LWT - Food Science and Technology 85 (2017) 110–120

Contents lists available at ScienceDirect

LWT - Food Science and Technology

journal homepage: www.elsevier.com/locate/lwt

Effects of combined treatment with ultraviolet-C irradiation and grape seed extract followed by supercooled storage on microbial inactivation and quality of *dongchimi*

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ARTICLE INFO

Article history:
Received 24 February 2017
Received in revised form
29 May 2017
Accepted 9 July 2017
Available online 10 July 2017

Keywords:
Dongchimi
Supercooling
Ultraviolet-C
Grape seed extract
Shelf life

ABSTRACT

Dongchimi is a watery variety of kimchi prepared using firm radish and condiments. Over-ripening is the most undesirable outcome of *dongchimi* fermentation, resulting in softening of texture and an undesirable taste. Herein, the effects of combined treatment with ultraviolet-C (UV-C) irradiation and grape seed extract (GSE) supplementation, followed by supercooled storage, on the quality of *dongchimi* were investigated. Microbial inactivation tests showed that 6 kJ/m^2 UV-C irradiation and 0.1% GSE supplementation before storage significantly reduced the populations of total aerobic bacteria, fungi, and lactic acid bacteria in *dongchimi*. Supercooled storage (−3 °C) delayed microbial growth in *dongchimi* compared to refrigeration (4 °C and 10 °C). Supercooled storage also suppressed changes in pH and titratable acidity in *dongchimi*. The hardness and colour of the radish slices did not vary with the treatments. Sensory evaluation results indicated that the qualities of *dongchimi* treated with the combination of UV-C and GSE followed by storage at −3 °C were better than those with other treatments. Thus, UV-C irradiation and GSE supplementation improved the final quality and extended *dongchimi* shelf life under supercooled storage at −3 °C without ice crystal nucleation and formation.

1. Introduction

Fermented vegetable preparations are an important constituent of human diet and are particularly popular in East Asian countries (Jang, Chung, Yang, & Kim, 2015; Lee, Shim, Park, Heo, & Kim, 2016). Kimchi is a traditional Korean fermented vegetable food that is now globally popular as a side dish because of its taste and health benefits (Lee, Jung, & Jeon, 2015). A watery variety of kimchi, called *dongchimi*, is prepared by fermentation of radish with a seasoning mixture comprising garlic, ginger, pungent green pepper, and Korean leek in 2%–4% salt water with approximately twice the volume of the vegetables (Jeong, Jung, Lee, Jin, & Jeon, 2013; Lee, Yoo, Ha, & Choi, 2012).

The high water and nutrient content of *dongchimi* promotes the growth of diverse pre-existing microorganisms during storage and distribution, thereby affecting its shelf life (Lee, Shin, Ko, & Oh, 2010). However, fermentation by lactic acid bacteria (LAB) can inhibit the growth of foodborne pathogens and viruses during storage (Lee et al., 2012). Excessive microbial and enzymatic activities continue during storage, decreasing the pH and increasing the acidity, resulting in a sour and bitter taste, off-odour, softening of radish tissue, and deterioration of *dongchimi* (Jeong et al., 2013; Kang, Lee, Min, & Min, 2003; Lee et al., 2010). Without thermal processing, *dongchimi* is preserved by refrigeration or chilling. However, this does not kill microorganisms; it only inhibits their growth. The shelf life of non-sterilised *dongchimi* during commercial refrigeration or chilling (4°C–10 °C) is approximately 10–15 days (Lee et al., 2010, 2012). To enhance the microbiological quality of *dongchimi*, effective, non-toxic, and easily applicable methods for its sterilization and storage are needed (Fukuma, Yamane, Itoh, Tsukamasa, & Ando, 2012; Oliveira, Ramos, Ramos, Piccoli, & Cristianini, 2015).

Ultraviolet-C (UV-C) irradiation is a well-established non-thermal processing technique for reducing microbial spoilage by eliminating natural microflora or foodborne pathogens from the contact surface of foods (Birmpa, Sfika, & Vantarakis, 2013; Chun, Kim, Chung, Won, & Song, 2009; Chun, Kim, Lee, Yu, & Song,

List of abbreviations: GSE, grape seed extract; LAB, lactic acid bacteria; UV-C, ultraviolet-C.

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http://dx.doi.org/10.1016/j.lwt.2017.07.011
0023-6438/

2010). UV-C generates crosslinks between neighbouring pyrimidine bases in DNA, resulting in cell death (Kim, Kim, & Song, 2009; Sommers & Sheen, 2015). UV-C has been approved by the Food and Drug Administration for use in juice products and potable water (Ukuku & Geveke, 2010). However, the kimchi processing industry has not explored UV-C irradiation because of limited information on its effects on quality and bacterial inactivation.

Grape seed extract (GSE) is a polyphenol-rich by-product derived from grape (*Vitis vinifera*) seed. It has well-documented antioxidant, antimicrobial, and anti-inflammatory properties (Ahn, Grun, & Mustapha, 2007; Perumalla & Hettiarachchy, 2011). Furthermore, the use of GSE along with other growth retardants (low temperature, irradiation, and low pH) has shown synergistic antimicrobial effects in various food and beverage systems (Chouchouli et al., 2013).

In kimchi storage, low temperature is a key factor for maintaining quality and taste. Increases in kimchi metabolites and microbial populations depend on temperature (Jeong et al., 2013). Because conventional refrigeration (4°C–10 °C) does not suppress bacterial growth, it can only be used to store kimchi for a few days. Storing kimchi at freezing temperature (−18 °C to −40 °C) is costly. Moreover, freezing would cause undesirable changes in the quality of kimchi because of ice crystallization, which results in irreversible tissue damage via structural rupture and other changes (Molina-García et al., 2004). In contrast to freezing, supercooling is the process of lowering the temperature of a product below its initial freezing point without the phase change of solidification by surmounting an energy barrier before nucleation starts (Farouk, Kemp, Cartwright, & North, 2013; Stonehouse & Evans, 2015). Storing foods in a supercooled state has three distinct advantages: maintaining freshness, retaining high quality, and suppressing microbial growth (Stonehouse & Evans, 2015).

