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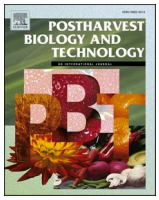

Combined effect of UV–C and passive modified atmosphere packaging to preserve the physicochemical and bioactive quality of fresh figs during storage

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ABSTRACT

Figs are an important constituent of the Mediterranean diet, widely consumed fresh. Due to their very short shelf life, postharvest techniques to preserve quality and safety should be implemented. The current work aimed to study the combined effect of a postharvest UV–C treatment (5 or 10 kJ m^{-2}) followed by packaging under passive modified atmosphere (MAP) on physicochemical and bioactive quality of fresh figs (cv. 'Colar') stored up to 12 d at 0 ºC (90–95% RH). As controls, UV–C untreated and air-stored (AIR) samples were used. The flesh firmness, skin colour, soluble solids content (SSC), titratable acidity (TA), pH, total phenolic content and total antioxidant activity were monitored. The steady-state modified atmosphere reached since day 8 was 17 kPa CO_2 and 4 kPa O_2. UV-C treated samples did not show visual decay incidence, while mycelial growth was observed in untreated figs on day 12. Figs treated with 10 kJ m^{-2} UV–C and stored under MAP conditions showed the highest flesh firmness with values of 0.6 N, which is 50% higher than in AIR. Skin darkening observed among samples was higher in 10 kJ m^{-2} with Chroma decreases of 2.6 units on day 12 under MAP, although panellists preferred this treatment according to its visual appearance. Higher SSC and TA differences were found in UVC-treated samples during storage. Moreover, 10 kJ m^{-2} UV–C and MAP induced the highest total phenolic content accumulation, with 260% and 540% higher values from day 4 to day 12 for skin and flesh, respectively. In conclusion, a 10 kJ m^{-2} UV–C treatment after harvesting followed by packaging under MAP conditions may be considered a good tool to preserve the physicochemical and bioactive quality of fresh figs during 12 d at 0 ºC.

1. Introduction

Fig trees (*Ficus carica*) are considered among the most ancient fruit cultivated around the world, being very characteristic in Mediterranean countries. Fig trees produce two types of fruit: figs, which develop on the current year's shoot growth and ripen in late summer or fall; and brebas, which develop in the spring on the previous year's shoot growth (Lisci and Pacini, 1994). Different fig cultivars (cvs) may be found with skin colours of fruit ranging from green, green-yellow, and amber-brown to dark tones. Fresh figs are highly appreciated for their sweet flavour, slight acidic nuances, and soft flesh texture, and most of the cvs are easily peeled by hand. Among the most important postharvest quality parameters of fresh figs are external colour and firmness, although other internal quality attributes like sugar/acid contents and flesh colour are crucial for consumer acceptance (Crisosto et al., 2010). In particular, characteristic violet, blue and red colours of fig skin and flesh are due to anthocyanins, being cyanidin–3–o–rutinoside the predominant one in dark–coloured cvs (Pereira et al., 2017). Furthermore, other antioxidant compounds (vitamin C, flavanols, phenolic acids, carotenoids, etc.) of figs contribute to their high antioxidant capacity and other

Abbreviations: MAP, Modified atmosphere packaging; SSC, Soluble solids content; TA, Titratable acidity; UV-C, Ultraviolet light, type C.

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health-promoting properties (Caliskan, 2015; Pereira et al., 2017).

Postharvest life of fresh figs is very short at room temperature, no more than 48 h, which may differ depending on fig cv due to different metabolic behaviour (mainly respiration rate and ethylene production), SSC/acids ratio, antioxidant compounds, etc. (Crisosto et al., 2010; Pereira et al., 2017). Cold storage at 0–1 ºC under 90–95% relative humidity (RH) has been recommended to reduce metabolic rates in fresh figs during postharvest life since most fig cvs are not chilling sensitive (Crisosto and Kader, 2007; Crisosto et al., 2011). Accordingly, the respiration rate of fresh figs at 0 ºC was reduced by ≈ 50% compared to their respiration rate at 5 ºC, while ethylene production was reduced by ≈ 60% (Colelli et al., 1991). In addition to cold storage, several postharvest treatments have been studied to extend the shelf life of fresh figs like modified atmosphere packaging (MAP), controlled atmospheres, edible coatings, calcium treatments and hot water dips, among others (Antunes et al., 2008; Colelli et al., 1991; Molinu et al., 2006; Villalobos et al., 2016).

Atmospheres with 5–10 kPa O_2 and 15–20 kPa CO_2 have been recommended to extend the shelf life of fresh figs (Crisosto and Kader, 2007). Furthermore, MAP of figs cv. 'Cuello Dama Negro' (a dark–coloured cultivar) with a microperforated film containing one hole per 50 mm stored at 0 ºC + 90–95% RH showed the best results in terms of physicochemical quality, being reached a steady state after 8 d with 12–14 kPa of O_2 and CO_2 (Villalobos et al., 2016). Controlled atmospheres containing CO_2 partial pressures of 15–20 kPa at 0–5 ºC have been also recommended to extend the shelf life of fresh dark–coloured figs cv. 'Mission' to 2 or 3 weeks, with a longer duration at 0 ºC (Colelli et al., 1991).

UV–C (250–280 nm) treatment is used to extend the shelf life of fruit and vegetables based on the high surface decontamination rates of this wavelength (Martínez-Hernández et al., 2015). UV–C is non–ionizing radiation considered a low-cost clean/green technology since it does not leave residues on the product such as other postharvest treatments like edible coatings or calcium treatments. Fresh figs cv. 'Bursa Siyahi' treated by UV–C (20 min, with a not specified dose) were still marketable at day 28 at 0–1 ºC + 90–95% RH in fruit packaged in open wooden boxes, contrary to samples treated with shorter UV–C times (Bal, 2012). Nevertheless, studies on the postharvest quality of UV-C treated fresh figs followed by storage under MAP at the recommended temperature of 0–1 ºC have not been published yet to the best of our knowledge.

