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Effect of Postharvest UVB Irradiation on the Fruit of cv. Dottato (*Ficus carica* L.)

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Abstract: Exposing fruits and vegetables to UVB radiation post-harvest is a technique used to modify secondary metabolites and prolong their shelf life. The aim of the present study was to evaluate the effects of UVB irradiation on the chemical and physical characteristics of fig cv. Dottato fruits. The UVB irradiation was 2.26 Wm^{-2}. Two exposure times were carried out: 10 and 60 min resulting in a UVB dose of 1.4 and 8.1 kJm^{-2}, respectively. In the control, the UVB was eliminated by a polyester film (control −UVB). After treatment, the fig fruits were stored and analyzed at different times until decay. Quality parameters (decay, weight loss, color, chlorophyll, and firmness) and physicochemical parameters (soluble solids content, pH parameters, and titratable acidity) were positively influenced by irradiation. Total and individual sugars increased gradually during the storage period in both the skin and the flesh, with glucose being higher after 10 days in the UVB treated samples. Total carotenoid content increased gradually during the storage period, with a marked increase in the +UVB fruit. The content of total and individual polyphenols was positively influenced by UVB treatment, with the UVB treated samples showing the highest values at both 7 and 10 days. The study showed an increase in by-products in both the skin and the flesh. This research confirms the effectiveness of UVB radiation in improving the nutritional qualities and shelf life of *Ficus carica* fruits.

Keywords: UV radiation; fig fruit; postharvest; qualitative parameters; bioactive compounds

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1. Introduction

In the context of climate change, several studies reported that alterations in UVB irradiation adversely affect plant morphometric characteristics (leaves, culms, and stems) and plant production (reduced biomass), as well as physiological and biochemical responses, up to and including DNA changes [1–4]. Studies on the effects of UVB radiation were initially conducted under controlled and limited environmental conditions (significantly lower photosynthetically active radiation than that of full sunlight) and with the addition of unrealistic radiation doses, overestimating the possible harmful effects of UVB radiation on plants [1].

In recent years, UV radiation has been considered not only as an environmental stressor, but also as an ecological factor essential for the morphogenesis, acclimation, and adaptation of plant life [5–8]. UVB can be a favorable agent; in fact, radiation influences

plants to synthesize secondary products, such as polyphenols and carotenoids, which are beneficial to humans. Several experiments have been conducted both increasing solar UVB with lamps in the field and in a controlled environment and excluding solar UVB with specific filters in the field [9–17]. In addition, several studies have focused on the postharvest UVB treatment of vegetables and fruits, both to stimulate nutritional and health aspects (synthesis of vitamins, antioxidants, and mineral elements) and to improve the shelf-life of crops. Since UVB irradiation is less harmful than UVC, UVB treatment could be a practical method to maintain post-harvest fruits and vegetables in place of chemical treatments. The post-harvest UVB treatment effects are reported in different fruits and vegetables, in particular, in apples [18–20] in peaches [21,22], in grapes [23,24], in tomatoes [25–27], in lemons [28], and in broccoli [29].

The fig is a very ancient fruit, it is one of the earliest fruits cultivated in the Mediterranean region; it is widely spread in most warm and temperate climates and is an important harvest worldwide for dry and fresh consumption. *F. carica* is considered a health plant with pharmaceutical properties (antispasmodic and anti-inflammatory) and is widely used for the treatment of gastrointestinal, respiratory, and cardiovascular problems [30,31], it is also a good source of vitamins, minerals, and bioactive compounds [32] and for this reason it is considered to be related to longevity [33]. Fig fruit is a syconium, when it is ripe, it has a skin with tones ranging from green to brown or purple, sometimes with the skin cracking upon ripeness and exposing the flesh. Between the skin and the flesh, there is a white inner rind. However, the special characteristics of fig fruit (thin skin, high water content), its easy spoilage during harvest and transport, and its short storage period make the supply of the fruit to markets extremely complex. To minimize postharvest losses and improve the shelf life of fresh fig, several preservation procedures have been used such as cold storage, effective modified atmosphere, packing, edible coating, ozone, chemical treatments, and UVC radiation [34,35]. Recently, UVC rays (10 kJm^{-2}) were used on *Ficus carica* cv. Colarto to preserve the physicochemical and bioactive qualities of fresh figs, evaluating the delays in browning and softening [36]; the same UV rays were also used to evaluate their sterilizing effect [37]. In the present work, *Ficus carica* fruits were subjected to UVB to assess the increase in nutritional compounds and, at the same time, to improve the shelf-life and quality parameters of the fresh fruit.

2. Materials and Methods

2.1. Plant Materials and Ultraviolet Irradiation

Fig fruits of the cultivar Dottato at commercial maturity were harvested in September 2021 in Southern Italy (Potenza, Basilicata), and immediately carried to the laboratory and stored in a refrigerator for 1 day at 4 °C. Fruit uniform in size and appearance, undamaged, was selected for the experiments. The experiment was conducted in a climatic chamber (air temperature and relative humidity settled to 5 °C and 80%, respectively.)

The inside of the climatic chamber contained an aluminum structure with 4 Q-Panel UVB 313 fluorescent lamps (Q-Panel, Cleveland, OH, USA) on the upper part, while below there was a shelf 70 cm away from the lamps on which the fruits were placed for irradiation. During the experiment the lamps were used in 2 ways: unfiltered UVB treatment (+UVB) and filtered, with a polyester film to eliminate the UVB component as control (−UVB); in Figure 1 the spectral irradiance of unfiltered and filtered fluorescent lamps is shown. The UV irradiance from the lamps, in the spectral range of 260 to 400 nm, was assessed by a double monochromator spectroradiometer (model. SR9910-PC, Macam Photometrics Ltd., Livingstone, UK). In the +UVB treatment, the supplemental UVB in the spectral interval of 280–315 nm was 2.26 W m^{-2}, while in terms of the ultraviolet biologically effective UVB dose ($UVB_{BE\ Caldwell}$) weighted using the generalized plant action spectrum [38], it was 1.91 Wm^{-2}, respectively, 1.5 and 6/7 times larger than what is measurable from the sun in the central hours of a clear summer day in central Italy. These differences are explained by the fact that lamps also emit wavelengths absent in the sun (below 300 nm); the potential greater biological effects of these wavelengths are well

considered by the Caldwell's action spectrum, with respect to a simple irradiance integral between 280 and 315 nm. Two irradiation times were applied: unfiltered lamps as UVB treatment for 10 (+UVB10) and 60 min (+UVB60) and −UVB filtered lamps as a control for 10 (−UVB10) and 60 min (−UVB60). The UVB doses irradiated to the fruits were 1.4 and 8.4 kJm^{-2} for +UVB10 and +UVB60, respectively (Table 1).