Hurdle technology (intentionally combining disinfection treatments and cold storage) can control microbial growth in foods, thereby extending the shelf life (Lan, Shang, Song, & Dong, 2016; Zhou, Xu, & Liu, 2010). Because storage temperatures of >1 °C for kimchi generally increase the growth of diverse LAB, which in turn influence the quality of kimchi, hurdle technology has been successfully used for kimchi products to improve microbiological safety and maintain the desirable physicochemical qualities (Kim, Bang, Beuchat, Kim, & Ryu, 2012).

Several strategies such as irradiation and addition of salts or natural/chemical preservatives to inhibit the growth of pre-existing microorganisms during *dongchimi* storage have been studied (Jang & Park, 2004; Kim, Kim, & Ham, 2005; Son, Choi, & Choi, 2005). However, the combined effects of irradiation, natural antimicrobials, and supercool storage on the microbiological and physicochemical qualities of *dongchimi* have never been investigated. Thus, the aim of this study was to (i) examine the effects of UV-C irradiation, GSE supplementation, and supercooled storage conditions on *dongchimi*; (ii) assess the microbiological quality; and (iii) suggest appropriate processing conditions.

2. Materials and methods

2.1. Sample preparation

Laboratory-scale batches of *dongchimi* were prepared according to the methods of Jeong et al. (2013) and Kim et al. (2012) with some modifications. The ingredients for *dongchimi* were purchased from a local market in Gwangju, South Korea, in 2016. Radishes were rinsed with tap water and cut into 150–200-g pieces using a knife sterilised by flaming before each use. Each batch of *dongchimi* was prepared with 2 L of distilled water, 1 kg of radish, 50 g of salt, 10 g of ground green onion, 5 g of ground garlic, and 3 g of ground ginger. The prepared materials were placed in a 5-L plastic container. *Dongchimi* was fermented at room temperature (approximately 20°C–22 °C) overnight in a biological incubator. After fermentation, the samples were irradiated with UV-C or supplemented with GSE. Non-treated samples, produced in the same manner, were used as the control.

2.2. UV-C irradiation and GSE supplementation

A customised chamber for UV-C irradiation equipped with a refrigeration system and four germicidal lamps (20 W, GL20; Sankyo Denki, Tokyo, Japan) was used (Fig. 1). The UV-C intensity was determined using a UV radiometer (UV-340; Lutron Electronic Ent. Co., Ltd., Taipei, Taiwan) calibrated at 254 nm. Applied UV-C intensity (dose rate, 2.5 W/m^2) was calculated as the mean of 20-min UV-C readings on each side of the stainless steel tray. Irradiation dose was calculated using equation (1):

$$D\left(\mathrm{kJ}/\mathrm{m}^2\right) = I\left(\mathrm{W}/\mathrm{m}^2\right) \times t(\mathrm{s}) \quad (1)$$

where D is the UV-C light dose, I is the UV-C intensity, and t is the exposure time. *Dongchimi* juice (100 mL) and five pieces of sliced radish were placed in Petri dishes (diameter: 138.5 mm) and directly irradiated with lamps on the upper surface at a distance of 15 cm at 4 °C. The samples were exposed UV-C irradiation (2, 4, 6, 8, or 10 kJ/m^2) in the dark to minimise photoreactivation of microorganisms, as described previously (Chun et al., 2010; Sommers & Sheen, 2015). After irradiation, GSE (DF-100; Food Additive Bank Co., Anseong, Korea) was dissolved in *dongchimi* juice to obtain a concentration of 0.1%. The GSE concentration was chosen based on the previous studies (Kim et al., 2012; Perumalla & Hettiarachchy, 2011) and a preliminary study using *dongchimi* samples.

2.3. Time–temperature profile of dongchimi

The time–temperature profiles of *dongchimi* juice samples were monitored using a button temperature logger (SL52T; Signatrol Ltd., Tewkesbury, UK). To determine the nucleation point, freezing point, and supercooling stage of *dongchimi*, the experimental run was performed at −10 °C ± 0.2 °C until ice crystals appeared.

2.4. Sample packaging and storage

Following UV-C irradiation and GSE supplementation, approximately 200 mL of *dongchimi* juice and 10 pieces of radish cubes were packed into 200-μm-thick polyethylene terephthalate bottles (Pack4U Co., Seoul, Korea) and stored under chilled (4 °C ± 1 °C and 10 °C ± 1 °C) or supercooled (−3 °C ± 0.5 °C) conditions under static air for 15 days. The *dongchimi* samples stored in the supercooled chamber (SG2-42A; Supercooler Co., Ltd., Incheon, Korea) were initially stored to 4 °C. Next, a step-cooling program (cooling rate, approximately −1 °C/h) was used to reduce the temperature to −3 °C. *Dongchimi* juice was collected from each sample at 0, 2, 4, 6, 9, 12, and 15 storage days and assayed for pre-existing microorganisms, pH, and acidity. Radish slices were analysed for texture and surface colour. All experiments were performed in triplicate.

2.5. Microbiological analysis

For microbiological analysis, *dongchimi* juice samples were diluted tenfold with peptone water (0.1% sterile peptone, w/v). For total aerobic bacteria counts, samples were plated onto 3M Petrifilm Aerobic Count Plates (3M Co., St. Paul, MN, USA) and incubated at 37 °C for 48 h. For LAB counts, diluted samples were plated onto