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Inactivation efficacy of a sixteen UVC LED module to control foodborne pathogens on selective media and sliced deli meat and spinach surfaces

Do-Kyun Kim[a], Dong-Hyun Kang[a,b,*]

[a] Department of Food and Animal Biotechnology, Department of Agricultural Biotechnology, Center for Food and Bioconvergence, and Research Institute for Agricultural and Life Sciences, Seoul National University, Seoul, 08826, Republic of Korea

[b] Institutes of Green Bio Science & Technology, Seoul National University, Pyeongchang-gun, Gangwon-do, 25354, Republic of Korea

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ABSTRACT

Based on the Minamata convention, prohibiting the use of mercury, UVC LED technology has been researched as a putative replacement for mercury lamps. In this study, the possibility of inactivating *Escherichia coli* O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes* on selective media and sliced deli meat and spinach surfaces by a simple UVC LED irradiation system was evaluated and inactivation rate constants of the bacteria were analyzed in survival curves with highly accurate modeling equations. The UVC LED irradiation system fulfilled 3 log reductions of *E. coli* O157:H7 and *S.*Typhimurium on their corresponding selective media within 1.35 s and 3.60 s, respectively. Log linear and Weibull model equations described the survival of bacteria on selective media very well based on the parameters of goodness of fit kinetic models, and 2–15 mJ/cm^2 D_{3d} and D_{5d} values were calculated. Pathogens inoculated onto sliced deli meat and spinach surfaces were reduced by 1.5–3 log reductions within 34 s of UVC LED irradiation. Significant differences in k values were observed in pathogens on selective media ($P < 0.05$), while relatively similar k values were obtained from food surfaces even though there were significant differences in some points ($P < 0.05$).

1. Introduction

Ready-to-eat (RTE) or ready-to-use (RTU) products have experienced popularity during recent decades, because of changes in lifestyles, in which consumers spend less time preparing food in order to spend their spare time doing things they value (Canada, 2010, pp. 1–11). Sales of minimally processed fresh produce have increased due to elevated interest in personal health (Sivapalasingam, Friedman, Cohen, & Tauxe, 2004). As a result, the number of foodborne outbreaks associated with these products has increased commensurate with raised consumption (Buck, Walcott, & Beuchat, 2003; Callejón et al., 2015; Lynch, Tauxe, & Hedberg, 2009; Olaimat & Holley, 2012). In 2018, there were extensive outbreaks involving romaine lettuce, RTE salad, deli meat, and chicken salad associated with *Escherichia coli* O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes*, which encompassed a total 555 cases, 217 hospitalizations, and 7 deaths (Control & Prevention, 2015). Because produce was reported as a putative source of foodborne outbreaks and surveillance reports indicate that produce may be the vehicle for the highest portion of multistate outbreaks (Crowe, Mahon, Vieira, & Gould, 2015; Nguyen et al., 2015; Painter et al., 2013), effective control methods are essential in order to ensure food safety.

Due to quality deterioration, however, thermal treatment is not appropriate for inactivating pathogens on fresh produce and RTE products; non-thermal processing, especially UV treatment, is an alternative intervention for reducing the incidence of foodborne outbreaks. UV treatment leads to pyrimidine dimer formation in genetic material including DNA and RNA, so that hindering DNA replication, ultimately results in cell death (Bintsis, Litopoulou-Tzanetaki, & Robinson, 2000; Franz, Specht, Cho, Graef, & Stahl, 2009; Guerrero-Beltr· n & Barbosa-C·novas, 2004; Yaun, Sumner, Eifert, & Marcy, 2004). For this purpose, low pressure mercury UV lamps (LP lamps), emitting a 254 nm peak wavelength, are widely used in UV irradiation.

The Minamata Convention on Mercury was approved by delegates from about 140 countries in the United Nations Environment Programme (UNEP), and will be initiated in 2020 (Kessler, 2013). According to the treaty, manufacturing of products containing mercury and their import/export will be prohibited to reduce the amount of mercury released into the environment to ensure human and environmental health (UNEP, 2013). Because, from 2020, use of LP lamps

* Corresponding author. Department of Food and Animal Biotechnology, Department of Agricultural Biotechnology, Seoul National University, Seoul, 08826, Republic of Korea.
E-mail address: kang7820@snu.ac.kr (D.-H. Kang).

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should be discontinued and development of a new UV irradiation system is imperative to promote fresh produce and RTE product safety.

