Available online at www.sciencedirect.com

SCIENCE DIRECT

Food Chemistry 89 (2005) 589–597

Food Chemistry

www.elsevier.com/locate/foodchem

Combined effects of irradiation and modified atmosphere packaging on minimally processed Chinese cabbage (*Brassica rapa* L.)

Hyun-Joo Ahn [a], Jae-Hyun Kim [a], Jae-Kyung Kim [a], Dong-Ho Kim [a], Hong-Sun Yook [b], Myung-Woo Byun [a,*]

[a] *Department of Radiation Food Science and Biotechnology, Korea Atomic Energy Research Institute, P.O. Box 105, Yusong, Daejeon 305-353, Republic of Korea*

[b] *Department of Food and Nutrition, Chungnam National University, Daejeon 305-764, Republic of Korea*

Received 7 January 2004; received in revised form 8 March 2004; accepted 8 March 2004

Abstract

Cut Chinese cabbage with air, CO_2 or CO_2/N_2 packaging was irradiated at doses up to 2 kGy and the microbiological and physicochemical qualities were investigated during a refrigerated storage for 3 weeks. Irradiation significantly reduced the microorganisms, and additionally, the modified atmosphere packaging (MAP) enhanced the reduction of the total aerobic and coliform bacteria during storage. Irradiation effectively inhibited the changes of the titratable acidity and pH, while a significant effect was not shown in the texture by irradiation. Antiradical and antioxidant activity, and the phenolic contents were slightly increased by irradiation at 0.5 kGy, while the phenolic contents were reduced by irradiation over 1 kGy. Our results suggest that irradiation at 1 kGy or above can be used to enhance the microbial safety of cut Chinese cabbage without a significant loss in the quality attributes.

Keywords: Irradiation; Modified atmosphere packaging; Minimal processing; Chinese cabbage; Microbial safety

1. Introduction

Consumer demand for minimally processed fresh produce has been increasing due to premium product quality, convenience, and fresh-like character (Ohlsson, 1994). Although great interest in minimally processed vegetable and fruit products exists little commercial success has been achieved (Gorney & Kader, 1996). Several preservation methods, including antioxidant treatment, modified atmosphere packaging (MAP), refrigeration, chlorine wash and irradiation have been applied to minimally processed produce (Ahvenainen, 1996; DeDaza, Alzaora, & Chanes, 1996; Hoover, 1997; Xu, 1999). In present day commercial processes for preparing fresh-cut lettuce, chlorine is used to control the microbial population in the wash water. King, Magnuson, Torok, and Goodman (1991) reported the microbial populations found on fresh-cut iceberg lettuce prepared with the use of chlorine water. However, according to Nguyen-the and Carlin (1994) chlorine cannot be relied on to eliminate pathogenic microorganisms such as *Listeria monocytogenes.*

It has been suggested that microorganisms in fresh-cut vegetables should be controlled with hurdle technology, for example, the addition of irradiation to the present chlorine-based commercial process (Fan, Niemira, & Sokorai, 2003a; Thayer, 1995; Wiley, 1994). Irradiation doses up to 1 kGy for fresh produce are permitted in the United States (FDA, 1995), while 1 kGy for mushrooms is permitted in Korea. Ionizing radiation is well known as the best method to eliminate pathogenic and spoilage microorganisms without compromising the nutritional properties or sensory quality of foods, and its use has been gradually increasing worldwide (WHO, 1999).

Kimchi, a representative Korean salted and fermented vegetable, has an important role in the diet and nutrition of Koreans (Lee, 1997), and has become popular throughout the world. The main material for

* Corresponding author. Tel.: +82-42-868-8060; fax: +82-42-868-8043.

E-mail address: mwbyun@kaeri.re.kr (M.-W. Byun).

0308-8146/$ - see front matter
doi:10.1016/j.foodchem.2004.03.029

manufacturing *Kimchi* is Chinese cabbage, and it is a widely used vegetable, especially in Asia. Therefore, the present study was designed to investigate the irradiation effects on minimally processed salted Chinese cabbage aimed at manufacturing *Kimchi*. Accordingly, Chinese cabbage was salted, packaged with a modified atmosphere, and irradiated. Thus, no information is available for minimally processed cut Chinese cabbage.

The purpose of this study is to provide information to help determine what role irradiation, in combination with a MAP, may have in improving and extending the quality of cut Chinese cabbage.

2. Materials and methods

2.1. Sample preparation

Salted Chinese cabbage (*Brassica rapa* L.) was prepared by the method of Mheen and Kwon (1984) with some modifications. The Chinese cabbages were washed with tap water, and then were cut into 4 cm × 5 cm pieces. The cut samples were drained and salted by dipping in a 15% salt solution for 3 h. After removal from the salt solution, the pieces were washed and drained. At this time, the salt concentration of the sample was $2.9 \pm 0.15\%$. Cut samples (200 g) were packed into oxygen-impermeable nylon bags (2 ml O_2/m^2/24 h at 0 °C; 20 cm × 20 cm; Sunkyung Co. Ltd, Seoul, Korea) for the 3 treatments. The bags were sealed in air or flushed with CO_2 (ultra pure CO_2, 99.999%) or CO_2/N_2 mixture (25% CO_2 + 75% N_2) using a packaging machine (Leepack, Hanguk Electronic, Kyungi, Korea), respectively. All the samples were stored in a 4 °C refrigerator before irradiation.