This study aimed to assess the effects of a UV–C treatment after harvest combined with a passive MAP on the physicochemical and bioactive quality of fresh figs cv. 'Colar' during storage at 0–1 ºC and 90–95% RH up to 12 d. This study specially focussed on external colour, firmness, SSC, titratable acidity (TA), pH and the main total bioactive compounds content, which were analysed throughout storage. Although the microbial quality was not measured, it will be addressed in future studies.

2. Materials and methods

2.1. Plant material

Figs (*Ficus carica* bífera cv. Colar; breba) were grown in the southeast of Spain, in the experimental farm of the Universidad Miguel Hernández (Elche, Spain). They were grown under open-air fields according to integrated pest management cultural practices. Figs were hand-harvested in the first morning hours (≈ 8–9 am) and transported by car about 100 km to the Pilot Plant of the Universidad Politécnica de Cartagena (Cartagena, Spain), where they were stored and precooled at 0–1 ºC until the next day when they were processed.

2.2. UV–C treatments, modified atmosphere packaging and storage

Figs free from defects (cracking, heterogeneous colour, etc.) with similar shape and size (equatorial diameter 46.7 ± 2.3 mm; longitudinal diameter 82.6 ± 3.9 mm; ostiole diameter 4.6 ± 0.6 mm; weight 75.3 ± 3.6 g) and uniform external violet colour were selected for the experiments. Handling, selection, UV–C treatments and packaging were accomplished in a sanitized cold room at 10 ºC.

The UV-C chamber used is fully described in our previous publications (Artés-Hernández et al., 2021). Briefly, it consisted of a chamber frame with two lamp banks. Each bank contained 15 UV–C unfiltered emitting lamps at 254 nm (TUV 36 W/G36 T8, respectively; Philips, Eindhoven, The Netherlands). One bank was on the top of the chamber and the other one was placed below it. The radiation chamber also had a fan continuously switched–on during UV–C treatments to renovate the air from inside of the chamber with the air from the cold room at 10 ºC. Figs were placed between the two lines of lamps at 17.5 cm above and below over a polystyrene net that minimized blockage of the radiation. The applied UV–C intensity (37.8 W m^{-2}) was measured as the mean of 18 readings on each side of the net using a VLX 254 radiometer ($\lambda = 254$ nm; Vilber Lourmat, Marne la Vallee, France), receiving both sides the same radiation intensity. The UV–C light intensity was kept constant during treatments and the applied dose was adjusted by the exposure time at a fixed distance. Applied UV–C radiation doses (treatments) were 5 kJ m^{-2} (hereinafter treatment "**D5**"; exposure time of 60 s) and 10 kJ m^{-2} (hereinafter "**D10**"; 120 s). Non–irradiated samples were used as control (hereinafter "**D0**"). These UV–C doses were selected based on preliminary tests to avoid skin damage after the UV-C treatment.

Eight figs (approximately 450 g) were placed into a rectangular basket (170 mm × 120 mm; 50 mm depth; 1.5 L), which was then thermally sealed on the top with a bioriented polypropylene (BPP) film of 40 μm thickness (Plásticos del Segura S.L., Murcia, Spain) to generate the passive MAP treatment (hereinafter "**MAP**"). The O_2 and CO_2 permeabilities of the film were 900 and 1100 mL m^{-2} d^{-1} atm^{-1}, respectively, at 23 ºC and 0% RH (data provided by the supplier). As a control, a regular air atmosphere treatment (hereinafter "**AIR**") was prepared in the same way but practising an incision (using a scalpel) on one of the longitudinal sides of the sealed film, allowing a gas exchange from the air inside the basket but avoiding excessive dehydration of figs caused by the forced–air circulation of the cold room. In that sense, weight loss of AIR samples was below 0.3% after 12 d (data not shown). Five baskets (replicates) per UV–C treatment, storage atmosphere, and sampling time were prepared. Samples were stored in a cold room at 0–1 ºC (90–95% RH) up to 12 d (quality sampling days: 0, 4, 8 and 12). At each sampling time, the following parameters were determined: MAP gas composition, external colour, firmness, SSC, TA, pH and sensory quality. Microbial analyses were not addressed in this study, although will be considered in future studies. Samples for analyses of total bioactive compounds (total phenolic compounds -TPC- and total antioxidant capacity -TAC-) were manually peeled at each sampling time, and the flesh and skin were immediately separated before freezing in liquid nitrogen. Frozen samples were then kept stored at –80 ºC until further analysis.

2.3. Internal package atmosphere evolution

The gas partial pressures (O_2 and CO_2) inside the baskets were monitored during storage. Headspace gas samples (1 mL) were withdrawn from the baskets with a gas-tight syringe and analysed in a gas chromatograph (GC; PerkinElmer Precisely Clarus 500, Massachusetts, USA) using the GC conditions and GC column previously reported (Álvarez-Hernández et al., 2019). Three measurements were made from each basket every sampling day.

2.4. Firmness and colour

The fig firmness was measured using a texture analyser (ELIB5K S.A. E. Ibertest; Madrid, Spain) equipped with a cylinder stainless steel probe (2 mm Ø). Previously, the peel was removed from the fig areas where the puncture test was made. Fig firmness was assessed using a puncture test on two equidistant points of the equatorial zone of the fruit by

penetration of 10 mm using a test speed of 0.8 mm s^{-1}. The peak force (N) was recorded.

