Effects of approved dose of e-beam irradiation on microbiological and physicochemical qualities of dried laver products and detection of their irradiation status

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Abstract Most commercial dried laver products show higher microbial contamination. This work evaluated effects of approved dose (7 kGy)—recommended in the Korean Food Code for algal food—of electron beam (E-beam) irradiation on microbiological, physicochemical and luminescence properties of dried laver products. E-beam irradiation caused dose-dependent microbial reductions. For example, a 4 kGy irradiation dose reduced coliform (<2.5 log CFU/g) to undetectable levels (<10 CFU/g), while a 7 kGy irradiation dose reduced total aerobic bacteria count (6.6 log CFU/g) by approximately 2 log cycles. Physicochemical attributes of dried lavers were not significantly ($p > 0.05$) affected before and after 7 kGy irradiation, but carotenoid content was significantly ($p < 0.05$) reduced at 10 kGy irradiation. Irradiated samples (>4 kGy) could be detected from non-irradiated ones by luminescence techniques. Overall, results indicated that <7 kGy irradiation is recommended along with other heat treatment for improving microbiological contamination by at most 4 log CFU/g in dried lavers.

Keywords Dried laver · Microbial load · Irradiation · Quality · Luminescence detection

Introduction

Laver is a term encompassing edible seaweed and tangle weed species of the genus *Porphyra* (*Pyropia*), family Bangiaceae, class Rhodophyceae, and division Rhodophyta. Laver is commonly eaten in the Republic of Korea and is mainly produced in the Asian countries of China, Japan, Taiwan, and the Republic of Korea [1]. In the Republic of Korea, the total production of laver in 2009 was 211,444 tons, and a significant production boom was recorded with total production of 390,314 tons in 2015. China is the largest producer of aquaculture products, producing 1,132,190 tons of laver in 2012, 62.1% of global production. The Republic of Korea accounts for 19% of global production (355,829 tons), closely followed by Japan (341,580 tons) [2, 3]. The main species of laver cultivated in the Republic of Korea are *Porphyra yezoensis* Ueda, *P. tenera* Kjellman, *P. seriata* Kjellman, and *P. dentata* Kjellman [1]. Most fresh laver is distributed as dried laver products because fresh laver is highly susceptible to changes in moisture, color and flavor. Dried laver products commercially used in the Republic of Korea are divided into traditional laver (*Jaeraegim*), stone laver (*Dolgim*), and green laver (*Paraegim*) [1]. Different types are prepared in the form of dried, seasoned and roasted laver products, primarily derived from laver. Laver is employed widely as an ingredient in Asian foods.

Several previous studies have reported higher microbial contamination in raw laver destined for unprocessed seaweed products [4–6]. Moreover, *Kimbab* is a popular ready-to-eat food in Korea and ready-to-eat foods have been reported to be a primary cause of food-borne outbreaks and diseases. The major food-borne pathogens in *Kimbab* were found to be the *Salmonella* spp., *Escherichia coli*, and *Staphylococcus aureus* [4, 5]. The total plate

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count of dried laver products was reported in the range of 1.57×10^5 – 4.96×10^6 , while coliform counts in green and stone lavers has been found to be 1.5×10^2 and 8.75×10^1 , respectively and *Bacillus cereus* count was reported to be 2.1×10^2 [6]. Contaminated rolled dried laver in *Kimbab* led to an outbreak of salmonellosis in Korea and contamination of dried laver was implicated as the cause of 3–11% of total food poisoning outbreaks in Korea in 2001 [5, 7]. Korean dried laver products are exported to Japan, the United States, China, Thailand, and Russia, and these countries have particular quarantine and trade regulations regarding microbial quality of dried laver for import. For both China and Russia, dried imported laver products should contain total aerobic bacterial count of $\leq 3 \times 10^4$ CFU/g [8] and $\leq 5 \times 10^4$ CFU/g [9], respectively. When the total aerobic bacterial count exceeds this limit, the export may be returned. According to set export criterion, the exported laver samples should adhere to the following specifications for microbial contamination: negative status for different pathogenic microorganisms (*Salmonella* spp., *Staphylococcus aureus*, *Vibrio parahaemolyticus*, *Listeria monocytogenes*, *E. coli* O157:H7, *Campylobacter jejuni*, *Clostridium perfringens* and *Yersinia enterocolitica*) and *Bacillus cereus* (<1000 CFU/g) [10]. Therefore, it is necessary to ensure that highly hygienic dried laver is maintained to meet the quarantine requirements for international trade.