The samples were irradiated in a cobalt-60 irradiator (Nordion International, Ottawa, Ontario, Canada). The source strength was about 100 kCi with a dose rate of 5 $kGy\,h^{-1}$ at 11 ± 0.5 °C. Dosimetry was performed using 5-mm diameter alanine dosimeters (Bruker Instruments, Rheinstetten, Germany), and the free radical signal was measured using a Bruker EMS 104 EPR Analyzer. The absorbed doses in this study were 0, 0.5, 1, and 2 kGy, and the actual doses were within ±2% of the target dose. After irradiation, the sample was analyzed, and the remainder of the samples were immediately stored at 4 °C for 3 weeks.

2.2. Microbial analysis

Samples (50 g) and 250 ml of sterile 0.1% peptone water (Difco Labs., Detroit, MI, USA) were homogenized using a stomacher lab blender (Model 400, Tekmar Co., Cincinnati, Ohio, USA). A series of decimal dilutions was prepared with sterile peptone. Plate count agar (Difco Labs., Detroit, MI, USA), incubated at 37 °C for 2 days, was used to determine the total aerobic bacteria. EMB agar (Difco) for the coliform bacteria and MRS agar (Difco) for the lactic acid bacteria were used and enumerated after 2 days of incubation at 35 °C. Microbial counts were expressed as $\log_{10}$ CFU/g.

2.3. Sample extraction

Samples (20 g) and distilled water (180 ml) or 80% ethanol were homogenized with a homogenizer (DIAX 900, Heidolph, Schwabach, Germany). Both homogenates were filtered with a filter paper (No. 4, Whatman International Ltd., Kent, UK), and then centrifuged (5000 rpm, 10 min, 4 °C). The supernatant of the water extract was used for pH and titratable acidity, and the ethanol extract was used for the analysis of the phenolic contents, DPPH radical-scavenging capacity and FRAP assay.

2.4. pH and titratable acidity

The pH of the extract was measured using a portable pH-meter (Orion 520A, Orion Research Inc., Boston, MA, USA). Titratable acidity was measured by titrating 20 ml of the extract with a 0.1 N NaOH solution to pH 8.3, and converting as lactic acid content (mg/dl).

2.5. Phenolic contents

Total phenolic contents were measured using the Folin–Ciocalteau colorimetric method (Gao, Bjork, Trajkovski, & Uggla, 2000). The extract (0.9 ml) was mixed with 0.1 ml of 50 units/ml of ascorbic oxidase and then incubated at 23 °C for 90 min to remove the ascorbic acid. Then the ascorbic acid-free extract (0.1 ml) was mixed with 0.2 ml of Folin–Ciocalteau reagent (Sigma Chemical Co., St. Louis, MO, USA) and incubated for 1 min at 23 °C. Then 3 ml/of 5% Na_2CO_3 were added. Absorbance at 765 nm was recorded for the mixtures after 2 h of incubation at 23 °C. Phenolic content was expressed as gallic acid equivalents.

2.6. DPPH radical-scavenging capacity

The free radical-scavenging effect was estimated according to the method of Blois (1958) with some modifications. The extract (1 ml) was added to 0.2 mM 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical (Sigma–Aldrich Co., St. Louis, MO, USA, 1 ml). The mixture was shaken and left to stand for 30 min at room temperature and measured at 517 nm with a spectrophotometer (model UV-1601PC, Shimadzu Co.). The DPPH radical-scavenging capacity was estimated from the difference between the absorbances with and without samples, and expressed as a percentage of the DPPH scavenging during storage for 2 weeks at 4 °C.

2.7. FRAP assay

The FRAP (ferric reducing/antioxidant power) assay was performed as previously described by Benzie and Strain (1996) using a spectrophotometer (Bio-Tek Instruments) with the function of an auto-rate assay. In the FRAP assay, reductants in the sample reduce the Fe(III)/tripyridyltriazine complex, present in stoichiometric excess, to the blue ferrous form, with an increase in the absorbance at 593 nm. Absorbance readings were taken after 0.5 s and every 30 s thereafter during the monitoring period for 5 min, and then the readings at 4 min were used as the FRAP value.

2.8. Texture measurement

The texture analysis for the sample was performed using a Texture Analyzer (Model TA-XT 2i, Stable micro systems Ltd., Surrey, UK). Puncture strength (N/mm) was measured by the method of Song, Kim, Yook, Kim, and Kim (2004) with some modifications, as the penetration force required for puncturing the sample using a 2-mm cylinder probe, and the data were processed by a texture expert software system (V. 1.22).

2.9. Statistical analysis

Experiments were designed as 4 (irradiation dose) $\times$ 3 (packaging) $\times$ 4 (storage) factorials. The study, from the sample preparation to the analysis, was done in triplicate, and the data were then analyzed by SAS software (V. 8.02, SAS Institute, Cary, NC). The general linear model procedure was processed and Duncan's multiple range test was used to compare the mean values at $P < 0.05$. Mean values and pooled standard errors of the mean (SEM) were recorded.

