Korean J Food Preserv, 29(5), 677-691 (2022)
https://doi.org/10.11002/kjfp.2022.29.5.677
pISSN: 1738-7248, eISSN: 2287-7428

Korean Journal of Food Preservation

Research Article

Effect of nano-foamed structure film packaging on the quality of young radish (*Raphanus sativus* L.) *kimchi* during storage under supercooled and refrigerated conditions

Miran Kang[1†], So Yoon Park[1,2†], Bo Sung Shin[3], Sung Moo Hong[4], Young Jin Choi[5], Ho Hyun Chun[1]*

[1]*Eco-Friendly Process Technology Research Group, World Institute of Kimchi, Gwangju 61755, Korea*
[2]*Department of Integrative Food, Bioscience and Biotechnology, Graduate School of Chonnam National University, Gwangju 61186, Korea*
[3]*Department of Optics and Mechatronics Engineering, Pusan National University, Busan 46241, Korea*
[4]*Interdisciplinary Department for Advanced Innovative Manufacturing Engineering, Pusan National University, Busan 46241, Korea*
[5]*GQINS, Gimhae 50878, Korea*

Abstract This study investigated changes in the quality and headspace O_2/CO_2 concentrations of young radish (*Raphanus sativus* L.) *kimchi* (YR-*kimchi*) packaged using a multilayer (ML) film with or without sachets containing a CO_2 absorber and nano-foamed structure (NFS) film, respectively, during storage at -2.2 or 4.0℃. Compared to that in YR-*kimchi* samples stored at 4.0℃, the total lactic acid bacteria count and titratable acidity of YR-*kimchi* samples stored at -2.2℃ increased rapidly until 21 days of storage, irrespective of the packaging. After 32 days of storage at 4.0℃, the reducing sugar content of young radish *kimchi* packaged in ML film, ML film with a CO_2 absorber sachet, and NFS film decreased by 54.9, 80.7, and 79.9%, respectively, compared to before storage. However, the salinity of YR-*kimchi* samples packaged with different film types showed negligible differences during storage at -2.2 and 4.0℃. No significant O_2 reduction or CO_2 accumulation was observed in the headspace of NFS film-packaged young radish *kimchi* stored at either temperature. Hence, these results indicated that NFS film packaging combined with supercooled (-2.2℃) storage improved the shelf life of YR-*kimchi* without packaging expansion during storage.

Keywords young radish *kimchi*, nano-foamed structure film, storage, quality

OPEN ACCESS

Citation: Kang M, Park SY, Shin BS, Hong SM, Choi YJ, Chun HH. Effect of nano-foamed structure film packaging on the quality of young radish (*Raphanus sativus* L.) *kimchi* during storage under supercooled and refrigerated conditions. Korean J Food Preserv, 29(5), 677-691 (2022)

Received: February 14, 2022
Revised: June 23, 2022
Accepted: July 11, 2022

†These authors contributed equally to this study.

***Corresponding author**
Ho Hyun Chun
Tel: +82-62-610-1761
E-mail: hhchun@wikim.re.kr

1. Introduction

The Korean *kimchi* market continues to grow due to the increase of dual-income households, emphasis on convenience in eating, and changes in economic and social aspects such as nuclear families (Kim et al., 2022; Nam et al., 2021). According to the "Survey on the *Kimchi* Industry in 2020" published by Korea Agro-Fisheries & Food Trade Corporation, the total supply of *kimchi* distributed in Korea in 2020 was approximately 1,774,975 tons. Among them, the supply of *kimchi* manufactured by domestic *kimchi* processing companies was 407,734 tons, accounting for 23% (Korea Agro-Fisheries & Food Trade Corporation, 2022). In addition, the export volume of *kimchi* in 2021 was 42,544 tons, reaching approximately 159.91 million USD. In 2021, the *kimchi* trade balance turned into a surplus for the first time since 2009 (Korea Agro-Fisheries & Food Trade Corporation, 2022).

Food packaging maintains the original value by safely protecting the product during distribution and providing consumer convenience for handling (Shao et al., 2021). The main packaging types used for *kimchi* are polyvinylchloride (PVC)/low density polyethylene (LDPE) trays, glass/plastic rigid containers, and polyethylene (PE)/polypropylene (PP)/multilayer pouch type films (Jeong and Yoo, 2016). PVC/LDPE trays are recyclable and have excellent transportability, but have the disadvantages of large volume and relatively high price (Park et al., 2011). Rigid containers have the advantages of reusability and excellent appearance after opening. However, their use is limited to *kimchi* packaging due to low space efficiency, economic feasibility, and risk of damage during transportation (Lee et al., 2012). The pouch-type plastic films can be manufactured to meet various *kimchi* packaging specifications, from small to large packaging, and are most widely used in the Korean *kimchi* industry because they are cheaper than plastic trays and rigid containers (Hong et al., 1995; Lee et al., 2019).

Generally, the temperature of refrigerated food display showcases in large discount stores or general retail stores is controlled in the range of 4-10℃ (Choi et al., 2020; González et al., 2013). After ~10 days in that temperature, the pH of *kimchi* decreases to 4.5 or less, thus increasing the acidity. In addition, the volume of the sealed *kimchi* film packaging expands due to the accumulation of CO_2 generated during the fermentation of lactic acid bacteria (Jaisan et al., 2019). Consumers do not favor *kimchi* stored in expanded packaging because it is perceived as overripened (Lee et al., 2001). In addition, when exported, *kimchi* transported by sea for an extended period may rapidly ferment when exposed to inappropriate temperatures. Accordingly, the sealed packaging may not withstand internal pressure and may be damaged, resulting in leakage (Hong et al., 1996). Therefore, it is important and urgent to develop packaging technology that can secure the stability of *kimchi* during storage or distribution to expand the consumption and export of *kimchi* produced in Korea.

A technique of attaching a CO_2 absorbent or a one-way gas release valve to the packaging film has been used by a small number of *kimchi* manufacturers to prevent packaging expansion or damage of plastic film pouch-packed *kimchi* during storage and distribution (Jeong et al., 2019; Shin et al., 2002). However, these packaging techniques have not been widely used in the *kimchi* industry because they increase the unit price of packaging or require the construction of separate packaging equipment (Lee et al., 2014). Non-perforated/perforated films with improved gas permeability by laser pulse superposition or micro perforators with hot needle technology are slow in manufacturing because a process of re-coating holes formed by physical processing with the thin film is required. In addition, these films have rough cross-sections, and microcracks may occur around the holes, which can cause leakage of liquid content in the package (Lee et al., 2014).

The nanofoam films developed in this study were manufactured by adding a foaming agent that responds to UV wavelengths to PE films with low light absorption and then form micro-nano

https://doi.org/10.11002/kjfp.2022.29.5.677

structures with laser radiation. These films can form nanoscale porous structures with gas permeability over the entire area. In addition, it is possible to improve the production rate of the films because the superposition of laser pulses during the processing of nanoform films is not necessary.

Previous studies have modeled the changes in packaging volume after packaging Chinese cabbage *kimchi* using laminated films with $Ca(OH)_2$ sachet (Jaisan et al., 2019), analyzed headspace CO_2 concentration change in packaging during storage of Chinese cabbage *kimchi* with micro-perforated film packaging, film packaging attached with a check valve, and vacuum packaging (Hong et al., 1996), and the effect of vacuum packaging, heat treatment, and combination of gamma irradiation on the quality of Chinese cabbage *kimchi* during storage at 35℃ (Kim et al., 1994). However, to date, there has been no study on the application of nanofoam film to improve the stability of *kimchi* packaging.

Therefore, in this study, we tried to secure basic data for a new *kimchi* packaging technique by analyzing the effect of the nanofoam film packaging on the microbiological and physicochemical qualities and packaging stability of young radish *kimchi* during supercooled and low temperature storage.

