Evaluation of capsaicinoid profile and antioxidant properties in dried Korean red pepper (*Capsicum annuum* L.) as affected by variable dose rates of electron beam and gamma ray irradiation

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Abstract The application of food irradiation is based on the parameters including energy (MeV), dose rate (kGy/s or kGy/h), and absorbed dose (kGy). Red pepper powders were treated with different dose rates of 1, and 5 kGy/s electron beam (EB) as well as 1.8 and 9 kGy/h gamma ray (GR) in separate experiments. Constant absorbed dose (3 kGy) was maintained to observe whether different dose rates affect the product quality. Total and individual capsaicinoids increased at low EB and GR dose rates. Vitamin C content decreased at all dose rates, except at low GR dose rate, where no significant difference was observed. Low EB dose rate led to a marked increase (21%) in the total phenolics than high dose rate (13%). In contrast, high GR dose rate increased the total phenolics than low dose rate. Maximum antioxidants (1.36 mg TE/mL) were observed at high EB dose rate, although low dose rate also increased the antioxidant activity. Results indicated that different dose rates delivering the same absorbed dose had significant impact on the product quality and that the efficacy of absorbed dose is dependent on applied dose rates. In other words, a constant absorbed dose applied to the product is influenced by dose rate of the irradiation treatment.

Keywords Red pepper · Irradiation · Capsaicinoids · Vitamin C · Phenolics · Antioxidant activity

Introduction

Red pepper powder (RPP, *Capsicum annuum* L.) is an exotic traditional Southeast Asian condiment prepared primarily by drying red pepper. Decontamination techniques are typically used after the grinding step (Schweiggert et al. 2006). Evaluation of various decontamination techniques used in spice production has focused on the effectiveness in reducing the microbial population. There is less emphasis on impact of these technologies on bioactives (capsaicin, dihydrocapsaicin, nordihydrocapsaicin, vitamin C, total phenolics) present as natural constituents and the antioxidant activities (DPPH and ABTS radical quenching properties) of the finished product. Among several food preservation methods, irradiation has replaced fumigants and thermal treatments as an effective method to improve food safety and to prevent negative effects on the nutritive and bioactive components (Lung et al. 2015). Past studies have investigated the effects of irradiation on these essential compounds despite microbial decontamination. Electron beam (EB) irradiation has been demonstrated to aid effective decontamination while preserving the chemical and antioxidant properties of dried mushrooms (Fernandes et al. 2015). However, Gámez et al. (2014) revealed that EB irradiation treatment of tomato products increased the antioxidant ability and *z*-lycopene content but decreased the *E*-lycopene content. Quality deterioration of spices is a critical factor on application of a sterilization process.

There has been no investigation on the quality components of RPP samples using different dose rates (kGy/time) of EB and gamma ray (GR) irradiation. The current study was initiated to explore the effect of different irradiation dose rates of EB (kGy/s) and GR (kGy/h) on capsaicinoids profile, vitamin C, total phenolics, and radical scavenging

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activities in RPP. Hence, this study aimed to (1) determine the acceptable irradiation dose rate for ensuring adequate levels of the bioactive components in RPP; and (2) evaluate the chemical qualities of RPP, including capsaicinoid contents, vitamin C, total phenolics, and antioxidant activity in non-irradiated and irradiated (selected dose rate) products. The degree of variation in the quality attributes of RPP after the application of different EB and GR dose rates was estimated with the ultimate goal of utilizing appropriate irradiation dose rate for commercial food processing.