The external colour of the figs was determined using a colourimeter (Chroma Meter CR–400, Minolta; Tokyo, Kanto, Japan) set at illuminant D65. The colourimeter was calibrated with a white reference plate 2º observer and 8–mm viewing aperture. Measurements were obtained using the standard tristimulus CIE $L^* a^* b^*$. Colour readings were taken at three equidistant points of the frig surface (excluding the peduncle and ostiole areas), and the 3 readings were automatically averaged by the device. Eight figs were monitored for each replicate. The skin colour was determined as L^*, or calculated as Chroma (C*) and Hue angle (ºHue) according to (Pathare et al., 2013).

2.5. Physicochemical quality

The juice from figs was obtained with a domestic food blender followed by filtration with a four-layer cheesecloth. The SSC was determined with a hand−held digital refractometer (N1, Atago, Tokyo, Japan) at 20 ºC and expressed as %. A pH meter (Basic20, Crison; Alella, Cataluña, Spain) was used for the pH determination of the juice. The fig juice was diluted (5 mL juice plus 45 mL of distilled water) to measure its TA by titration with 0.1 M NaOH to pH 8.1 (model 716 DMS Titrino, Metrohm, Herisau, Switzerland) and then expressed in % (g malic acid per 100 g).

2.6. Informal sensory analysis

Informal sensory analyses were performed by five people (two women and three men aged 30–70 years), who were untrained but habitual regular consumers of figs. Visual appearance, flavour, aroma, texture and overall quality were assessed using a five-point hedonic scale of acceptability (1: extremely bad; 2: bad; 3: fair, limit of usability; 4: good; 5: very good). Figs stretch marks were also scored using an incidence and severity scale (5: none; 4: light; 3: fair, limit of usability; 2: severe; and 1: extreme).

2.7. Total phenolic content and total antioxidant capacity

The TPC and TAC were determined using the same extract, which was prepared with 50 mg of ground (using a mill; IKA, A 11 Basic, Berlin, Germany) frozen sample (either skin or flesh) + 3 mL methanol and allowed to homogenise for 1 h at 4 ºC on an ice bed in an orbital shaker (Stuart, SSM1, Stone, UK) at 200 rpm. Subsequently, extracts were centrifuged at 13,500 ×*g* for 30 min at 4 ºC and the supernatants were used as TPC/TAC extracts.

The TPC was analysed by the Folin–Ciocalteu reagent method (Singleton and Rossi, 1965), but with some modifications (Formica-Oliveira et al., 2016). Briefly, a 19 μL aliquot of the TPC/TAC extract was placed on a flat–bottom 96–well polystyrene plate (Greiner Bio-One, Frickenhausen, Germany) and 29 μL of 1 N Folin–Ciocalteu reagent (Sigma, St Louis, MO, USA) was added. The latter mixture was incubated for 3 min at room temperature in darkness. After incubation, 192 μL of a solution containing 38 mM Na_2CO_3 and 500 mM NaOH was added, and the reaction was carried out for 1 h at room temperature in darkness. Then, absorbance was measured at 750 nm using a microplate reader (Tecan Infinite M200, Männedorf, Switzerland). TPC was expressed as gallic acid equivalents (GAE) in mg kg^{-1}. Each of the five replicates was analysed in triplicate.

TAC was determined using the 2,2–diphenyl–1–picrylhydrazil (DPPH) method (Brand–Williams et al., 1995) with some modifications (Formica-Oliveira et al., 2016). Briefly, a solution of 0.7 mM DPPH (Sigma, St Louis, MO, USA) in methanol was prepared 2 h before the assay and the absorbance was adjusted to 1.10 ± 0.02 (515 nm) immediately before use. A 21-μL aliquot of the diluted TAC extract was placed on a flat–bottom 96–well polystyrene plate and 194 μL of the adjusted DPPH solution was added. Then, absorbance was measured at 515 nm after 30 min of incubation (room temperature) using the microplate reader. TAC results were expressed as ascorbic acid equivalents in mg kg^{-1}. Each of the five replicates was analysed in triplicate.

2.8. Statistical analyses

An ANOVA for each quality attribute was performed and values reported for treatment and storage period were compared to find significant differences. The Tukey's multiple range test at $p < 0.05$ was conducted using the SPSS software (v. 21, IBM, USA).

3. Results and discussion

3.1. Gas composition throughout the storage period

The gas composition of samples under MAP followed the expected behaviour, characterized by CO_2 accumulation and O_2 consumption (Fig. 1), because of the interplay between film, respiration and the external atmosphere. High CO_2 and O_2 changes were observed in the first 4 d, with O_2 and CO_2 values of 8 and 12 kPa, respectively, in the **D0** samples. O_2 partial pressures of all samples did not show ($p > 0.05$) variations (changes <3 kPa) from day 6 to day 12. The steady-state modified atmosphere, reached at 8 d, was 17 kPa CO_2 and 4 kPa O_2. The achieved steady state of our study is close to the recommended ranges (5–10 kPa O_2 and 15–20 kPa CO_2) for fresh figs (Crisosto and Kader, 2007; Gross et al., 2016).

From gas composition data of Fig. 1, it could be inferred that UV–C treatments reduced the product respiration on day 8, and that the respiration intensity of samples treated with UV-C might be higher than samples not treated on days 4, 12 and 15. The gas composition of MAP is continuously changing, being considered a dynamic system, and affects the respiration rate of samples. Hence, the respiration rate of treated samples must be specifically determined in future studies. The results of the effect of UV-C treatment on respiration are variable in the literature. For example, (Cote et al., 2013) showed that UV-C irradiation does not affect the respiration rate of tomatoes. But, (Vunnam et al., 2014) reported that UV-C-treated cherry tomatoes had the highest respiration rate. According to (Bal, 2012; Colares and de Oliveira, 2020), CO_2 peaks were retarded as the UV–C dose increased, probably owing to the reduced fig metabolism induced. The CO_2 production control with UV-C may be explained by the microbicidal activity of UV-C (Gross et al., 2016). Nevertheless, the microbial quality of figs was not determined in this study, nor in the studies of Bal (2012) and Colares & de Oliveira (2020). (Yang et al., 2014) reported that one of the reasons that UV treatment can delay senescence development is that it can reduce the respiration rate of fruits and vegetables during postharvest storage. In