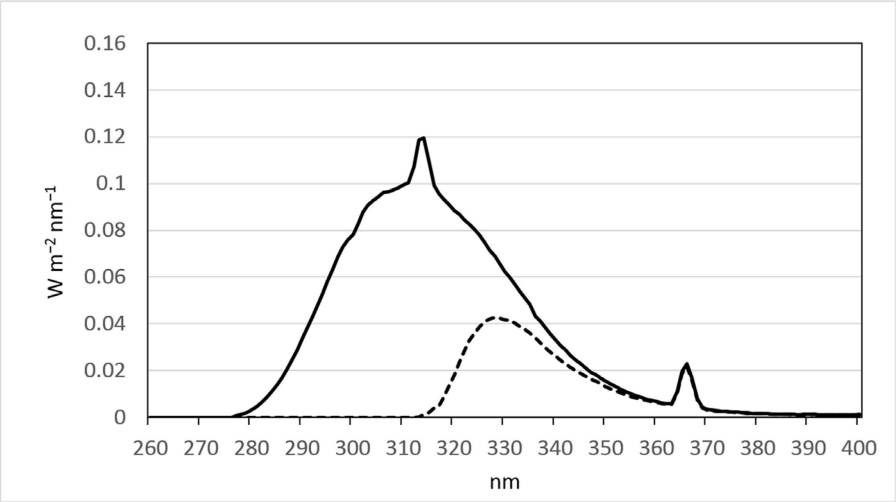

Figure 1. Spectral irradiance of Q-Panel UVB 313 fluorescent lamps, unfiltered (solid line) and filtered with polyester film (dotted line). The intensity of the lamps was the same as that used for the experiment.

Table 1. UVB (280–315 nm) and $UVB_{BE\ Caldwell}$ doses in the two irradiation treatments (in kJm^{-2}).

Treatment	UVB (280–315)	$UVB_{BE\ Caldwell}$
+UVB10	1.4	1.2
+UVB60	8.4	7.2

The supplemental dose in 1 h of $UVB_{BE\ Caldwell}$ in the +UVB60 treatment represent the radiation which could be a little higher than what could be received from the sun in July on a day with clear skies in central Italy. Before each treatment, figs of similar weight were randomly distributed on the shelf under the lamps. Each treatment was repeated on both sides of fig fruits. Eight figs per replicate were settled in a randomized complete block design with three replications per treatment. After treatment, the fig fruits were stored in the dark at 5 °C and were analyzed at different times: immediately after treatment (T0), after 7 days (T1) and 10 days (T2).

2.2. Determination of Morpho-Anatomy and Fruit Quality Parameters

The surface of the fruits was characterized by microscopic observation using a Gaia3 Tescan scanning electron microscope (SEM). The skin was cut at the equatorial zone of the fruit. The samples were covered by a silver-film (Emitech K575X, Emitech Ltd., Ashford, UK) and examined by SEM at 20 KV. The firmness of fig samples was measured on the equatorial part of the fruit, on the left and right side, using a penetrometer (Fruit Pressure Tester mod. FT 327, Effegi, Alfonsine, Italy), with a cylindrical test probe with a diameter of 8 mm, expressed in kgf. The determination of the color of the skin and the flesh of the figs was carried out before chemical analysis, using a Minolta CR-200 chronometer (Minolta, Ramsey, NJ, USA). The spoilage percentage was calculated based on the appearance and color of the fruit. A grid with 20 meshes was applied to each photo of the fruit, and the meshes where at least one point of deterioration was present were counted, determined by color ranging from yellow to dark brown. The titratable acidity (TA) was determined on

0.5 mg of fruit flesh in 25 mL of distilled water, after centrifugation at 9000 rpm for 3 min, with a Brix-acidity Meter Master Kit, Pal-BX/Acid F5, Atago, Japan. The pH was measured on the fig skin and the flesh with a Microprocessor pH Meter 211, Hanna Instruments, Italy. Weight loss was determined as a percentage using the formula: $(WTx - WT_0/WT_0) \times 100$, where WT_0 is the starting weight and WTf is the ending weight. The total soluble solids were recorded with a digital Wine Refractometer HI 9811 and expressed in % Brix.

2.3. Chemical Analysis

2.3.1. Chemicals, Standards, and Reagents

The chemicals used in the analysis, such as caffeic acid, apigenin, quercetin-3-O-rutinoside, and gallic acid standards, were of analytical grade and were obtained from Sigma Chemical Co. (St. Louis, MO, USA). The water used was Milli-Q from Millipore (Bedford, MA, USA).

2.3.2. Determination of Sugar Content

Carbohydrate concentrations were analyzed by high performance liquid chromatography according Petruccelli et al. [39]. In summary, fig fruit flesh and skin (20 mg) were extracted in bidistilled water (2 mL, pH 7, for 5 min) and centrifuged (5 min at 10,000$\times$ *g* at 4 °C); afterwards the solution was filtered and placed in vials for HPLC analysis. The analysis was carried out using the LC Flexar system (PerkinElmer, Waltham, MA, USA); sugar separation was obtained using a Shodex Sugar SC 1011 column (8 mm by 300 mm; Showa Denko GmbH, Munich, Germany). The mobile phase was water, Milli Q grade, with a flow rate of 0.5 mL/min. In the fig samples, the sugars were identified and quantified by comparing the retention times and peak area with standard carbohydrates. Analyses of soluble carbohydrates were performed in triplicate.

2.3.3. Determination of Chlorophyll, Total Carotenoids and Total Phenolic Content

The concentration of chlorophyll and carotenoids was determined with the protocol used by Faraloni et al. [40]. Briefly, fig skin and flesh samples (0.5 and 1.5 g, respectively) were extracted with 5 mL of 90% acetone for 15 min and centrifuged at 4000$\times$ *g* for 5 min. Chlorophyll and total carotenoid amounts were evaluated spectrophotometrically in 90% acetone extracts, as reported by Lichtenthaler et al. [41]. The results were expressed as mg/g FW.

The determination of the total polyphenolic content (TPC) was conducted using a Folin–Ciocalteu assay as reported by Petruccelli et al. [39]. Fig samples of the skin (0.5 g) and the flesh (1.5 g) were extracted with a 5 mL ethanol/acidified water (7/3, *v*/*v*) solution and centrifuged at 3500 rpm at 4 °C for 15 min. For the colorimetric analysis of total polyphenols, the reaction mixture was read at 730 nm, with a Varian Cary 50 UV-visible spectrophotometer scan. The results were expressed as mg of gallic acid equivalent per g of fresh weight (mg GAE/g FW). Distilled water was used as a blank and pure gallic acid was used as a standard (Sigma-Aldrich, Milan, Italy).

All of the analyses were performed in triplicate.

2.3.4. Polyphenols HPLC-DAD-MS Analysis

The determination of phenolic compounds was determined according to Petruccelli et al. [39]. The sample extraction procedure was the same as the one used to determine total polyphenols and HPLC analyses were performed using an HP-1100 liquid chromatograph equipped with a DAD detector (Agilent-Technologies, Palo Alto, CA, USA). The column was a Poroshell, 150 $\times$ 3 mm, 2.7 µm from Agilent Technologies. The HPLC system was also interfaced with an MSD API Electrospray mass spectrometer (Agilent Technologies, Palo Alto, CA, USA) operating in negative and positive ionization mode. Identification of phenolic compounds was carried out by comparing their UV-vis and mass spectra with literature data and retention times relative to available external standards. Individual polyphenolic compounds were quantified directly by HPLC-DAD using a five-point regres-

sion curve ($r^2 \geq 0.998$) based on authentic standards. The calibration was performed at the wavelength of maximum UV-vis absorbance. More specifically, quercetin derivatives were measured at 350 nm, hydroxycinnamic derivatives at 330 nm, and flavones at 330 nm using quercetin-3-O-rutinoside, caffeic acid, and apigenin as standard compounds. Each analysis was performed in triplicate.