UVC light emitting diodes (UVC LED) are a strong candidate for replacing the LP lamps. UVC LEDs can compensates for several limitations of LP lamps, including no mercury use, robustness, and compact size to incorporate into various inactivation systems (Shin, Kim, Kim, & Kang, 2016; Würtele et al., 2011). UVC LED showed temperature-independent intensity compared to LP lamps, and effectively inactivated the major pathogens and human enteric virus surrogates (Kim, Kim, & Kang, 2017a, 2017b; Shin et al., 2016). Aerosolized microorganisms were effectively inactivated in a chamber type UVC LED irradiation system, and enhanced bactericidal effect using a pulsed UVC LED system was demonstrated (Kim & Kang, 2018a, 2018b).

Inactivation of pathogens via UVC LED has been focused on water disinfection due to the penetration issue (Beck et al., 2017; Oguma, Kita, Sakai, Murakami, & Takizawa, 2013; Rattanakul & Oguma, 2018). Therefore, UVC LED technology has been limited to control microbial conmatination on surfaces in food industry. Foodborne pathogens on sliced cheese and sausage were effectively inacitvated by UVC LED irradiation (Kim & Kang, 2018a; Kim, Kim, & Kang, 2016). Through assessment of surface characteristics, hydrophobicity was the main factor of the pathogen inactivaion because of bacterial stacking structure influenced by contact angle of inoculation droplets (Kim & Kang, 2020).

In order to ensure microbiological safety of fresh produce and RTE products, an optimal UVC LED array module was constructed and the efficacy of the system for inactivating foodborne pathogens on selective media surfaces and on fresh produce and RTE surfaces was evaluated in this study. Also, inactivation rate constants (k) were calculated from fitted model equations to assess the inactivation efficacy of the UVC LED module.

2. Materials and methods

2.1. Experimental setup

Fig. 1 shows the UVC LED module used in this study. An electronic printed circuit board (PCB; 250 × 25 mm) linearly connected to sixteen UVC LED package chips and a bar type module (LG Innotek Co., Seoul, Korea) was constructed corresponding to a 280 nm peak wavelength, which was utilized in a previous research (D.-Kim & Kang, 2018b). An aluminum frame coated with carbon was also made to install the UVC LED module, and molds which can contain selective media and fit the frame were constructed. Distance between the UVC LED module and selective media surfaces was approximately 3 cm. The 3 cm interval was optimized to maximize intensity and uniform irradiation of the UVC LED module based on optical angle which the angle between LED light directivity, which will be described in the Discussion section (Fig. 2). Petri factor, indicating evenness of irradiation distribution of an UV emitter over the entire area of surfaces, was measured as over 0.9, indicating a nearly uniform distribution of UVC light (Bolton & Linden, 2003). A DC power supply (TPM series, Toyotech; Incheon, Korea) provided 1.6 A constant electric current, and 12 V was obtained at the UVC LED module.

The molds were sterilized by autoclaving and approximately 35 ml of selective media, including Sorbitol MacConkey Agar (SMAC; Difco) for *Escherichia coli* O157:H7, Xylose Lysine Desoxycholate Agar (XLD; Difco) for *Salmonella* Typhimurium, and Oxford Agar Base with antimicrobial supplement (OAB; MB Cell, Seoul, Korea) for *Listeria monocytogenes*, were poured into them inside a sterile biosafety hood.

2.2. Irradiance measurements

Irradiance intensity of the UVC LED module was measured with a spectrometer (AvaSpec-ULS2048-USB2-UA-50, Avantes; Apeldoorn, Netherlands) calibrated for a range of 200–400 nm which includes the entire ultraviolet wavelength spectrum. Because the distance between the UVC LED module and media surfaces was 3 cm, an optical probe was installed at the same interval and integral irradiance of the UVC LED module from 240 to 280 nm values which covers the UVC range was measured. The probe was scanned over half the area of the media surface (Kim et al., 2017a, 2017b; Kim et al., 2016). The measured irradiance values were divided by the maximum intensity and averaged to calculate the petri factor. The final irradiance levels were normalized by multiplying the maximum intensity by the petri factor.

2.3. Bacterial strains and culture preparation

Escherichia coli O157:H7 (ATCC 35150, ATCC 43889, and ATCC 43890), *Salmonella* Typhimurium (ATCC 19585, ATCC 43971, and DT 104), and *Listeria monocytogenes* (ATCC 15313, ATCC 19111, and ATCC 19115) were obtained from the Bacterial Culture Collection at Seoul National University (Seoul, Korea). Stock cultures were grown in Tryptic Soy Broth (TSB; Difco, Becton Dickinson and company; Sparks, MD, USA) at 37 °C for 24 h, and stored at – 80 °C (0.7 ml of TSB culture with 0.3 ml of sterile 50% glycerol solution). To obtain working cultures, bacteria were each streaked onto Tryptic Soy Agar (TSA; Difco), incubated at 37 °C for 24 h and stored at 4 °C.