The ionizing energy of γ -rays and electron beams (e-beam) has been approved for food irradiation for the purposes of: microbial reduction, insect disinfestation, and shelf-life extension, among others. In the Republic of Korea, algal foods may be irradiated at maximum 7 kGy for microbial decontamination, and should be labeled if so [10]. Analytical methods for the detection of irradiated foods include: photostimulated luminescence (PSL), thermoluminescence (TL), electron spin resonance, and gas chromatography–mass spectrometry (GC–MS) for hydrocarbons [11].

The purpose of this study was to assess the effect of approved dose of irradiation (max. 7 kGy) on microbial reduction and physicochemical quality changes in three kinds of Korean typical dried lavers. Moreover, detection markers of irradiated dried lavers were investigated by using luminescence analysis for routine regulatory compliance testing.

Materials and methods

Materials and irradiation

Three types of dried laver products were procured from a local market in Daegu, Republic of Korea, classified as:

Traditional laver (TL), stone laver (SL), and green laver (GL). Irradiation was carried out at room temperature (RT) at doses of 1, 4, 7, and 10 kGy at a dose rate of 2.1 kGy/h using an electron accelerator (ELV-4, 10 MeV; Fujifilm, Tokyo, Japan) at EB-Tech, Daejeon, Korea. Verification of absorbed doses was performed by ceric-cerous and cellulose triacetate dosimeters. All samples were kept in a dark room at RT during experiments.

Microbiological analysis

All laver samples were analyzed for microbial counts (total aerobic bacteria and coliforms). Five grams of each laver sample was mixed with 45 mL of sterile peptone water. Several dilutions of each mixture were subsequently prepared by plating on plate count agar and Desoxycholate agar media (Difco, Sparks, Maryland, USA) for total aerobic bacteria and coliforms, respectively. Microbial counting was carried out after completion of an incubation period of 24–48 h at 30 and 37 °C, respectively.

Determination of Hunter's color values

Hunter's color values *L* (lightness/darkness), *a* (redness/greenness), and *b* (yellowness/blueness) were determined using a colorimeter (CR-200; Minolta, Osaka, Japan). Measurements were taken at three random locations on the packaged surface of laver samples and the mean values were reported. The total color difference (ΔE) was calculated from the obtained Hunter's color values as $\sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$. The *L*, *a*, and *b* values of the standard plate were 97.66, −0.36, and 1.92, respectively.

Determination of chlorophyll and carotenoid contents

The chlorophyll and carotenoid contents of laver were determined according to the method described by Lee et al. [12]. Chlorophyll was extracted with acetone and methanol (1:1, v/v) (Duksan Pure Chemicals, Gyeonggi, Korea), partitioned into diethyl ether (Duksan Pure Chemicals, Gyeonggi, Korea), and dehydrated with Na_2SO_4 . Similarly, carotenoid analysis was performed by the extraction of carotenoids via saponification with KOH (Duksan Pure Chemicals, Gyeonggi, Korea). Chlorophyll and carotenoid contents were quantified spectrophotometrically by measuring the absorbance at 663 and 447 nm, respectively, using an ultraviolet–visible spectrophotometer (Optizen 2120UV, Mecasys).

PSL analysis for detection of irradiated samples

Photostimulated luminescence (PSL) measurements were performed using a pulsed PSL system (serial 0021; Scottish Universities Research and Reactor Center, Glasgow, UK). The measurement of photon counts (PCs) and the interpretation of results were performed according to the standard method EN 13751 [13].