2. Materials and methods

2.1. Materials

Young radish *kimchi* produced in July 2021 from PPEC Global Kimchi (Iksan, Korea) was purchased and used as samples for this study. Young radish *kimchi*, purchased as experimental material in a refrigerated state, was transported to a laboratory in Gwangju and stored for approximately 15 h in low-temperature storage set at -1℃ before packaging and storage experiments. The main ingredient of young radish *kimchi* is salted ponytail radish (84%). The seasoning used for mixing contains onion, glutinous rice paste, green onion, red pepper powder, refined salt, garlic, shrimp fish sauce, anchovy fish sauce, kelp base, red pepper, ginger, anchovy powder, xanthan gum, and lactic acid starter.

2.2. Packaging and storage methods

Each 400 g of young radish *kimchi* was packed and sealed in multilayer (ML) film pouches [polyethylene terephthalate (PET)/aluminum (AL)/PE, 17.5×22.5 cm, 0.1 mL O_2/m^2·day·atm, GQGONE Co., Gimhae, Korea] with or without a CO_2 absorber sachet, and nano-foamed structure (NFS) breathable film pouch (17.5×22.5 cm, 40,000 mL O_2/m^2·day·atm, GQGONE Co., Gimhae, Korea). NFS breathable films have a double-layer structure in which the outer and inner layers are adhered. After laminating PET/AL/LDPE for the outer layer, micro-perforations were formed to secure ventilation passages. In the inner layer, several nanostructures (pores/channels) were formed by irradiating a pulsed laser beam (AONano 355-5-30-V, Advanced Optowave Co., Ronkonkoma, NY, USA) onto a film in which LDPE with low light absorption in the UV range of 200-400 nm and a foaming agent (azodicarbonamide) with relatively high light absorption were mixed.

In preliminary experiments, the freezing and supercooling points of young radish *kimchi* samples were -1.9±0.1℃ and -4.5±0.3℃, respectively. Therefore, the supercooling storage temperature was set to -2.2℃, which is lower than the freezing point of the samples. Packed young radish *kimchi* samples were stored at -2.2±0.3℃ and 4.0±1℃ for 32 days, and the quality and changes of headspace gas concentration in the package were analyzed. A young radish *kimchi* sample packaged in an ML film pouch without a CO_2 absorbers sachet was used as a control group.

2.3. Microbial analysis

The microbial analysis was conducted based on the standard analysis method of AOAC and food code (Cheon et al., 2016). Young radish *kimchi* samples (20 g) were placed in a sterile stomacher bag containing 180 mL of sterile physiological saline (0.85% NaCl) and homogenized for 3 min with a stomacher (Bagmixer R400, Interscience Inc., Saint Nom, France). After serially diluting the homogenate solution, 1 mL of each dilution was inoculated into the medium. A 3M Petrifilm™ lactic acid bacteria count plate (Petrifilm LAB, 3M Co., St. Paul, MN, USA) and 3M Petrifilm™ yeast and mold count plate (Petrifilm YM, 3M Co.) were used as total lactic acid bacteria, yeast, and mold, respectively. Total lactic acid bacteria were cultured at 37℃ for 48 h, and yeast and mold at 25℃ for 72 h. After culturing, media that produced 30-300 colonies were selected. Red colonies were counted for total lactic acid bacteria, and green-blue and multi-colored colonies for yeast and mold, respectively. The number of detected microorganisms was expressed as colony forming unit per gram (CFU/g).

2.4. Analysis of pH and titratable acidity

pH and titratable acidity were measured by standard AOAC methods. Young radish *kimchi* samples were homogenized using a blender (HR1390, Philips, Guangzhou, China) to measure pH and titratable acidity. The pH of the homogenized samples was measured using a multiparameter benchtop meter (Orion VERSA STAR 90, Thermo Fisher Scientific Inc.) equipped with a pH electrode (Orion 8157BNUMD ROSS Ultra pH/ATC Triode, Thermo Fisher Scientific Inc., Chelmsford, MA, USA).

For titratable acidity analysis, 1 g of *kimchi* samples were accurately weighed, diluted 50 times with distilled water, and filtered. The filtrates (20 mL) were titrated with 0.01 N NaOH solution until pH reached 8.3, and the consumed volume of 0.01 N NaOH solution was measured. According to the following equation, titratable acidity was expressed as the amount of lactic acid (%).

Titratable acidity (%)
= [Consumed 0.01 N NaOH volume (mL) × 0.0009 × 0.01 N NaOH solution factor × Dilution factor] / Sample weight (g) × 100

2.5. Analysis of reducing sugar content and salinity

The reducing sugar content was analyzed using the dinitrosalicylic acid (DNS) method (Cheon et al., 2016). After diluting pulverized samples 50-fold with distilled water, 1 mL of the diluted sample solutions was mixed with 3 mL of DNS reagent and heated in a water bath at 100℃ for 5 min. The solutions were cooled at room temperature and then 16 mL of distilled water was added. The absorbance of the reaction solutions was measured using a UV-Vis spectrophotometer (UV-1800, Shimadzu Scientific Instruments Inc., Columbia, MD, USA) at 550 nm. The standard calibration curve was prepared by reacting standard substance glucose (Sigma-Aldrich Co., St. Louis, MO, USA) with various concentrations of the DNS reagent. The reducing sugar content was expressed in mg/g.

Salinity was measured using a digital salinity meter (PAL-ES3, Atago Co. Ltd., Tokyo, Japan) after filtering the solutions of the pulverized samples with two layers of gauze according to the method

https://doi.org/10.11002/kjfp.2022.29.5.677

reported by Li et al. (2017).

2.6. Analysis of headspace O_2 and CO_2 concentrations inside film packaging

The changes in O_2 and CO_2 concentrations (%) inside each film packaging containing young radish *kimchi* samples during storage were measured by attaching a septum to the film surface using a headspace gas analyzer (Checkpoint 3 premium, Dansensor, Ringsted, Denmark) according to the method by Lee et al. (2018).

2.7. Statistical analysis

All results obtained by repeating the experiments three times or more were analyzed and expressed as mean±standard deviation. For the significance of the results, a one-way analysis of variance test was performed as a statistical analysis using the Statistical Package for the Social Science (SPSS, Version 19, SPSS Inc., Chicago, IL, USA) software program. Post hoc testing was performed using Duncan's multiple range test ($p<0.05$).