All strains of the pathogens were cultured in 5 ml TSB at 37 °C for 24 h and harvested by centrifugation at 4000 × g for 20 min at 4 °C. Pelleted cells were washed with sterile 0.2% peptone water (PW; Bacto, Becton, Dickinson and Company; Sparks, MD, USA) three times and the final pellets were resuspended in 9 ml PW, corresponding to approximately 10^8–10^9 CFU/ml. A mixed pathogen culture cocktail was produced by combining the resuspended pelleted cells.

2.4. Sample preparation

Sliced deli meat and spinach were purchased at a local grocery market in Seoul, Korea. Food samples were stored under refrigeration (4 °C) and used within two days. The food samples were cut into 30 × 30 mm pieces with a sterile knife immediately before inoculation in order to fit into the empty sterile aluminum mold.

2.5. Inoculation

The mixed bacteria culture cocktail was 10-fold serially diluted three times with 0.2% sterile peptone water (PW) resulting in a final concentration of approximately 5–6 log CFU/ml. For inoculation, 0.1 ml aliquots of selected bacterial suspension were spread onto the selective in the aluminum molds. In order to obtain countable numbers of colonies on the tested media, two levels of sequential tenfold serial dilutions were spread-plated. After inoculation, the media were dried for approximately 5 min at room temperature prior to UV treatment.

For food samples, including sliced deli meat and spinach, 0.1 ml aliquots of the mixed bacteria culture suspension were inoculated onto the food surfaces, but different inoculation methods were used; one-tenth ml of suspension was spread on to sliced deli meat with sterile disposable spreader and the same volume of bacterial suspension was spot-inoculated onto spinach. Five or 30 min drying was conducted inside a biosafety hood at room temperature (21 °C) for sliced deli meat or spinach, respectively.

2.6. UV treatments

The inoculated selective media were irradiated for up to 4.5 s, at which time 7.26 mJ/cm^2 energy was delivered to surfaces. Treatment time was controlled by the programmable DC power supply. For food samples, higher UVC irradiation of up to 21.6 s was applied, because pathogens on food samples were expected to be inactivated less (Kim & Kang, 2018a).

After treatment, the treated selective media were directly put into sterile polyethylene bags to avoid desiccation and incubated for

