV-C treatment*. - Phytopathology, 93(3): 349-355.

HARO-MAZA J.F., GUERRERO-BELTRÁN J.A., 2013 - *Efecto de la radiación UV-C en frutas y verduras*. - Temas Selectos de Ingenieria Alimentos, 7(1): 68-77.

JEONG M.A., JEONG R.D., 2018 - *Applications of ionizing radiation for the control of postharvest diseases in fresh produce: recent advances*. - Plant Pathol., 67(1): 18-29.

JIA K., ZHANG Q., XING Y., YAN J., LIU L., NIE K., 2020 - *A development-associated decrease in osmotic potential contributes to fruit ripening initiation in strawberry (*Fragaria ananassa*).* - Front. Plant Sci., 11: 1035.

JIA S., ZHANG N., JI H., ZHANG X., DONG C., YU J., SHIJIE Y., CUNKUN C., LIANG L., 2022 - *Effects of Atmospheric cold plasma treatment on the storage quality and chlorophyll metabolism of postharvest tomato.* - Foods, 11(24): 4088.

KADER A.A., 1992 - *Postharvest technology of horticultural crops.* - University of California, Agriculture and Natural Resources, Publ. No., 3311, pp. 535.

KING G.A., WOOLLARD D.C., IRVING D.E., BORST W.M., 1990 - *Physiological changes in asparagus spear apical after harvest*. - Physiol. Plantarum, 80(3): 393-400.

KOHLI D., CHAMPAWAT P.S., JAIN S.K., MUDGAL V.D., SHAHI N.C., 2022 - *Mathematical modelling for drying*

*kinetics of asparagus roots (*Asparagus racemosus *l.) and determination of energy consumption*. - Biointerface Res. Appl. Chem., 12: 3572-3589.

LESCANO G., NARVAIZ P., KAIRIYAMA E., 1993 - *Gamma irradiation of asparagus (*Asparagus officinalis*, var.* Argenteuil*)*. - *LWT-Food Sci. Echnol.,* 26(3): 411-416.

LI W., ZHANG M., HAN-QING Y., 2006 - *Study on hypobaric storage of green asparagus*. - J. Food Eng.*,* 73(3): 225-230.

LU Q., YANG D., XUE S. 2023 - *Effects of postharvest gamma irradiation on quality maintenance of Cara Cara navel orange (*Citrus sinensis *L. Osbeck) during storage*. - LWT, 115017.

MA C.M., SUN Z., CHEN C.B., ZHANG L.L., ZHU S.H., 2014 - *Simultaneous separation and determination of fructose, sorbitol, glucose and sucrose in fruits by HPLC-ELSD*. - Food Chem., 145: 784-788.

MANI F., HANNACHI C., 2015 - *Physiology of potato sprouting*. - J. New Scie. Agric. Biotechnol., 17: 591-602.

MICHAILIDIS M., KARAGIANNIS E., POLYCHRONIADOU C., TANOU G., KARAMANOL K., MOLASSIOTIS A., 2019 - *Metabolic features underlying the response of sweet cherry fruit to postharvest UV-C irradiation*. - Plant Physiol. Biochem.*,* 144: 49-57.

MILLÁN-SOTO G., GUTIERREZ-SALDAÑA A.H., ESQUEDA-VALLE M.C., GARDEA A.A., TIZNADO-HERNÁNDEZ, M.E., OROZCO-AVITIA J.A., 2019 - *Respiratory metabolism of* Agave angustifolia *Haw. clonal lines at different temperatures.* - Plant Cell Tiss. Organ. Cult., 125: 71-80.

MUY-RANGEL M.D., SILLER-CEPEDA J., DÍAZ-PÉREZ J., VALDÉZ-TORRES B., 2004 - *Effect of storage conditions and waxing on water status and postharvest quality of cucumber.* - Rev. Fitotecnia Mex., 27(2); 157-165.

OROZCO A., MILLAN-SOTO G., GUTIERREZ A., ESQUEDA M., GARDEA A., 2022 - *Selección temprana de líneas clonales de Agave angustifolia sensu lato. por calorespirometría*, pp. 131-144. - In: ESQUEDA M., A. GUTIÉRREZ, and M.L. ROBERT (eds.) *Ecología y biotecnología aplicada al manejo Sostenible de Agave en Sonora*. - Ciad, Unison, Cicy y Editorial Fontamara, pp. 229.

PEGIOU E., MUMM R., ACHARYA P., DE VOS R.C., HALL R.D., 2020 - *Green and white asparagus (*Asparagus officinalis*): A source of developmental, chemical and urinary intrigue*. - Metabolites, 10(1): 17.

PIMENTEL R.M.D.A., WALDER J.M.M., 2004 - *Gamma radiation in papaya harvested at three stages of maturation.* - Scientia Agricola, 61: 146-150.