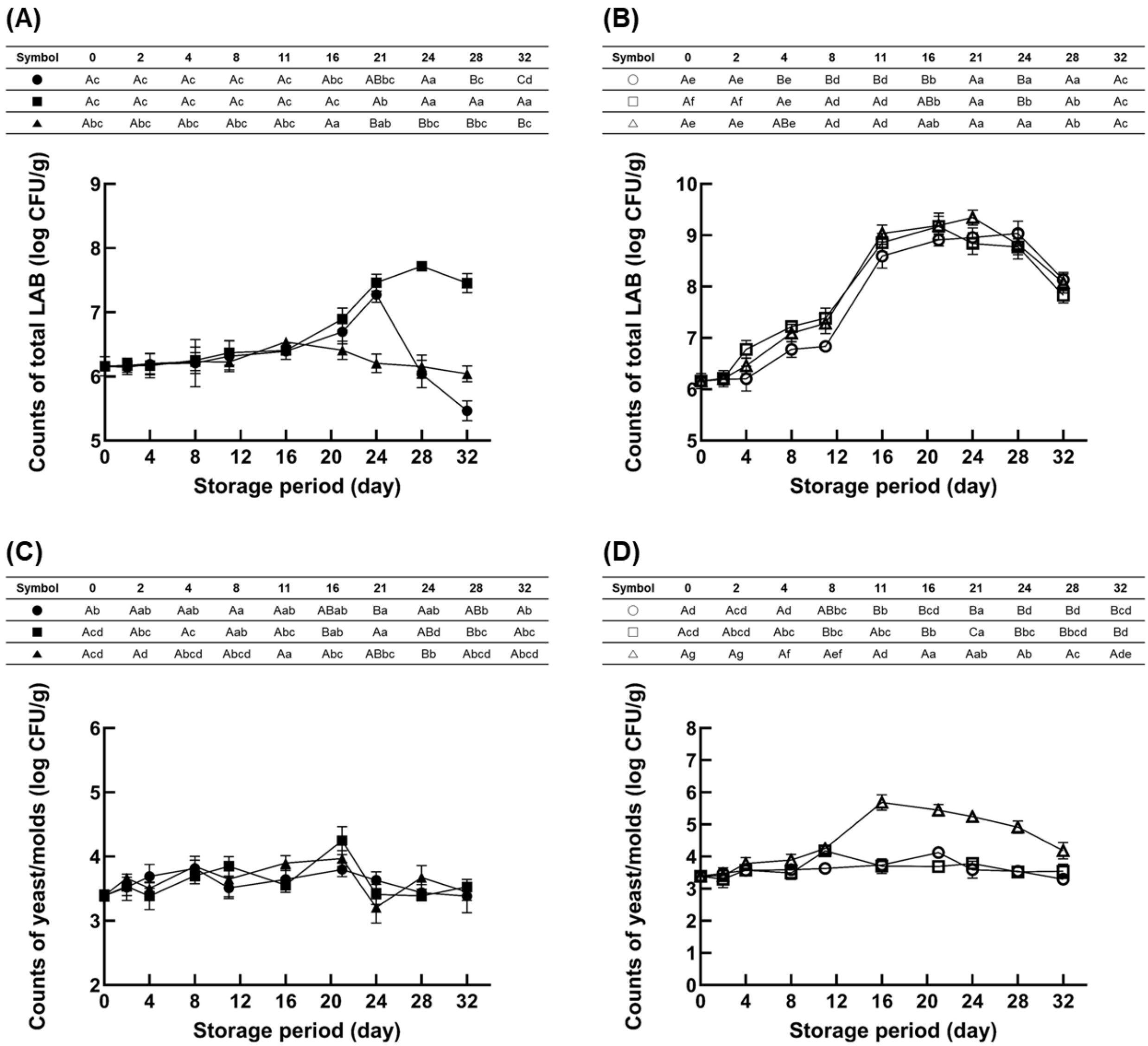
3. Results and discussion

3.1. Changes in the number of microorganisms in young radish kimchi during storage

Kimchi exhibits differences in the rates of fermentation and ripening according to the raw and secondary material content, salinity, packaging method, and storage conditions (Choi et al., 2016). Fig. 1 shows changes in the total number of lactic acid bacteria, yeast, and mold of young radish *kimchi* samples packaged with ML film (control group), ML film with CO_2 absorbers sachet (CDA-film treated group), or NFS breathable film (NFS-film treated group) while storing at -2.2℃ and 4.0℃. At the beginning of storage, the total number of lactic acid bacteria in young radish *kimchi* was 6.2 log CFU/g. The total number of lactic acid bacteria in the young radish *kimchi* samples of the control, CDA-film treated, and NFS-film treated groups when stored at -2.2℃ for 16 days were 6.4-6.5 log CFU/g and the difference was not significant ($p>0.05$) (Fig. 1(A)). Meanwhile, the total number of lactic acid bacteria in the young radish *kimchi* samples stored at 4.0℃ for 16 days in the control, CDA-film treated, and NFS-film treated groups was 8.6-9.0 log CFU/g. Therefore, these results suggest that the storage temperature of -2.2℃, which is below the freezing point of young radish *kimchi*, can effectively inhibit the growth of lactic acid bacteria present in the *kimchi* (Fig. 1(B)).

The change of the headspace gas concentration due to the gas permeability difference of the food packaging film selectively affects the growth of microorganisms (Cayré et al., 2005). According to Argyri et al. (2015), when pickled green table olives were stored at 4℃ for 12 months after packaging in a modified atmosphere of 70% N_2 and 30% CO_2, the number of lactic acid bacteria was maintained lower than before storage. Similarly, after 11 days of storage at 4.0℃, the total number of lactic acid bacteria in the control group with a packaging headspace CO_2 concentration of 38% or higher was 6.8 log CFU/g, which was approximately 0.5 log CFU/g lower than that of the CDA-film or NFS-film treated groups (Fig. 1(B)). During storage at 4.0℃ for 32 days, the total number of lactic acid bacteria in the *kimchi* samples of the control, CDA-film treated, and NFS-film treated groups reached approximately 9 log CFU/g after 28, 21, and 16 days, respectively. Therefore, the packaging method affected the growth pattern of total lactic acid bacteria in the *kimchi* during low-temperature storage.

During storage at -2.2 for 32 days, the number of



(A)

Symbol	0	2	4	8	11	16	21	24	28	32
●	Ac	Ac	Ac	Ac	Ac	Abc	ABbc	Aa	Bc	Cd
■	Ac	Ac	Ac	Ac	Ac	Ac	Ab	Aa	Aa	Aa
▲	Abc	Abc	Abc	Abc	Abc	Aa	Bab	Bbc	Bbc	Bc

(B)

Symbol	0	2	4	8	11	16	21	24	28	32
○	Ae	Ae	Be	Bd	Bd	Bb	Aa	Ba	Aa	Ac
□	Af	Af	Ae	Ad	Ad	ABb	Aa	Bb	Ab	Ac
△	Ae	Ae	ABe	Ad	Ad	Aab	Aa	Aa	Ab	Ac

(C)

Symbol	0	2	4	8	11	16	21	24	28	32
●	Ab	Aab	Aab	Aa	Aab	ABab	Ba	Aab	ABb	Ab
■	Acd	Abc	Ac	Aab	Abc	Bab	Aa	ABd	Bbc	Abc
▲	Acd	Ad	Abcd	Abcd	Aa	Abc	ABbc	Bb	Abcd	Abcd

(D)

Symbol	0	2	4	8	11	16	21	24	28	32
○	Ad	Acd	Ad	ABbc	Bb	Bcd	Ba	Bd	Bd	Bcd
□	Acd	Abcd	Abc	Bbc	Abc	Bb	Ca	Bbc	Bbcd	Bd
△	Ag	Ag	Af	Aef	Ad	Aa	Aab	Ab	Ac	Ade

Fig. 1. Changes in the counts of total lactic acid bacteria (A and B) and yeast/molds (C and D) in young radish *kimchi* in different packaging films during supercooled and refrigerated storage. ●, control (−2.2℃); ■, CDA-film (−2.2℃); ▲, NFS-film (−2.2℃); ○, control (4.0℃); □, CDA-film (4.0℃); △, NFS-film (4.0℃). CDA, carbon dioxide absorber; NFS, nano-foamed structure. Each point represents the mean for triplicates and error bars show standard deviations. A–C and a–g, the upper and lower letters within the same column and row, respectively, indicate statistically significant differences ($p<0.05$).

yeast and mold in the young radish *kimchi* samples of the control, CDA-film treated, and NFS-film treated groups was maintained at 3.4-4.3 log CFU/g (Fig. 1(C)). After storing at 4.0℃ for 16 days, the number of yeast and mold in the NFS-film treated group was 5.7 log CFU/g. On the other hand, the number of yeast and mold in the control and CDA-film treated groups was 3.7 log CFU/g, indicating numbers of yeast and mold according to the packaging method were significantly different ($p<0.05$) (Fig. 1(D)). The pH range for yeast and mold growth was 2.0-8.5. In other words, yeast and mold can grow even in an acidic environment below pH 4 (Martínez-Ferrer, 2002). In this study,

https://doi.org/10.11002/kjfp.2022.29.5.677

the number of yeast and mold in the young radish *kimchi* samples in the control, CDA-film treated, and NFS-film treated groups after storing at 4.0℃ for 24 days was at or above the initial level of storage. Therefore, it is considered that the low pH environment caused by lactic acid fermentation does not significantly affect the growth change of yeast and mold. Similar to this study result, Moon et al. (2019) reported that the pH of Chinese cabbage *kimchi* decreased from 5.5 to 4.0, and the number of yeast was maintained at 3.2-4.6 log CFU/g during storage at 6℃ for 6 weeks, suggesting that the yeast numbers were not affected by the decrease in pH. On the other hand, yeast mainly found in *kimchi* comes from raw materials belonging to the genus *Saccharomyces*, *Pichia*, *Candida*, and *Kazachstania* (Kang et al., 2019). In this study, yeast was predominantly present over mold in young radish *kimchi* in the control, CDA-film treated, and NFS-film treated groups during the storage, based on the identification method for yeast and mold in yeast and mold selective media (data not shown).