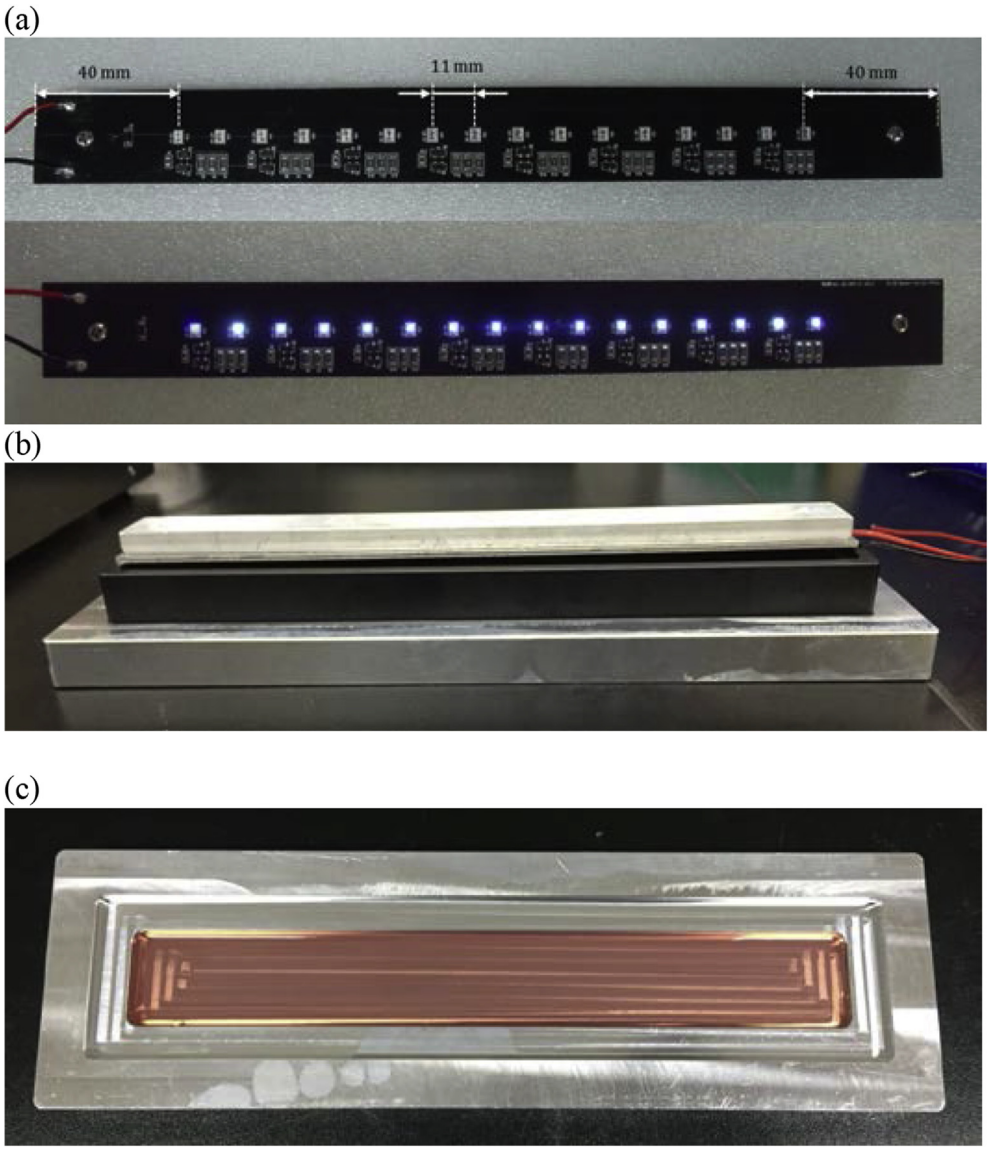

Fig. 1. UVC LED module (a) and UVC irradiation system (b, c) used in this research.

24–48 h 37 ˚C. Treated food samples were transferred to a stomacher bags (Labplas, Inc., Canada) containing sterile 30 ml PW and homogenized with a Stomacher (EasyMix; AES Chemunex, France). One ml stomached sample aliquots were tenfold serially diluted into 9 ml 0.2% PW, and 0.1 ml of selected diluents were spread plated onto 90 mm diameter petri dishes of selective media described previously and incubated 24–48 h at 37 ˚C. Characteristic colonies from both irradiated selective media molds and food experiments were enumerated; white colonies for *E. coli* O157:H7 and black colonies for *S*. Typhimurium and *L. monocytogenes*.

2.7. Modeling of survival curves

All experiments were performed with duplicate samples and repeated three times or with three trials, and bacterial survival population curves from media and food surfaces inactivation were fitted with the two highly predictive model equations by using GInaFiT (Geeraerd, Valdramidis, & Van Impe, 2005). The Log linear model equation is described as:

$$\mathrm{LogN} = \mathrm{LogN_0} - (k_{max} \times t / \mathrm{Ln}(10)) \quad (1)$$

where k_{max} indicates a specific inactivation rate.

The Weibul model equation is described as:

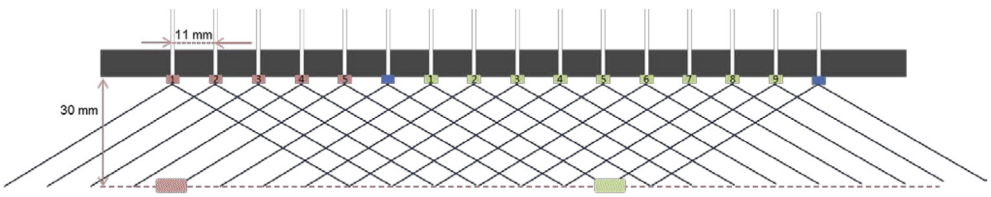

Fig. 2. Optimization of distance between UVC LED module and sample surfaces.

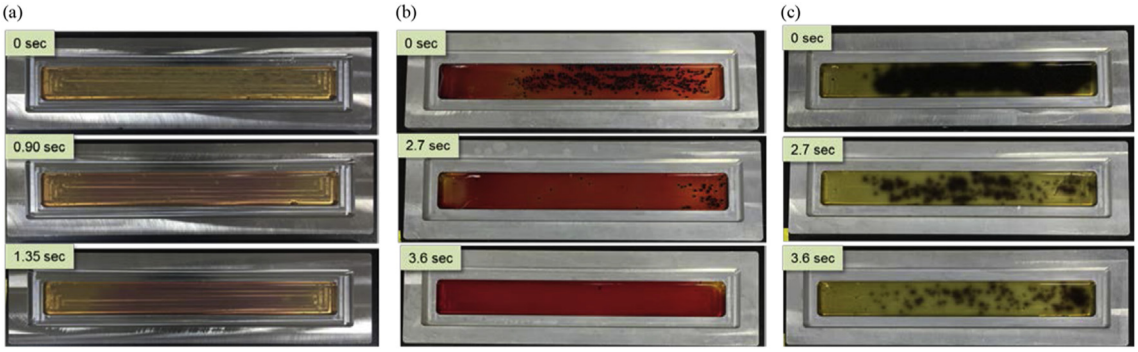

Fig. 3. Inactivation of foodborne pathogens (*E. coli* O157:H7 (a), *S*. Typhimurium (b), and *L. monocytogenes* (c)) on selective media (SMAC for *E. coli* O157:H7, XLD for *S*. Typhimurium and OAB for *L. monocytogenes*) after designated UVC LED treatment times.

$$LogN = LogN0 - (t / \alpha)^{\beta} \quad (2)$$

where α represents the dosage for one log reduction at the first stage of inactivation and β represents the shape of the line, such as upward concavity of a curve when $\beta < 1$, downward concavity when $\beta > 1$, and a linear curve when $\beta = 1$.

