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Valorization of ultraviolet-C (UV-C) dose validation in spices: Changes in phenolic contents and antioxidant activity during storage of UV-C-treated dried spices powder

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ORIGINAL ARTICLE

Abstract

In this work, ultraviolet-C (UV-C) radiation was applied at dose levels of 0, 0.5, 1, 1.5 and 2.0 kJ.m^{-2} to evaluate changes on the antioxidant capacity of dried fennel seeds, chilli pepper, and coriander seeds powder during storage. The samples' total phenolic content (TPC), total flavonoid content (TFC), 2,2-diphenyl-1-picrylhydrazyl activity, and ferric-reducing antioxidant power (FRAP) were evaluated prior to and after storage for 6 and 12 months at 25°C and a relative humidity of 45%. The results showed that spices treated with UV-C doses had significantly greater content of TPC, TFC and FRAP during storage, compared to untreated samples. The validation of UV-C dose, as investigated by the partial least squares regression analysis, stated the most valid dose for each dried spice that improved its phenolic content and antioxidant activity prior to and after storage. These findings revealed that UV-C irradiation could help alleviate losses and sustain spices' quality and shelf life as a postharvest treatment method.

Keywords: antioxidant capacity; PLS validation; storage; UV-C

Introduction

Herbs and spices, such as fennel (*Foeniculum vulgare*), chilli pepper (*Capsicum annum* L.) and coriander (*Coriandrum sativum*), are aromatic plant species recognised globally as culinary spices. They are health and colouring balanced additives in the food processing industry because of their potential food additive and health benefits (Barros *et al.*, 2010; Bhagya *et al.*, 2017; Gori *et al.*, 2012; Rather *et al.*, 2012). Studies showed that fennel's antioxidant and microbial properties could serve as natural botanical additives (Diao *et al.*, 2014; Telci *et al.*, 2009). Moreover, Wangensteen *et al.* (2004) observed free radical scavenging and lipid peroxidation inhibition activity of coriander. Pepper contains several antioxidant compounds that significantly impact disease conditions and are essential for human health (Ogiso *et al.,* 2008). However, high contamination levels and changes in the quality of spices during growth, harvest, drying, storage and transportation are significant constraints for products' shelf life, resulting in poor consumer acceptance (Eliasson *et al.*, 2015).

The food safety management has grown considerably in qualitative and quantitative metrics. One of the key challenges facing food production, processing and preservation is satisfying the expectations of consumers who prefer the best-quality fresh, nutritious, attractive, low-priced, and safe to eat products. Therefore, an increased awareness is observed in applying natural antibacterial and food preservatives for extension of the shelf life of foods (Bajpai *et al.*, 2012).

Hence, several innovative postharvest management methods are suggested to preserve the shelf life and quality of spices. Ultraviolet-C (UV-C) radiation (100–280 nm) is explored as an effective unconventional physical treatment for postharvest sanitation and to enhance the quality of dried spices. The UV-C treatment of some herbs at a dose of up to 10 kJ.m^{-2} prevents bacterial and fungal growth and improves their antioxidant properties (Hassan *et al.*, 2020). Moreover, exposure of carambola fruit slices to UV-C at a dose of 12.5 kJ.m^{-2} enhances its phenolic antioxidants and reduces spoilage of fresh and stored samples (Moreno *et al.*, 2017). In addition, Ferriccioni *et al.* (2019) demonstrated that UV-C doses alone and with other thermal methods effectively controlled the microbial load in dried spices.

In addition, exposure of fresh-cut rocket slices to UV-C dose of 20 kJ.m^{-2} sharply reduced the microbial growth (Hassan *et al.*, 2020). Cote *et al.* (2013) also revealed that a UV-C dosage of 4.0 kJ.m^{-2} with increasing intensity in only 5% of tomatoes demonstrated postharvest rot after 9 days of storage. In addition, significantly higher 2,2-diphenyl-1-picrylhydrazyl (DPPH) antioxidant activity and high increment of phenolic compounds were reported in mangoes after exposure to UV-C during 12- and 18-day storage, respectively (González-Aguilar *et al.*, 2007; Pristijono *et al.*, 2018).

In spite of several studies describing the impact of UV-C on foodstuffs, changes in the antioxidant capacity of UV-C-treated food, particularly after storage, have not been evaluated directly. Thus, this research estimated the efficacy of UV-C doses to prevent decay and maintain the antioxidant properties of fennel, chilli and coriander seeds during storage. Further, it validated the UV-C dose to maintain phenolic and antioxidant activity in fennel seeds, chilli pepper and coriander seeds.

Materials and Methods

Collection of spice samples and preparation

Samples of fennel seeds, chilli pepper and coriander seeds were obtained as seeds and dried fruit. The spices were cautiously freed from external matter, milled finely (0.4 mm), and preserved at 4°C so that these could be used for further studies.