3.2. Changes in pH and titratable acidity of young radish kimchi during storage

The changes in pH and titratable acidity of young radish *kimchi* samples in the control, CDA-film treated, and NFS-film treated groups during storage at -2.2℃ and 4.0℃ are shown in Fig. 2. The pH of young radish *kimchi* at the initial stage of storage was 6.1. The pH of young radish *kimchi* in the control, CDA-film treated, and NFS-film treated groups was maintained at 4.9 or higher during storage at -2.2℃ for 32 days (Fig. 2(A)), while that of those stored at 4.0℃ was less than 5 after 11 days of storage, and further decreased to 4.1-4.2 at the end of storage (Fig. 2(B)).

The titratable acidity of young radish *kimchi* before storage was 0.3%. During storage at -2.2℃ for 32 days, the titratable acidity of the control and NFS-film treated groups was maintained at 0.5% or less (Fig. 2(C)). On the other hand, the titratable acidity of the CDA-film treated group stored at -2.2℃ increased to 0.7% at the end of storage, showing a significant difference compared to the control or NFS-film treated group ($p<0.05$).

pH and acidity are important indicators of changes in *kimchi* quality. In general, the fermentation stages of *kimchi* are divided into immature, optimum ripening, over-ripening, and rancid stages. It is known that the optimum-ripening stage is when pH of 4.2-4.5 and titratable acidity of 0.6-0.8% are reached (Jang et al., 2015; Ryu et al., 2019). Changes in pH and titratable acidity of young radish *kimchi* stored at -2.2℃ differed depending on the types of packaging films. However, none of the young radish *kimchi* samples packaged with ML-film, CDA-film, and NFS-film reached the optimum-ripening stage. Therefore, it is considered that the -2.2℃ storage temperature condition can effectively extend the quality maintenance period by suppressing changes in the pH and acidity of *kimchi* during storage. The titratable acidity of the control, CDA-film, and NFS-film treated groups stored at 4.0℃ was increased to 0.8, 1.0, and 0.9% after 16 days of storage, respectively, as the storage period elapsed. Therefore, there was a significant difference between the treatment groups ($p<0.05$) (Fig. 2(D)). On the other hand, the titratable acidity of the control, CDA-film treated, and NFS-film treated groups after storage at 4.0℃ for 32 days was 1.2-1.3%. Therefore, there was no significant difference between treatment groups (Fig. 2(D)). Shin et al. (2002) reported that the attachment of the $NaCO_3$/zeolite mixture-based CO_2 absorbers

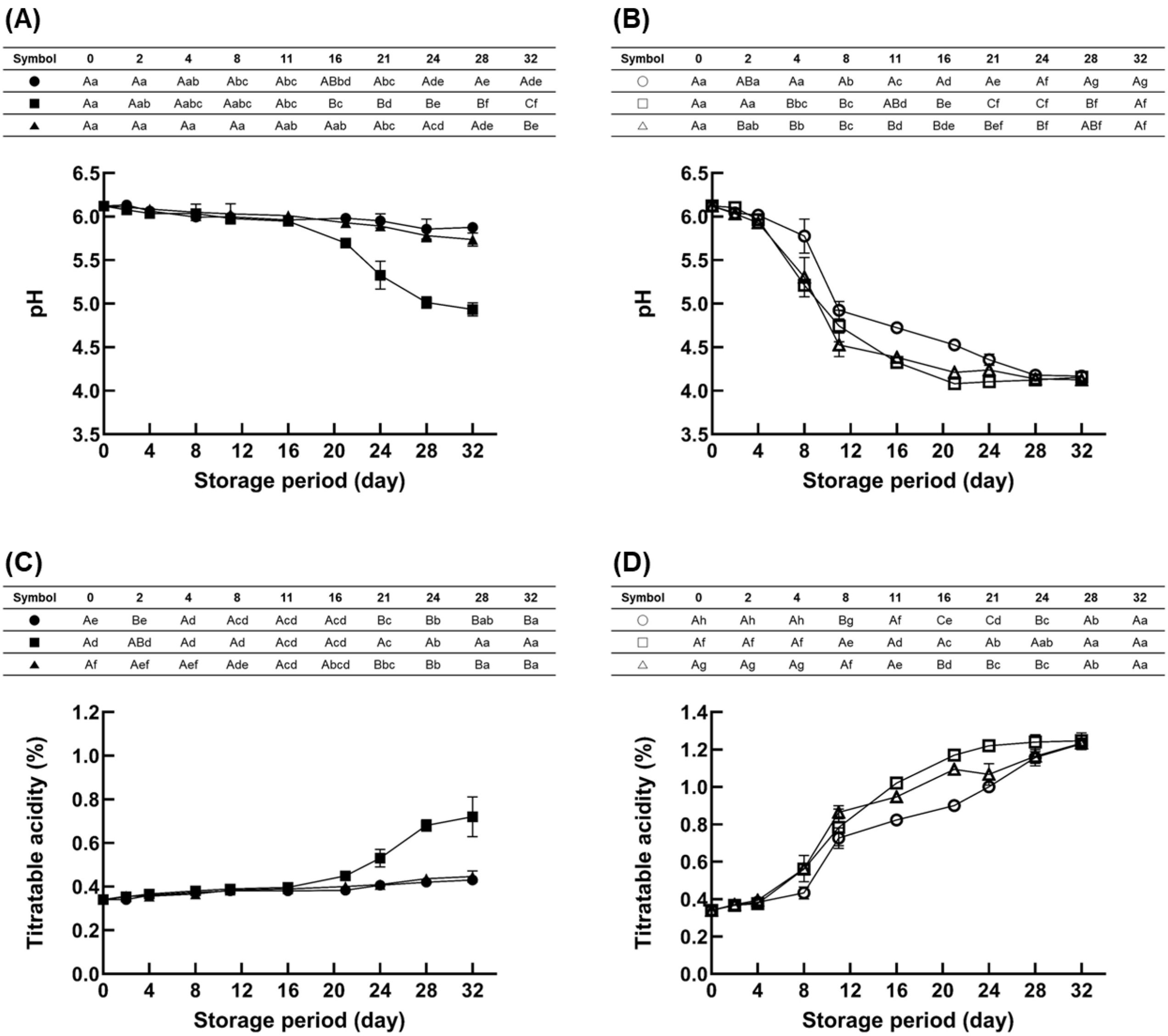


Fig. 2. Changes in the pH (A and B) and titratable acidity (C and D) of young radish *kimchi* in different packaging films during supercooled and refrigerated storage. ●, control (−2.2℃); ■, CDA-film (−2.2℃); ▲, NFS-film (−2.2℃); ○, control (4.0℃); □, CDA-film (4.0℃); △, NFS-film (4.0℃). CDA, carbon dioxide absorber; NFS, nano-foamed structure. Each point represents the mean for triplicates and error bars show standard deviations. A-C and a-h, the upper and lower letters within the same column and row, respectively, indicate statistically significant differences ($p<0.05$).

sachet did not significantly affect the change in titratable acidity of *kimchi* when stored at 15℃ for 8 days after attaching the CO_2 absorbers sachet to the ML film containing sliced cabbage *kimchi*. Lee et al. (2018) reported that when sliced cabbage *kimchi* was packed in PP trays with or without O_2 scavenger prepared using sodium metabisulfite and stored at 0 and 10℃ for 12 weeks, the total number of lactic acid bacteria, pH, and titratable acidity were significantly different depending on whether O_2 scavenger was attached. The changes in pH and titratable acidity of *kimchi* during storage correlate with the initial total number and the growth rate of lactic acid bacteria, and are also affected by the

 https://doi.org/10.11002/kjfp.2022.29.5.677

headspace gas concentration and storage temperature inside the packaging film as external environmental factors, considering the results of these studies.