2.8. Statistical analysis

All experiments were duplicate-plated and replicated three times. All data were analyzed with ANOVA using the Statistical Analysis System (SAS Institute, Cary, NC, USA) and Duncan's multiple range test to determine if there were significant differences ($P < 0.05$) in mean values of log reduction of microorganism populations.

3. Results

3.1. Inactivation of foodborne pathogens on media surfaces

Fig. 3 shows inactivation of pathogens after designated irradiation times on selective media surfaces treated by the UVC LED module. As expected, increased treatment time resulted in higher inactivation of all three pathogens. Based on Fig. 3, all three pathogens were first inactivated at the center of the media surface, and then pathogens on each side were controlled by the UVC LED module. Among the three pathogens, *E. coli* O157:H7 was the most vulnerable to control by UVC LED irradiation so that only 1.35 s UVC LED treatment achieved almost total inactivation, while *S*. Typhimurium and *L. monocytogenes* needed much longer treatment times to control.

Fig. 4 shows the numerical reduction of pathogens on selective media treated with the UVC LED module. As irradiation dosage increased, pathogen reductions increased linearly. For achieving 3 log reductions, 1.35 s and 3.60 s were needed for *E. coli* O157:H7 and *S*. Typhimurium, respectively. But the given treatment times were not enough to effect 3 log reduction of *L. monocytogenes*. Among the pathogens, *E. coli* O157:H7 was the most UV sensitive followed by *S*. Typhimurium and *L. monocytogenes* in terms of required irradiation times to achieve the same log reductions.

3.2. Model equations fitting analysis

Two potentially applicable equations were fitted to the bacterial survival populations and the results are shown in Table 1. Data of all three pathogens were analyzed by Log linear and Weibull models, and these models described the survival populations of pathogens very well via low MSE (< 0.05) and high R^2 (> 0.99) values. The D_{3d} and D_{5d}, which indicate dose necessity for achieving 3- and 5-log reductions, respectively, are presented in Table 1. For Log linear modeling, 2.2, 5.9, and 9.3 mJ/cm^2 dosages were needed to fulfill 3 log reduction and 3.5, 9.8, and 15.4 mJ/cm^2 for 5 log reduction of *E. coli* O157:H7, *S*. Typhimurium and *L. monocytogenes*, respectively. Similarly, in Weibull modeling, 2.1, 5.9, and 9.2 mJ/cm^2 and 3.0, 9.5, and 15.0 mJ/cm^2 were needed to fulfill 3- and 5-log reductions. The D_{3d} and D_{5d} values between Log linear and Weibull models were not significantly different ($P > 0.05$). Among the tested pathogens, *E. coli* O157:H7 had the lowest D_{xd} values followed by *S*. Typhimurium and *L. monocytogenes*, and those values were significantly different ($P < 0.05$) in both model equations.

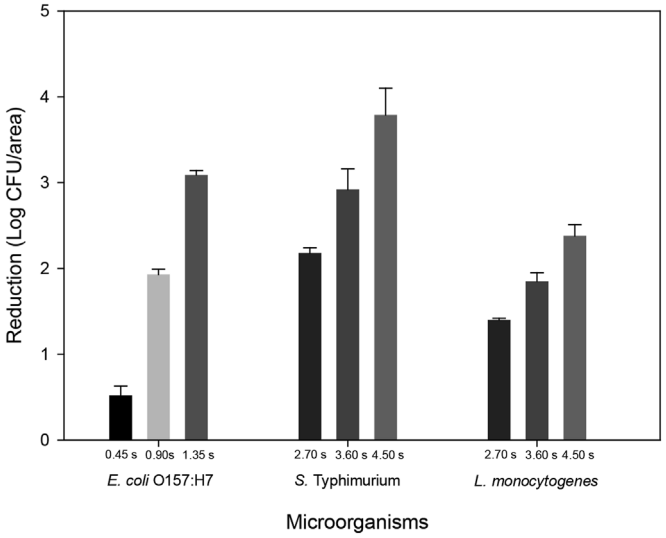

Fig. 4. Log reduction of foodborne pathogens on each selective medium (Sorbitol MacConkey agar; *E. coli* O157:H7, Xylose Lysine Desoxycholate Agar; *S*. Typhimurium, Oxford Agar Base with antimicrobial supplement; *L. monocytogenes*) after different UVC LED treatment times.