UV-C treatment and storage conditions

Ultraviolet-C treatment was conducted in a fabricated cavity (65 × 90 × 45 cm), as described by Hassan *et al.* (2020). The samples were sealed in plastic bags prior to irradiation. They were placed at a distance of 15 cm during exposure to a UV-C source (75 W) with the emission of 254 nm (G75 T8 220 V, Philips, the Netherlands) at separate doses of 0.5, 1.0, 1.5 and 2.0 kJ.m^{-2}. UV-C-treated samples were stored at laboratory conditions (temperatue: 25°C, and relative humidity: 45%) along with untreated samples for 6 and 12 months.

Phenolic compounds and antioxidants extraction

The samples' methanolic extraction was conducted using absolute methanol in a sample–extraction solvent ratio of 1:25 (2 g/50 mL). The mixture was shaken at room temperature for 24 h and vacuum-dried (Talhaoui *et al.,* 2014).

Total phenolic content (TPC) assessment

The sample extract's TPC was estimated using the Folin–Ciocalteu colorimetric method as described by Waterhouse (2002). A blend of sample extract (20 µL), double H_2O (1.58 mL), Folin-Ciocalteu's (100 µL) and Na_2CO_3 (300 µL) was subjected to 2-h incubation at 20°C in darkness. Then, 5 mL of the solution was observed in UV spectrophotometer at 765 nm. A standardisation curve (R^2 = 0.9672) was constructed using different concentrations of gallic acid.

Total flavonoid content (TFC) assessment

The TFC (mg quercetin/g) of the control samples and treated sample extracts was measured using colorimetric assay as reported by Kim *et al.* (2003). An aliquot blend of the sample extract (1 mL), 5% $NaNO_2$ (300 µL), and 10% $AgCl_3$ (300 µL) was reacted for 5 min at 25°C. Then, 0.1-N NaOH (2 mL) was added. Distilled water was added to the blend to make the final solution volume to 10 mL. After 30-min incubation of the reaction mixture, the absorbance was discovered at 510 nm. A standardisation curve of quercetin (R^2 = 0.974) was prepared.

2,2-Diphenyl-1-picrylhydrazyl (DPPH) activity measurement

The method reported by Chang *et al.* (2001) was applied to measure the DPPH antiradical activity of spice extracts. Roughly, a reaction mixture of sample extracts (0.1 mL), 50-mM Tris-HCl buffer solution (pH 7.4, 0.9 mL) and DPPH methanolic solution (1 mL) was prepared, mixed well, and kept in dark (20°C for 20 min). Then, absorbance of the mixture was calculated using a UV spectrophotometer at 517 nm. The DPPH was measured as Trolox equivalents per 100-g sample (µmol TE/100 g).

Ferric-Reducing Antioxidant Power (FRAP) measurement

The FRAP assay for pearl millet extracts was performed according to the procedure stated by Oyaizu (1986). The FRAP blends were detected at 593 nm, compared to a blank, using a UV–VIS spectrophotometer (UV-VIS PD-303 UV). Trolox was used as a standard for constructing standardisation curves; FRAP is measured as micromoles (μmol) Trolox equivalent (TE) g^{-1} DW.

Statistical analysis

Data were analysed for equality of differences and normality using the Shapiro–Wilk and Levene's normality tests, respectively ($p < 0.05$). Two-way ANOVA was used to analyse the main effects of UV-C doses and storage time and their interfaces using the XLSTAT software. The Fisher's least significant difference (LSD) test was applied to calculate significant differences between the treatments. The partial least squares regression (PLS) test was conducted using XLSTAT software (Tenenhaus *et al.*, 2005).

Results and Discussion

Effect of UV-C on the TPC of fennel seeds, chilli pepper and coriander seeds

Changes observed in the TPC of UV-C-treated fennel seeds, chilli pepper and coriander seeds prior to and after storage are given in Table 1. It was observed that the TPC of fennel seeds, chilli pepper, and coriander seeds increased significant ($p < 0.0001$) after UV-C treatment. The respective highest value of TPC after chilli pepper, fennel seeds and coriander seeds were exposed to UV-C 2.0 kJ.m^{-2} were 69.23, 86.18 and 67.72 mg GAE/g DW. Interestingly, the TPC of the samples was found to be significantly high ($p < 0.0001$) following 12 months of storage, particularly for the treated samples (Table 1). The results agreed with the study which stated that the UV-C treatment followed by storage significantly increased the phenolic profile of table grapes (Sheng *et al.*, 2018). Moreover, the TPC of the UV-C-treated Israeli Deglet Noor dates was enhanced when stored for up to 5 months (Dassamiour *et al.*, 2022). Similarly, UV-C also stimulated the accumulation of phenolic content in soybeans (Winter and Rostàs, 2008).

