Low-pressure mercury vapor UV (LP-UV) lamps have long been used for bacterial inactivation, but due to certain disadvantages, such as the possibility of mercury leakage, deep-UV-C light-emitting diodes (DUV-LEDs) for disinfection have recently been of great interest as an alternative. Therefore, in this study, we examined the basic spectral properties of DUV-LEDs and the effects of UV-C irradiation for inactivating foodborne pathogens, including Escherichia coli O157:H7, Salmonella enterica serovar Typhimurium, and Listeria monocytogenes, on solid media, as well as in water. As the temperature increased, DUV-LED light intensity decreased slightly, whereas LP-UV lamps showed increasing intensity until they reached a peak at around 30°C. As the irradiation dosage and temperature increased, E. coli O157:H7 and S. Typhimurium experienced 5- to 6-log-unit reductions. L. monocytogenes was reduced by over 5 log units at a dose of 1.67 mJ/cm². At 90% relative humidity (RH), only E. coli O157:H7 experienced inactivation significantly greater than at 30 and 60% RH. In a water treatment study involving a continuous system, 6.38-, 5.81-, and 3.47-log-unit reductions were achieved in E. coli O157:H7, S. Typhimurium, and L. monocytogenes, respectively, at 0.5 liter per minute (LPM) and 200 mW output power. The results of this study suggest that the use of DUV-LEDs may compensate for the drawbacks of using LP-UV lamps to inactivate foodborne pathogens.
reasons, a new type of flowthrough water disinfection system was
designed for the present study in order to prevent the loss of UV
treatment radiation. The system can be applied to sterilize munic-
ipal water.

The objectives of this study were to examine the basic proper-
ities of DUV-LEDs, such as the spectrum and intensity relative to
the distance between the LED and the subject and the arrangement
of LEDs. Also, the efficacy of UV-C irradiation for inactivating E.
coli O157:H7, Salmonella enterica serovar Typhimurium, and L.
monocytogenes on solid media at various temperatures and levels
of relative humidity (RH), as well as the comparison of batch and
continuous water treatment systems, were investigated.

MATERIALS AND METHODS

Collimated UV radiation design. Four DUV-LED modules (LG Innotek
Co., Seoul, Republic of Korea) were connected to an electronic printed
circuit board (PCB) to get a constant electric current of 20 mA from a DC
power supply (TPM series; Toyotech, Incheon, Republic of Korea). All of
these LEDs emitted a single wavelength, 275 ± 3 nm. Several spatial ar-
rangements of four DUV-LEDs were devised and analyzed to clearly fix
the optimal LED configuration that produced collimated radiation. Fig-
ure 1 shows the five kinds of LED arrangements that were tested in this
study (11).

Experimental setup. Four LED modules were arranged at each cor-
ner at a distance of 6 cm from each other and with a 4-cm distance
between the LEDs and a petri dish. This design showed generally equal
intensity across the whole petri dish (90-mm diameter) at a level 4 cm
above the sample. More concisely, the Petri factor, which indicates the
area of even distribution of irradiated light on a petri dish, was higher
than 0.9, which provides a nearly ideal and uniform exposure of the
whole petri dish to UV irradiation (17). The PCB with LEDs and in-
oculated media was placed in a constant-temperature chamber (IL-11;
Lab Companion, Daejeon, Republic of Korea) to optimize the treat-
ment conditions. The petri dish was located directly below the LEDs to
receive maximum UV exposure (Fig. 2).

Irradiance measurements. Radiation intensities were compared be-
tween DUV-LEDs and an 8-W LP-UV lamp (G6T5; Sankyo Denki, Ka-
nagawa, Japan) by increasing the time and temperature. The irradiance
levels of the DUV-LEDs and the LP lamp were measured with a spectrom-
eter (AvaSpec-ULS2048-USB2-UA-50; Avantes, Apeldoorn, Nether-
lands) calibrated for a 200- to 400-nm range within the UV spectrum. To
reveal the best arrangement of LEDs in the PCB and to decide the most effective distance between the PCB and the material accepting light, an optical probe was placed 2, 4, 6, and 8 cm above the LED and the peak irradiance value of the spectrum was read. In order to calculate the Petri factor over a petri dish, the optical probe scanned and took measurements of 7.95 cm², which corresponds to the area of one-eighth of the petri dish surface. The area that could be representative of the whole petri dish was measured for every 5 mm (17). The intensity of each point was divided by the maximum intensity of the relevant configuration, and the Petri factor was calculated as the average ratio of the intensities. The maximum intensity value was multiplied by the Petri factor to obtain the corrected irradiance, which indicates the average fluence (UV dose) rate.