3.3. Inactivation of foodborne pathogens on sliced deli meat and spinach surfaces

Survival populations of pathogens on food surfaces treated by UVC LED irradiation are presented in Fig. 5. Similar to the media surface inactivation, pathogens were inactivated almost linearly in accordance with irradiation dose increase for both foods, but much higher dosages were needed for effective inactivation. For sliced meat, approximately 1.0–1.6 log reductions of the three pathogens were fulfilled at 21.6 mJ/cm^2. The inactivation trends of *E. coli* O157:H7 and *S*. Typhimurium were similar and *L. monocytogenes* was the least inactivated among the pathogens. For spinach, approximately 2.4–2.6 log reductions of the three pathogens were achieved at 21.6 mJ/cm^2.

Table 1
Goodness of fit kinetic model equations for survival populations of three foodborne pathogens on selective media treated with the UVC LED module and the calculated D_{3d} and D_{5d} values which indicate UV dosages necessary for 3- or 5-log reductions derived from each model.

Pathogen	Log linear model				Weibull model			
	MSE	R^2	D_{3d}	D_{5d}	MSE	R^2	D_{3d}	D_{5d}
E. coli O157:H7	0.0010	0.9997	2.19 ± 0.05[a] Aa	3.54 ± 0.06 Aa	0.0464	0.9921	2.10 ± 0.02 Aa	3.04 ± 0.03 Ab
S. Typhimurium	0.0050	0.9987	5.88 ± 0.42 Ba	9.77 ± 0.74 Ba	0.0022	0.9997	5.92 ± 0.37 Ba	9.51 ± 1.01 Ba
L. monocytogenes	0.0009	0.9994	9.27 ± 0.46 Ca	15.44 ± 0.80 Ca	0.0010	0.9997	9.17 ± 0.68 Ca	15.01 ± 1.66 Ca

[a] Data represent means ± standard deviations from three replications. Values followed by the same uppercase letters within columns and lowercase within D_{xd} values of each model equation are not significantly different ($P > 0.05$).

3.4. Inactivation rate constant for foodborne pathogens following UVC LED irradiation

The inactivation rate constants (k; cm^2/mJ) were calculated from the slopes of the Log linear model equations for selective media, sliced deli meat and spinach and shown in Table 2. The k values of selective media were significantly greater followed by values for spinach and sliced deli meat, for all three pathogens ($P < 0.05$). Among the pathogens different results were observed; for selective media, *E. coli* O157:H7 showed the greatest k value followed by *S.* Typhimurium, and *L. monocytogenes* ($P < 0.05$), and for sliced deli meat, k values of *E. coli* O157:H7 and *S.* Typhimurium were not significantly different. However, for spinach, *L. monocytogenes* showed the greatest k value followed by *S.* Typhimurium, and *E. coli* O157:H7 and these values for *L. monocytogenes* and *E. coli* O157:H7 were significantly different ($P < 0.05$).

Table 2
Inactivation rate constants (k) for foodborne pathogens on selective media and food surfaces.

Pathogens	Inactivation rate constant, k (cm^2/mJ)[a]		
	Selective medium	Sliced deli meat	Spinach
E. coli O157:H7	1.47 ± 0.01[b] Aa	0.06 ± 0.01 Ca	0.11 ± 0.02 Ba
S. Typhimurium	0.52 ± 0.04 Ab	0.07 ± 0.00 Ca	0.13 ± 0.02 Bab
L. monocytogenes	0.33 ± 0.02 Ac	0.05 ± 0.01 Cb	0.16 ± 0.01 Bb

[a] Inactivation rate constant was determined from the slope of surviving population lines applied to the Log-linear model equation.
[b] Data represent means ± standard deviations from three replications. Values followed by the same uppercase letters within rows and lowercase within columns are not significantly different ($P > 0.05$).

4. Discussion

Ready-to-eat foods and some fresh produce do not require further processing before consumption; consequently, the number of foodborne outbreaks related to these products has increased (Bennett et al., 2018; Buck et al., 2003; Olaimat & Holley, 2012). Sliced cooked and cured meat products are categorized as having high risk of *L. monocytogenes* contamination, because these RTE products support the growth of this psychrotrophic pathogen not only under ideal conditions (moderate pH and water activity), but also during relatively long periods of storage at chilled temperature (Mataragas, Zwietering, Skandamis, & Drosinos, 2010). Many investigations focused on inactivation of foodborne microorganisms in fresh produce and RTE products have been reported (Birmpa, Sfika, & Vantarakis, 2013; Ha, Ryu, & Kang, 2012; Jeong & Kang, 2017; Kim, Lee, Kim, & Rhee, 2018), but the treatment interventions described did require specific systems to treat the samples such as specialized chambers for heating, gamma irradiation, or ultrasound treatment.