Finally, samples were sliced to uniform thickness and then placed in disposable 50 mm diameter Petri dishes (Sterilin™ type 122; Bibby Scientific, Glasgow, UK). Without further preparatory steps, the Petri dishes were placed in a sample chamber and the measurement of PCs induced by radiation treatment was carried out. A personal computer automatically recorded the results as PCs/min. Measurements of PCs for all samples were performed in triplicate under the same instrumental and laboratory conditions. Samples with <700 PCs/min were regarded as non-irradiated while those with >5000 PCs/min were identified as irradiated. Samples with 700–5000 PCs/min were regarded as intermediate and required further investigation.

TL analysis for detection of irradiated samples

Thermoluminescence (TL) analysis was carried out in accordance with the specifications described in the standard protocol EN 1788 [14]. The density separation method was employed for the separation of silicate minerals from 400 g of each laver sample. After separation, clean stainless steel discs were used for the deposition of silicate minerals followed by overnight storage at 50 °C in a dry oven. A TL reader (Harshaw TLD™ 4500; Thermo Fisher Scientific, Waltham, Massachusetts, USA) was used for recording TL measurements within the temperature range of 50–400 °C at a heating rate of 60 °C/s. The first TL measurements of the extracted minerals were used to obtain the first TL curve (TL₁). For normalization of the TL response, re-irradiation of the samples was performed at a low dose (1 kGy). Then, the samples were again subject to overnight storage in a laboratory-scale dry oven under the same conditions as used for the first TL measurements, and a second set of measurements were taken to obtain a second TL curve (TL₂). Full-process blanks were prepared and analyzed alongside the laver samples. Differentiation between the irradiated and non-irradiated laver samples was performed based on two decisive factors: [1] TL₁ shape, and [2] TL ratio (TL₁/TL₂). Evaluation of the TL ratio (TL₁/TL₂) was performed over the temperature range of 150–250 °C. Based on the TL shape and ratio, samples were regarded as irradiated if they had a TL ratio >0.1, a relatively higher TL intensity, and a TL peak before 250 °C.

Statistical analysis

All measurements were performed in triplicate and the results were shown as mean ± standard deviation. Microsoft Excel (Microsoft Office, ver. 2007, Redmond, Washington, USA) and Origin 8.0 (OriginLab, Northampton, Massachusetts, USA) were used for data analysis. Analysis of variance (ANOVA) was carried out and data significance was analyzed at the $p \leq 0.05$ significance level using Duncan's multiple-range test.

Results and discussion

Microbial reduction by an approved dose of irradiation

The initial microbial contamination levels of the dried laver samples were confirmed and the sterilization effect of e-beam irradiation at doses of 1–10 kGy was evaluated. The results of microbial analyses are presented in Fig. 1.

Fig. 1 Total plate counts (A) and coliform (B) c Intensecounts of dried laver of different kinds according to the E-beam irradiation. TL, Traditional lavers; SL, Stone lavers; GL, Green lavers. Values with different *small letters* (a–e) within the same *bar* are significantly different at $p < 0.05$ based on Duncan's multiple range test

The total aerobic bacteria counts of the non-irradiated TL, SL, and GL samples were 6.34, 6.60, and 5.46 log CFU/g, respectively. TL and SL showed higher total aerobic bacteria counts than GL (Fig. 1A). In 4 kGy-irradiated samples, a slight decreasing tendency (non-significant) was observed in total aerobic bacteria when compared with control samples (0 kGy). TL showed marked decrease as compared to SL and GL. In comparison with control, the 7 kGy dose caused significant reduction of total aerobic bacteria in all e-beam irradiated dried laver types. A dose-dependent decrease was observed in 10 kGy irradiated samples of three kinds of laver. However, total aerobic bacteria proved very resistant to e-beam irradiation and even an approved dose (7 kGy) was insufficient to reduce the initial loads down to the acceptable microbial loads in three kinds of laver samples. Even though 10 kGy irradiation caused a significant reduction in TL, it was not enough reduction to reach acceptable levels in SL and GL (<4 log CFU/g).