3. Results and discussion

3.1. Microbial populations

Both irradiation and packaging effects on minimally processed salted Chinese cabbage were observed in the populations of the total aerobic, coliform and lactic acid bacteria (Table 1). The initial populations of the total aerobic bacteria in salted Chinese cabbage were significantly reduced by gamma irradiation at 0.5 kGy or above ($P < 0.05$). Approximately a 2–3 log CFU/g was reduced by irradiation, while the non-irradiated control showed the highest populations in the samples. Chervin and Boisseau (1994) reported that the growth of aerobic and lactic microflora on shredded carrots was inhibited by irradiation at 2 kGy and chlorination, and the sensory analysis panellists preferred the irradiated vegetables. MA packaging effects were also observed, and the aerobic bacteria, under 100% CO_2 or 25% CO_2/75% N_2 conditions, showed significantly lower levels compared to the aerobic packaging ($P < 0.05$). As this atmosphere contained higher carbon dioxide levels, it inhibited the aerobic microbial growth. Zagory (1999) reported that an elevated CO_2 condition extends the lag phase of the bacterial growth and can slow the propagation of the bacteria. Irradiation effects, which reduced the levels of aerobic bacteria in salted Chinese cabbage, were maintained, irrespective of its packaging condition, during storage for 3 weeks at 4 °C. At 3 weeks, aerobic bacteria were not detected in the samples irradiated at 2 kGy. Coliform bacterial counts in the samples were also reduced by irradiation, and the combined treatment of irradiation and MA packaging was helpful in reducing the populations at all the storage durations. After 3 weeks of storage, coliform bacteria in the Chinese cabbage treated with both irradiation and MA packaging were not detected, while the samples under an aerobic conditions showed a 2–4 $\log_{10}$ CFU/g. These results indicated that the combined treatment of irradiation and MA packaging is more useful for inhibiting the growth of the aerobic and coliform bacteria than when these treatments are used alone. However, the growth patterns in the lactic acid bacteria were somewhat different from the total aerobic or coliform bacteria. Lactic acid bacteria increased substantially during storage, coinciding with the higher levels of the CO_2 packaging conditions. After storage, a higher CO_2 condition showed significantly higher levels of lactic acid bacteria than the aerobic ones, but irradiation reduced the lactic acid bacteria in the salted Chinese cabbage even at a higher CO_2. This result was very consistent with the study of Brackett (1987). He reported that a low O_2 is likely to favour the microaerophilic microbes, such as *Listeria* spp. and lactic acid bacteria. Other workers have reported that storage in reduced O_2 and elevated CO_2 increased the edible shelf life of several products from 14 to 21 days (Berrang, Brackett, & Beuchat, 1990). In this study, the cut Chinese cabbage contained 3% of salt, which might be somewhat helpful for inhibiting microbial growth.

Results indicated that the irradiation at 2 kGy and MA packaging were effective in gaining the microbial safety of the fresh-cut and salted Chinese cabbage during refrigerated storage. Some studies have shown that a smaller irradiation dose can be applied for microbial safety. Prakash, Manley, DeCosta, Caporaso, and Foley (2002) reported that irradiation at 0.5 kGy can reduce the microbial counts of diced tomatoes substantially to improve the microbial shelf life without any adverse effects on the sensory qualities. Therefore, irradiation effects on various, vegetables and fruits for the development of minimally processed foods should be carried out. Thayer and Rajkowski (1999) concluded that ionizing radiation could penetrate the entire product to

Table 1
Microbial populations ($\log_{10}$ CFU/g) of minimally processed salted Chinese cabbage treated with modified atmosphere packaging and irradiation during refrigerated storage