Materials and methods

Chemicals

Standards (capsaicin, dihydrocapsaicin, gallic acid, trolox) and chemicals (1,1-diphenyl-2-picryl hydrazyl (DPPH), 2,2'-azino-bis(3-ethylbenzthiazoline-6-sulfonic acid) (ABTS)) were purchased from Sigma-Aldrich (Darmstadt, Germany). Solvents (acetonitrile—HPLC grade; methanol and ethanol—analytical grade) were supplied by Honeywell Burdick and Jackson (Ulsan, Korea) and Duksan (Ansan, Korea), respectively. Other chemicals obtained were as follows: ascorbic acid, Folin–Ciocalteu reagent (Junsei Chemical Co. Ltd., Tokyo, Japan), sodium carbonate, potassium persulfate (Duksan, Ansan, Korea), and metaphosphoric acid (Daejung, Siheung, Korea).

RPP procurement, sample preparation, and irradiation treatments

RPP samples were procured from an organic spices trading company in Daegu, South Korea, and mixed for vacuum packaging in polyethylene plastic bags (300 g per bag, dimensions 29 cm × 19 cm, thickness < 1 cm) for irradiation treatment. The photograph of packaged RPP is shown in Fig. 1. Besides the non-irradiated control, one set of the samples were irradiated at 3 kGy by an accelerated EB source with 1 and 5 kGy/s dose rates separately at 27 ± 2 °C in a linear electron accelerator facility (ELV-8, EBtech, Daejeon, South Korea). The accelerator conditions were 10 MeV beam energy with 10 kW power and 100 mA current. Another set of samples were irradiated at the Korean Atomic Energy Research Institute (Jeongeup, Korea) with 3 kGy absorbed dose using a cobalt-60 GR source (AECL, IR-79, MDS Nordion International Co. Ltd., Ottawa, Ontario, Canada) at dose rates 1.8 and 9 kGy/h. The samples were arranged in a single layer without stacking during the irradiation treatment. After irradiation, the irradiated samples along with the control were kept at 4 °C for further analysis within a week.

Fig. 1 Photograph of red pepper powder sample used in the study

Dosimetry

Uniformity of the absorbed doses in packaged RPP were ensured using 5 mm diameter alanine dosimeters (Bruker BioSpin, Rheinstetten, Germany). Three dosimeters were sealed in a polyethylene bag and each bag was attached to the front top left (FTL), middle (M), and back bottom right (BBR) of the samples for each set of irradiation conditions. The alanine dosimeter reader was calibrated using international standards recommended by the UK National Physics Laboratory (ISO/ASTM 2002). The dose uniformity ratios (max/min ratios) of both irradiation sources were 1.1 (Table 1).

Analysis of capsaicinoid contents using high-performance liquid chromatography (HPLC)

Analysis of capsaicinoids was carried out according to a modified method of Topuz et al. (2011). RPP (0.2 g) and 4 mL acetonitrile were mixed and subjected to 15 min ultrasonication, followed by centrifugation at 3000 g for 15 min. The extraction procedure was repeated and both supernatants were mixed well. One milliliter of the supernatant was filtered using 0.45 µm membrane syringe filter (Millipore Corporation, Bedford, MA, USA) before injection into the HPLC system to determine the capsaicin, dihydrocapsaicin, and nordihydrocapsaicin contents.

The supernatant (10 µL) was injected into the HPLC equipment (1260 Infinity; Agilent Technologies, CA, USA) with C18 column (µBondapak, 3.9 mm × 300 mm; Waters Co., Milford, MA, USA) and eluted with isocratic mobile phase (1 mL/min) of acetonitrile and deionized water (45:55, v/v) at room temperature (25 °C). The constituents were detected with an Agilent 1260 Infinity

Table 1 Absorbed dose of irradiated red pepper powder at various locations in the package

Irradiation type	Energy	Dose rate	Target dose (kGy)	Position	Absorbed dose (kGy)	Delivered dose (kGy)
Electron beam	10 MeV	1 kGy/s	3	FTL	2.69 ± 0.01 ^a	2.85
				M	2.83 ± 0.02 ^a	
				BBR	3.04 ± 0.01 ^a	
		5 kGy/s		FTL	2.60 ± 0.01 ^a	2.79
				M	2.81 ± 0.01 ^a	
				BBR	2.96 ± 0.01 ^a	
Gamma ray	Co-60	1.8 kGy/h		FTL	2.51 ± 0.02 ^a	2.63
				M	2.76 ± 0.01 ^a	
				BBR	2.62 ± 0.01 ^a	
		9 kGy/h		FTL	2.97 ± 0.01 ^a	2.86
				M	2.76 ± 0.47 ^a	
				BBR	2.84 ± 0.02 ^a	