The increment of phenolic content in treated samples during storage could be due to variations in the expression mechanism of phenolic compounds' biosynthetic genes, principally the phenylalanine ammonia-lyase enzyme (PAL), which responds to the abiotic stress action of UV-C light. Sheng *et al.* (2018) stated that the UV-C treatment activated the PAL expression in table grapes by more than 1.81-fold after 2 weeks of storage. Moreover, applying UV-C to *Gnetum parviflorum* significantly increased its PAL (Deng *et al.*, 2017).

Effect of UV-C on the TFC of fennel seeds, chilli pepper and coriander seeds

Effect of UV-C dose on the TFC of fennel seeds, chilli pepper and coriander seeds prior to and after storage is presented in Table 2. The TFC of fennel seeds and chilli

Table 1. Effect of UV-C treatments followed by storage on the total phenolic content (mg GAE/g) of chilli pepper, fennel seeds, and coriander seeds.

UV-C dose	Fennel seeds			Chili pepper			Coriander seeds		
	0 month	6 months	12 months	0 month	6 months	12 months	0 month	6 months	12 months
0.0 kJ.m^{-2}	32.6±1.73^{k}	56.3±1.73^{h,i}	56.7±1.73^{h,i}	37.8±1.13^{j}	57.8±1.73^{f,g}	64.2±0.65^{d,e}	34.4±1.13^{j}	31.0±1.13^{k}	31.4±4.71^{k}
0.5 kJ.m^{-2}	41.9±1.73^{j}	72.1±1.73^{f}	75.5±1.73^{e}	41.9±1.73^{i}	67.2±1.13^{c,d}	68.4±1.13^{b,c}	43.5±1.13^{i}	48.0±1.13^{h}	55.9±1.13^{f}
1.0 kJ.m^{-2}	59.3±1.13^{h}	82.7±1.73^{d}	88.3±1.73^{b,c}	42.4±1.13^{i}	68.4±2.26^{b,c}	70.6±1.13^{b}	52.5±1.13^{g}	57.0±1.13^{e,f}	60.8±1.73^{d}
1.5 kJ.m^{-2}	66.1±2.26^{g}	86.4±1.13^{c}	90.9±1.13^{a,b}	48.8±1.73^{h}	70.2±1.73^{b}	70.9±1.13^{b}	58.2±1.13^{e}	60.8±0.65^{d}	67.6±1.73^{b}
2.0 kJ.m^{-2}	75.5±1.73^{e}	90.2±1.73^{a,b}	92.84±2.35^{a}	55.2±2.35^{g}	75.5±1.73^{a}	77.0±1.73^{a}	63.8±1.13^{c}	63.8±1.13^{c}	75.5±1.73^{a}
Two-way ANOVA									
Dose (D)		569.8***			93.16***			914.7***	
Storage (S)		828.3***			924.6***			80.06***	
D×S		10.05***			3.43**			20.08***	
SE±		0.573			0.937			0.717	
LSD		1.66			2.719			2.079	

SE: standard error of the mean; LSD: Fisher's least significant difference; NS: not significant. Different letters within a column indicate a factor-specific significant difference ($p < 0.05$, Tukey's honestly significant difference [HSD] test). **$p < 0.01$, ***$p < 0.001$.

Table 2. Effect of UV-C treatments followed by storage on the total flavonoid content (mg QE/g DW) of chilli pepper, fennel seeds, and coriander seeds.

UV-C dose	Fennel seeds			Chili pepper			Coriander seeds		
	0 month	6 months	12 months	0 month	6 months	12 months	0 month	6 months	12 months
0.0 kJ.m^{-2}	34.03±6.36^{g,h}	27.1±4.17^{h,i}	22.9±4.17^{i}	10.4±4.17^{g,h}	11.8±2.41^{g,h}	11.81±2.41^{g,h}	42.3±6.36^{e,f}	24.3±6.36^{g}	25.6±2.41^{g}
0.5 kJ.m^{-2}	47.9±4.17^{f,g}	50.6±2.41^{e,f}	60.4±8.33^{d,e}	13.1±2.41^{g,h}	14.5±4.17^{g,h}	14.6±4.17^{g,h}	59.0±6.36^{b,c}	60.4±4.17^{b,c}	63.1±6.36^{a,b}
1.0 kJ.m^{-2}	59.0±6.36^{d,e}	63.1±6.36^{d}	78.4±6.33^{c}	22.9±4.17^{d,e}	17.3±2.41^{f,g}	20.1±2.41^{e,f}	61.8±4.17^{a,b}	64.5±4.17^{a,b}	68.7±4.17^{a}
1.5 kJ.m^{-2}	79.58±4.17^{b,c}	82.6±2.14^{b,c}	85.4±4.17$^{a–c}$	25.6±2.41^{d}	35.4±4.17^{c}	39.6 ±4.17^{b}	47.92±4.17^{e}	49.3±2.41^{d,e}	54.8±6.36^{c,d}
2.0 kJ.m^{-2}	89.5±4.17^{a,b}	89.5±4.17^{a,b}	93.7±4.17^{a}	27.08±4.17^{d}	43.75±4.17^{a}	45.1±6.36^{a}	47.9±4.17^{e}	49.3±6.36^{d,e}	54.8±8.67^{c,d}
Two-way ANOVA									
Dose (D)		181.96***			116.5***			53.26***	
Storage (S)		1.85 ns			4.72*			2.30 ns	
D×S		4.18**			6.82***			3.89**	
SE±		1.630			1.153			2.692	
LSD		8.19			4.732			7.813	