Storage (week)	Packaging	Total aerobic bacteria					Coliform bacteria					Lactic acid bacteria				
		0[A]	0.5	1	2	SEM[B]	0[A]	0.5	1	2	SEM[B]	0[A]	0.5	1	2	SEM[B]
0	Air	7.3ax	5.8bx	5.3bcx	4.5cx	0.56	6.4ax	5.7a	3.9b	2.7c	0.56	6.7ax	6.0ab	5.4bx	3.3c	0.23
	CO_2	5.6ay	4.1bz	3.9bz	3.0cy	0.21	5.7ay	5.3b	3.4c	2.3d	0.34	5.8ay	5.7a	4.9by	3.0c	0.97
	CO_2/N_2	5.9ay	5.2aby	4.4bcy	3.2cy	0.35	4.9az	4.6a	3.7b	2.4c	0.88	6.0ay	6.2a	4.3bz	3.5b	1.23
	SEM[C]	0.19	0.04	0.14	0.23		0.07	0.14	0.34	0.21		0.24	0.13	0.22	0.38	
1	Air	7.0ax	6.7ax	4.7b	4.0b	0.64	6.2ax	4.9b	4.9bx	3.3c	0.09	6.4a	6.1a	4.4by	3.0cy	0.20
	CO_2	5.4ay	4.9by	4.1b	3.5c	0.34	5.1ay	4.5ab	3.8by	3.2 b	0.24	6.8a	6.6ab	5.2by	4.6cx	0.56
	CO_2/N_2	5.8ay	5.0by	4.2c	3.8d	0.47	5.7axy	4.1b	3.5cy	2.8d	0.30	6.5a	6.1ab	5.1bx	4.3cx	0.31
	SEM[C]	0.22	0.15	0.36	0.78		0.42	0.23	0.11	0.17		0.29	0.37	0.16	0.63	
2	Air	8.2ax	8.0ax	7.1bx	5.2cx	0.19	6.8ax	6.0abx	5.6bx	3.9c	0.31	7.2a	6.0b	5.1c	4.2dy	0.32
	CO_2	5.9aay	5.4aay	5.1ay	3.3bz	0.32	5.3ay	4.7ay	3.3bz	2.8c	0.24	7.5a	5.9b	5.6b	5.1bx	0.30
	CO_2/N_2	6.2ay	5.7aby	5.2by	4.3cy	13	5.1ay	4.5by	4.3by	2.5c	0.18	7.1a	6.2ab	5.0b	5.0bx	0.15
	SEM[C]	0.25	0.22	0.62	0.14		0.23	0.18	0.35	0.23		0.33	0.31	0.52	0.23	
3	Air	6.2a	5.0bx	3.8cx	d[D]	0.32	4.0ax	3.3ax	2.4b	c	0.45	6.1ay	6.0a	4.5by	cy	0.36
	CO_2	4.7a	3.4by	2.3cy	d	0.27	y	y	–	–	–	7.2ax	5.9b	5.1bcx	4.1cx	0.23
	CO^2/N_2	5.0a	4.9ax	2.5by	c	0.20	y	y	–	–	–	7.0ax	6.2ab	5.3bcx	4.3cx	0.26
	SEM[C]	0.31	0.25	0.22	–		0.14	0.07	0.23	–		0.39	0.31	0.41	0.13	

Values with different letters (a–d) within a row differ significantly ($P < 0.05$).
Values with different letters (x–z) within a column differ significantly ($P < 0.05$).
[A] Irradiation dose (kGy).
[B] SEM: Standard error of the mean ($n = 12$).
[C] SEM: Standard error of the mean ($n = 9$).
[D] Not detected ($< 2.0\ \log_{10}$ CFU/g).

inactivate the pathogens, and it is a promising technology that could be used to improve the safety of ready-to-eat fruits and vegetables.

3.2. pH and titratable acidity

Immediately after gamma irradiation, effects of MA packaging and irradiation were not shown in the pH of salted Chinese cabbage (Table 2). During storage for 3 weeks, the pH was gradually decreased in all the samples. After storage, an irradiation effect was observed, and a decrease of the pH in the Chinese cabbage only with the aerobic packaging was significantly inhibited by gamma irradiation. A packaging effect was also observed, and the pH of the non-irradiated sample with MA packaging was lower than that of the aerobic packaging at 1 week. This result might be correlated with the growth of the lactic acid bacteria, because the populations of the lactic acid bacteria under MA packaging were significantly higher than under aerobic packaging.

Titratable acidity (TA) of the minimally processed salted Chinese cabbage during storage is shown in Table 3. Generally, the TA of salted Chinese cabbage for *Kimchi* (Korean fermented vegetable) manufacture increases during storage, due to the growth of the lactic acid bacteria immediately after salting (Song et al., 2004). Accordingly, the TA for all the samples increased during storage. A statistically significant difference was observed immediately after gamma irradiation, and the irradiated samples showed a low TA compared to the non-irradiated control ($P < 0.05$). These irradiation effects were maintained during storage. Production of lactic and acetic acid from lactic acid bacteria in stored vegetable has been reported (Carlin, Nguyen-the, Cudennec, & Reich, 1989; Marchetti, Casadei, & Guerzoni, 1992). Our results showed that irradiation reduced the lactic acid bacteria levels in the Chinese cabbage, and consequently, the changes of the pH and TA were inhibited by gamma irradiation. MA packaging caused the increase of the TA in some samples, which were the kGy-irradiated samples in storage for 0 and 2 weeks, but a significant effect of the packaging environments was not found in the other storage. Prakash et al. (2002) reported that gamma irradiation at 0.5 to 3.7 kGy had no significant effect on the pH, or the titratable acidity of fresh-cut tomatoes for 8 days of storage. However, the present results have suggested that irradiation could inhibit the changes of the pH and TA of cut Chinese cabbage stored for 3 weeks.