FTL front top left, M middle, BBR back bottom right

Delivered dose = Average of FTL, M, and BBR

^aValues are mean ± standard deviation from three replications. Values with same letters within the column are not significantly different at $p > 0.05$ by Duncan's multiple range test

multiple wavelength detector set at 280 nm with a run time of 25 min. The capsaicin, dihydrocapsaicin, and nordihydrocapsaicin contents were expressed in mg/100 g dry mass.

HPLC quantification of vitamin C content

Sample (0.5 g) was added to 8 mL of 3% metaphosphoric acid, followed by centrifugation at 3000 g for 15 min, then filtered, and cleaned using 0.45 µm membrane filter before injection into the above HPLC equipment with C18 column. The eluent (isocratic mobile phase, 0.5 mL/min) was a mixture of acetonitrile and deionized water (45:55, v/v) at 25 °C with a run time of 15 min at 254 nm. Quantification of vitamin C was performed using ascorbic acid as an external standard (Topuz and Ozdemir 2007).

Total phenolics content (TPC) assay

Phenolics were extracted from 0.1 g of RPP irradiated at different dose rates with 30 mL methanol. This mixture was ultrasonicated for 30 min and incubated in the dark for another 30 min. The extraction was repeated three times with centrifugation at 4000 g for 10 min. The pooled supernatants were used for analysis (Zhou et al. 2016). TPC was determined using the Folin–Ciocalteu (Singleton and Rossi 1965). The extract (0.2 mL), distilled water (1.8 mL) and Folin–Ciocalteu reagent (0.5 N, 0.2 mL) were mixed. After 6 min, aqueous Na₂CO₃ (7%, 2 mL) was added, mixed thoroughly using a vortex and measured

colorimetrically at 750 nm. TPC was expressed as mg of gallic acid equivalents (mg GAE/g dry mass).

DPPH radical scavenging activity

Variations in the antioxidant activity of irradiated RPP at different dose rates were assessed according to a modified method of Awe et al. (2013) with the stable DPPH free radical. The absorbance of DPPH solution in ethanol was adjusted to 1.000 ± 0.002 at 517 nm. After mixing the aqueous RPP extract (1:49 w/v, 1 mL) and DPPH solution (5 mL), the decrease in radical concentration was observed using UV/Vis spectroscopy. The DPPH radical scavenging activity was measured as trolox equivalent (TE).

ABTS radical scavenging activity

Equal quantities of freshly prepared 7 mM ABTS and 2.4 mM potassium persulfate solutions were mixed and diluted in ethanol to an absorbance of 0.700 ± 0.002 at 734 nm as measured using a spectrophotometer. Each of the 1 mL aqueous extracts (1:49 w/v) and 4 mL of the ABTS solution were mixed. Absorbance was recorded after 5 min and antioxidant activity is expressed in terms of trolox equivalent (TE) (Re et al. 1999).

Determination of moisture content and water activity

Approximately, 1 g of RPP sample placed on an aluminum plate was analyzed for moisture content using an infrared

moisture determination balance (FD-720, Kett electric laboratory, Japan) and recorded as dry weight (%). The analysis was repeated five times ($n = 5$). The water activity of RPP (5 g) was measured with a humidity indicator (AM3, Rotronic, Bassesdorf, Switzerland) in a dedicated vessel. The analysis was repeated three times ($n = 3$).