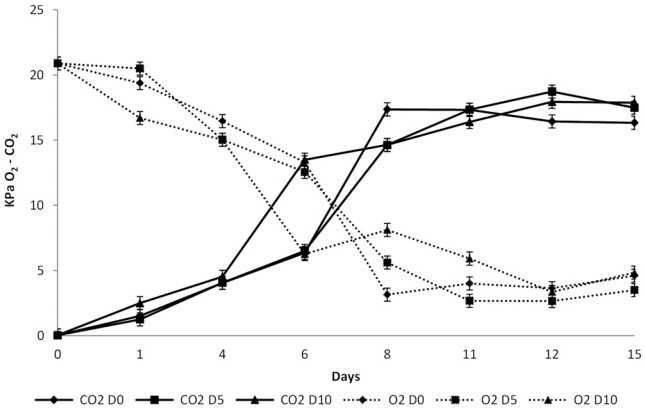

Fig. 1. Gas composition of fresh figs (cv. 'Colar') treated with different UV-C doses (D0, 0 KJ m^{-2}; D5, 5 KJ m^{-2}; D10, 10 KJ m^{-2}) under modified atmosphere packaging at 0 ºC (mean±SD).

peach fruit, treatment with UV-C (3.0 kJ m^{-2}) reduced the respiratory rate and delayed the onset of respiratory climacteric at 20 °C by reducing the activity of succinate dehydrogenase and cytochrome C oxidase as important respiratory enzymes in plant cells and maintaining mitochondrial integrity (Yang et al., 2014). Furthermore, Ahmed et al. (2013) reported that UV–C inhibited ethylene production in tomatoes, which in turn down-regulated the expression of genes encoding cell wall degrading enzymes, probably being one of the possible mechanisms of UV–C delaying tomato fruit softening.

3.2. Firmness

Fig firmness decreased throughout the storage period from 0.75 N (day 0) to 0.3–0.6 N (day 12) (Table 1). Firmness loss that occurs during fruit maturation is owed to changes in the carbohydrate contents, like pectin disintegration and other polysaccharides, leading to product softening. The most important enzymes that catabolize the solubility of these polysaccharides are pectinmethylesterase (PME, EC 3.1.1.11) and polygalacturonase (PG, EC 3.2.1.15 (Hamauzu et al., 1997). UV-C dose and atmosphere condition showed significant effects on firmness. On days 8 and 12, the AIR condition led to the highest firmness values for different UV-C doses. In addition, the **D5**- and **D10**-treated figs showed the highest firmness values for AIR and MAP conditions on days 8 and 12, respectively. This finding may be explained by a hypothetical protective effect of UV–C on the integrity of plant cells, since UV–C can decrease the transcription of a set of genes related to PME, PG, and endoglucanases, which are involved in cell wall degradation (Pombo et al., 2009). UV–C preservation of fig firmness is in accordance with texture scores of panellists (see Section 3.5). Texture, together with skin colour, is the main quality parameter that highly influences the consumer purchase decision. In addition, figs with syrup or juice output observed through the ostiole are directly related to over-ripened fruit with less texture. The most appreciated texture of figs varies depending on fruit type and consumer preferences, although most consumers prefer a firm texture for most fig cvs. Thus, it would be crucial to score the fig texture (see the results of the "Informal sensory analysis" section) due to the different texture preferences of consumers depending on the fig cultivar.

3.3. Colour

Figs showed initial luminosity (L^*), colour intensity (Chroma) index and Hue of 25.3, 5.3 and 14.711, respectively (Table 1). These values are in accordance with previous data for the same fig cultivar (Guillén et al., 2010). According to statistical analysis, storage time, atmosphere condition and UV-C does have a significant effect on L^* and Hue. But only UV-C dose has a significant effect on Chroma. The colour of dark-coloured figs is mostly determined by the concentration of pigments, mainly anthocyanins (mostly cyanidin 3–O–rutinoside) followed by carotenoids (mostly lycopene), which are synthesized during ripening and senescence processes while chlorophylls are degraded (Guilleń et al., 2015; Solomon et al., 2006). In that sense, the darkening of fig skin during storage is characterized by decreases in L^* values. Regarding atmosphere conditions, no significant ($p > 0.05$) Chroma differences were found among AIR and MAP conditions in UV-C untreated samples (**D0**) on day 12. Guillén et al. (2010) did not find remarkable Chroma differences among AIR or MAP conditions for the same fig cultivar stored for 12 d at 2 ºC. In that sense, the high CO_2 and lower O_2 achieved during MAP allowed to reduce the fig metabolism leading to lower anthocyanin, and the biosynthesis of other phenolic compounds.

Figs treated with the highest dose showed darker colour than the

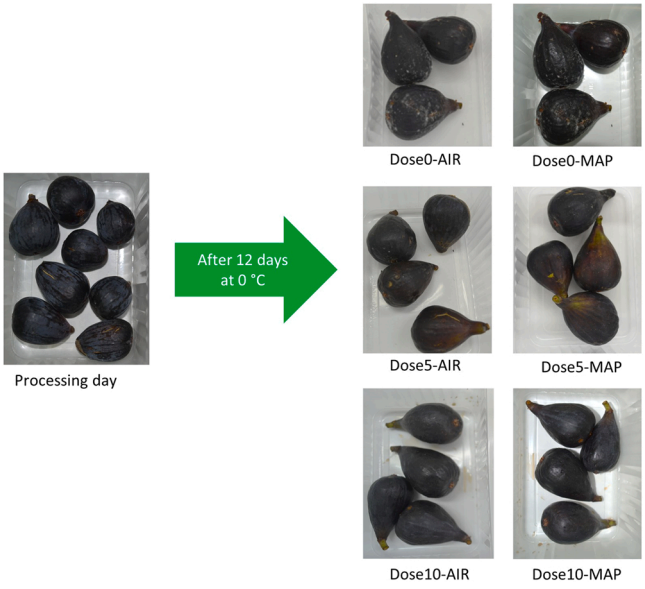

Fig. 2. Fresh figs (cv. 'Colar') on processing day and stored for 12 days under air conditions (AIR) or modified atmosphere packaging (MAP), previously treated with different UV-C doses (0, 5 or 10 kJ m^{-2}).