3.3. Phenolic contents and antioxidant activity

Total soluble phenolic compounds were monitored in the Chinese cabbage during refrigerated storage (Table 4). Generally, gamma irradiation at 1 kGy or above significantly reduced the phenolic contents in the cut Chinese cabbage irrespective of the packaging conditions during storage; however, an the increase of the total phenolics by irradiation at 0.5 kGy was observed in some samples. There have been different results reported for irradiation effects on the phenolic compounds in the

Table 2
pH of minimally processed salted Chinese cabbage treated with modified atmosphere packaging and irradiation during refrigerated storage

Storage (week)	Packaging	Irradiation dose (kGy)				SEM[A]
		0	0.5	1	2	
0	Air	6.48	6.61	6.57	6.64	0.098
	CO_2	6.53	6.55	6.46	6.49	0.045
	CO_2N_2	6.46	6.58	6.61	6.56	0.076
	SEM[B]	0.065	0.126	0.016	0.024	
1	Air	6.62x	6.61y	6.67	6.68x	0.069
	CO_2	6.60xy	6.66x	6.65	6.65xy	0.131
	CO_2/N_2	6.56y	6.63xy	6.63	6.61y	0.125
	SEM[B]	0.013	0.101	0.091	0.062	
2	Air	6.29by	6.58a	6.58a	6.60a	0.047
	CO_2	6.75ax	6.60ab	6.62ab	6.57b	0.131
	CO_2/N_2	6.67xy	6.58	6.58	6.60	0.048
	SEM[B]	0.061	0.093	0.120	0.203	
3	Air	5.91bz	6.03ab	6.49a	6.46a	0.221
	CO_2	6.52x	6.57	6.51	6.54	0.078
	CO_2/N_2	6.35y	6.47	6.46	6.49	0.072
	SEM[B]	0.161	0.034	0.067	0.082	

Values with different letters (a,b) within a row differ significantly ($P < 0.05$).
Values with different letters (x–z) within a column differ significantly ($P < 0.05$).
[A] SEM: Standard error of the mean ($n = 12$).
[B] SEM: Standard error of the mean ($n = 9$).

Table 3
Titratable acidity (mg/dl) of minimally processed salted Chinese cabbage treated with modified atmosphere packing and irradiation during refrigerated storage

Storage (week)	Packaging	Irradiation dose (kGy)				SEM[A]
		0	0.5	1	2	
0	Air	0.52	0.48	0.47	0.40y	0.094
	CO_2	0.54a	0.50ab	0.47b	0.46bx	0.013
	CO_2/N_2	0.55a	0.46b	0.45b	0.47bx	0.037
	SEM[B]	0.011	0.034	0.050	0.099	
1	Air	0.49	0.47	0.43	0.45	0.091
	CO_2	0.51b	0.57a	0.57a	0.58a	0.011
	CO_2/N_2	0.63	0.50	0.58	0.53	0.034
	SEM[B]	0.018	0.032	0.024	0.071	
2	Air	0.59a	0.49b	0.48b	0.46cy	0.045
	CO_2	0.58	0.59	0.54	0.56x	0.021
	CO_2/N_2	0.57	0.59	0.60	0.61x	0.046
	SEM[B]	0.031	0.017	0.065	0.010	
3	Air	0.59a	0.51b	0.43c	0.42c	0.030
	CO_2	0.51a	0.50a	0.43b	0.47ab	0.031
	CO_2/N_2	0.54	0.48	0.40	0.37	0.012
	SEM[B]	0.039	0.020	0.029	0.038	

Values with different letters (a–c) within a row differ significantly ($P < 0.05$).
Values with different letters (x,y) within a column differ significantly ($P < 0.05$).
[A] SEM: Standard error of the mean ($n = 12$).
[B] SEM: Standard error of the mean ($n = 9$).

Table 4
Phenolic compounds (μg/g sample) of minimally processed salted Chinese cabbage treated with modified atmosphere packaging and irradiation during refrigerated storage

Storage (week)	Packaging	Irradiation dose (kGy)				SEM[A]
		0	0.5	1	2	
0	Air	125a	118b	117by	120b	12.4
	CO_2	124b	130a	115cy	116c	5.09
	CO_2/N_2	128a	122b	122bx	119c	8.45
	SEM[B]	10.7	9.50	3.16	7.22	
1	Air	129ax	125b	126bx	120c	4.56
	CO_2	117y	119	118y	119	2.64
	CO_2/N_2	119y	116	120y	115	10.2
	SEM[B]	4.34	8.83	3.22	2.93	
2	Air	134ax	131ax	126bx	123b	9.32
	CO_2	112bz	115ay	113ay	111b	10.1
	CO_2/N_2	123ay	129ax	114by	117b	8.79
	SEM[B]	4.05	8.39	10.2	7.75	
3	Air	146ab	162ax	136b	129b	9.57
	CO_2	133a	129bz	128b	131ab	5.65
	CO_2/N_2	130b	140ay	130b	123b	11.0
	SEM[B]	2.21	9.72	3.83	5.10	

Values with different letters (a–c) within a row differ significantly ($P < 0.05$).
Values with different letters (x–z) within a column differ significantly ($P < 0.05$).
[A] SEM: Standard error of the mean ($n = 12$).
[B] SEM: Standard error of the mean ($n = 9$).