3.3. Changes in reducing sugar content and salinity of young radish kimchi during storage

Table 1 shows the changes in reducing sugar content of young radish *kimchi* in the control, CDA-film treated, and NFS-film treated groups during storage at -2.2℃ and 4.0℃. The reducing sugar content of young radish *kimchi* at the initial storage stage was 61.2 mg/g. During storage at -2.2℃, the reducing sugar content of young radish *kimchi* in the control, CDA-film treated, and NFS-film treated groups showed a tendency to decrease as the storage period increased. After 32 days of storage, the reducing sugar content was 44.1-49.0 mg/g. The decrease in reducing sugar content in the control, CDA-film treated, and NFS-film treated groups during storage at 4.0℃ was faster than when stored at -2.2℃ (Table 1). When stored at 4.0℃ for 32 days, the reducing sugar contents of young radish *kimchi* in the CDA-film and NFS-film treated groups were 11.8 and 12.3 mg/g, respectively. On the other hand, the reducing sugar content of young radish *kimchi* in the control group was 27.6 mg/g, which showed a significant difference compared with the CDA-film or NFS-film treated groups ($p<0.05$) (Table 1). The difference in reducing sugar content decrease in young radish *kimchi* during storage according to the packaging method is related to the gas composition of the headspace inside the packaging and the fermentation rate of lactic acid bacteria. Similar to the results of this study, Chung et al. (2002) reported that the reducing sugar content of onion *kimchi* packaged in multi-layer film during storage at 5℃ decreased as the storage period increased, which is related to changes in pH and acidity. Based on these results, the residual reducing sugar content in *kimchi* can be used as a quality indicator when evaluating the quality stability of *kimchi* during storage.

Table 2 shows the salinity changes of young radish *kimchi* in the control, CDA-film, and NFS-

Table 1. Changes in the reducing sugar content (mg/g) of young radish *kimchi* in different packaging films during supercooled and refrigerated storage

Storage temperature (℃)	Type of packaging films	Storage period (day)									
		0	2	4	8	11	16	21	24	28	32
-2.2	Control	61.2±1.6[1)]^{Aa}[2)]	58.7±0.9^{Ab}	57.8±0.9^{ABb}	56.9±0.2^{Abc}	55.4±1.3^{Acd}	55.1±0.9^{Ade}	53.2±0.7^{Aef}	53.7±1.6^{Adef}	51.8±0.9^{Af}	49.0±0.6^{Ag}
	CDA-film	61.2±1.6^{Aa}	58.6±1.0^{Ab}	56.3±1.1^{ABbc}	56.2±1.6^{Abc}	55.1±1.9^{Ac}	53.7±1.8^{Ac}	51.0±2.0^{Ad}	50.3±0.9^{Bd}	48.6±1.8^{Ad}	44.1±1.0^{Be}
	NFS-film	61.2±1.6^{Aa}	60.4±0.6^{Aa}	59.3±1.3^{Aa}	56.7±0.6^{Ab}	55.4±0.5^{Abc}	53.4±1.2^{Ad}	53.5±0.7^{Acd}	50.6±0.7^{Be}	49.8±1.8^{Ae}	47.3±1.3^{Af}
4.0	Control	61.2±1.6^{Aa}	54.2±2.7^{Bb}	52.8±4.8^{Cb}	53.3±3.5^{ABb}	49.6±3.5^{Bbc}	50.0±1.1^{Bbc}	46.6±2.4^{Bcd}	45.6±2.2^{Ccd}	43.2±2.9^{Bd}	27.6±1.5^{Ce}
	CDA-film	61.2±1.6^{Aa}	58.4±1.6^{Ab}	54.7±2.5^{BCc}	52.3±1.9^{Bcd}	50.1±0.6^{ABd}	37.4±1.6^{De}	35.0±0.2^{De}	27.9±0.8^{Ef}	27.6±1.1^{Df}	11.8±0.4^{Dg}
	NFS-film	61.2±1.6^{Aa}	54.7±2.1^{Bb}	52.4±0.0^{Cbc}	51.2±1.9^{Bbc}	49.6±5.7^{Bc}	43.1±2.6^{Cd}	39.3±1.4^{Cde}	36.4±0.8^{Def}	34.7±1.6^{Cf}	12.3±2.8^{Dg}

[1)]Each value is mean±SD (n=3).
[2)]Mean values in the same column (A-E), row (a-g) followed by different letters are significantly different according to Duncan's multiple range test ($p<0.05$).

Table 2. Changes in the salinity (%) of young radish *kimchi* in different packaging films during supercooled and refrigerated storage

Storage temperature (℃)	Type of packaging films	Storage period (day)									
		0	2	4	8	11	16	21	24	28	32
-2.2	Control	1.9±0.1$^{1)Aa2)}$	1.8±0.1^{Aab}	1.8±0.1^{Aab}	1.8±0.1^{ABab}	1.9±0.1^{Aa}	1.7±0.1^{Bb}	1.8±0.1^{Bab}	1.8±0.1^{Aab}	1.8±0.1^{Bab}	1.8±0.1^{Bb}
	CDA-film	1.9±0.1^{Aa}	1.9±0.1^{Aa}	1.8±0.1^{Aa}	1.9±0.1^{ABa}	1.9±0.1^{Aa}	1.9±0.1^{ABa}	1.9±0.2^{ABa}	1.9±0.1^{Aa}	1.9±0.1^{ABa}	1.8±0.1^{ABa}
	NFS-film	1.9±0.1^{Aa}	1.8±0.1^{Aa}	1.8±0.1^{Aa}	1.8±0.1^{Ba}	1.9±0.1^{Aa}	1.8±0.1^{ABa}	1.9±0.1^{ABa}	1.9±0.1^{Aa}	1.9±0.1^{ABa}	1.9±0.1^{ABa}
4.0	Control	1.9±0.1^{Aab}	1.9±0.1^{Aab}	1.9±0.1^{Aab}	1.8±0.1^{Bb}	1.9±0.1^{Aab}	1.9±0.1^{ABab}	2.0±0.1^{Aa}	1.9±0.1^{Aab}	2.0±0.1^{Aa}	1.9±0.1^{Aab}
	CDA-film	1.9±0.1^{Aa}	1.9±0.1^{Aa}	1.9±0.1^{Aa}	2.0±0.1^{Aa}	1.9±0.1^{Aa}	1.9±0.1^{Aa}	1.9±0.1^{ABa}	1.9±0.1^{Aa}	2.1±0.1^{Aa}	1.9±0.1^{ABa}
	NFS-film	1.9±0.1^{Aa}	1.9±0.1^{Aa}	1.8±0.1^{Aa}	1.8±0.1^{Ba}	1.9±0.2^{Aa}	1.9±0.1^{ABa}	1.9±0.1^{ABa}	1.9±0.1^{Aa}	1.9±0.1^{ABa}	1.9±0.1^{ABa}