The initial contamination of coliform in dried laver samples was 1.87–2.49 log CFU/g (Fig. 1B). The highest coliform count (2.49 log CFU/g) was observed in TL, and SL showed the lowest coliform count (1.87 log CFU/g) among all control samples. The coliform was effectively sterilized by e-beam irradiation at less than 4 kGy, thus resulting in coliform counts of <10 CFU/g (Fig. 1B). In the case of the irradiated samples, e-beam irradiation sufficiently decontaminated all three laver sample types. No coliform growth was observed even in 1 kGy-irradiated samples of the TL and SL, while the coliform count was significantly ($p < 0.05$) reduced in GL samples as compared to control samples irradiated at 1 kGy. All other irradiated samples at 4, 7 and 10 kGy showed coliform counts below detection levels (<10 CFU/g) and e-beam irradiation sufficiently sterilized all three kinds of laver samples to undetectable coliform levels. Our results are in good agreement with the findings of Jo et al. [15], who reported that the irradiation of dried laver at a 3 kGy dose reduced microbial contamination levels only to 1.7 log cycles, and γ -irradiation alone could not control microorganisms effectively. In contrast, Ahn et al. [16] reported that the initial contamination level in dried laver was 3.2×10^6 CFU/g, which was subsequently reduced to about 1×10^6 CFU/g after γ -irradiation at doses of 5–10 kGy. Therefore, it was concluded that other sterilization methods along with γ -irradiation are necessary to effectively sterilize dried laver, which is often highly contaminated with microorganisms. Other studies have reported reductions in microbial contamination levels by γ -irradiation or e-beam irradiation treatments in seed sprouts [17], ground black pepper [18], and Chinese cabbage seeds and sprouts [19].

Effects of irradiation on Hunter's color values

Hunter's color scale consists of L , a , and b color values and enables uniform color measurements at visible wavelengths. Overall, the ionizing irradiation treatment (electron beam in this case) may cause changes in color attributes of plant matrices depending on the food commodity, the applied dose level and the type of applied irradiation. The changes in color properties may result from induced physiological changes, including: changes in respiration rate, loss of firmness, and discoloration [20]. The measured Hunter's color values of the laver samples are shown in Table 1. The lightness (L) did not differ significantly ($p < 0.05$) between the irradiated and non-irradiated samples. However, the redness (a) of the irradiated laver samples was slightly increased depending on dose. SL showed more variation in redness compared to TL and GL. The yellowness (b) was decreased in TL and SL, but GL showed improved redness in a dose-dependent manner. Irradiated TL and SL samples demonstrated less yellowness (b) than non-irradiated samples, while irradiated GL samples showed more yellowness (b) than non-irradiated samples. The overall color difference (ΔE) showed an increasing tendency with irradiation in all samples. The ΔE values of all samples at 10 kGy were between 0.00 and 2.54 (trace-noticeable). Overall GL color difference was negligible, even at 4 kGy irradiation. Similar results have been reported by others with respect to effects of e-beam irradiation on the color properties of blueberries (*Vaccinium corymbosum* L.) [21] and romaine lettuce (*Lactuca sativa* L.) [20].

Effects of irradiation on chlorophyll and carotenoid content

Chlorophyll and carotenoids are two of the major pigment components commonly found in laver. The concentrations of chlorophyll and carotenoids in the irradiated and non-irradiated laver samples are shown in Fig. 2. The chlorophyll content of the non-irradiated laver samples was between 665.77 and 702.30 mg/100 g dry weight (DW). TL and SL showed similar chlorophyll content, while that of GL were slightly lower. No significant difference in chlorophyll content was observed between non-irradiated samples and those irradiated at doses of 1–7 kGy, whereas SL samples irradiated at 10 kGy showed a slight decrease in chlorophyll content (Fig. 2A). Therefore, e-beam irradiation at higher dose levels can cause a reduction in chlorophyll content, possibly due to the termination of chlorophyll biosynthesis by selective destruction upon irradiation exposure or the radiation-induced degradation of chlorophyll precursors. Reyes and Cisneros-Zevallos [22] reported the sensitivity of carotenoid pigments caused