PRAKASH A., ORNELAS-PAZ J., 2019 - *Irradiation of fruits and vegetables*, pp. 563-589. - In: YAHIA E.M. (ed.) *Postharvest technology of perishable horticultural commodities*. Woodhead Publishing, pp. 739.

PREUSS S.B., BRITTA A.B., 2003 - *A DNA-damage-induced cell cycle checkpoing in* Arabidopsis. - Genetics, 164: 323-334.

RAJKOWSKI K.T., LATIFUL, M., 2012 - *Irradiation of seeds and sprouts*, pp. 295-316. - In: XUETONG F., and C.H. SOMMERS (eds.) *Food irradiation research and technology*. Blackwell Publishing and the Institute of Food Technologists, pp 446.

RODRÍGUEZ-BURGOS A., CARRILLO-LOPEZ A., OSUNA-ENCISO T., MANUEL B.S., SAÑUDO-BARAJAS A., CONTRERAS-MARTINEZ R., ZAZUETA-MORALES J.J., VEGA-GARCÍA, M.O., DOLORES M.R., 2015 - *Growth dynamics and water potential components of three summer squash (*Cucurbita pepo *L.) Cultivars*. - Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 43(2): 420-425.

SERGIO L., GONNELLA M., RENNA M., LINSALATA V., GATTO M.A., BOARI F., DI VENERE D., 2019 - *Biochemical traits of asparagus cultivars and quality changes in two differently coloured genotypes during cold storage*. - LWT., 101: 427-434.

SINGH V., HEDAYETULLAH M., ZAMAN P., MEHER J., 2014 - *Postharvest technology of fruits and vegetables: An overview*. - J. Postharvest Technol.*,* 2(2): 124-135.

SINHA R.P., HÄDER D.P., 2002 - *UV-induced DNA damage and repair: a review*. - Photoch. Photobiol. Sci.*,* 1(4): 225-236.

SIOMOS A.S., 2003 - *Quality, handling and storage of white asparagus*, pp. 16-85. - In: DRIS R., R. NISKANEN, and S.N. JAQIN (eds.) *Crop management and postharvest handling of horticultural products*. Science Publishers, NH, USA, pp. 88.

SIOMOS A.S., SFAKIOTAKIS E.M., DOGRAS C.C., 2000 - *Modified atmosphere packaging of white asparagus spears: composition, color and textural quality responses to temperature and light*. - Sci. Hortic.*,* 84(1-2): 1-13.

VERDES-TEODOR A., VOCHITA G., CREANGA D., 2019 - *On some genotoxic effects of UV-C radiation in root meristems in* Cucurbita pepo *L*. - Rom. Reports Phys.*,* 71(707): 1-11.

VERLINDEN S., SILVA S.M., HERNER R.C., BEAUDRY R.M., 2014 - *Time-dependent changes in the longitudinal sugar and respiratory profiles of asparagus spears during storage at 0°C*. - J. Am. Soc. Hortic. Sci.*,* 139(4): 339-348.

VILLANUEVA M.J., TENORIO M.D., SAGARDOY M., REDONDO A., SACO M.D., 2005 - *Physical, chemical, histological and microbiological changes in fresh green asparagus (*Asparagus officinalis*, L.) stored in modified atmosphere packaging*. - Food Chem.*,* 91(4): 609-619.

WADSÖ L., HANSEN L.D., 2015 - *Calorespirometry of terrestrial organisms and ecosystems*. - Methods, 76: 11-19.

WANG L.X., CHOI I.L., KANG H.M., 2020 - *Effect of High CO_2 treatment and MA packaging on sensory quality and physiological-biochemical characteristics of green asparagus (*Asparagus officinalis *L.) during postharvest storage.* - Horticulturae*,* 6(4): 84.

WANG L.X., CHOI I.L., LEE J.H., KANG H.M., 2019 - *The effect of high CO_2 treatment and MA packaging on asparagus quality and shelf life during cold storage*. - J. Agricultural, Life Environ. Sci., 31(2): 41-49.

WI S.G., CHUNG B.Y., KIM J.S., KIM J.H., BAEK M.H., LEE J.W., KIM Y.S. 2007 - *Effects of gamma irradiation on*

morphological changes and biological responses in plants. - Micron., 38(6): 553-564.

WU L., YANG H., 2016 - *Combined application of carboxymethyl chitosan coating and brassinolide maintains the postharvest quality and shelf life of green asparagus*. - J. Food Process Preserv., 40(2): 154-165.

YANG Z., CAO S., SU X., JIANG Y. 2014 - *Respiratory activity and mitochondrial membrane associated with fruit senescence in postharvest peaches in response to UV-C treatment*. - Food Chem., 161: 16-21.

ZENG F., LUO Z., XIE J., FENG S. 2015 - *Gamma radiation control quality and lignification of bamboo shoots (*Phyllostachys praecox *f.* prevernalis*.) stored at low temperature*. - Postharvest Biol. Technol., 102: 17-24.