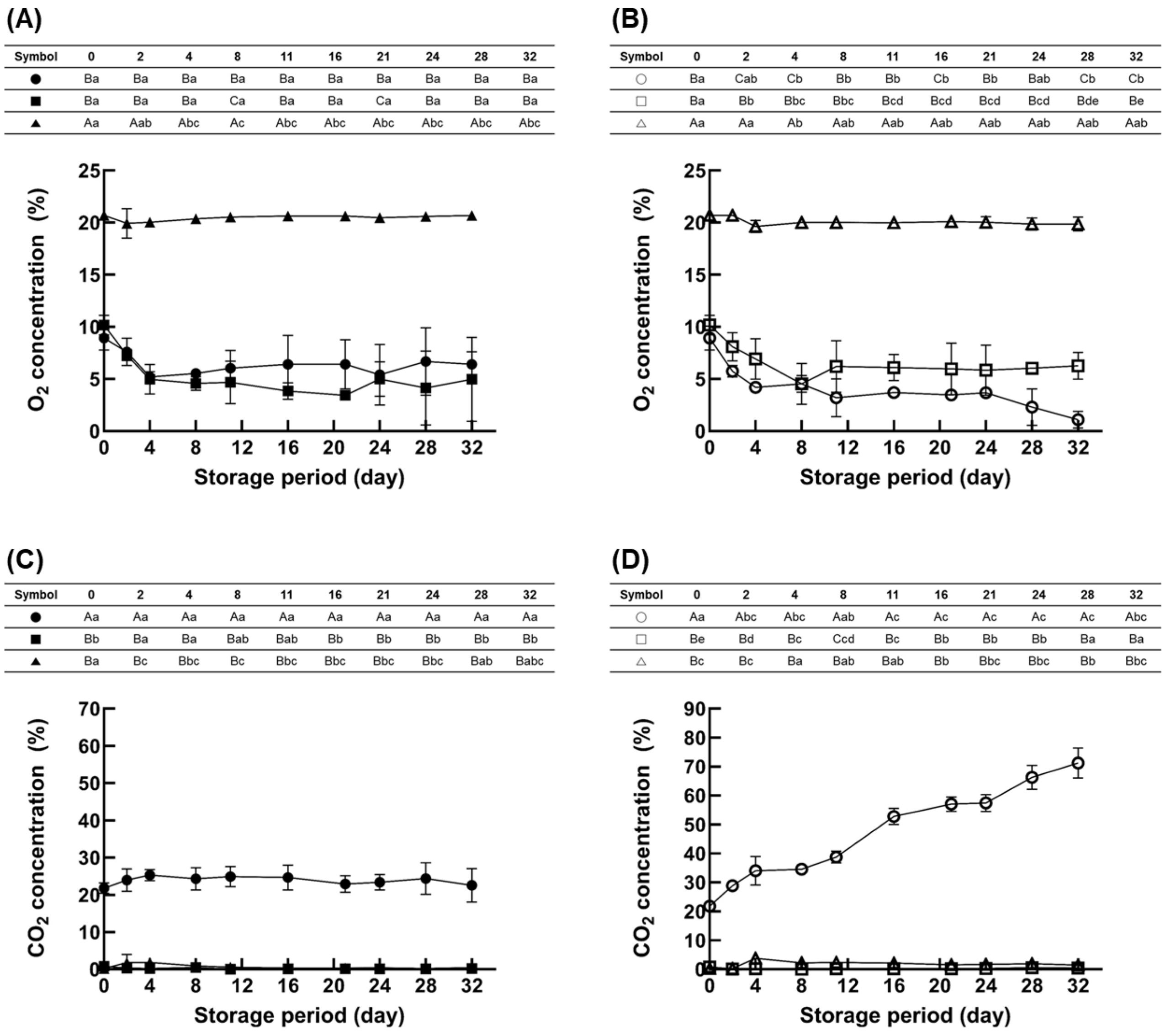
1)Each value is mean±SD (n=3).
2)Mean values in the same column (A-B) or row (a-c) followed by different letters are significantly different according to Duncan's multiple range test ($p<0.05$).

film treated groups during storage at -2.2℃ and 4.0℃. During storage at -2.2℃ for 32 days, the salinity of young radish *kimchi* in the control, CDA-film treated, and NFS-film treated groups was maintained at 1.7-1.9%. In this study, no significant difference in the salinity of young radish *kimchi* was observed according to the difference in gas permeability of packaging materials and the presence or absence of CO_2 absorbers sachet attachment ($p>0.05$). Similar to storage at -2.2℃, the salinity of young radish *kimchi* in the control, CDA-film, and NFS-film treated groups during storage at 4.0℃ was maintained at 1.8-2.1%, and there was no significant difference between treatments ($p>0.05$).

3.4. Changes in headspace O_2 and CO_2 concentrations in film packaging of young radish kimchi during storage

Changes in the internal headspace gas concentration and package expansion of tightly packed *kimchi* during storage or distribution are affected by the growth rate of lactic acid bacteria present in *kimchi*, storage temperature, and air permeability of packaging materials (Cayré et al., 2005). Fig. 3 shows the headspace O_2 and CO_2 concentrations in the film packaging of young radish *kimchi* according to the packaging method during storage at -2.2℃ and 4.0℃. At the beginning of storage, the headspace O_2 concentrations of the control and CDA-film treated groups were 8.9 and 10.2%, respectively, which were significantly different from that (20.7%) of the NFS-film treated group ($p<0.05$). After storing at -2.2℃ for 32 days, the O_2 concentration of the control group was 6.4%, similar to the initial storage. The O_2 concentration of the CDA-film treated group was 5.0%, which was reduced by approximately 5% compared with the value at the initial storage (Fig. 3(A)). After 32 days of storage at 4.0℃, the headspace O_2 concentrations of the control and CDA-film treated groups were 1.1 and 6.3%, respectively. On the other hand, the headspace O_2 concentration of the NFS-film treated group was 19.9-20.7% and 19.6-20.7%, respectively, during storage at -2.2℃ and 4.0℃ for 32 days, maintaining the atmospheric O_2 level (Fig. 3(B)).

https://doi.org/10.11002/kjfp.2022.29.5.677



(A)

Symbol	0	2	4	8	11	16	21	24	28	32
●	Ba	Ba	Ba	Ba	Ba	Ba	Ba	Ba	Ba	Ba
■	Ba	Ba	Ba	Ca	Ba	Ba	Ca	Ba	Ba	Ba
▲	Aa	Aab	Abc	Ac	Abc	Abc	Abc	Abc	Abc	Abc

(B)

Symbol	0	2	4	8	11	16	21	24	28	32
○	Ba	Cab	Cb	Bb	Bb	Cb	Bb	Bab	Cb	Cb
□	Ba	Bb	Bbc	Bbc	Bcd	Bcd	Bcd	Bcd	Bde	Be
△	Aa	Aa	Ab	Aab	Aab	Aab	Aab	Aab	Aab	Aab

(C)

Symbol	0	2	4	8	11	16	21	24	28	32
●	Aa	Aa	Aa	Aa	Aa	Aa	Aa	Aa	Aa	Aa
■	Bb	Ba	Ba	Bab	Bab	Bb	Bb	Bb	Bb	Bb
▲	Ba	Bc	Bbc	Bc	Bbc	Bbc	Bbc	Bbc	Bab	Babc

(D)

Symbol	0	2	4	8	11	16	21	24	28	32
○	Aa	Abc	Abc	Aab	Ac	Ac	Ac	Ac	Ac	Abc
□	Be	Bd	Bc	Ccd	Bc	Bb	Bb	Bb	Ba	Ba
△	Bc	Bc	Ba	Bab	Bab	Bb	Bbc	Bbc	Bb	Bbc

Fig. 3. **Changes in the O_2 (A and B) and CO_2 (C and D) concentrations (%) in the headspace of packaged young radish *kimchi* during supercooled and refrigerated storage.** ●, control (-2.2℃); ■, CDA-film (-2.2℃); ▲, NFS-film (-2.2℃); ○, control (4.0℃); □, CDA-film (4.0℃); △, NFS-film (4.0℃). CDA, carbon dioxide absorber; NFS, nano-foamed structure. Each point represents the mean for triplicates and error bars show standard deviations. A-C and a-e, the upper and lower letters within the same column and row, respectively, indicate statistically significant differences ($p<0.05$).