SE: standard error of the mean; NS = not significant; LSD: Fisher's least significant difference. Different letters within a column indicate a factor-specific significant difference ($p < 0.05$, Tukey's honestly significant difference [HSD] test). ** $p < 0.01$, *** $p < 0.001$.

pepper was found to increase significantly after UV-C treatments , and this increased with addition in UV-C doses of 0.5, 1.0, 1.5 and 2.0 kJ.m^{-2} ($p < 0.0001$). However, the TFC of coriander seeds increased considerably (64.5 mg QE/g DW; $p < 0.0001$) with UV-C dose of up to 1.0 kJ.m^{-2} but decreased to 47.9 mg QE/g DW as the UV-C dose was increased to 1.5–2.0 kJ.m^{-2}. The TFC of treated fennel seeds, chilli pepper, and coriander seeds increased considerably during storage for 6 and 12 months.

In case of fennel seeds, a significant accumulation of flavonoid was observed during storage irrespective of dosage, and the results showed that the UV-C at a dose of 2.0 kJ.m^{-2} increased total flavonoid to 93.73 mg QE/g DW at 12 months of storage. However, in the case of chilli pepper, the TFC was reduced to 17.36 and 20.14 mg QE/g DW at a UV-C dose 1.0 kJ.m^{-2} after 6 and 12 months, respectively. In the case of coriander seeds, increase in UV-C dose to 1.5 and 2.0 kJ.m^{-2} declined TFC in the range of 47.92–54.86 mg QE/g DW without any change in storage period. Our results were similar to the literature. During 5 weeks of refrigerated storage, flavonoids increased significantly by 3% in irradiated mango juice (Santhirasegaram *et al.*, 2015). In addition, Liu *et al.* (2012) stated that the total flavonoid content of tomato fruits increased after UV-C irradiation at 0.4 or 0.8 J.cm^{-2}, followed by storage at 14°C for 35 days. Shen *et al.* (2013) observed that the flavonoid content of *Satsuma mandarin* was rapidly enhanced by a UV-C dose of 3.0 kJ.m^{-2} for the first 3 days of storage, without significant change even after 9 days of storage. Similarly, a rapid increment in grape flavonoids was observed by UV-B and UV-C treatments, followed by rapid decrease and continuous reduction after 21 days. This was associated with the expression of some genes related to flavonoid pathways, such as *chalcone synthase* (*CHS*) and *flavanone 3* (*F3H*) genes, because of UV-C treatment (Sheng *et al.*, 2018).

Effect of UV-C on the antioxidant activity of fennel seeds, chilli pepper and coriander seeds

Variations in the antioxidant activity (DPPH and FRAP) of the UV-C-treated fennel seeds, chilli pepper and coriander seeds during storage are presented in Tables 3 and 4, respectively. As shown in Table 3, all treated spices showed a significant increase ($p < 0.0001$) in the rate of DPPH scavenging, compared to control samples during storage.

The DPPH activity of fennel seeds showed an increment of up to 9.91 μmol TE/g at a UV-C dose of 1.0 kJ.m^{-2}, followed by an immediate slight decrease at UV-C doses of 1.5 and 2.0 kJ.m^{-2} and during storage. A high scavenging activity in chilli pepper (9.42 μmol TE/100 g) and coriander (9.98 μmol TE/100 g) was observed at a UV-C dose of 2.0 kJ.m^{-2} during 12 months of storage. Li *et al.* (2017) demonstrated that a UV-C dose of 3.0 kJ.m^{-2} and cold storage enhanced litchi's DPPH scavenging activity. At the same time, rambutan and longan were affected negatively and showed reduced antioxidant activity after exposure to UV radiation. Moreover, Sari *et al.* (2016) reported an increased antioxidant capacity of pineapple fruit treated with UV-C doses of 13.2, 26.4 and 39.6 kJ.m^{-2} during cold storage for 4 weeks. However, UV-C treatment dose of 25 kJ.m^{-2} did not alter the antioxidant activity of fresh-cut rocket leaves during cold storage (Gutiérrez and Rodríguez, 2019). The difference in antioxidant activity

Table 3. Effect of UV-C treatments followed by storage on the 2,2-diphenyl-1-picrylhydrazyl (DPPH; μmol TE/100 g DW) activity of chilli pepper, fennel seeds, and coriander seeds.