foods. Villavicencio, Mancini-Filho, Delincee, and Greiner (2000) reported that irradiation at 10 kGy significantly reduced the total phenolics in Macaçar bean. However, Fan, Toivonen, Rajkowski, and Sokorai (2003b) reported that irradiation induced phenolics synthesis in fresh-cut iceberg lettuce treated by warm water dipping. During irradiation the free radicals generated may act as stress signals and may trigger stress responses in the vegetables, resulting in an increased antioxidant synthesis (Fan et al., 2003b). Breitfellner, Solar, and Sontag (2002) reported that radiolysis of the phenolics, such as gallic acid, 4-hydroxybenzoic acid, cinnamic acid, *p*-coumaric acid and caffeic acid, in aqueous solutions led to their efficient degradation and to a notable hydroxylation; however, in the complex matrix of the food no hydroxylation products were formed and only the concentration of 4-hydroxybenzoic acid was affected by irradiation. These results indicated that water or other food components in foods might affect the synthesis or degradation of the phenolics. Packaging effects were also observed, and phenolics under aerobic conditions significantly increased during storage. Howard, Griffin, and Lee (1994) reported that the increase of the phenolics in air is related to the polymerization of the phenols catalyzed by microbial oxidases. The study by Amanatidou, Slump, Gorris, and Smid (2000) was consistent with our results, and they reported that high carbon dioxide conditions were effective in reducing the total phenolics, in minimally processed carrots when compared to the air conditions.

Antiradical capacity of the minimally processed Chinese cabbage after irradiation is shown in Table 5. Immediately after irradiation, the stable DPPH radical-scavenging capacity was reduced by irradiation at 2 kGy, while the antiradical capacity of the irradiated Chinese cabbage was higher than that of the non-irradiated control after storage. Fan et al. (2003b) reported that the antioxidant activity of iceberg lettuce was increased by irradiation from 0.5 to 2 kGy, and this result was positively correlated with the phenolics contents. Packaging effects were shown in some irradiated samples after storage, and the radical-scavenging activity under a MAP was higher than under aerobic packaging even with a lower phenolics content. These results were somewhat different with the phenolic contents explained above. Cao, Sofic, and Prior (1996) reported that phenolics and ascorbic acid are major antioxidants in fruit and vegetables, and the MAP was effective in retaining the ascorbic acid levels. Although the phenolic content, as an antioxidant, under air was higher than under MAP, ascorbic acid may play an important role in maintaining the antioxidative activity of the Chinese cabbage with a MAP.

A similar result was shown in the FRAP value (Table 6). Irradiation at 0.5 kGy caused an antioxidant activity increase at week 0. Results indicated that irradiation at 0.5 kGy increased or maintained the antioxidant activity of the minimally processed Chinese cabbage.

3.4. Texture

Immediately after irradiation, the puncture strength of the minimally processed Chinese cabbage did not show a consistent change in response to the irradiation dose during refrigerated storage (Table 7). After 3 weeks of storage, a reduction of the puncture strength in Chinese cabbage with aerobic packaging was observed, while the MAP was effective in maintaining the texture property. Amanatidou et al. (2000) reported that carrots

Table 5
DPPH radical-scavenging capacity (%) of minimally processed salted Chinese cabbage treated with modified atmosphere packaging and irradiation during refrigerated storage

Storage (week)	Packaging	Irradiation dose (kGy)				SEM[A]
		0	0.5	1	2	
0	Air	45.9a	47.9a	36.8b	37.4b	2.05
	CO_2	41.6b	47.3a	46.7a	44.8b	1.71
	CO_2/N_2	41.5ab	42.4a	42.0a	40.5b	0.87
	SEM[B]	2.09	0.96	2.11	1.78	
1	Air	40.9	42.3	39.7y	42.1	1.27
	CO_2	35.5b	34.1b	44.3ax	47.9a	0.85
	CO_2/N_2	40.7b	48.7a	46.4ax	45.4a	0.19
	SEM[B]	1.25	1.08	0.97	0.73	
2	Air	38.4	36.5y	37.1y	39.3y	2.01
	CO_2	40.2	43.5x	41.3x	45.0xy	0.97
	CO_2/N_2	38.4c	35.5cy	45.1bx	48.3ax	1.09
	SEM[B]	1.20	2.50	1.09	0.99	
3	Air	41.6b	44.2a	42.2aby	45.9a	0.86
	CO_2	42.8b	43.5b	47.2ax	47.9a	2.21
	CO_2/N_2	45.9	48.2	48.0x	49.2	1.11
	SEM[B]	1.50	1.31	0.38	1.41	

Values with different letters (a–c) within a row differ significantly ($P < 0.05$).
Values with different letters (x,y) within a column differ significantly ($P < 0.05$).
[A] SEM: Standard error of the mean ($n = 12$).
[B] SEM: Standard error of the mean ($n = 9$).