The headspace CO_2 concentration of the control group before storage was 21.8%, which was significantly different from the 0.8 and 0.2% of the CDA-film and NFS-film treated groups (Fig. 3(C)). After 32 days of storage, the headspace CO_2 concentration of the control group stored at -2.2℃ was 22.5%. On the other hand, the headspace CO_2 concentration of the control group stored at 4.0℃ increased to 71.2% (Fig. 3(C) and (D)). In addition, the internal expansion of the film packaging was visually identified in the control group after storing at 4.0℃ for 32 days (Fig. 4).

In *kimchi*, lactic acid, acetic acid, alcohol, and CO_2 are produced by heterolactic fermentation

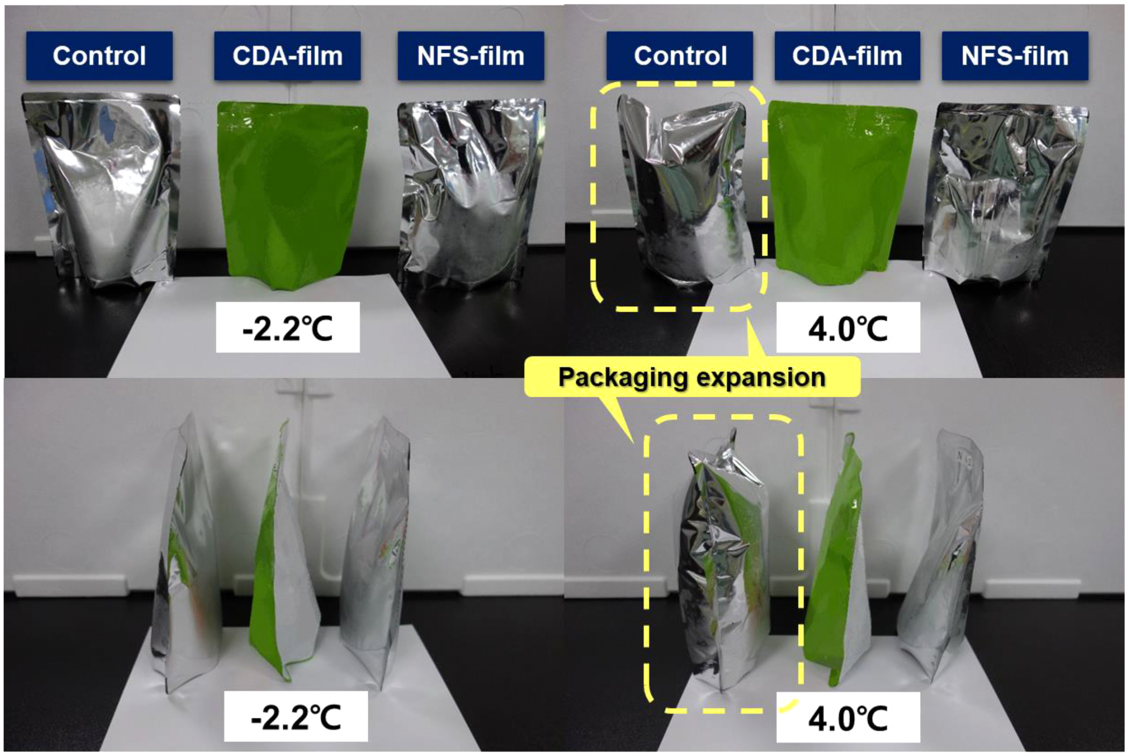


Fig. 4. Appearance of different packaging films containing young radish *kimchi* after 32 days of supercooled (−2.2℃) and refrigerated (4.0℃) storage. CDA, carbon dioxide absorber; NFS, nano-foamed structure.

during storage at refrigerator temperature. The accumulated CO_2 in the packaging adversely affects the marketability of *kimchi* by causing packaging expansion or damage (Hong et al., 2000). Lee et al. (2019) reported that the headspace CO_2 concentrations inside the packaging had a wide range of 0-65%, and the changing pattern during storage differed according to the content of calcium hydroxide and zeolite and the storage temperature when sliced cabbage *kimchi* was packaged in a film pouch containing calcium hydroxide and zeolite stored at 0-10℃ for 28 days. On the other hand, the headspace CO_2 concentrations of the CDA-film and NFS-film treated groups were 0-0.8% and 0.2-3.8%, respectively, during storage at -2.2℃ and 4.0℃ for 32 days. In addition, no deformation due to package expansion was observed (Fig. 4). Therefore, the integration of NFS-film packaging and supercooled storage can effectively control O_2 depletion or CO_2 accumulation in the headspace of the *kimchi* packaging without a CO_2 adsorbent attachment. In the future, additional research is needed to evaluate the sensory quality of *kimchi* using NFS-film packaging and supercooled storage technology in actual distribution sites.

4. Conclusions

This study analyzed the effect of NFS-film packaging on the microbiological and physicochemical quality and packaging stability of young radish *kimchi* during supercooling and refrigeration storage. During storage at -2.2℃, the total number of lactic acid bacteria in the control group increased to approximately 7 log CFU/g on the 24th day of storage and showed a decreasing trend. On the

https://doi.org/10.11002/kjfp.2022.29.5.677

other hand, the total number of lactic acid bacteria in the NFS-film treated group was maintained at approximately 6 log CFU/g during storage at the same temperature. During storage at 4.0℃ for 32 days, the total number of lactic acid bacteria in the control, CDA-film treated, and NFS-film treated groups reached a maximum of 9.0, 9.2, and 9.3 log CFU/g, respectively. During storage at -2.2℃, the number of yeast and mold in the control, CDA-film treated, and NFS-film treated groups was maintained at 3.4-4.3 log CFU/g. Meanwhile, the number of yeast and mold in the NFS-film treated group was significantly higher than those of the control and CDA-film treated groups after 16 days of storage at 4.0℃ ($p<0.05$). The decrease in pH and reducing sugar content, and the increase in titratable acidity were faster in the control, CDA-film, and NFS-film-treated groups when stored at 4.0℃ than when stored at -2.2℃. The packaging method also affected changes in pH, reducing sugar content, and titratable acidity of young radish *kimchi* during storage. During storage at -2.2℃ and 4℃ for 32 days, the salinity of young radish *kimchi* in the control, CDA-film, and NFS-film treated groups was 1.7- 2.1%, and there was no significant effect depending on the storage temperature and packaging method. After 8 days of storage at -2.2℃ and 4.0℃, the headspace O_2 concentrations of the control and the CDA-film treatment groups were approximately 6% or less, but the headspace O_2 concentration of the NFS-film treatment group was maintained at 19.9- 20.7%. During storage at 4.0℃, the CO_2 concentration of the control group increased as the storage period elapsed. Therefore, the CO_2 concentration was 71.2% after 32 days of storage, and package expansion was observed. On the other hand, the headspace CO_2 concentrations of the CDA-film and NFS-film treated groups were maintained at 0-0.8% and 0.2-3.8%, respectively, during storage at -2.2℃ and 4.0℃ for 32 days. In conclusion, the combination of NFS-film packaging and supercooled storage at -2.2℃ can be used to extend the period of maintaining the quality of young radish *kimchi* and prevent package expansion and damage.

Acknowledgements

This work was supported by Korea Institute of Planning and Evaluation for Technology in Food, Agriculture and Forestry (IPET) through the Technology Commercialization Support Program (Project No. 821013-3), funded by Ministry of Agriculture, Food and Rural Affairs (MAFRA), Republic of Korea.

Conflict of interests

The authors declare no potential conflicts of interest.