2.3.5. Statistical Analysis

The data are reported as the mean and standard deviation (SD) calculated from three replicates. Significant differences between +UVB treated and −UVB control fruit at each sample time were assessed by a one-way analysis of variance (ANOVA) followed by a Tukey post hoc test at a 95% confidence level. Statistical analysis was carried out using Statgraphics Centurion XV (Manugistics Inc., Rockville, MD, USA). The same data were also submitted to a principal component analysis (PCA) in order to evaluate the difference between UVB treatments over time and identify the most significant variables in the dataset. The analysis was performed using XLSTAT v.2023 software (Addinsoft™1995–2009).

3. Results and Discussion

3.1. Morpho-Anatomy and Fruit Quality Parameters

The analyses of whole fruit quality parameters (weight loss, firmness, and decay evaluation) are shown in Figure 2. After irradiation no macroscopic damage was observed in the fruits; suggesting that UVB treatments did not negatively affect the fig fruits. After the treatments (T0), the analysis of the average fruit weight showed no statistically significant differences between control (42.6 g) and UVB treated fruits (41.5 g). During storage after all treatments, as expected, there was a decline in the weight of the fruits (expressed as loss of weight percentage), however, the UVB treatments affected the weight of the figs. The weight loss of the fruits, after being in storage for 7 days (T1) and 10 days (T2) for 10′ exposure (+UVB10) was 30.5% and 42.1%, respectively, that is 4.7 and 5.1 percentage points (pp) less compared to the control (−UVB10), respectively. For 60 min exposure (+UVB60), the weight loss was 33.2% at T1 and 41.4% at T2, so 3.5 and 3.2 pp less than the control (−UVB60, Figure 2), respectively. The analyses of fruit firmness, carried out on the whole fruit, showed a different performance in +UVB treated figs, in comparison to the control fruits (Figure 2). During storage, fruit firmness decreased in all samples and reached a minimum level on the 10th day. The firmness values were higher in +UVB treated fruits as reported in Figure 2, +UVB60 recorded 0.15 and 0.12 kgf more than the control after 7 and 10 days in storage, respectively, while +UVB10 showed 0.09 and 00.4 kgf more than −UVB10 at T1 and T2, respectively. The positive effects of radiation on firmness are in agreement with the results obtained with weight loss. In addition, Figure 2 shows the chroma (C*), lightness (L*), and hue angle (H°) parameters and total chlorophyll content. Initially, all samples were green in color; later, during storage, the skin of the fig fruits changed color, varying from green to brown. This trend, as shown in Figure 2, was more evident in −UVB fruits, where the brown color covered almost the entire surface of the fruit at time T2. During the storage period (T1 and T2), the C*, L*, and H° values decreased in all of the fruits. However, significantly higher H° values were in the UVB treated fruit. At T1 H° was 111.3° and 112.2°, respectively, in +UVB10 and +UVB60, and at T2, it was 102.7° and 107.6°, respectively. This may result in a greener tone of the skin. In green fruits, color is prevalently determined by chlorophyll a and b pigments. At T0 no statistically significant difference was observed in the total chlorophyll content, which was about 20 mg/mg (Figure 2); although, during storage, the content decreased and at T2, the −UVB samples showed a chlorophyll loss of about 39 percent while the UVB treated samples showed a loss of about 29 percent compared to the initial condition. Figure 2 shows the percentage of fruit decay assessed by visual and microscopic analysis. Areas of fig fruit decay, evidenced by color change and/or the presence of fungi and bacteria, increased with the storage period and were visible in all samples, with the highest values at the end of the experiment (Figure 2). The average decay value of the −UVB fruits was 58.5% at

day 7, then increased to 76.8% at day 10, while the +UVB fruits showed average values of 39.5% and 64.1% after 7 and 10 days of storage, respectively. UVB irradiation appears to reduce the incidence of decay, and this trend was markedly significant in +UVB60, which performed the best in both the T1 and T2 storage periods. After 7 days, +UVB60 showed only 27% decay, at T2, only 61.2% (Figure 2).

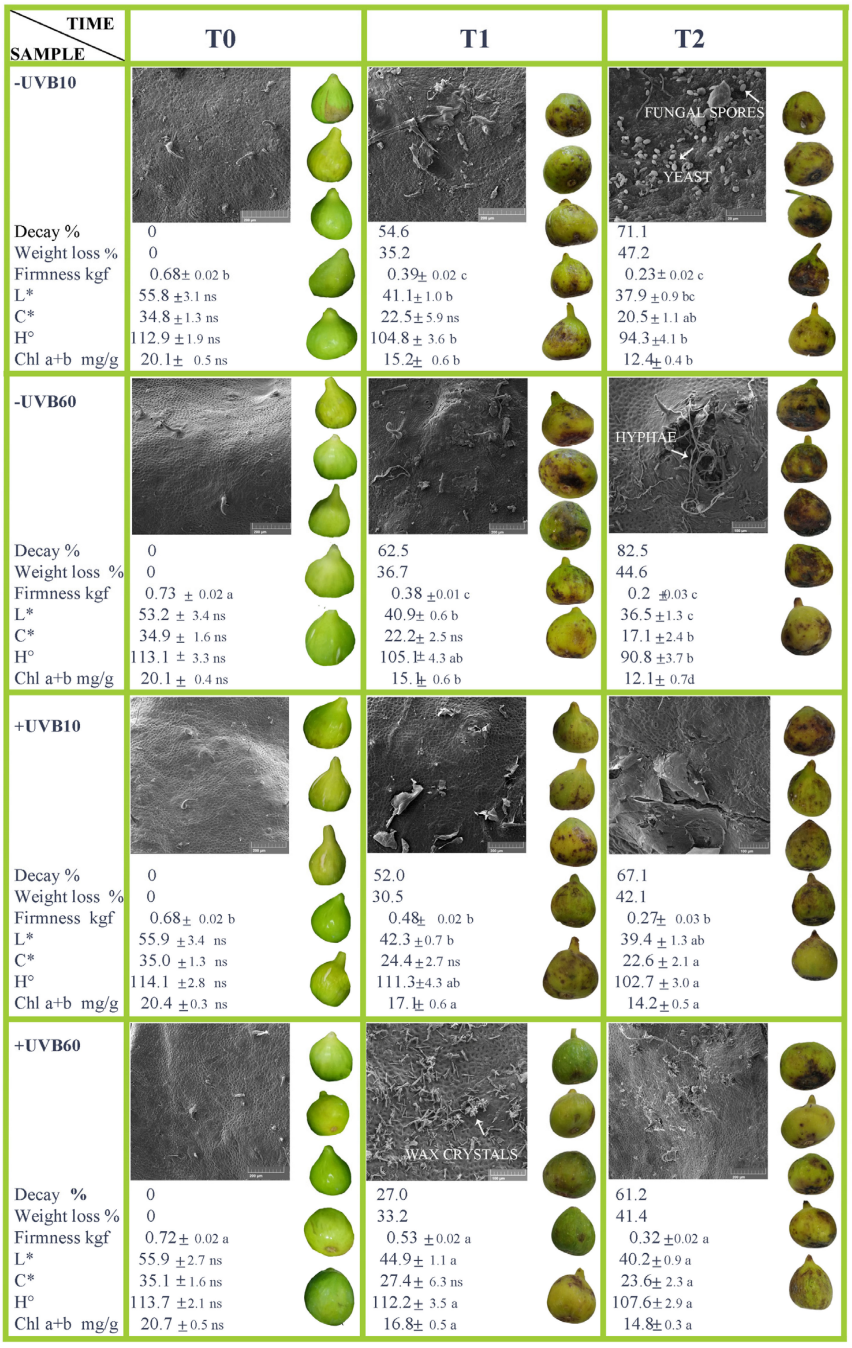

Figure 2. Effect of UVB treatments (+UVB10 and +UVB60) on Dottato fig fruits and relative controls (−UVB10 and −UVB60) at T0 (immediately after the treatment), T1 (after 7 days) and T2 (after 10 days) of storage. Decay (%); Weight loss (%); Firmness (kgf). L*, C*, and H° represent color parameters: L* is lightness, C* is chroma, and H° is the hue angle; Chl a+b total chlorophyll (mg/g). Photomicrography of fig cuticular surface. Photos of the development of 5 figs during storage. Data are means (n = 5) ± SD. Different letters indicate significant differences ($p < 0.05$) using Tukey's test, ns = not significant.