Table 1 Hunter's color value of E-beam irradiated dried laver products

Sample ¹⁾	Hunter's parameter ²⁾	Irradiation dose (kGy)				
		0	1	4	7	10
TL	L*	41.28 ± 1.41 ^{3)a}	40.78 ± 1.65 ^{ab}	39.52 ± 1.17 ^{abc}	39.04 ± 1.39 ^{bc}	38.84 ± 0.44 ^c
	a*	0.11 ± 0.08 ^c	0.15 ± 0.03 ^{bc}	0.19 ± 0.04 ^b	0.32 ± 0.08 ^a	0.34 ± 0.04 ^a
	b*	3.31 ± 0.11 ^a	3.13 ± 0.26 ^{ab}	3.06 ± 0.17 ^b	2.84 ± 0.10 ^c	2.65 ± 0.12 ^c
	ΔE	0.00 ^c	0.53 ^d	1.78 ^c	2.30 ^b	2.54 ^a
SL	L*	40.52 ± 1.20 ^a	39.62 ± 0.96 ^{ab}	39.41 ± 0.63 ^{ab}	39.01 ± 0.98 ^{bc}	38.13 ± 0.72 ^c
	a*	0.75 ± 0.11 ^c	1.10 ± 0.12 ^b	1.16 ± 0.09 ^{ab}	1.21 ± 0.12 ^{ab}	1.27 ± 0.11 ^a
	b*	3.05 ± 0.14 ^a	2.60 ± 0.11 ^b	2.58 ± 0.09 ^b	2.52 ± 0.16 ^b	2.48 ± 0.24 ^b
	ΔE	0.00 ^c	1.07 ^d	1.28 ^c	1.67 ^b	2.51 ^a
GL	L*	41.38 ± 0.38 ^a	41.13 ± 1.42 ^a	41.05 ± 1.52 ^a	40.07 ± 1.70 ^{ab}	39.30 ± 0.67 ^b
	a*	0.60 ± 0.04 ^c	0.67 ± 0.07 ^{bc}	0.66 ± 0.11 ^{bc}	0.74 ± 0.08 ^b	0.85 ± 0.08 ^a
	b*	2.86 ± 0.36 ^b	3.00 ± 0.37 ^{ab}	3.10 ± 0.22 ^{ab}	3.24 ± 0.41 ^{ab}	3.38 ± 0.14 ^a
	ΔE	0.00 ^c	0.30 ^d	0.41 ^c	0.74 ^b	2.16 ^a

¹⁾TL Traditional lavers, SL Stone lavers, GL Green lavers

²⁾L*: Degree of lightness (white +100 ↔ 0 black)

a*: Degree of redness (red +100 ↔ -80 green)

b*: Degree of yellowness (yellow +70 ↔ -80 blue)

ΔE: Overall color difference ($\sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$)

³⁾Values are mean ± SD (n = 5)

by irradiation treatment and concluded that exposure to irradiation treatment may lead to reduced carotenoid content. This is possibly due to the oxidation process and the induction of free radicals which may affect the carotenoid content, resulting in the formation of peroxy and epoxides radicals. The carotenoid content of irradiated laver samples were lower than those of non-irradiated samples. All non-irradiated laver samples showed carotenoid contents of 22.39–26.32 mg/100 g DW. The TL carotenoid content was not significantly altered by irradiation (Fig. 2B), whereas that of SL and GL slightly decreased at irradiation doses of 1, 4, and 7 kGy. Larger decreases in the carotenoid content of SL and GL were detected after irradiation at 10 kGy. Similar results were reported by Kim et al. [23], who found that carotenoids were highly sensitive to irradiation and showed dose-dependent decreases in concentration after γ -irradiation.

PSL detection characteristics of irradiated dried lavers

PSL analysis is a screening method that involves the measurement of the PCs emitted from food matrices upon exposure to infrared rays at a certain temperature. Most food materials contain mineral debris consisting of silicates and other inorganic particles (such as feldspar, calcite, and quartz), and energy is stored by these materials upon