UV-C dose	Fennel seeds			Chili pepper			Coriander seeds		
	0 month	6 months	12 months	0 month	6 months	12 months	0 month	6 months	12 months
0.0 kJ.m^{-2}	8.4±0.05[i]	8.3±0.03[j]	9.3±0.06[e]	8.3±0.07[i]	8.4±0.05[h]	8.8±0.04[f]	8.7±0.09[h]	8.6±0.06[h,i]	8.5±0.11[i]
0.5 kJ.m^{-2}	8.7±0.04[g]	9.5±0.03[d]	9.7±0.05[b]	8.8 ±0.03[f]	8.6±0.03[g]	9.0±0.05[d]	9.1±0.05[g]	9.2±0.04[f]	9.3±0.03[e]
1.0 kJ.m^{-2}	8.9±0.05[f]	9.9±0.08[a]	9.9±0.02[a]	8.9±0.04[e]	9.0±0.05[d]	9.1±0.02[c]	9.2±0.02[f]	9.5±0.04[d]	9.6±0.05[c]
1.5 kJ.m^{-2}	8.6±0.02[h]	9.6±0.02[c,d]	9.7±0.03[b]	9.0±0.02[d]	9.1±0.01[c]	9.2±0.04[b]	9.3±0.04[e]	9.8±0.04[b]	9.8±0.05[b]
2.0 kJ.m^{-2}	8.6±0.03[h]	9.7±0.05[c]	9.7±0.03[b]	9.1±0.03[c]	9.2±0.03[b]	9.4±0.04[a]	9.5±0.04[d]	9.9±0.04[a]	9.9±0.03[a]
Two-way ANOVA									
Dose (D)		935.9***			425.07***			684.8***	
Storage (S)		1041.3***			284.30***			67.43***	
D×S		101.8***			10.01***			18.12***	
SE±		0.024			0.021			0.015	
LSD		0.040			0.061			0.078	

SE: standard error of the mean; NS = not significant; LSD: Fisher's least significant difference. Different letters within a column indicate a factor-specific significant difference ($p < 0.05$, Tukey's honestly significant difference [HSD] test). **$p < 0.01$, ***$P < 0.001$.

Table 4. Effect of UV-C treatments followed by storage on the ferric-reducing antioxidant power (FRAP; μmol TE/100 g DW) of chilli pepper, fennel seeds, and coriander seeds.

UV-C dose	Fennel seeds			Chili pepper			Coriander seeds		
	0 month	6 months	12 months	0 month	6 months	12 months	0 month	6 months	12 months
0.0 kJ.m^{-2}	15.1±0.08[l]	14.8±0.07[m]	11.6±0.17[n]	14.3±0.06[i]	14.2±0.03[i]	14.2±0.05[i]	12.6±0.08[k]	11.8±0.07[l]	10.3±0.31[m]
0.5 kJ.m^{-2}	15.9±0.07[k]	20.7±0.05[j]	22.8±0.05[h]	16.3±0.11[h]	17.0±0.10[g]	16.2±0.13[h]	13.3±0.03[j]	15.4±0.11[i]	21.2±0.13[f]
1.0 kJ.m^{-2}	22.5±0.05[i]	23.4±0.07[g]	24.6±0.09[c]	18.5±0.09[f]	18.9±0.08[e]	18.6±0.14[f]	16.2±0.10[h]	19.3±0.15[g]	22.2±0.08[e]
1.5 kJ.m^{-2}	23.6±0.06[f]	23.9±0.10[e]	25.5±0.13[b]	19.1±0.10[d]	19.7±0.11[c]	20.2±0.23[b]	19.3±0.13[g]	24.3±0.05[c]	25.4±0.08[a]
2.0 kJ.m^{-2}	24.3±0.14[d]	24.4±0.11[d]	25.8±0.05[a]	19.8±0.06[c]	20.0±0.05[b]	20.8±0.15[a]	22.8±0.03[d]	25.0±0.08[b]	25.7±0.08[a]
Two-way ANOVA									
Dose (D)		2145***			3369.7***			2005***	
Storage (S)		481.8***			28.974***			2487***	
D×S		1295***			27.377***			1358***	
SE±		0.084			0.376			0.109	
LSD		0.14			0.192			0.158	

SE: standard error of the mean; NS: not significant; LSD: Fisher's least significant difference. Different letters within a column indicate a factor-specific significant difference ($p < 0.05$, Tukey's honestly significant difference [HSD] test). **$p < 0.01$, ***$p < 0.001$.

could be attributed to different effects of phytochemicals to UV-C exposure and the association between antioxidant activity and phenolic content.

The FRAP of control samples and UV-C-treated samples prior to and after storage is shown in Table 4. As shown in the table, FRAP of samples was significantly affected ($p < 0.0001$) by the UV-C doses and storage time. The highest FRAP values of 25.83, 25.74 and 20.85 mg TE/g DW for fennel seeds, coriander seeds, and chilli pepper, respectively, were obtained at a UV-C dose of 2.0 kJ.m^{-2} after storage for 12 months. Comparable results were found in the study conducted by Li *et al*. (2017). In addition, high antioxidant levels were observed by Robles-Sánchez *et al.* (2009) in blueberries and by González-Aguilar *et al.* (2007) in mangoes. The results obtained by Dassamiour *et al.* (2022) with Israeli Deglet Noor dates revealed an increase in Fe^{3+} chelating activity of irradiated dates because of water loss, leading to the accumulation of antioxidant molecules with the best construction for free radical scavenging.