Statistical analysis

All experimental analyses were repeated at least 3 times and the results were reported as mean $\pm$ standard deviation. The data were analyzed using one-way ANOVA procedure and Duncan's multiple range test (SAS Institute, Cary, NC, USA). A value of $p < 0.05$ was used to indicate significant difference.

Results and discussion

Dose rate (kGy/time) is one of the several factors that influence the irradiation treatment. To evaluate the feasibility of the irradiation dose rates, the quality properties of RPP were measured. To date, no study has investigated the effect of irradiation dose rate (kGy/time) on the TPC, individual capsaicinoid profile, vitamin C content, and antioxidant activities of RPP. The concentration of the bioactive components such as capsaicinoids, total phenolics, vitamin C as well as DPPH and ABTS free radical quenching were analyzed before and after EB and GR irradiation at four different dose rates with an absorbed dose of 3 kGy.

Effect of irradiation at different dose rates on capsaicinoids content

The pungent constituents in red pepper are capsaicin, dihydrocapsaicin, and nordihydrocapsaicin (Schweiggert et al. 2006) and therefore, their concentrations were evaluated. Table 2 shows the change in the capsaicinoids content of the samples after each treatment. The HPLC profiles depicting the effects of variable EB and GR dose rates on the capsaicinoids content of irradiated RPP are shown in Fig. 2. The total capsaicinoids content varied between 66.7 and 105.9 mg/100 g (58.8% increase). The results indicated that the capsaicin, dihydrocapsaicin, and nordihydrocapsaicin contents increased at low dose rates (1 kGy/s, 1.8 kGy/h) of both EB and GR irradiation, respectively. The maximum total capsaicinoids (105.9 mg/100 g, 103.3 mg/100 g) content including capsaicin, dihydrocapsaicin, and nordihydrocapsaicin were observed in the RPP samples irradiated with a low dose rate of GR (1.8 kGy/h) and EB (1 kGy/s), respectively.

Cheok et al. (2017) reported that high thermal treatment (80 °C, 21.6 min) caused a significant ($p < 0.05$) decrease by 62.18, 64.72, and 62.95% in the contents of capsaicin, dihydrocapsaicin, and nordihydrocapsaicin, respectively. Cheon et al. (2015) reported a significantly ($p < 0.05$) increased capsaicinoid levels in RPP after minimal heat treatment at 65 °C. Also, irradiated paprika showed increase in the capsaicinoids content as observed by Topuz and Ozdemir (2004). Irradiation treatment may result in conversion of molecules and enhanced extraction yield, thereby increasing the inherent constituents.

Table 2 Impact of variable dose rates (kGy/time) on capsaicinoids content in powdered red pepper before and after irradiation

Capsaicinoids (mg/100 g)	Non-irradiated (absorbed dose — 0 kGy)	Irradiation treatment (Absorbed dose — 3 kGy)			
		Electron beam (10 MeV)		Gamma ray (Co-60)	
		Dose rate (kGy/s)		Dose rate (kGy/h)	
		1	5	1.8	9
Capsaicin	35.8 $\pm$ 0.63 ^a	40.9 $\pm$ 0.32 ^d	39.9 $\pm$ 0.10 ^c	41.5 $\pm$ 0.25 ^d	38.6 $\pm$ 0.38 ^b
Dihydrocapsaicin	29.5 $\pm$ 0.63 ^a	33.2 $\pm$ 0.85 ^c	32.8 $\pm$ 0.28 ^c	34.0 $\pm$ 0.68 ^d	31.6 $\pm$ 0.18 ^b
Nordihydrocapsaicin	ND ^{1a}	28.4 $\pm$ 0.43 ^b	28.0 $\pm$ 0.15 ^b	29.0 $\pm$ 0.07 ^c	27.9 $\pm$ 0.51 ^b
Total ²	66.7 $\pm$ 1.02 ^a	103.3 $\pm$ 1.47 ^c	102.1 $\pm$ 0.26 ^c	105.9 $\pm$ 0.96 ^d	99.1 $\pm$ 0.51 ^b