SEM image of the epidermis of the figs revealed that at T0 there were no changes in cuticle morphology between the controls and UVB treated samples, but during the storage periods, the figs developed several changes in the fruit surface layer. After 7 days (T1), the control (−UVB10 and −UVB60) and +UVB10 fruits showed a skin with an irregular surface, sometimes with cracks and wax platelets with irregular-wavy edges, while +UVB60 showed a surface sprinkled with more or less extensive, flat or granular wax plates, and some areas were covered with wax crystals (Figure 2). At time T2, on the surface of the control fruits, the presence of microorganisms, such as bacteria, yeasts, spores, and fungal hyphae, was also observed. In UVB treated fruits, fungal hyphae are also evident, although in smaller amounts than in the controls, and cracks and wax plaques are intensified. Crystals waxes are still present in +UVB60.

Ficus carica fruits are characterized by a short post-harvest period and marketing window. It is known that during the ripening and storage period, fruit quality parameters can decline rapidly; fig fruits are particularly susceptible to weight loss, softening, skin cracking and color change [42]. Green-skinned figs change color from green to yellow to brown; these changes are determined by the degradation of pigments, particularly chlorophylls a and b [43,44]. An interesting result of this work is that the UV treatment effectively preserved the quality of the fruit by decreasing weight and texture loss. UV treatments act as natural inhibitors of water loss leading to the closure of the stomata in the fruit skin, changes in surface wax deposition, and/or the slowing down of the respiration and transpiration processes [45–47]. Cuticular wax, a hydrophobic layer that provides a protective barrier to the plant, plays a significant role in maintaining fruit quality. It protects organs from non-stomatal water loss, maintains tissue turgidity, regulates temperature fluctuations, and prevents the invasion of pathogenic microorganisms [42,43]. Our results showed the presence of wax crystals and extensive plaques in UVB treated fruits. It has already been reported that epicuticular waxes change structure in response to stress or UVB. The reorganization of the waxes into horizontal plaques allows the surface to acquire greater reflectance than smooth surfaces [44]. The reorganization of waxes into crystals has been observed in papayas and apples [45,46] in response to thermal stress to fill the cracks in the cuticle and prevent water loss and pathogen entry. Weight loss and changes in the cuticular layer are related to changes in firmness; the loss of firmness in a fruit is the result of changes in membranes, cell walls, subcellular organelles, and the degradation of various metabolites [47]. It has been suggested that the maintaining of firmness by fruits treated with ultraviolet light could be associated with the activation of the activity of certain enzymes involved in fruit softening and the reduction of the activity of enzymes that degrade the cell wall. Our results agree with those of previous authors who have observed positive effects of UVB treatment at different doses and times, in different species, such as lime [48,49], broccoli [29], peach [50], apple [20], cherry [51], and strawberry [52].

Soluble solid content (SSC) and pH, determined on both skin and flesh, are shown in Figure 3A,B. The skin of all samples registered an increase of SSC during the storage period (T1, T2). The average value of SSC at T0 was about 20% °Brix; (Figure 3A). At T1, a higher value in SSC was observed in −UVB10 (22.6%), while +UVB60 recorded the lowest value (21.3%). At T2 the trend became more pronounced, the −UVB figs recorded a greater accumulation of SSC (about 23%) than the UVB treated fruits (Figure 3A). In flesh, no statistically significant difference was observed in SSC values at T0. Whereas at T1 and T2, the maximum value was recorded in −UVB10 and the minimum in +UVB60 (Figure 3B). The pH measured in the skin and flesh showed a slight increase in values from the T0 to T2 periods (Figure 3C,D). In particular, the skin at T1 and T2 in +UVB10 and +UVB60 registered a pH slightly lower than the control: in +UVB10 it was lower than in −UVB10 by 0.07 at T1 and 0.21 at T2, while in +UVB60 it was 0.13 and 0.15 lower than in −UVB60 at T1 and T2, respectively (Figure 3C). In the flesh at T0 and T1, no statistically significant difference were recorded among the samples.

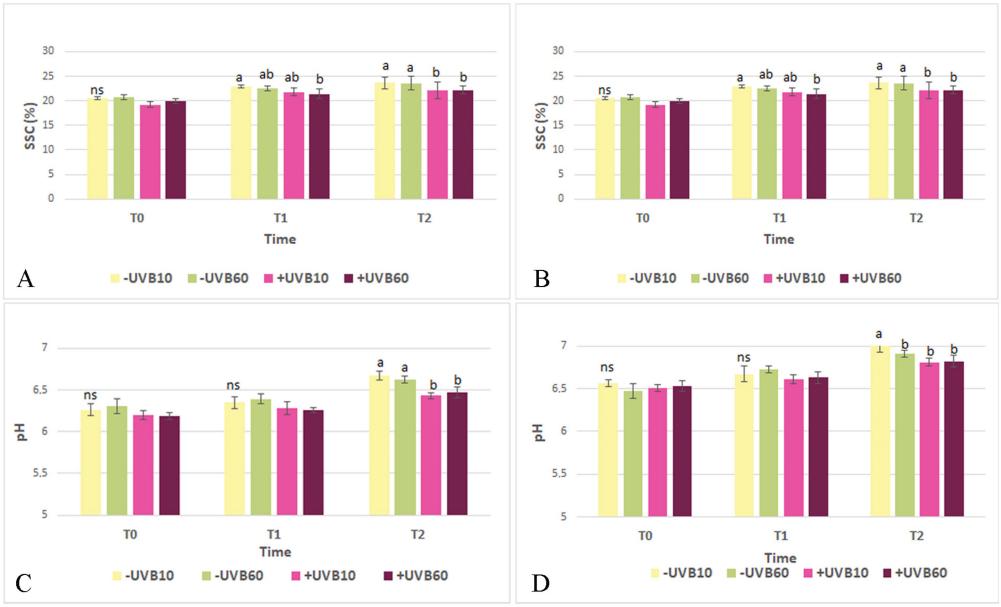

Figure 3. +UVB10 and +UVB60 treatment for solid soluble content in skin (**A**) and flesh (**B**); pH in skin (**C**) and pH flesh (**D**) on fig fruits cv. Dottato and relative controls (−UVB10 and −UVB60). T0 (immediately after the treatment), T1 (after 7 days) and T2 (after 10 days) of storage. Data are means (n = 3) ± SD. Different letters above each column indicate significant differences among the treatments (Tukey's test $p < 0.05$), ns = not significant.