PLS regression validation of UV-C dose

The PLS regression established the interaction impact of UV-C treatments and storage time on the antioxidant activity of fennel seeds, chilli pepper and coriander seeds (Figures 1A–1C). As illustrated in Figure 1A, the UV-C doses solely or followed by storage were clustered according to their effect on the TPC, TFC, DPPH and FRAP of fennel seeds. The PLS demonstrated that the UV-C treatment of fennel seeds, primarily those exposed to the UV-C doses of 1.5 and 2.0 kJ.m^{-2} and stored for 6 and 12 months, exhibited a progressive valid action for most of the studied parameters. However, the UV-C dose of 2.0 kJ.m^{-2} observed for 6 months of storage exhibited the most optimum and valid dose for the most studied parameters. The PLS validation of UV-C doses on the antioxidant activity of chilli pepper is described in Figure 1B. According to PLS regression model, the UV-C doses were clearly clustered into low and high doses according to their influence on antioxidants. The PLS validation model showed that the UV-C dose of 2.0 kJ.m^{-2} was the optimistic validation dose for the most tested parameters. Figure 1C shows the PLS validation model describing the most valid interaction between sole UV-C doses or followed by storage as well as the TPC, TFC, DPPH and FRAP of the coriander seeds. Accordingly, the UV-C treatment doses were clustered according to their impact on antioxidant capacity. The PLS results displayed a progressive validation score for treated coriander seeds, mainly at UV-C doses of 1.5 and 2.0 kJ.m^{-2}, on evaluated parameters. Consequently, PLS established that applying UV-C treatment dose of 2.0 kJ.m^{-2}, followed by 6 months