^{a-d}Mean $\pm$ standard deviation from three replications. Values with different letter in the same row are significantly different ($p < 0.05$) by Duncan's multiple range test

¹Not detected—Peak width (min) $\leq$ 0.06

²Total (capsaicin + dihydrocapsaicin + nordihydrocapsaicin)

Effect of irradiation at different dose rates on vitamin C content

Vitamin C is the most sensitive antioxidant to food processing methods. Therefore, to maintain the vitamin C content at a desired level in decontaminated products, irradiation treatments should be optimized so that detrimental effects on such micronutrients are minimized. In addition, conditions that allow for a high concentration of

vitamin C with marked stability must be selected. Table 3 shows the change in vitamin C content of RPP as a function of variable dose rate effects under different irradiation conditions. In both EB and GR irradiated RPP, the vitamin C content decreased with the increase in the irradiation dose rates. However, the RPP irradiated at 3 kGy with low dose rate of GR (1.8 kGy/h) contained a higher level (4.75 mg/g) of vitamin C than the samples irradiated at 3 kGy (1.21 mg/g) with high dose rate (9 kGy/h). No

Fig. 2 HPLC chromatograms of irradiated red pepper powder at different dose rates (kGy/time)

significant ($p > 0.05$) difference in vitamin C content was observed between non-irradiated and the samples irradiated at 1.8 kGy/h. This indicated that the degradation of vitamin C during irradiation proceeded via dose rate- and time-dependent reactions.

In contrast to our result, vitamin C of processed RPP products were not detected (< 10 mg/100 g), according to the food composition table (RDA 2001). This low market quality of RPP in terms of vitamin C content may be due to the applied drying process.

Irradiation dose rate effects on TPC

EB and GR irradiation treatment of RPP at different dose rates (1, 5 kGy/s and 1.8, 9 kGy/h) had a significant ($p < 0.05$) effect on the TPC (Table 3). The TPC of RPP irradiated with 1 kGy/s significantly ($p < 0.05$) increased by 21% as compared to the non-irradiated control. This observation agrees with a previous study on mangoes irradiated at 1.5 and 3.1 kGy, which led to slightly higher phenolic content than that of the control (Moreno et al. 2007). Dixit et al. (2010) observed the maximum enhancement of TPC in Hara soya genotype (38%, green seed coat) as well as two other genotypes, NRC37 and Kalitur with 28 and 20%, respectively on 2 kGy GR irradiation.

Lee et al. (2003) indicated significant increase (0.12–0.20 mM) in TPC of rice hull on far-infrared radiation (FIR, 50 min). FIR cleaved and liberated the phenolics that were covalently bound either to high molecular weight compounds or subunits of polymers. Oufedjikh et al. (2000) reported an increase in the TPC of 0.3 kGy irradiated and stored Moroccan citrus fruits. Phenolics content increased in potato tubers exposed to low GR dose (Pendharkar and Nair 1995). The irradiation-induced flavonoid metabolism leading to increased phenolics concentration has been documented in citrus fruits such as Clementines and mandarins subjected to an X-ray dose of 0.8 kGy (Shen et al. 2013).

The difference in the levels of phenolic compounds on irradiation are attributed to the type of phenolics present in the spices. Variyar et al. (1998) observed increased phenolic content in gamma irradiated clove and nutmeg due to the presence of highly susceptible hydrolysable tannins, while cardamom and cinnamon with condensed tannins did not exhibit an increase on irradiation. Harrison and Were (2007) suggested that gamma irradiation (12 kGy) degrades large phenolic compounds to small constituents by releasing them from glycosidic linkages as observed by the increased phenolic content in almond skin extracts. Modified cell structures as a stress response of the tissues to irradiation, enhanced extractability and permeability that facilitates contact between the enzymes and substrates

results in the buildup of phenolic compounds (Moreno et al. 2006).