Table 1
Flesh firmness and colour (Chroma and L^*) of fresh figs (cv. 'Colar') treated with different UV-C doses and stored under modified atmosphere packaging for 12 d at 0 ºC (mean±SD). Statistical differences ($p < 0.05$) among values are represented with different letters.

Storage time	Atmosphere condition	UV-C dose (kJ m^{-2})	Firmness (N)	L^*	Chroma	Hue
Initial			0.75 ± 0.01^{a}	25.4 ± 0.7^{efgh}	$5.31 \pm 0,95^{cdef}$	$14,711 \pm 2374^{abcde}$
Day 4	AIR	0	0.30 ± 0.05^{g}	25.9 ± 1.1^{cdef}	6.46 ± 2.38^{abcde}	7967 ± 4464^{def}
		5	0.40 ± 0.07^{ef}	$25.7 \pm 1,7^{defg}$	5.91 ± 3.71^{abcdef}	$8052 \pm 16,886^{cdef}$
		10	0.38 ± 0.01^{efg}	26.2 ± 1.8^{bcde}	6.00 ± 2.04^{abcdef}	$12,618 \pm 10,088^{abcdef}$
	MAP	0	0.57 ± 0.03^{fg}	26.8 ± 1.9^{abc}	6.67 ± 2.66^{abcd}	$6509 \pm 12,110^{ef}$
		5	0.41 ± 0.04^{ef}	25.0 ± 1.2^{fghij}	5.37 ± 2.56^{cdef}	8439 ± 7555^{bcdef}
		10	$0.34 \pm 0,09^{fg}$	25.3 ± 1.2^{efghi}	5.25 ± 1.90^{cdef}	$9186 \pm 10,764^{bcdef}$
Day 8	AIR	0	0.42 ± 0.05^{ef}	24.6 ± 1.1^{hijk}	6.44 ± 1.14^{abcde}	7431 ± 4419^{def}
		5	0.57 ± 0.07^{bc}	24.5 ± 1.2^{hijk}	4.21 ± 1.78^{f}	5161 ± 5435^{f}
		10	0.60 ± 0.06^{b}	24.05 ± 0.7^{jk}	4.43 ± 1.75^{ef}	$5492 \pm 10,510^{f}$
	MAP	0	0.46 ± 0.06^{de}	25.2 ± 0.9^{fghi}	6.99 ± 2.04^{abc}	$15,572 \pm 7773^{abcd}$
		5	0.52 ± 0.05^{bcd}	24.2 ± 0.7^{jk}	5.53 ± 1.41^{bcdef}	$13,235 \pm 5930^{abcdef}$
		10	0.37 ± 0.06^{efg}	23.9 ± 0.6^{k}	4.72 ± 1.78^{cdef}	$5024 \pm 10,252^{f}$
Day 12	AIR	0	0.51 ± 0.07^{cd}	25.7 ± 1.1^{defg}	$6.69 \pm 11,41^{abcd}$	$9817 \pm 24,050^{abcdef}$
		5	0.37 ± 0.08^{efg}	24.9 ± 1.2^{fghij}	4.57 ± 2.64^{def}	5740 ± 6500^{f}
		10	0.59 ± 0.05^{bc}	24.9 ± 1.2^{fghij}	5.35 ± 1.39^{fcdef}	$16,869 \pm 14,365^{abc}$
	MAP	0	0.34 ± 0.08^{fg}	24.9 ± 0.9^{ghij}	7.66 ± 3.77^{a}	$10,032 \pm 12,338^{abcdef}$
		5	0.36 ± 0.04^{fg}	24.5 ± 1.1^{hijk}	7.08 ± 5.59^{abc}	$18,376 \pm 22,285^{a}$
		10	0.40 ± 0.05^{ef}	24.4 ± 1.0^{ijk}	4.35 ± 2.51^{f}	$8652 \pm 10,339^{bcdef}$

other treatments (Fig. 2), although panellists preferred this treatment according to its visual appearance (see Section 3.5). UV–C treatments had a significant effect on L^*, Hue and chroma parameters (Table 1). This fact could be explained by a higher elicitation of anthocyanins biosynthesis by UV–C radiation, as observed in other fruit (Maghoumi et al., 2013; Martínez-Hernández et al., 2020), which acts as abiotic stress as hereby found with the highest UV–C dose.

3.4. Physicochemical quality

Figs showed initial SSC, TA, and pH of 18.4%, 0.121% and 5.34, respectively (Table 2). These initial physicochemical parameters are in accordance with previously reported data for the same fig cultivar (Guillén et al., 2010). Fructose is the predominant sugar in this and other dark-coloured fig cvs, closely followed by glucose, with higher contents in the flesh than in the fig skin (Tsantili, 1990; Villalobos, 2015; Viuda-Martos et al., 2015). Attending to organic acids, malic acid is the predominant one in this and other dark-coloured fig cvs, with higher contents in the flesh compared to the fig skin (Villalobos, 2015; Viuda-Martos et al., 2015).