Table 6
FRAP value (μM FRAP/g of sample) of minimally processed salted Chinese cabbage treated with modified atmosphere packaging and irradiation during refrigerated storage

Storage (week)	Packaging	Irradiation dose(kGy)				SEM[A]
		0	0.5	1	2	
0	Air	280b	313ay	245by	266b	20.0
	CO_2	273b	302ay	284bx	258b	10.5
	CO_2/N_2	272b	367ax	263bxy	263b	14.9
	SEM[B]	19.80	11.7	10.4	9.53	
1	Air	331a	302b	305b	323ab	9.04
	CO_2	301b	362a	360a	303b	13.6
	CO_2/N_2	358a	327ab	315bc	304c	21.0
	SEM[B]	158	8.63	21.4	10.4	
2	Air	375ax	325a	281b	250b	10.44
	CO_2	316y	291	301	296	8.69
	CO_2/N_2	374x	325	300	310	16.5
	SEM[B]	17.2	10.0	20.0	19.2	
3	Air	360ay	295by	310aby	299by	19.6
	CO_2	410x	375xy	388x	386x	21.0
	CO_2/N_2	408x	414x	386x	390x	13.5
	SEM[B]	15.8	25.0	16.3	20.6	

Values with different letters (a–c) within a row differ significantly ($P < 0.05$).
Values with different letters (x,y) within a column differ significantly ($P < 0.05$).
[A] SEM: Standard error of the mean ($n = 12$).
[B] SEM: Standard error of the mean ($n = 9$).

Table 7
Puncture strength (N/mm) of minimally processed salted Chinese cabbage treated with modified atmosphere packaging and irradiation during refrigerated storage

Storage (week)	Packaging	Irradiation dose (kGy)				SEM[A]
		0	0.5	1	2	
0	Air	0.34b	0.40ax	0.33b	0.38ab	0.021
	CO_2	0.35	0.36y	0.36	0.36	0.017
	CO_2/N_2	0.33	0.36y	0.34	0.35	0.009
	SEM[B]	0.008	0.010	0.039	0.026	
1	Air	0.33	0.31	0.35	0.34	0.013
	CO_2	0.34	0.36	0.34	0.34	0.040
	CO_2/N_2	0.33	0.34	0.34	0.34	0.018
	SEM[B]	0.012	0.007	0.006	0.019	
2	Air	0.35b	0.43a	0.35b	0.37b	0.005
	CO_2	0.34	0.35	0.32	0.33	0.011
	CO_2/N_2	0.34b	0.35ab	0.37a	0.37a	0.007
	SEM[B]	0.011	0.010	0.027	0.013	
3	Air	0.36a	0.31by	0.32by	0.29by	0.023
	CO_2	0.35	0.41x	0.38x	0.36x	0.002
	CO_2/N_2	0.32c	0.38ax	0.37ax	0.36bx	0.016
	SEM[B]	0.010	0.008	0.009	0.012	

Values with different letters (a–c) within a row differ significantly ($P < 0.05$).
Values with different letters (x,y) within a column differ significantly ($P < 0.05$).
[A] SEM: Standard error of the mean ($n = 36$).
[B] SEM: Standard error of the mean ($n = 27$).

stored in air were significantly softer after 12 days of storage, and the loss of firmness under air may be related to an increased proliferation of the pectolytic pseudomonas. Fan et al. (2003b) reported that irradiation had no effect on the firmness or Hunter colour parameters of the minimally processed iceberg lettuce but increased the antioxidant and phenolic contents. In this study, the CIE $L^*a^*b^*$ value was analyzed, and the irradiation or packaging effects were not observed (data not shown).

In conclusion, the present study has demonstrated that gamma irradiation is useful for assuring the microbial safety of minimally processed Chinese cabbage without a significant loss of quality. Accordingly, a workable dose range for irradiating fresh-cut Chinese cabbage is 1–2 kGy when considering the microbial safety. Thus, a combination with a MAP is helpful for retaining the physicochemical quality rather than the microbial safety during storage. Therefore, a low-dose irradiation might be an appropriate technology for manufacturing minimally processed vegetables and fruits.

Acknowledgements

This research was supported under the Nuclear R&D Program by the Ministry of Science and Technology in Korea.

References

Ahvenainen, R. (1996). New approaches in improving the shelf life of minimally processed fruits and vegetables. *Trends in Food Science and Biotechnology, 7*, 179–187.

Amanatidou, A., Slump, R. A., Gorris, L. G. M., & Smid, E. J. (2000). High oxygen and high carbon dioxide modified atmospheres for shelf-life extension of minimally processed carrots. *Journal of Food Science, 65*, 61–66.

Benzie, I. F. F., & Strain, J. J. (1996). The ferric reducing ability of plasma as a measure of antioxidant power: The FRAP assay. *Analytical Biochemistry, 239*, 70–76.

Berrang, M. E., Brackett, R. E., & Beuchat, L. R. (1990). Microbial, color and textural qualities of fresh asparagus, broccoli and cauliflower stored under controlled atmosphere. *Journal of Food Protection, 53*, 391–395.

Blois, M. S. (1958). Antioxidant determination by the use of a stable free radical. *Nature, 181*, 1190–1200.

Brackett, R. E. (1987). Microbiological consequences of minimally processed fruits and vegetables. *Journal of Food Quality, 10*, 195–206.

Breitfellner, R., Solar, S., & Sontag, G. (2002). Effect of gamma irradiation on phenolic acids in strawberries. *Journal of Food Science, 67*, 517–521.

Cao, G., Sofic, E., & Prior, R. L. (1996). Antioxidant capacity of tea and common vegetables. *Journal of Agricultural and Food Chemistry, 44*, 3426–3431.