Effect of irradiation at different dose rates on DPPH radical scavenging activity of RPP

The depletion of DPPH after the addition of antioxidants can be measured by UV/visible spectroscopy ($\lambda_{\text{max}} = 517$ nm) (Foti and Ruberto 2001). In our experiments, ethanol solutions of DPPH were mixed with aqueous RPP extracts prepared from non-irradiated as well as EB and GR treated samples (dose rates 1, 5 kGy/s and 1.8, 9 kGy/h), and the changes in DPPH concentration were monitored by UV/vis spectroscopy. The presence of antioxidants in the RPP extract caused substantial inhibition of the DPPH free radical after the addition of various sample extracts compared to the blank as shown in Table 3. The obtained values confirmed that the radical-scavenging activity of the aqueous extracts prepared from the non-irradiated RPP is distinguishable from those prepared from the EB- and GR-treated samples at dose rates of 5 kGy/s or 9 kGy/h. However, the extracts prepared from the RPP samples processed at a low GR dose rate (1.8 kGy/h) showed lower ability to neutralize DPPH.

Calucci et al. (2003) reported 14% reduction in ascorbate of 10 kGy GR irradiated RPP samples. Similar to the TPC, the antioxidant activities increased after the application of a high dose rate (9 kGy/h) in the GR-irradiated samples and a low dose rate in the EB-irradiated samples. The DPPH radical scavenging activity of rice hull extracts increased (47.74–81.60%) after FIR treatment for 60 min (Lee et al. 2003). Choi et al. (2009) reported rise in antioxidant activity of gamma-irradiated seaweeds. The increased scavenging activity might be due to the radiolysis-induced breakdown and depolymerization to low molecular weight subunits, which exposed their hydroxyl groups as well as decreased intramolecular hydrogen bonding.

Effect of irradiation at different dose rates on ABTS radical scavenging activity of RPP

The trolox equivalent (TE) values of RPP subjected to EB irradiation at 1 and 5 kGy/s dose rates were 2.33 and 2.36 mg TE/mL, respectively in the ABTS radical-scavenging assay. The corresponding values for RPP subjected to GR irradiation at 1.8 and 9 kGy/h were 2.27 and 2.30 mg TE/mL (Table 3). Although the antioxidant activities increased at low EB and GR dose rates, the antioxidant activities of RPP irradiated by high dose rates were higher than those irradiated by low dose rates in the ABTS radical scavenging assay. In contrast to the DPPH radical scavenging activity, the variations above were

Table 3 Changes in vitamin C, total phenolics, DPPH and ABTS radical scavenging activities of irradiated red pepper powder at different dose rates (kGy/time)

Irradiation source	Dose rate	Absorbed dose (kGy)	Vitamin C (mg/g)	Total phenolics (mg/g)	DPPH (mg TE/mL)	ABTS (mg TE/mL)
Control (non-irradiated)		0	4.77 ± 0.07 ^d	55.6 ± 0.25 ^a	1.25 ± 0.01 ^a	2.29 ± 0.07 ^a
Electron beam (10 MeV)	1 kGy/s	3	4.49 ± 0.03 ^c	67.3 ± 0.51 ^e	1.29 ± 0.01 ^b	2.33 ± 0.01 ^a
	5 kGy/s		3.71 ± 0.04 ^b	62.8 ± 0.28 ^d	1.36 ± 0.01 ^c	2.36 ± 0.01 ^a
Gamma ray (Co-60)	1.8 kGy/h		4.75 ± 0.04 ^d	58.4 ± 1.40 ^b	1.23 ± 0.02 ^a	2.27 ± 0.07 ^a
	9 kGy/h		1.21 ± 0.02 ^a	60.5 ± 0.75 ^c	1.29 ± 0.00 ^b	2.30 ± 0.06 ^a

^{a–e}Mean ± standard deviation from three replications. Values with different letter in the same column are significantly different ($p < 0.05$) by Duncan's multiple range test