Time of storage had a significant effect on the acidity and pH of samples and had no significant effect on the SSC parameter (Table 2). An SSC decrease of 1.9 units (ºBrix) was observed on day 8 in **D0** samples, regardless ($p > 0.05$) of AIR or MAP conditions, followed by an increase from day 8 to day 12 of 1.5 ºBrix. A similar SSC behaviour has been registered with the same trend for AIR or MAP conditions, for the same fig cultivar stored at 2 ºC (Guillén et al., 2010). This SSC peak has been reported in other similar dark-coloured figs (cv. 'Cuello Dama Negro') mainly due to fructose (increased by ≈62/43% (skin/flesh) after 14 d at 0 ºC) and glucose (increased by ≈57/32% (skin/flesh) after 14 d at 0 ºC) (Villalobos, 2015). Guillén et al. (2010) observed that the SSC peak was delayed (day 16) in their study at 2 ºC compared to the SSC peak (12 d) of our study at 0 ºC. This sugar consumption in the first days of storage may be attributed to the acclimatization of figs to the cold storage temperature using sugars as substrates for respiration. Consequently, respiration was increased as observed from the CO_2 accumulation (commented in Section 3.1) probably as a response of plant cells to this abiotic stress (chilling temperature) as a self–regulation mechanism of this non–chilling sensitive fruit. Indeed, such acclimation response was very probably delayed in the study of Guillén et al. (2010) due to the higher storage temperature. The observed subsequent sugar peaks may be owed to the conversion of organic acids into sugars (energy sources during stress conditions), as occurred during fig maturation (Crisosto et al., 2010; Tsantili, 1990). Indeed, organic acids were reduced during storage, with 0.02–0.005 TA units lower on day 12 (Table 2), as was previously found for malic and citric acid contents (Villalobos, 2015). In general, pH values are in accordance with TA data, with increments due to organic acid reduction (Table 2).

UV–C treatments anticipated the above–commented SSC peak to day 8, with increments of 1.1–1.4 ºBrix from day 0 to day 8 for MAP samples, without differences ($p > 0.05$) between **D5** or **D10** UVC-treated samples (Table 2). A similar SSC behaviour was observed for **D0** samples. Finally, the SSC of UVC–treated samples on day 8 was reduced to values similar ($p > 0.05$) to **D0** samples on day 12. TA of UVC–treated samples also experimented with a decrease at day 8, as previously observed for **D0** samples, being increased at day 12 to levels of 0.108–0.125%. **MAP–D5** and **MAP–D10** samples showed the highest TA values on day 12, which were similar ($p > 0.05$) to day 0 values. The pH values followed an equivalent behaviour to TA (Table 2).

Sugar and organic acid contents of figs, in particular, must be studied together since this binomial is of high importance for fruit acceptance by the consumer (Crisosto et al., 2010). In that sense, different SSC or TA data measured in samples might not be perceived by consumers when consuming the product. It may be explained, in addition to the sensory threshold, by the close sensory interconnection between sugar and organic acids in fruit. Indeed, no differences were found for **MAP–D10** samples (which achieved the best flavour scores among the rest of the treatments) between day 8 and day 12 in the informal sensory analysis. The latter finding is contrary to SSC and TA measured data, since SSC peak/TA minimum values were registered ($p < 0.05$) at day 8, while SSC decreased and TA increased from day 8 to day 12.

Table 2
Soluble solids content (SSC), titratable acidity (TA) and pH of fresh figs (cv. 'Colar') treated with different UV-C doses and stored under modified atmosphere packaging for 12 d at 0 ºC (mean±SD). Statistical differences ($p < 0.05$) among values are represented with different letters.

Storage time	Atmosphere condition	UV-C dose (kJ m^{-2})	SSC (%)	TA (%)	pH
Initial			18.4 ± 0.5^{cde}	0.121 ± 0.007^{bc}	5.34 ± 0.03 ^{h}
Day 4	AIR	0	18.0 ± 0.8 ^{cd}	0.095 ± 0.004^{de}	5.78 ± 0.04^{fg}
		5	17.1 ± 1.6^{abc}	0.108 ± 0.022 ^{cd}	5.92 ± 0.24^{ef}
		10	17.9 ± 0.9^{bcd}	0.090 ± 0.024^{def}	5.65 ± 0.13 ^{g}
	MAP	0	18.0 ± 0.6 ^{cd}	0.103 ± 0.011^{cde}	5.93 ± 0.14^{ef}
		5	18.7 ± 0.4^{def}	0.110 ± 0.008^{bcd}	6.42 ± 0.12^{ab}
		10	18.4 ± 0.2^{cde}	0.107 ± 0.007 ^{cd}	5.89 ± 0.06^{ef}
Day 8	AIR	0	16.6 ± 1.6^{ab}	0.095 ± 0.011^{de}	6.14 ± 0.07 ^{cd}
		5	18.4 ± 0.4^{cde}	0.089 ± 0.006^{def}	6.40 ± 0.11ab
		10	21.2 ± 0.6 ^{g}	0.143 ± 0.018^{a}	6.27 ± 0.11^{bc}
	MAP	0	16.5 ± 0.2^{a}	0.088 ± 0.006^{def}	6.02 ± 0.10^{ef}
		5	19.6 ± 0.6^{ef}	0.099 ± 0.004^{cde}	6.53 ± 0.19^{a}
		10	19.8 ± 1.9^{fg}	0.095 ± 0.015^{de}	6.36 ± 0.05^{b}
Day 12	AIR	0	18.0 ± 0.9 ^{cd}	0.116 ± 0.007^{bcd}	5.90 ± 0,07^{ef}
		5	18.5 ± 0.3^{def}	0.108 ± 0.006^{cde}	5.87 ± 0.05^{ef}
		10	18.2 ± 1.2 ^{cd}	0.114 ± 0.022^{bcd}	5.93 ± 0.20^{ef}
	MAP	0	17.9 ± 0.9 ^{cd}	0.101 ± 0.007^{cde}	5.87 ± 0.07^{ef}
		5	17.9 ± 0.2^{bcd}	0.124 ± 0.003^{b}	5.90 ± 0.07^{ef}
		10	17.5 ± 0.1^{abcd}	0.125 ± 0.008^{b}	5.86 ± 0.04^{ef}