In this study, we constructed a simple UVC LED treatment system to inactivate foodborne pathogens on selective media and food surfaces, and inactivation rate constants, UV sensitivities, were calculated using model equations.

Sixteen UVC LEDs were placed and connected onto an electronic printed circuit board (PCB), and a carbon coated aluminum frame was built to maintain consistent distance (3 cm) between UVC LEDs and sample surfaces (Fig. 1). The distance was determined by calculating the optimized length to maximize intensity and irradiance overlaps on the treatment surface via 120° optical angle of UVC LEDs (Fig. 2). Intensity distribution and light intensity are in a trade-off relationship, which means uniform intensity needs a longer distance between a light emitting source and a surface, but in that case light intensity is

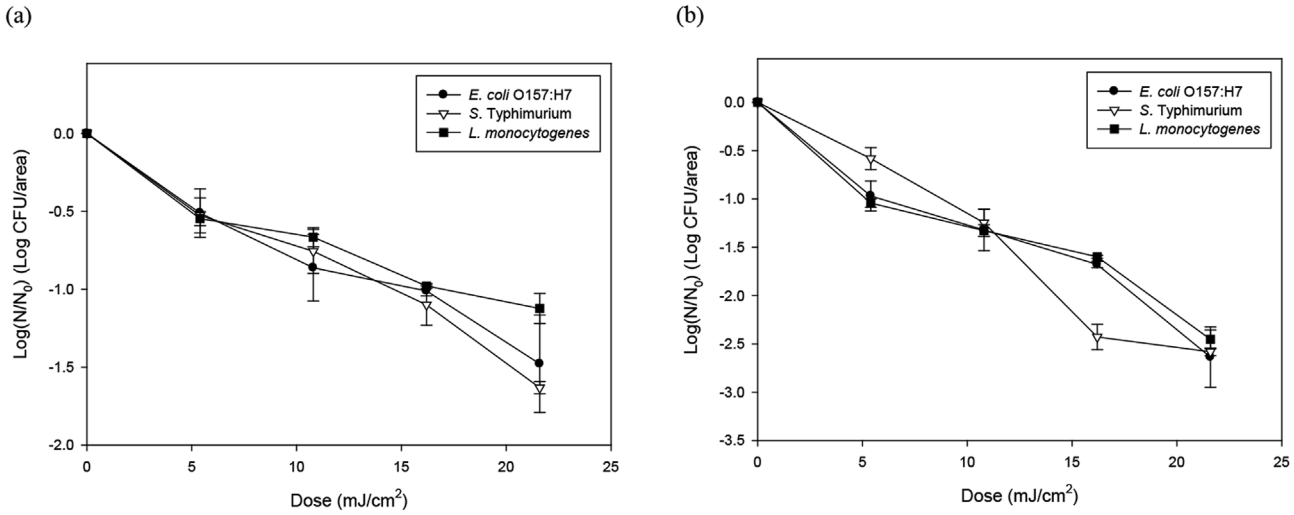

Fig. 5. Survival curves of *E. coli* O157:H7, *S.* Typhimurium, and *L. monocytogenes* after UVC LED irradiation on sliced deli meat (a) and spinach (b) surfaces.

dramatically decreased by the inverse square law. Therefore, developing the optimized balance between these two factors is prerequisite before constructing a UVC irradiation system. With this new irradiation system, theoretically, a single spot in the middle of the target surface can be irradiated by nine UVC LEDs, while a spot at the surface edge would only be illuminated by five–UVC LEDs. The intensity at the middle of the surface was approximately 40% greater than that at the edge (data not shown). Accordingly, foodborne pathogens on selective media were effectively inactivated from the middle of the media surface and, as treatment time increased, the inactivation range broadened crosswise (Fig. 3).