exposure to ionizing irradiation. This stored energy is released upon stimulation with light at certain wavelengths. PSL was adopted by the European Committee for Standardization as a standard method for screening foodstuffs (such as shellfish, herbs, spices, and seasonings) as defined in standard EN 13751 [13]. According to PSL analysis, samples with <700 PCs/min can be distinguished as non-irradiated, while samples with >5000 PCs/min can be identified as irradiated. PSL signals do not always show a linear dose–response relationship, likely due to the variable distribution of mineral grains on the surfaces of samples [24]. Therefore, the quantity and quality of fine grains of inorganic minerals on the surface of samples can contribute to determining the sensitivity of PSL [25]. Table 2 shows the results of the PSL analyses of the control (non-irradiated) and e-beam-irradiated dried laver samples. The non-irradiated TL, SL, and GL samples showed 461, 476, and 451 PCs/min, respectively. All non-irradiated samples showed < 700 PCs/min, demonstrating the confident detection of their non-irradiated status by PSL. All dried laver samples showed intermediate results 1009–1122 PCs/min at the irradiation dose of 1 kGy, while the samples exposed to irradiation doses of 4, 7, and 10 kGy showed 5373–9175 PCs/min (above the threshold value of 5000 PCs/min) and were thus correctly classified as irradiated. Previous studies have reported similar findings for navel oranges [24], garlic and potatoes [26], and Korean

Fig. 2 Chlorophyll (A) and carotenoid (B) contents of dried laver of different kinds according to E-beam irradiation. *TL* Traditional lavers; *SL* Stone lavers; *GL* Green lavers. Values with different small letters (*a–c*) within the same bar are significantly different at $p < 0.05$ based on Duncan's multiple range test

cinnamon powder [25]. The results of this study show that all the dried laver samples had enough contaminating minerals to produce PSL signals that can be used for rapid screening to determine their irradiation status. However, a confirmatory technique such as TL needs to be applied for improved reliability and validation of the results.

TL detection characteristics of irradiated dried lavers

As specified by the European standard EN 1788 [14], the TL analytical technique is regarded as the most promising

Fig. 3 TL glow curves of dried laver of different kinds according to the E-beam irradiation. *TL* Traditional lavers, *SL* Stone lavers, *GL* Green lavers

method for detecting the irradiation status of foodstuffs and food ingredients. This method is applicable to all food materials from which sufficient contaminating silicate mineral dust particles can be separated. Feldspar and quartz are two well-known minerals of silicate origin that can be used to determine irradiation status [26]. When solid materials are heated to the temperature range of 50–400 °C, light is emitted along with black body radiation

Table 2 Photostimulated luminescence properties of dried laver of different kinds according to E-beam irradiation (Photon counts/min)

Coded name	Irradiation dose (kGy)				
	0	1	4	7	10
TL	461.33 ± 50.90 ¹⁾ (–)	1122.67 ± 456.58(M)	7471.33 ± 4501.28(+)	6555.33 ± 1614.56(+)	7196.00 ± 1573.70(+)
SL	476.00 ± 49.69(–)	1080.00 ± 148.39(M)	5574.00 ± 752.68(+)	5839.33 ± 871.02(+)	6131.00 ± 933.41(+)
GL	451.33 ± 49.17(–)	1009.67 ± 232.09(M)	5373.33 ± 660.02(+)	6545.33 ± 1728.82(+)	9175.00 ± 898.07(+)

¹⁾Mean ± SD (n = 5)

Table 3 TL ratio (TL₁/TL₂) of minerals separated from dried laver products

Sample	Irradiation dose (kGy)	TL ₁ ¹⁾ (1st measured)	TL ₂ ²⁾ (2nd measured)	TL ratio ³⁾ (2nd measured/1st measured)
TL	0	1.177 ± 0.14 ⁴⁾	215.055 ± 2.694	0.005 ± 0.001
	1	24.877 ± 1.141	210.140 ± 0.198	0.118 ± 0.005
	4	22.026 ± 1.392	125.505 ± 10.119	0.176 ± 0.003
	7	132.785 ± 8.309	277.750 ± 9.122	0.478 ± 0.014
	10	188.415 ± 0.969	142.575 ± 3.825	1.322 ± 0.029
SL	0	1.730 ± 0.347	177.360 ± 18.526	0.010 ± 0.003
	1	25.551 ± 2.434	58.730 ± 2.871	0.435 ± 0.020
	4	67.505 ± 6.781	109.090 ± 9.376	0.618 ± 0.009
	7	161.785 ± 11.151	235.810 ± 14.439	0.686 ± 0.005
	10	325.050 ± 16.051	284.450 ± 16.617	1.143 ± 0.010
GL	0	1.701 ± 0.270	53.544 ± 6.515	0.032 ± 0.001
	1	24.670 ± 2.051	53.560 ± 4.045	0.460 ± 0.004
	4	54.980 ± 0.212	152.070 ± 4.766	0.362 ± 0.010
	7	31.424 ± 0.458	50.858 ± 1.049	0.618 ± 0.022
	10	20.168 ± 1.884	20.250 ± 1.626	0.995 ± 0.013