3.5. Informal sensory analysis

The sensory characteristics of samples were scored with an informal sensory analysis. Visual appearance (colour, dehydration, absence of skin cracking -or splitting- and other defects, etc.) and firmness of figs are the main sensory attributes that highly influence the consumer purchase decision. On day 8, the visual appearance of samples was not affected with scores ranging from 3.4 to 4 (data not shown). On day 12, **MAP–D0** samples showed the lowest visual appearance scores (below the limit of usability, i.e., 3) (data not shown), with mycelial growth observed in untreated (**D0**) samples. In addition, **MAP–D0** showed the highest visual dehydration scores on day 12, in accordance with firmness data (Section 3.3). Similarly, MAP samples with the lowest UV–C dose showed visual appearance and dehydration scores of 2.6 and 3, respectively, on day 12. Like dehydration scores and firmness data (Section 3.3), **MAP–D0** and **MAP–D5** samples showed the lowest texture scores (≈2) on day 12, followed by **AIR–D0** and **AIR–D5** samples (2.3–2.7). The higher dehydration, and consequently less firmness and visual appearance, observed in MAP samples compared to AIR

conditions could be explained by an incipient skin cracking, although not visually observed in samples during the 12 d–storage period of our study (Fig. 2). Indeed, Bal (2012) only observed cracking in figs after more than 14 d of storage at 0–1 ºC reaching incidences of 15–20% after 21–28 d. Cracking of figs has been related to pressure differences inside the fig, which can be owed to low temperatures and high RH during fruit ripening (Crisosto et al., 2011), such as that reached into the baskets used for MAP due to water vapour accumulation. Thus, incipient cracking/disruption of plant cells would lead to the observed lower texture of samples. Contrary, the highest UV–C dose minimized those negative effects, being scored these samples with minimum dehydration and better texture, which also led to better visual appearance scores on day 12. Similarly, 5 kJ m^{-2} UV–C was insufficient to reduce skin cracking of figs after 14 d at 0–1 ºC, while 10 kJ m^{-2} UV–C reduced the cracking incidence of samples (Bal, 2012). This finding may be explained by the protective effect of UV–C on the integrity of plant cells previously commented on in Section 3.2.

The flavour of samples ranged from 3 to 3.5 on day 8 (data not shown). Nevertheless, figs treated with the highest UV–C dose were scored with the highest flavour levels for MAP and AIR samples with values of 3.5 and 3.3 on day 12, while the remaining samples were below the limit of usability. Regarding aroma, no high differences were found among scores of all samples on day 12, with values ranging from 3.5 to 4, being off–odours not detected (1–1.3) for any of the samples. Nevertheless, this sensory characterization of samples must be studied in future studies following a descriptive sensory analysis.

3.6. Phenolic compounds and total antioxidant capacity

The initial TPC of skin and flesh were 1349 and 359 mg kg^{-1}, respectively (Table 3). Dark–coloured fig cvs show higher levels of TPC than brown–, green–, and yellow-green–coloured cvs, with higher levels in the skin compared to the flesh (Pereira et al., 2017). In particular, fig cv. 'Colar' showed the highest quercetin–3–O–rutinoside and high contents of cyanidin–3–O–rutinoside among 9 cvs (3 of them dark–coloured) (Pereira et al., 2017). TPC of skin and flesh decreased ($p < 0.05$) from day 0 to day 4 by 60–65 and 65–70%, respectively, followed by an increment during the rest of storage. This behaviour may be explained by the use of phenolic compounds as antioxidant compounds in response to the acclimatization of figs to chilling temperature, being considered an abiotic stress, followed by a high biosynthesis of these compounds (Cisneros-Zevallos, 2003). Similar behaviour was previously reported on other dark–coloured cvs (Villalobos, 2015).

MAP induced higher TPC increments than AIR on day 12 with increments of 130/230% (skin/flesh) and 44/53% for **MAP–D0** and **AIR–D0**, respectively, comparing values of day 4 with day 12. Hence, **MAP-D0** samples showed the highest TPC values for the skin and flesh on day 12. Such higher phenolic accumulation under MAP may be owed to the high–CO_2 ranks that probably inhibited the activity of the polyphenol oxidase (PPO; EC 1.14.18.1) enzymes responsible for polyphenol compounds oxidation leading to browning. In particular, atmospheres with CO_2 levels higher than 5 kPa inhibited PPO activity (Rocha and Morais, 2001). The highest UV–C dose, combined with MAP, induced the highest TPC increments from day 4 to day 12 with 260% and 540% (**D5/D10**) higher values ($p < 0.05$) for skin and flesh, respectively. UV–C is considered an abiotic stress able to enhance the activity of phenylalanine ammonia-lyase activity (PAL; EC 4.3.1.24), the key enzyme in the biosynthesis pathway of phenolic compounds (Formica-Oliveira et al., 2017; Zhang et al., 2021). Generated ROS after UV treatment play an important role in the biosynthesis of secondary metabolites, but there is another complementary proposed hypothesis in which UV-C could share the same photoreceptors as UV-B, since the action spectrum of UVR8 protein (main UV-B photoreceptor) and PAL induction is ranged from 250 to 310 nm, in where the UV-C region is included. Therefore, such photoreceptors could be also activated by UV-C light (Darré et al., 2022).