Table 4 Moisture content and water activity of irradiated red pepper powder at different dose rates (kGy/time)

Irradiation source	Dose rate	Absorbed dose (kGy)	Moisture (%)	Water activity (a_w)
Control (non-irradiated)		0	13.6 ± 0.19 ^b	0.54 ± 0.00 ^a
Electron beam (10 MeV)	1 kGy/s	3	14.0 ± 0.37 ^{bc}	0.58 ± 0.00 ^c
	5 kGy/s		14.2 ± 0.15 ^c	0.59 ± 0.00 ^d
Gamma ray (Co-60)	1.8 kGy/h		14.0 ± 0.66 ^{bc}	0.60 ± 0.00 ^e
	9 kGy/h		12.8 ± 0.22 ^a	0.56 ± 0.01 ^b

^{a–e}Mean ± standard deviation from at least three replications. Values with different letters in the same column are significantly different ($p < 0.05$) by Duncan's multiple range test

negligible (not significant) compared to the non-irradiated sample. Low dose gamma irradiation of soybean genotypes induced breakdown of glycosides and released free isoflavones thereby enhancing the antioxidant activity (Variyar et al. 2004, Dixit et al. 2010). New compounds with high antioxidant and solubility are formed on gamma irradiation of dry rosemary. The presence of such compounds in the rosemary extract explains the increased antioxidant activity in irradiated samples (Pérez et al. 2007).

Effect of irradiation at different dose rates on moisture content and water activity of RPP

The effect of different EB (kGy/s) and GR (kGy/h) dose rates on the moisture content of RPP is shown in Table 4. The moisture content of the non-irradiated RPP control sample was 13.6%. The data showed that GR irradiation at a high dose rate (9 kGy/h) decreased the moisture content in RPP. The moisture reduction in the GR-treated sample was likely due to the higher temperature of the products and irradiation as compared to the EB treatment. The temperature of the product may increase by 5 °C at a dose of 10 kGy (Sádecká 2007). The moisture content of RPP may vary from 6 to 12% (Sharma et al. 2005). Rico et al. (2010) found that the irradiation of dried red pepper at a

10 kGy dose promoted a reduction in the moisture. However, the moisture of lotus remained unchanged on gamma irradiation (6 kGy) as compared to the control (Khattak and Simpson 2009). Composition of cell membranes and connective tissues change (Josephson and Peterson 2018) due to radiation induced depolymerization of polysaccharides (Wilkinson and Gould 1998) resulting in softening of foods and water release.

The water activity of the non-irradiated RPP control sample was 0.54 and a significant change ($p < 0.05$) was observed in the water activity, irrespective of the irradiation conditions (Table 4). GR irradiation resulted in an increased water activity in the RPP. The increase in the water activity of RPP following GR irradiation might be due to the decrease in moisture content and the amount of other organic compounds. Although thermal treatments can lower the moisture content and water activity to the level required for preventing the growth of microorganisms, the quality of the final product will be unpalatable. To improve the purity and safety of the spice products, monitoring some of the physical characteristics such as moisture is desirable (Abba et al. 2009). Optimization of the irradiation process for the post-harvest preservation of spices and herbs contributes to the physical, chemical, and microbiological stability of the spices.

Conclusion

The current study compared the efficiency of irradiation treatments with different dose rates on RPP and their effects on the bioactive constituents of the irradiated and non-irradiated samples. It is more effective to use low EB and GR dose rates to overcome the loss of quality components observed at high irradiation dose rates. The aqueous RPP extracts showed substantial ability to inhibit DPPH and ABTS radicals, and these free radical scavenging activities were influenced by both EB and GR irradiation treatments up to dose rates of 5 kGy/s and 9 kGy/h, respectively. This approach does not show detrimental effects on the quality of RPP. Thus, they can be utilized during decontamination interventions as they have very important implications on food quality, since spices such as RPP are added to a variety of foods. Eventually, this approach may enhance the food quality in industrial applications.

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