However, at T1 there was a slight increase in pH in all samples, with higher values in the −UVB fruit (6.67 in −UVB10 and 6.72 in −UVB60) compared to the +UVB10 (6.61) and +UVB60 (6.63). The same trend was observed at T2, where −UVB10 showed the higher pH with 7.02 and −UVB60 6.91, while +UVB10 and +UVB60 registered a pH of 6.81 and 6.82, respectively (Figure 3D). Generally, pH increased in all skin and flesh samples during the storage period, but in UVB treated samples, the process was slower. In addition, the process was attenuated in the flesh, probably due to poor UV penetration through the pericarp layers, as reported by Santin [53]. The titratable acidity (TA), measured in percentage, decreased during the storage period in both UVB treated and control fruits, the phenomenon was more evident in the latter, where acidity decreased more markedly (Figure 4).

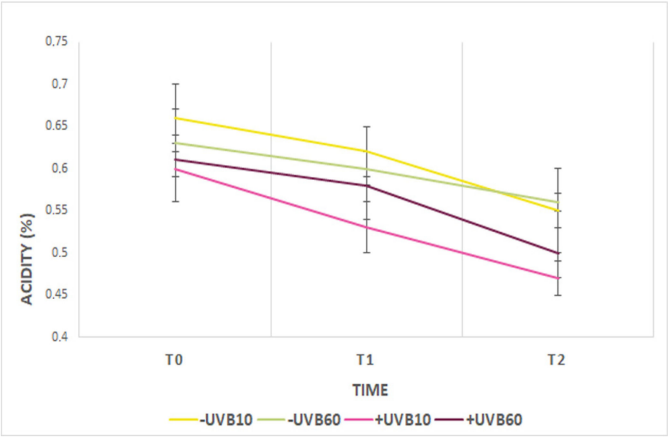

Figure 4. The percentage of titratable acidity (TA), in control (−UVB) and treated (+UVB) fig fruit at different times (T0, T1, T2).

Physicochemical parameters (SSC, pH, and TA) are the primary determinants related to sensory peculiarities (flavor sensory profiles, color, and taste) and the ripening and maturity of fig fruit [54]. During ripening and post-harvest storage, fig is subjected to various biochemical and physiological changes in physicochemical parameters that result in rapid deterioration and a reduced shelf-life. In particular, there is an increase in the content of soluble solids, as a consequence of the degradation of starch and pectin substances, and a decrease in TA due to the reduced metabolism during ripening and respiration. In this study, the quality parameters confirmed the observed trend during the ripening and storage of fig fruits. However, a less pronounced increase was observed in UVB treated fruits. Our results are in accordance with those in Abdipou, Hu, 2020. The color parameters measured on fig fruit flesh are summarized in Figures S1–S3. At postharvest time, lightness and chroma decreased gradually following a natural trend, as observed in the skin, while hue angle increased slightly showing, however, statistically insignificant differences. Regarding lightness, at T1 +UVB60 recorded the highest value (69.59), while at T2 both treatments showed the highest values compared to the controls. Chroma showed no differences in the values of the samples at T1, while after 10 days of storage, the treated samples recorded slightly higher values than the control. UVB treatments appear to have a limited effect on L* but have almost no effect on C* and H°.

3.2. Chemical Analysis

To characterize the effects of UVB treatment on fig fruits, changes in sugars and secondary metabolites (carotenoides and polyphenols) in both flesh and skin tissue exposed to 1.4 and 8.4 kJ m^{-2} UVB (+UVB10 and +UVB60, respectively) were evaluated.

3.2.1. Sugar Content

Fig fruits are considered 'monosaccharide accumulating fruits'; glucose and fructose are the main soluble sugars in the flesh and the skin, whereas sucrose is present in much lower concentrations or absent [55–57]. The levels of glucose and fructose sugars in the flesh and the skin are shown in Figure 5. Sucrose, which was determined to be only present in trace amounts or absent, was not quantified in this study. The results showed that the content of total and individual sugars increased gradually during the storage period in both the skin and the flesh of all samples (Figure 5A,B). In the skin, at T0, the average total sugar content in the UVB treated fruits was 608.91 mg/g, while in the control fruits it was 599.66 mg/g, of which about 53% was glucose and 47% was fructose for all samples. No statistically significant difference was observed between the −UVB and +UVB (Figure 5A). After 7 days of storage, statistically significant differences were observed in the total sugar content: UVB treated fruit showed an increase of about 46 mg/g, in particular, the increase was attributable to glucose which ranged from 357.22 mg/g in +UVB60 to 326.7 mg/g in −UVB10. At T2, both glucose and fructose increased moderately (Figure 5A). +UVB had an average glucose value of 367.5, while the control figs had an average of 340.5 mg/g. The fructose registered an average of 329.2 mg/g in the UVB irradiated skin, and 307.4 mg/g in the −UVB skin. The same trend was observed in the soluble sugars of the flesh. No statistically significant difference was found at T0 (Figure 5B). At T1, the sugar content increased in the UVB treated samples and continued to grow even at time T2. After 10 days of storage, the total sugar content ranged from 758 mg/g in +UVB60 to 693.6 mg/g in −UVB60 (Figure 5B). In our results, differences were observed between UVB treated and control samples, whereas the duration of treatment (10 and 60 min) did not affect the total and individual soluble sugar content (Figure 5B).

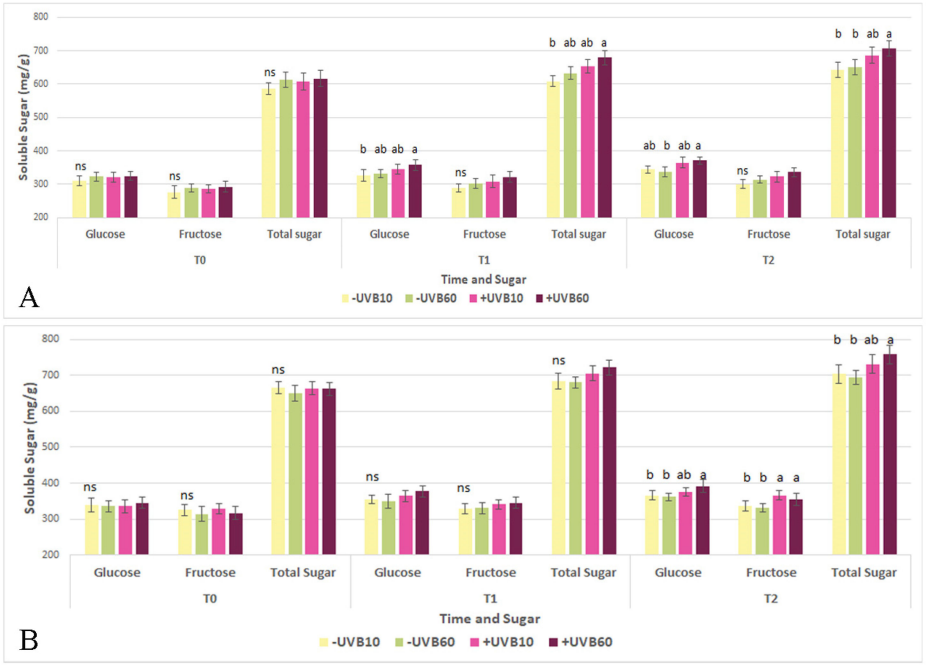

Figure 5. Change in glucose, fructose, and total sugar content in the skin (**A**) and the flesh (**B**) of cv. Dottato, 10′ (+UVB10) and 60′ (+UVB60) UVB treatments and relative controls (−UVB10 and −UVB60) at T0 (immediately after the treatment), T1 (after 7 days), and T2 (after 10 days) of storage. Data are means (n = 3) ± SD. The different letters above each column indicate significant differences among the treatments (Tukey's test $p < 0.05$), ns = not significant.