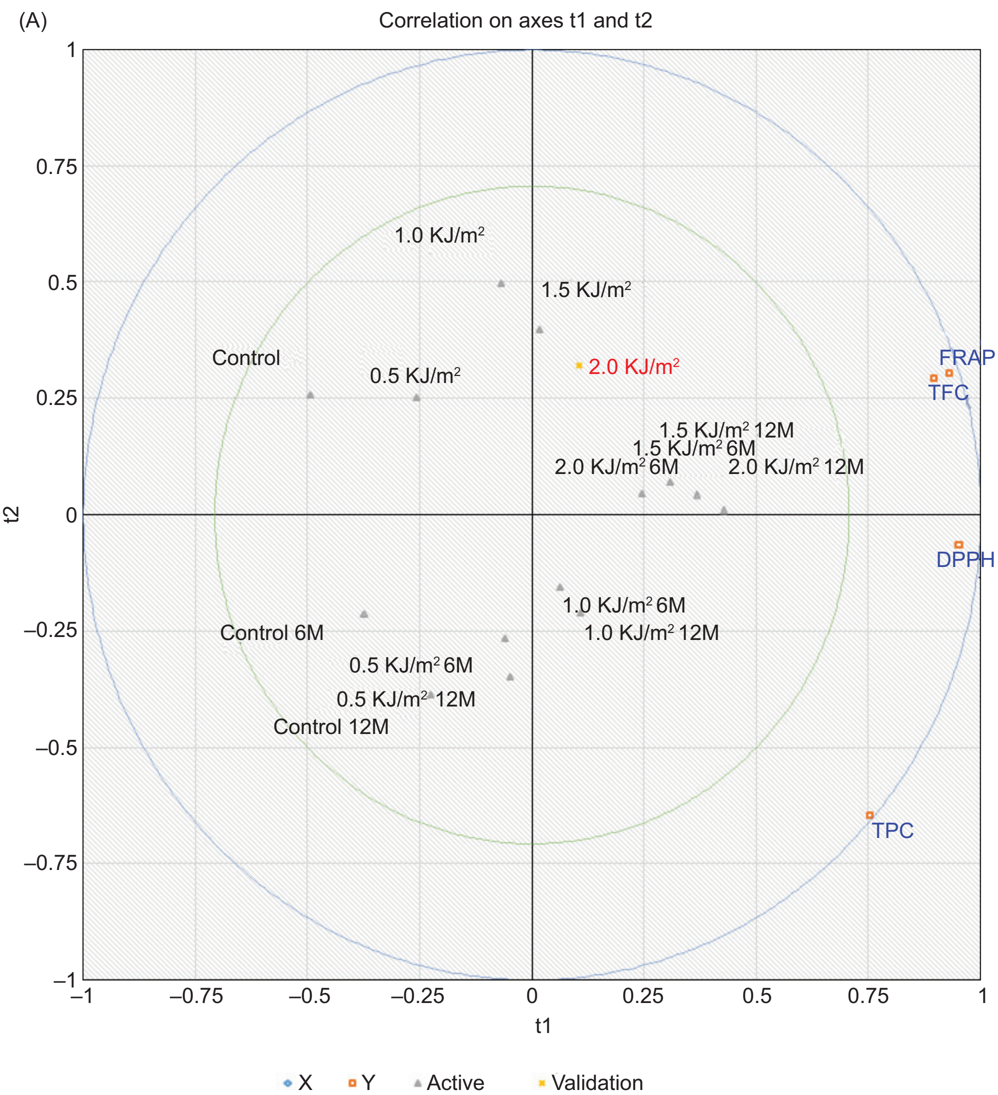

Figure 1. Partial least squares regression analysis (PLS) validation of different doses of ultraviolet-C (UV-C) radiation of phytochemical compounds and antioxidant activities of (A) fennel seeds, (B) chilli pepper, and (C) coriander seeds.

(*continues*)

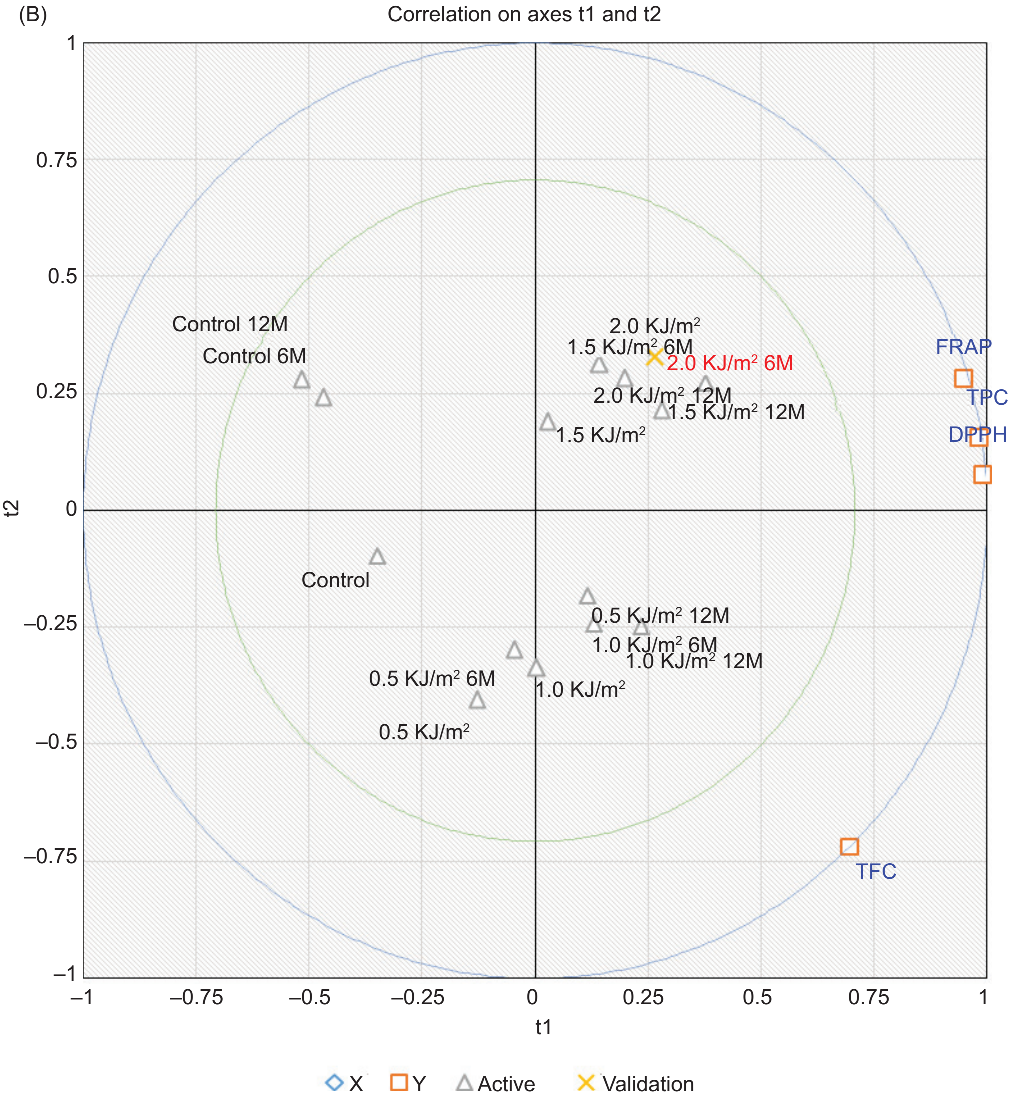

Figure 1. Continued

of storage, was the valid treatment for coriander seeds. According to PLS validation models, the maximum UV-C dose used in this study, that is 2.0 kJ.m^{-2}, reflected the suitable dose applicable for fennel seeds, chilli peppers and coriander seeds, and could be used in food manufacturing.