The initial TAC of skin and flesh were 541 and 72.4 mg kg^{-1}, respectively (Table 3). Differences < 20% were found for TAC levels of samples on day 12 compared to their respective initial levels. However, TAC increments of 460–530% were observed in the flesh of samples stored under MAP from day 0 to day 4, which may be to the biosynthesis of other antioxidant compounds different from phenolics. The phenolic enhancements observed on day 12 were not found from TAC data (Table 3), which is in agreement with previous studies that did not find correlations between TPC (determined by the Folin–Ciocalteu method) and TAC data (determined by the DPPH method) in dark–coloured fig cvs stored at 0 ºC up to 21 d (Villalobos, 2015). This fact may be explained since TAC is not correlated with anthocyanin contents (Ferreyra et al., 2007). Furthermore, degradation of other antioxidant compounds of figs (e.g. vitamin C, carotenoids, etc.) during storage could lead to the absence of increased TAC values (except at day 4) as observed for TPC on day 12. In addition, the TAC of figs may differ depending on the method used (DPPH, ABTS, FRAP, ORAC, etc.) as early reported (Villalobos, 2015), since the different antioxidant compounds present in plant products may react in different degrees depending on the used TAC method (Dudonné et al., 2009).

Table 3
Total phenolic content (TPC; mg kg^{-1}) and total antioxidant capacity (TAC; mg kg^{-1}) of fresh figs (cv. 'Colar') treated with different UV-C doses and stored under modified atmosphere packaging for 12 d at 0 ºC (mean±SD). Statistical differences ($p < 0.05$) among values are represented with different letters.

Storage time	Atmosphere condition	UV-C dose (kJ m^{-2})	TPC		TAC	
			Skin	Flesh	Skin	Flesh
Initial			1348.9 ± 160.9^{c}	358.5 ± 91.4^{d}	540.7 ± 41.3^{a}	72.4 ± 12.9^{def}
Day 4	AIR	0	540.0 ± 18.6^{hi}	126.3 ± 28.3^{fgh}	464.6 ± 25.4^{cd}	76.3 ± 10.1^{cdef}
		5	481.3 ± 40.7^{i}	108.8 ± 3.2^{gh}	518.3 ± 19.1^{abc}	83.6 ± 4.2^{cdef}
		10	536.2 ± 69.0^{hi}	104.8 ± 8.8^{h}	424.2 ± 65.1^{d}	79.0 ± 5.9^{cdef}
	MAP	0	470.7 ± 189.5^{i}	185.2 ± 50.3^{efgh}	533.0 ± 30.2^{ab}	410.8 ± 39.2^{b}
		5	700.3 ± 44.8^{gh}	110.5 ± 27.9^{gh}	522.0 ± 23.6^{ab}	457.7 ± 74.5^{a}
		10	540.5 ± 47.6^{hi}	108.4 ± 23.4^{gh}	534.2 ± 4.4^{ab}	408.2 ± 43.6^{b}
Day 8	AIR	0	809.9 ± 31.4^{efg}	556.2 ± 8.4^{c}	544.8 ± 29.5^{a}	70.2 ± 7.7^{def}
		5	753.5 ± 53.9^{fg}	583.6 ± 32.0^{bc}	530.1 ± 37.7^{ab}	82.1 ± 10.1^{cdef}
		10	883.1 ± 69.4^{efg}	541.0 ± 39.5^{c}	515.1 ± 15.5^{abc}	61.2 ± 9.1^{ef}
	MAP	0	$927.0 \pm 0,4^{def}$	587.0 ± 45.2^{bc}	522.6 ± 34.6^{ab}	107.6 ± 11.8^{c}
		5	838.4 ± 56.5^{efg}	648.3 ± 14.6^{ab}	510.2 ± 27.0^{abc}	101.1 ± 5.9^{cd}
		10	787.6 ± 55.3^{efg}	621.9 ± 14.1^{abc}	514.2 ± 14.9^{abc}	83.5 ± 6.4^{cdef}
Day 12	AIR	0	780.2 ± 69.4^{efg}	192.9 ± 35.3^{efg}	498.8 ± 32.4^{abc}	87.5 ± 2.9^{cdef}
		5	967.0 ± 64.9^{de}	199.8 ± 7.8^{ef}	426.0 ± 60.5^{d}	91.0 ± 5.6^{cdef}
		10	1568.1 ± 273.6^{b}	600.7 ± 15.7^{bc}	478.5 ± 17.2^{bcd}	95.5 ± 9.3^{cde}
	MAP	0	1082.0 ± 126.3^{d}	617.2 ± 37.7^{abc}	494.5 ± 37.9^{abc}	69.5 ± 10.5^{def}
		5	1634.0 ± 17.1^{b}	215.5 ± 14.4^{ef}	492.2 ± 25.8^{abc}	59.6 ± 3.8^{f}
		10	1922.0 ± 129.9^{a}	691.4 ± 47.5^{a}	511.1 ± 23.2^{abc}	84.5 ± 8.1^{cdef}

4. Conclusions

The combination of a UV-C treatment after harvest with MAP is firstly reported in this study as a tool to preserve the physicochemical and bioactive quality of fresh figs during storage. A UV-C dose of 10 kJ m^{-2} preserved flesh firmness, which could be linked to a protective effect of UV-C on plant cells of fig surface against cell wall degrading enzymes. Such UV-C dose induced biosynthesis of phenolic compounds of figs after 12 d at 0 ºC, which was reflected in sugar and acid changes that act as energy pools in these biosynthesis pathways. UV-C treatment avoided mycelial growth observed in untreated samples, although further microbial analyses are needed to characterize the growth of other microbial groups under different UV-C doses during storage. Hence, the combination of a UV-C treatment of 10 kJ m^{-2} with passive MAP not only kept fresh fig quality but even enhanced health-promoting attributes.

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CRediT authorship contribution statement

Manoel Souza: Investigation, Data curation. **Francisco Artés Calero**: Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Monia Jemni**: Investigation, Data curation, Formal analysis. **Francisco Artés Hernández**: Conceptualization, Methodology, Resources, Writing – review & editing, Supervision. **Ginés Benito Martínez Hernández:** Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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