In several fruits, the composition and proportion of sugars determines the quality of taste, the sweetness, and the flavor. Furthermore, they influence the quality of processed products and play an important role in the synthesis of aromatic substances and secondary metabolites [58,59]. UV treatments have been associated with an increase in soluble sugars, as observed in UVC-treated apples (9.0 kJm^{-2}, [60]), UVB treated peaches (1.44 kJm^{-2}, [61]), UVB treated lemons (22 kJm^{-2}, [28]), and UVA-, UVB-, and UVC-treated sweet oranges (100 $\mu mol\ m^{-2}\ s^{-1}$, [62]. Therefore, the modulation of the sugar concentration during fruit storage can prevent post-harvest losses and maintain sensory characteristics. Some authors have suggested physiological mechanisms of UV action on the increase of carbohydrate binding to enzymatic factors such as sucrose-hydrolyzing and synthesizing enzymes: invertase, sucrose synthase, and sucrose phosphate synthase [28]. Our findings agree with the abovementioned studies. In *Ficus carica* fruit, it was observed that different postharvest treatments influence the accumulation of sugar content in the first 15 days of storage without negatively influencing important fig quality parameters [63,64].

3.2.2. Total Carotenoids and Polyphenolic Content

Polyphenols and carotenoids are "bioctive non-nutrient "compounds produced in plants and are responsible for several physiological functions such as the color of fruit and/or the plant defense system [65,66]. Furthermore, they contribute to fruit quality and are used to assess shelf life. But the importance of secondary metabolites is linked to their potential beneficial effects for the consumer; in fact, an abundance of literature confirms that they are the most promising source of beneficial health substances, well known for their antioxidant potential [67,68]. *F. carica* fruits contain beneficial natural antioxidant substances [69,70] that promote beneficial health activities (antifungal, antibacterial, anthelmintic, anticarcinogenic) [71]. The concentration of total carotenoids and polyphenols in fig fruits (skin and flesh) in UVB and −UVB treatments is shown in Figure 6. Our results showed that the accumulation of carotenoids and polyphenols is greater in the skin than in the flesh of the fruit. Regarding the content of total carotenoids, our results showed

a gradual increase during the storage period in all samples. In the skin, the content of total carotenoids increased at T1 by 35.4% for +UVB10 and 20.4% for +UVB60 compared to the control (Figure 6A). At the end of the storage period (T2), total carotenoids showed a marked increase in all UVB treated samples, with values ranging from 7.74 mg/g in +UVB10 to 5.52 mg/g in −UVB10. Comparing exposure times, our results showed that fruits irradiated for 10 min showed no statistically significant difference ($p < 0.05$) with those irradiated with UVB for 60 min (Figure 6A).

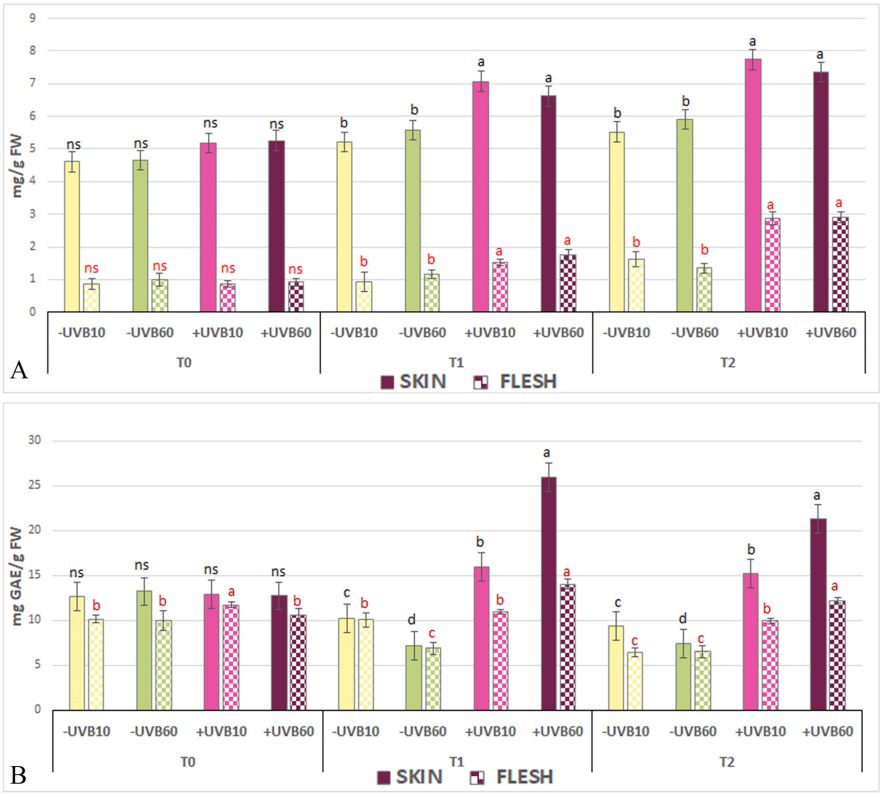

Figure 6. Total carotenoids (**A**) and polyphenols (**B**) in cv. Dottato, skin (full-color columns) and flesh (color columns with pattern) for UVB treatments (+UVB10; +UVB60) and relative controls (−UVB10 and −UVB60) at T0 (immediately after the treatment), T1 (after 7 days), and T2 (after 10 days) of storage. Data are means (n = 3) ± SD. The different letters above each column indicate significant differences among the treatments (Tukey's test $p < 0.05$), ns = not significant.

The same trend was observed in the flesh, with a gradual increase during the storage period. The highest values were observed at T2, where the UVB treated fruit had an average of 2.89 mg/g, while in the control fruit, the carotenoid content was 1.48 mg/g. No statistically significant difference was observed between the two UVB irradiation times (Figure 6A).

Regarding polyphenols, analyses were conducted of the skin and flesh and are shown in Figure 6B. At T1, an increase in polyphenols was observed in the skin of the UVB treated fruit, i.e., +UVB10 recorded a value of 15.89 mg/g and +UVB60 of 25.91 mg/g, compared to T0 where they measured 12.87 and 12.71 mg/g, respectively. At the end of the storage period (T2), total polyphenols showed a slight decrease in all samples. However, their decrease was slower in the UVB treated fruit. +UVB10 showed a difference of 5.82 mg/g compared to −UVB10, while +UVB60 showed a difference of 14.84 mg/g compared to −UVB60 (at T2). Furthermore, our results showed statistically significant differences at both T1 and T2 comparing the irradiation times (+UVB10 and +UVB60); the highest results were observed in +UVB60 with values of 25.91 at T1 and 21.26 at T2 (Figure 6B). The flesh presented similar results to the skin, with an increase in total polyphenols in the UVB

treated samples in the first 7 days of storage (T1) and a decrease in the control ones. At T1, the values ranged from 6.89 mg/g in −UVB60 to 14.02 mg/g in +UVB60. At T2, all samples showed a decrease in total polyphenol content, however, the UVB treated fruits showed the highest values with 9.91 mg/g in +UVB10 and 12.18 mg/g in +UVB60. Comparing irradiation times (10 and 60 min), our results showed no negative effects on polyphenol content and +UVB60 showed higher total polyphenol contents than +UVB10 at both T1 and T2.