Author contributions

Conceptualization: Chun HH. Data curation: Shin BS, Choi YJ. Formal analysis: Kang M, Park SY, Chun HH. Visualization: Hong SM. Writing - original draft: Kang M, Park SY. Writing - review & editing: Chun HH.

Ethics approval

This article does not require IRB/IACUC approval because there are no human and animal participants.

ORCID

Miran Kang (First author)
https://orcid.org/0000-0002-9765-7564
So Yoon Park (First author)
https://orcid.org/0000-0002-9080-8585
Bo Sung Shin
https://orcid.org/0000-0001-8358-5718
Sung Moo Hong

https://orcid.org/0000-0002-6267-1358
Young Jin Choi
https://orcid.org/0000-0001-5060-5962
Ho Hyun Chun (Corresponding author)
https://orcid.org/0000-0002-4937-9010

References

Argyri AA, Nisiotou AA, Pramateftaki P, Doulgeraki AI, Panagou EZ, Tassou CC. Preservation of green table olives fermented with lactic acid bacteria with probiotic potential under modified atmosphere packaging. LWT-Food Sci Technol, 62, 783-790 (2015)

Cayre ME, Garro O, Vignolo G. Effect of storage temperature and gas permeability of packaging film on the growth of lactic acid bacteria and *Brochothrix thermosphacta* in cooked meat emulsions. Food Microbiol, 22, 505-512 (2005)

Cheon SH, Seo HY, Chung YB, Chun HH. Effects of electron beam irradiation on microbial inactivation and quality of kimchi paste during storage. Int J Food Sci Technol, 51, 470-479 (2016)

Choi Y, Kang J, Lee Y, Seo Y, Lee H, Kim S, Lee J, Ha J, Oh H, Kim Y, Byun KH, Ha SD, Yoon Y. Quantitative microbial risk assessment for *Clostridium perfringens* foodborne illness following consumption of *Kimchi* in South Korea. Food Sci Biotechnol, 29, 1131- 1139 (2020)

Choi YJ, Hwang YS, Hong SW, Lee MA. Quality characteristics of *Kimchi* according to garlic content during fermentation. J Korean Soc Food Sci Nutr, 45, 1638-1648 (2016)

Chung DO, Park ID, Kim JO. Quality changes of *Rosemary-onion Kimchi* by packaging materials during storage. Korean J Food Sci Technol, 34, 1043-1047 (2002)

Gonzalez D, Vitas AI, Diez-Leturia M, Garcia-Jalon I. *Listeria monocytogenes* and ready-to-eat seafood in Spain: Study of prevalence and temperatures at retail. Food Microbiol, 36, 374-378 (2013)

Hong SI, Park JS, Park NH. Quality changes of commercial *Kimchi* products by different packaging methods. Korean J Food Sci Technol, 27, 112-118 (1995)

Hong SI, Park NH, Park WS. Packaging techniques to prevent winter *Kimchi* from inflation. Korean J Food Sci Technol, 28, 285-291 (1996)

Hong SI, Park WS. Use of color indicators as an active packaging system for evaluating *Kimchi* fermentation. J Food Eng, 46, 67-72 (2000)

Jaisan C, An DS, Lee DS. Modeling volume change for active flexible package of CO_2-producing *Kimchi*. Food Packag Shelf Life, 20, 100303 (2019)

Jang JY, Lee ME, Lee HW, Lee JH, Park HW, Choi HJ, Pyun YR, Kim TW. Extending the shelf life of *Kimchi* with *Lactococcus lactis* strain as a starter culture. Food Sci Biotechnol, 24, 1049-1053 (2015)

Jeong S, Yoo SR. *Kimchi* packaging technology: An overview. Korean J Packag Sci Technol, 22, 41-47 (2016)

Jeong SY, Lee HG, Lee JS, Yoo SR. Critical review on active technologies to regulate the levels of carbon dioxide and oxygen for *Kimchi* packaging. J Korean Soc Food Cult, 34, 233-239 (2019)

Kang SE, Kim MJ, Kim TW. Diversity and role of yeast on *Kimchi* fermentation. J Korean Soc Food Cult, 34, 201-207 (2019)

Kim IS, Jeong SH, Jeong GY. An analysis of the impact of changes in *Kimchi* imports on the Korean *Kimchi* industry. Korean J Org Agric 30, 151-170 (2022)

Kim YJ, Hong SI, Park NH, Chung TY. Effect of packaging material on the quality of *Kimchi* during storage. Korean J Food Sci Technol, 26, 62-67 (1994)

Korea Agro-Fisheries & Food Trade Corporation. A survey on 2020 *Kimchi* Industry in Korea. Korea Agro-Fisheries & Food Trade Corporation, 11-1543000-003632-10 (2022)

 https://doi.org/10.11002/kjfp.2022.29.5.677

Lee DS, Kwon HR, An DS, Chung M, Lee KS, Yang DJ. Technology innovation in *Kimchi* packaging for marketing in food supply chain. Korean J Packag Sci Technol, 18, 1-8 (2012)

Lee DS, Shin DH, Lee DU, Kim JC, Cheigh HS. The use of physical carbon dioxide absorbents to control pressure buildup and volume expansion of kimchi packages. J Food Eng, 48, 183-188 (2001)

Lee HG, Jeong S, Yoo S. Development of food packaging materials containing calcium hydroxide and porous medium with carbon dioxide-adsorptive function. Food Packag Shelf Life, 21, 100352 (2019)

Lee JS, Jeong S, Lee HG, Cho CH, Yoo S. Development of a sulfite-based oxygen scavenger and its application in *Kimchi* packaging to prevent oxygen-mediated deterioration of *Kimchi* quality. J Food Sci, 83, 3009-3018 (2018)

Lee JY, Hwang KS, Yoo SR. Current cases of domestic and foreign packaging industry and cases of *Kimchi* packaging technology. Food Preserv Process Ind, 13, 33-40 (2014)

Li Z, Rui J, Li X, Li J, Dong L, Huang Q, Huang C, Wang Z, Li L, Xuan P, Tang Y, Chen F. Bacterial community succession and metabolite changes during doubanjiang-meju fermentation, a Chinese traditional fermented broad bean (*Vicia faba* L.) paste. Food Chem, 218, 534-542 (2017)

Martinez-Ferrer M, Harper C, Perez-Munoz F, Chaparro M. Modified atmosphere packaging of minimally processed mango and pineapple fruits. J Food Sci, 67, 3365-3371 (2002)

Moon EW, Kim SY, Dang YM, Park B, Park EJ, Song HY, Yang J, Yoon SR, Seo HY, Ha JH. Comparison of microbial and physicochemical properties between *pogi Kimchi* and *mat Kimchi*. J Korean Soc Food Cult, 34, 217-223 (2019)

Nam GW, Jeong M, Heo EJ, Chang OK, Kim MG, Kwak HS, Suh SH. Quantitative microbial risk assessment of pathogenic *Escherichia coli* in commercial *Kimchi* in South Korea. Food Sci Biotechnol 30, 1455-1464 (2021)

Park HY, Ahn JA, Seo HJ, Choi HS. Quality characteristics of small packaging *Kimchi* according to packing material and storage temperature. Korean J Food Cook Sci, 27, 63-73 (2011)

Ryu EH, Yang JS, Lee MJ, Kim SH, Seo HY, Jung JH. Antioxidant effects of *Kimchi* supplemented with black raspberry during fermentation protect against liver cirrhosis-induced oxidative stress in rats. Nutr Res Pract, 13, 87-94 (2019)

Shao P, Liu L, Yu J, Lin Y, Gao H, Chen H, Sun P. An overview of intelligent freshness indicator packaging for food quality and safety monitoring. Trends Food Sci Technol, 118, 285-296 (2021)

Shin DH, Cheigh HS, Lee DS. The use of Na_2CO_3-based CO_2 absorbent systems to alleviate pressure buildup and volume expansion of *Kimchi* packages. J Food Eng, 53, 229-235 (2002)