Conclusions

Post-storage UV-C treatment doses of 0.5, 1.0, 1.5 and 2.0 kJ.m^{-2} were appropriate for non-conventional handling and to increase phytochemical compounds in the dried spices of fennel seeds, chilli pepper and coriander seeds. The UV-C treatment significantly enhanced the TPC and TFC of all spices in a dose–time-dependent manner. Moreover, a free radical scavenging activity was observed in exposed spice seeds, compared to control samples. The PLS validation model assured that the UV-C treatment of 2.0 kJ.m^{-2} could be considered the most valid dose for fennel seeds, chilli pepper and coriander seeds; this could be recommended for food manufacturing. Moreover, UV-C treatment could be applied as an effective postharvest protection method to preserve the quality and for safety of spices in order to prolong their shelf life.

Conflicts of Interest

The authors declared no conflict of interest.

Author Contributions

Akram A. Qasem and Mohamed A. Ibraheem: formal analysis, investigation and data curation. Mshari A.H.

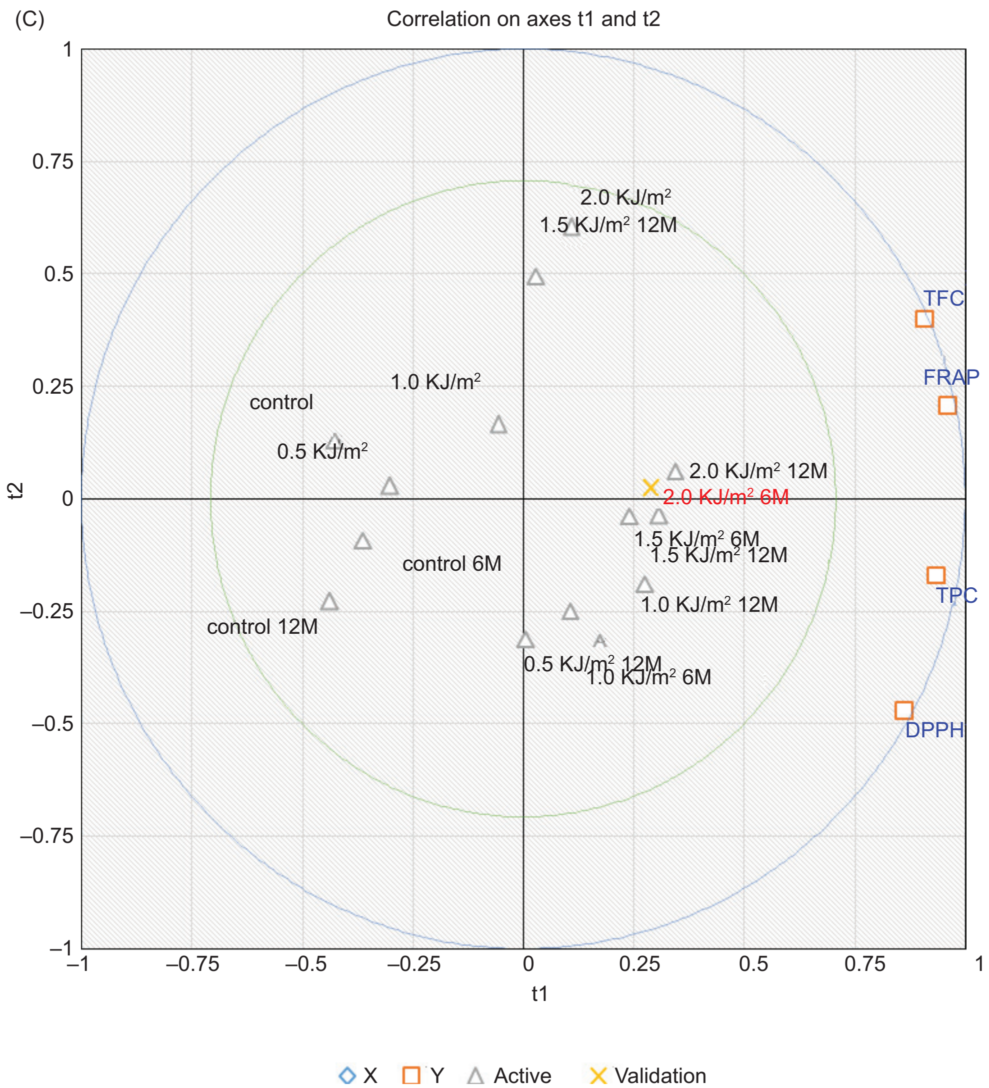

Figure 1. Continued

Hamami and Yaser I. Al-Shoqairan: methodology and visualisation. Mohamed Saleh Alamri: project administration and funding acquisition. Salah A. Al Maiman: writing—original draft preparation. Amro B. Hassan: supervision, writing—review and editing.

Data Availability Statement

All data obtained are contained in the article.

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