3.2.3. Individual Polyphenolic Content

The phenolic content of fig fruit (cv. Dottato) detected by HPLC analysis is shown in Figure 7. The main compounds detected in the skin and the flesh were 4 flavonoids (isoschaftoside; schaftoside, quercetin-3-O-rutinoside also known as rutin, and quercetin-3-O-malonyl glucoside) and 2 phenolic acids (5-O-caffeoylquinic acid and caffeoylmalic acid), confirming previous work that identified them as the main classes of phenolic compounds detected in different tissues [72]. All phenols traced in the skin and flesh showed a similar general trend over time: an increase after 7 days of storage, and a decrease at T2 except for +UV60. In the skin, at T0, statistically significant differences were observed in caffeoylmalic acid, quercitin-3-O-malonyl glucoside, and schaftoside, where the two treatments (+UV10 and +UV60) had higher values than the controls (Figure 7A,D,E). At T1 in the two phenolic acids and rutin, the UVB treated samples showed higher values than the control. At time T2, all UVB-treated compounds recorded higher values than the controls. In particular, in +UV60, caffeoylmalic acid (9.09 mg/L), rutin (168.65 mg/L), and quercetin-3-O-rutinoside (18.98 mg/L) showed the highest values (Figure 7A,C,D). In the flesh, the concentration of all flavonoids was about 40% lower than in the skin. Our results showed that the main phenolic compounds (caffeoylmalic acid, rutin, and quercetin-3-O-malonyl) had statistically significant differences between UVB treated and control samples at both T1 and T2 (Figure 7A,C,D). The higher concentration of single polyphenols detected in the irradiated samples was in agreement with the increase in total polyphenols observed at T2 in the skin.

Our results agree with previous studies reporting that postharvest irradiation with UV radiation of different spectra (UVA; UVB and UVC) increases the amount of total and single carotenoids and polyphenols. UVB has been used in fruits and green leafy vegetables: Castagna et al. [26,73] using UVB (1.69 Wm^{-2}) observed an increase in carotenoids in tomato skin and flesh; Assumpção et al. [74] treating persimmon and guava fruits with UVB 2.92 kJm^{-2} observed an increase in both total carotenoids and β carotene.

Other authors found a marked effect on the phenolic profiles of peach skin and flesh after treatments with UVB 1.39 and 8.33 kJm^{-2} [53]; in apples, a 219 kJm^{-2} dose of UVB resulted in an increase in flavonoids [20]. The increase in flavonoids found in our study is not surprising because these compounds act as protective pigments from the damaging effects of UV radiation that include both reactive oxygen species (ROS) and UVB screening molecules [75,76]. Several authors have highlighted the important role of photoreceptors, such as UVR8, in modulating specific metabolic pathways, influencing the expression of several genes that control UVB acclimation [21,76]. Recent studies have suggested that the irradiation of fruit with UVB regulates the level of genes involved in flavonoid biosynthesis, as observed in peaches [21,77], apples [78], and blueberries [79]. Pluskota et al. [80] suggested that UV stress leads to an increase in phenylalanine ammonia lyase (PAL), a key enzyme in the biosynthesis of phenolic compounds. It is known that in most fruits (e.g., apples, peaches, apricots, pears, quinces, citrus fruits, and figs), a higher content of substances showing biological activity is found in the skin than in the flesh [81–84]. This trend was observed in our results, which, while reporting an increase in by-products in both flesh and skin, showed a higher concentration in the latter tissue. These effects could be explained by the characteristics of the skin, as the outer part of the fruit is more prone to the synthesis of phenolic compounds and represents the natural defense barrier able to mitigate UV stress [77].

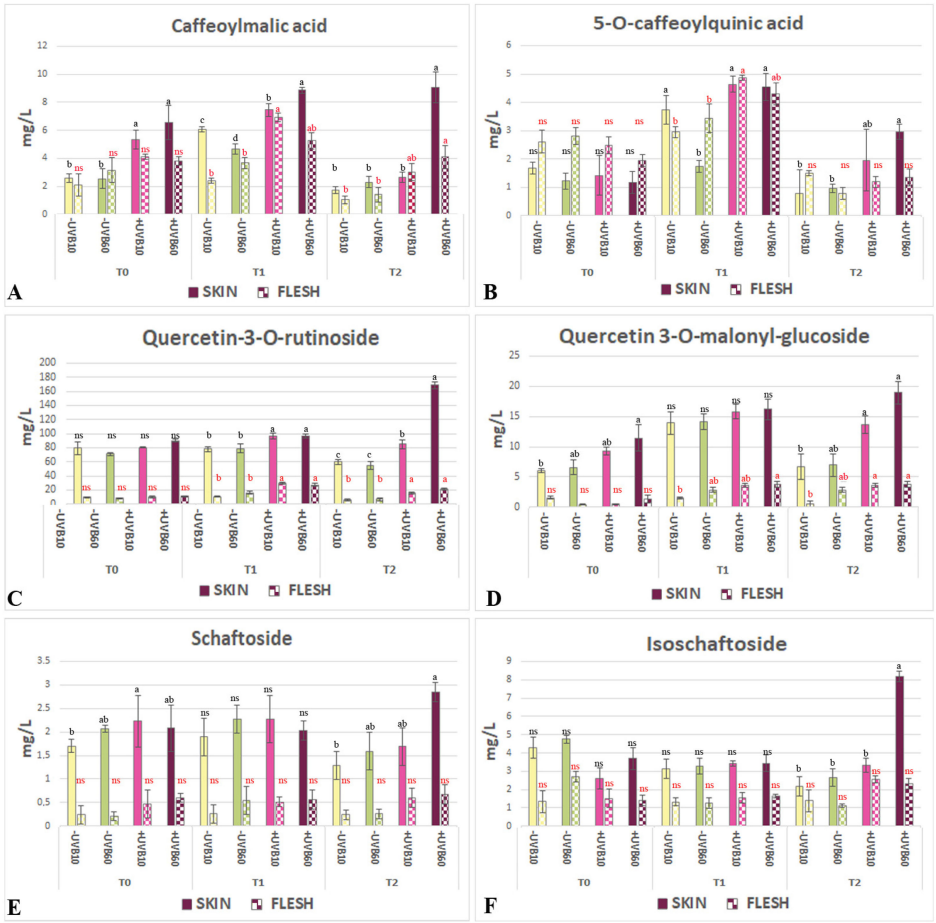

Figure 7. Individual polyphenols in the skin (full-color columns) and the flesh (color columns with pattern) for two different treatments (+UVB10 and +UVB60) on fig fruits and relative controls (−UVB10 and −UVB60) at T0 (immediately after the treatment), T1 (after 7 days), and T2 (after 10 days) of storage. (**A**) Caffeoylmalic acid, (**B**) 5-O-caffeoylquinic acid, (**C**) Quercetin-3-O-rutinoside, (**D**) Quercetin-3-O-malonyl glucoside, (**E**) Schaftoside, (**F**) Isoschaftoside. Data are means (n = 3) ± SD. The different letters above each column indicate significant differences among the treatments (Tukey's test $p < 0.05$), ns = not significant.