¹⁾Integrated TL₁ intensity at 150–250 °C²⁾Integrated TL₂ intensity at 150–250 °C³⁾TL₁ intensity/TL₂ intensity⁴⁾Mean ± SD (n = 10)

owing to the release of charged carriers trapped inside the food materials from thermal stimulation [14]. The shape and intensity of the TL curve provides information about the radiation exposure history of the samples. Minerals (i.e., silicon compounds) separated from irradiated foods show strong TL peaks in the range 150–250 °C, while those separated from non-irradiated foods exhibit TL peaks above 300 °C. The TL curves for irradiated and non-irradiated TL, SL, and GL samples are shown in Fig. 3. The TL curves of the minerals extracted from the non-irradiated dried laver samples by the density gradient method all showed maximum peaks at 300 °C or higher. This result confirms the absence of irradiation history of the non-irradiated dried laver samples, and these high-temperature TL peaks may represent a geographical signal. Moreover, all the irradiated samples exhibited TL curve peaks within the temperature range of 180–210 °C, and the intensities of the TL curves also showed significant rises with corresponding increases in irradiation dose from 1 to 10 kGy. Variable TL intensities are produced by different inorganic minerals after irradiation; therefore, after the measurement of the first TL curve (TL₁), a normalization step is necessary for normalizing the TL response. Hence, the same minerals isolated from the laver samples were re-irradiated at a fixed dose (1 kGy). After this normalization step, a second TL curve (TL₂) was measured and the reliability of the TL analysis was confirmed by determining the TL ratio (TL₁/TL₂). TL normalization can be used to discriminate the irradiation status of samples. The European standard

EN 1788 [14] specifies that samples with a TL ratio of ≤0.1 are judged as non-irradiated, while samples with a TL ratio of >0.1 are regarded as irradiated. Table 3 shows the TL ratio results of the minerals isolated from the dried laver samples. All non-irradiated dried laver samples showed TL ratios of ≤0.1, confirming their non-irradiated status. Irradiated dried laver samples exhibited TL ratios between 0.122 and 1.342, which is in accordance with the specification of the European standard EN 1788 [14] for irradiated samples. Therefore, the capability of the TL method to distinguish e-beam irradiated dried laver samples was confirmed. Other studies have also reported the use of TL for the accurate evaluation of the irradiation history of foodstuffs including kiwi fruit [27] and fresh mushrooms [28].

In conclusion, as one of the microbial-decontamination methods for Korean traditional dried lavers, the effect of irradiation at approved doses from the Korean Food Code (max. 7 kGy) was assessed on microbial reduction and physicochemical changes in three kinds of dried laver products: traditional laver, stone laver, and green laver. Among microbial populations in commercial dried lavers, coliform was easily destroyed with 4 kGy of e-beam, while total aerobic bacteria (6.6 log CFU/g) were partially resistant to irradiation at 7 kGy, resulting in a reduction of less than 2 log cycles and thus insufficient for reducing microbial loads up to less than 4 log CFU/g in dried laver products [8, 9]. Physicochemical quality attributes of the dried laver were barely affected by irradiation up to 7 kGy,

but carotenoid content was significantly reduced at 10 kGy ($p < 0.05$). Luminescence analysis (PSL and TL) was able to discriminate irradiated dried lavers from a non-irradiated control. The results indicated that an approved dose (max. 7 kGy) of electron beam for algal food in Korea is insufficient for decontaminating microorganisms in dried laver products, and thus irradiation (less than 7 kGy) along with other combined treatments including heat is recommended for improving the microbiological quality of dried laver products, especially those destined for export.

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Compliance with ethical standards

Conflict of interest The authors have no conflict of interest.

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