Carlin, F., Nguyen-the, C., Cudennec, P., & Reich, M. (1989). Microbiological spoilage of ready-to-use grated carrots. *Sciences Des Aliments, 9*, 371–386.

Chervin, C., & Boisseau, P. (1994). Quality maintenance of "ready-to-eat" shredded carrots by gamma irradiation. *Journal of Food Science, 59*, 359–361.

DeDaza, M. S. T., Alzaora, S. M., & Chanes, J. W. (1996). Combination of preservation factors applied to minimal processing of foods. *Critical Reviews in Food Science and Nutrition, 36*, 629–659.

Fan, X., Niemira, B. A., & Sokorai, K. J. B. (2003a). Use of ionizing radiation to improve sensory and microbial quality of fresh-cut green onion leaves. *Journal of Food Science, 68*, 1478–1483.

Fan, X., Toivonen, P. M. A., Rajkowski, K. T., & Sokorai, K. J. B. (2003b). Warm water treatment in combination with modified atmosphere packaging reduces undesirable effects of irradiation on the quality of fresh-cut iceberg lettuce. *Journal of Agricultural and Food Chemistry, 51*, 1231–1236.

FDA (1995). Section 179.26: Ionizing radiation for the treatment of food. In *Code of federal regulations: Food and drugs*. Title 21. Washington, DC: US Government Printing Office (pp. 389–390).

Gao, X., Bjork, L., Trajkovski, V., & Uggla, M. (2000). Evaluation of antioxidant activities of rosehip ethanol extracts in different test system. *Journal of Science of Food and Agriculture, 80*, 2021–2027.

Gorney, J. R., Kader, A. A., (1996). Fresh cut fruit products. In *Fresh-cut products maintaining quality and safety*. Postharvest Horticulture Series No. 10. Davis, California: University of California (pp. 14.1–14.10).

Hoover, D. G. (1997). Minimally processed fruits and vegetables: reducing microbial load by nonthermal physical treatments. *Food Technology, 51*, 66–71.

Howard, L. R., Griffin, L. E., & Lee, Y. (1994). Steam treatment of minimally processed carrots sticks to control surface discoloration. *Journal of Food Science, 59*, 356–358.

King, A. D., Magnuson, J. A., Torok, T., & Goodman, N. (1991). Microbial flora and storage quality of partially processed lettuce. *Journal of Food Science, 56*, 459–461.

Lee, C. H. (1997). Lactic acid fermented foods and their benefits in Asia. *Food Control, 8*, 259–269.

Marchetti, R., Casadei, M. A., & Guerzoni, M. E. (1992). Microbial population dynamics in ready-to-use vegetable salads. *Italian Journal of Food Science, 2*, 97–108.

Mheen, T. I., & Kwon, T. W. (1984). Effect of temperature and salt content on *Kimchi* fermentation. *Korean Journal of Food Science and Technology, 16*, 443–450.

Nguyen-the, C., & Carlin, F. (1994). The microbiology of minimally processed fresh fruits and vegetables. *Critical Reviews in Food Science and Nutrition, 34*, 371–401.

Ohlsson, T. (1994). Minimal processing – preservation methods of the future – an overview. *Trends in Food Science and Technology, 5*, 341–344.

Prakash, A., Manley, J., DeCosta, S., Caporaso, F., & Foley, D. (2002). The effects of gamma irradiation on the microbiological, physical and sensory qualities of diced tomatoes. *Radiation Physics and Chemistry, 63*, 387–390.

Song, H. P., Kim, D. H., Yook, H. S., Kim, M. R., & Kim, K. S. (2004). Nutritional, physiological, physicochemical and sensory stability of gamma irradiated *Kimchi* (Korean fermented vegetables). *Radiation Physics and Chemistry, 69*, 85–90.

Thayer, D. W. (1995). Use of irradiation to kill enteric pathogens on meat and poultry. *Journal of Food Safety, 15*, 181–192.

Thayer, D. W., & Rajkowski, K. T. (1999). Developments in irradiation of fresh fruits and vegetables. *Food Technology, 53*, 62–65.

Villavicencio, A. L. C. H., Mancini-Filho, J., Delincee, H., & Greiner, R. (2000). Effect of irradiation on anti-nutrients (total phenolics, tannins and phytate) in Brazilian beans. *Radiation Physics and Chemistry, 57*, 289–293.

WHO (1999). High dose irradiation. In *Wholesomeness of food irradiated with doses above 10 kGy*. WHO Technical Report Series 890. Geneva: World Health Organization (pp. 9–37).

Wiley, R. C. (1994). Preservation methods for processed refrigerated fruits and vegetables. In R. C. Wiley (Ed.), *Preservation methods for processed refrigerated fruits and vegetables* (pp. 66–134). New York: Chapman & Hall.

Xu, L. (1999). Use of ozone to improve the safety of fresh fruits and vegetables. *Food Technology, 53*, 58–61.

Zagory, D. (1999). Effects of post-processing handling and packaging on microbial populations. *Postharvest Biology and Technology, 15*, 313–321.