3.2.4. Principal Component Analysis

In order to evaluate the effect of the different treatments (T0−UVB10, T0−UVB60, T0+UVB10, T0+UVB60, T1−UVB10, T1−UVB60, T1+UVB10, T1+UVB60, T2−UVB10, T2−UVB60, T2+UVB10, T2+UVB60) on the fig samples and identify the most significant variables in the data set, a principal component analysis (PCA) was performed. The results of the PCA revealed a clear clusterization of the different treatments over time (UVB treated and control samples), based on their effect on fig samples (Figure 8). The first three principal components (PCs) explained a total variance of 92.97% in the model. A plot of the percentage of variance explained by eleven PCs and eigenvalues associated with the eleven PCs is provided Figure 8A. The first principal component (PC1) explained 65.30% of total variance. Parameters with the highest positive weight on PC1 were related to sugar (total sugar, fructose, glucose, Brix°, in the flesh and the skin) as well as pH, weight loss, and decay, whereas parameters like firmness, color parameters, and acidity had the most significant negative weight. The second component (PC2) explained 22.17% of the variability, and showed strong loadings for total polyphenols, but also for sugars and carotenoids, in both the flesh and the skin. Finally, carotenoids in the skin showed the highest contribution to the third principal component PC3, accounting for 5.50% of the variability. The comparison of the plot scores for PC1, PC2, and PC3 in Figure 8B–D

allows for obtaining a view of the treatment dispersion and clusterization based on their effects on the fig samples. In particular, for the first two PCs, the treatments were grouped into three main groups corresponding to the different time points: 0, 7, and 10 days. The first group included treatments at time T0, the second group treatments at time T1, and the third group treatments at time T2. The distance between these groups was determined prevalently by the natural physiological change in different PC1 parameters during the storage period. Furthermore, each of these groups was composed of two subgroups: the "control" subgroup and the "UVB-treated" subgroup. The distance between these subgroups increased with time, and the most discriminating factor was the polyphenol content, but also of importance were the other parameters such as the content of carotenoids and the sugar content. The groups plotted for PC1 and PC3 were very similar to those for the PC1 and PC2plot. In the final plot, the treatments were divided into two groups: the "control group" and the group "treated with UVB". The results obtained through the PCA analysis make it clear that UVB treatments significantly influence the physical and chemical characteristics of the treated samples, thus confirming the key role of UVB radiation in improving the nutritional qualities and shelf life of *Ficus carica* fruits, as reported in the literature for several species [21,23,25,77,78].

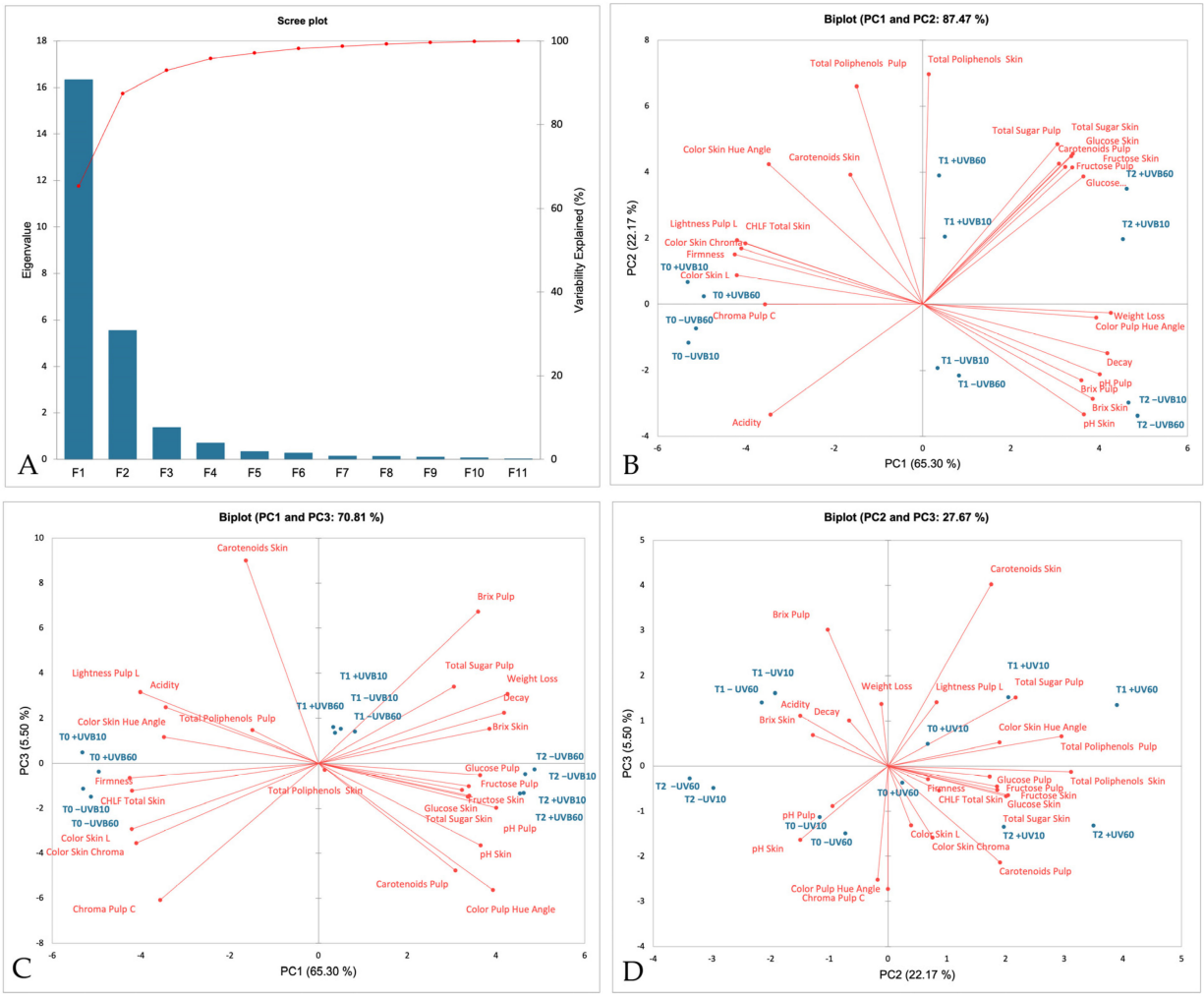

Figure 8. (**A**) Screen plot obtained from the PCA (F1–F11) denoting the eleven principal components for the total parameters studied; (**B**–**D**) loading plots of the first, second and third principal components showing the positions of the different UVB treatments over time and the different parameters studied.

4. Conclusions

The post-harvest period is critical for climacteric fruits such as figs, because storage conditions cause metabolic changes that lead to a general deterioration of quality parameters. The interesting result of this study is the beneficial impact of UVB on the physicochemical quality parameters of fig fruit. The results indicate that UVB irradiation (1.4 and 8.4 kJm^{-2}) can preserve post-harvest quality and contribute to the shelf-life extension of fresh fruit. UVB treatment reduced the loss of firmness and color indices while maintaining the integrity and control of decay. It also had a positive influence on primary and secondary metabolites. UVB influenced the concentration of soluble sugars, preventing post-harvest losses and increasing the content of important health compounds such as carotenoids, flavonoids, and phenols. Finally, another interesting result was that the UVB treatment probably directs its effects not only at the skin, but also at the flesh. UVB can be a promising ecological tool to improve the shelf life of fresh figs during storage. However, further experimental investigations are needed to assess the effectiveness of the technique and apply it on a commercial scale. Our subsequent studies will involve the use of UVB lamps (LED) with a UVB-only emission spectrum (280–315 nm) to re-evaluate the effects on fig by-products.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app132413003/s1, Figure S1: Color parameter of the flesh: Lightness title; Figure S2: Color parameter of the flesh: Chroma; Figure S3: Color parameter of the flesh: Hue angle.

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