Pathogens on the surface of each selective medium were effectively inactivated within 4.5 s using the UVC LED module (Fig. 4). Increased irradiation time resulted in greater inactivation levels of these three major foodborne pathogens, and quite different levels of UV sensitivity emerged. *E. coli* O157:H7 showed the greatest sensitivity to UVC LED irradiation, so that 1.35 s (2.18 mJ/cm^2) irradiation could achieve over 3 log reduction. *S.* Typhimurium was inactivated by 3 log after 3.6 s (5.81 mJ/cm^2) UVC LED irradiation; however, the maximum irradiation time (~7.26 mJ/cm^2) could not achieve 3 log reductions of *L. monocytogenes*. The results are consistent in prior studies using LP lamps. Kim et al. reported that 1.4 log reduction of *E. coli* O157:H7 in lettuce at 80 mJ/cm^2, while 1.2 log reduction was achieved in *L. monocytogenes* at the same dosage (Kim et al., 2013). Also, approximately 1 log reduction of *E. coli* O157:H7 was observed in fresh-cut clover spouts, but *L. monocytogenes* was reduced by 0.7 log level at 100 mJ/cm^2 (Y. Kim, Kim, & Song, 2009). These different levels of UVC irradiation sensitivity were also observed by several other researchers (Beauchamp & Lacroix, 2012; Guerrero-Beltrán & Barbosa-Cánovas, 2005; Kim et al., 2017a). Because of some factors, such as cell size, photoproduct generation, cell wall thickness, and ability of DNA repair, different resistance against UVC irradiation was observed (Lopez-Malo & Palou, 2005, pp. 464–484; Tran & Farid, 2004). Especially, *L. monocytogenes* showed the least DNA damage when 279 nm peak wavelength UVC LED irradiation was imposed, in which distinctive reduction patterns in bacterial strains were drawn (Kim et al., 2017a).

In terms of UV dosage values necessary for 3- or 5- log reduction (D_{3d} or D_{5d}), this trend of different inactivation rates was also consistent (Table 1). The two modeling equations, Log-linear and Weibull equations, described the survival curves of pathogens on selective media very well based on low MSE (< 0.05) and high R^2 (> 0.99) values. The D_{3d} values of both equations for inactivating pathogens on media surfaces were 2.1, 5.9, and 9.2 mJ/cm^2 for *E. coli* O157:H7, *S.* Typhimurium and *L. monocytogenes*, respectively. From Fig. 4 and D_{3d} values, quite similar dosages were calculated in actual and expected values of irradiation dosages for 3 log reductions for *E. coli* O157:H7 and *S.* Typhimurium, which indicated that the model equations were fitted very well to depict survival populations of pathogens.

In contrast to selective media, survival curves of the three pathogens on sliced deli meat and spinach were quite comparable (Fig. 5). After 34 s irradiation (21.6 mJ/cm^2), 1.0 to 1.6 and 2.5 to 2.6 log reductions were achieved for sliced deli meat and spinach surfaces, respectively, and similar downward slope values were obtained in the survival curves for the three foodborne pathogens.

The inactivation rate constant (k value), indicating log reduction levels after treatment with unit irradiation dose (1 mJ/cm^2), was the highest for selective media followed by those of spinach and sliced deli meat and those values were significantly different ($P < 0.05$). The order of k value of each bacterium on selective media were *E. coli* O157:H7 > *S.* Typhimurium > *L. monocytogenes* ($P < 0.05$), while those on food samples were quite similar compared to selective media even though there were significant differences within each food sample ($P < 0.05$). This hysteresis between media and food surfaces was due to the screening effect engendered by surface roughness and method of bacterial inoculation (Adhikari, Syamaladevi, Killinger, & Sablani, 2015; Fransisca & Feng, 2012; Syamaladevi et al., 2015). Selective media, having ideal surfaces with low roughness, do not provide locations for bacteria to hide from UV irradiation and also bacterial suspension was spread onto the surfaces evenly so that the bacteria can be distributed and arranged in a thin uniform layer over the entire surface. Therefore, on selective media, bacteria are readily exposed to UV light. However, food surfaces are complex and diverse (Kwon, Song, & Kang, 2018; Park & Kang, 2017), so that bacteria can easily avoid exposure to germicidal light. Also, spot inoculated bacteria develop a stacked structure of bacterial cells, which lead to UV light hindrance when penetrating the bacterial spots (Adhikari et al., 2015; Syamaladevi et al., 2015).

5. Conclusion

In this study, we evaluated the efficacy of a simple UVC LED irradiation system for inactivating three major foodborne pathogens on selective media and food surfaces. This system can achieve over 3 log reduction of *E. coli* O157:H7 and *S.* Typhimurium within 1.35 and 4.5 s, respectively, on selective media, and 1.5 to 2.5 log reductions of all three pathogens on sliced deli meat and spinach surfaces, respectively, within 34 s. Through this innovative non-thermal treatment, enhanced microbiological safety of fresh produce and RTE products can be fulfilled without incurring quality deterioration.

CRediT authorship contribution statement

Do-Kyun Kim: Conceptualization, Data curation, Investigation, Writing - original draft, Writing - review & editing. **Dong-Hyun Kang:** Funding acquisition, Supervision.

Declaration of competing interest

The authors declare no competing financial interest.

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