**Culture preparation and inoculation.** Each strain of *E. coli* O157:H7 (ATCC 35150, ATCC 43889, and ATCC 43890), *S. Typhimurium* (ATCC 19585, ATCC 43971, and DT 104), and *L. monocytogenes* (ATCC 7644, ATCC 19114, and ATCC 19115) were obtained from the Bacterial Culture Collection at Seoul National University (Seoul, Republic of 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 plus 0.3 ml of sterile 50% glycerol solution). To obtain working cultures, bacteria were streaked onto tryptic soy agar ( rsa) (Difco), incubated at 37°C for 24 h, stored at 4°C, and used within 3 days.

**Bacterial strains and inoculum conditions.** Three strains of *E. coli* O157:H7 (ATCC 35150, ATCC 43889, and ATCC 43890), *S. Typhimurium* (ATCC 19585, ATCC 43971, and DT 104), and *L. monocytogenes* (ATCC 7644, ATCC 19114, and ATCC 19115) were obtained from the Bacterial Culture Collection at Seoul National University (Seoul, Republic of 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 harvested by centrifugation at 4,000 × g for 20 min at 4°C, and the supernatant was discarded. The cell pellets obtained were resuspended in sterile 0.2% Bacto peptone (Becton, Dickinson and Company, Sparks, MD, USA) and centrifuged. This washing procedure was performed three times. The final pellets were resuspended in 9 ml sterile 0.2% Bacto peptone water (PW), corresponding to approximately 10⁶ to 10⁸ CFU/ml. The resuspended pellets of each strain of all the pathogen species were combined to constitute a 3-pathogen mixed-culture cocktail.

For experiments performed on medium surfaces, in order to set a control solution, the mixed-culture cocktail was 10-fold serially diluted three times (10⁻³ dilution) with 0.2% sterile PW, resulting in a final concentration of approximately 5- to 6-log CFU/ml. For inoculation, the culture suspension was further 10-fold serially diluted with 0.2% sterile PW to obtain countable colonies. One-tenth milliliter of selected diluents was spread plated onto selective or nonselective medium. Sorbitol MacConkey agar (SMAC) (Difco), xylose lysine desoxycholate agar (XLD) (Difco), and Oxford agar base with antimicrobial supplement (MOX) (MB Cell, Seoul, Republic of Korea) to allow even irradiation. The sample was mixed continuously with a magnetic stirrer (HY-HS11; Han-yang Science, Seoul, Republic of Korea) to adjust the humidity to 30, 60, and 90% RH, with the temperature maintained at 25°C.

**Bacterial enumeration.** After UV treatment of water, 1-ml sample aliquots were 10-fold serially diluted in 9-ml blanks of 0.2% PW, and 0.1 ml of sample or diluent was spread plated onto the selective media described previously to enumerate the three pathogens. All selective agar media were incubated at 37°C for 24 to 48 h, and typical colonies were counted.

**Enumeration of injured cells.** Assessing the generation of injured cells was performed only for media subjected to dose and temperature treatments and for the batch water treatment. The OV method was used to count injured cells of *S. Typhimurium* and *L. monocytogenes* cells. To obtain countable numbers of colonies on the tested media, two levels of sequential 10-fold serial dilutions were spread plated. After inoculation, the media were dried for approximately 30 min prior to UV treatment.

For water treatment, sterile distilled water (DW) was used. In the case of the small-scale batch system for water decontamination, 0.1 ml of mixed-culture cocktail was inoculated into 25 ml of DW at room temperature. For the continuous water decontamination system, 8 ml of culture cocktail was inoculated into 2 liters of DW.

**UV treatment.** In order to minimize photoreactivation, all DUV-LED-treated petri dishes were covered with aluminum foil. Inoculated samples were treated with 275-nm DUV-LEDs at 5.57-μW/cm² intensity for 0, 0.5, 1, 3, and 5 min at room temperature. DUV-LED doses were calculated by multiplying DUV-LED intensities by the irradiation times. For testing at different temperatures, DUV-LED irradiation was applied to samples for 1 min at 0, 4, 15, 25, and 37°C. For all temperature tests, samples were kept at a controlled temperature inside the chamber for 5 min prior to treatment to allow equilibration. For examining the impact of RH on DUV-LED irradiation, a temperature and humidity chamber (TH-TG-300; JEIO Tech, Daejeon, Republic of Korea) was used to adjust the humidity to 30, 60, and 90% RH, with the temperature maintained at 25°C.

For the small-scale water decontamination system, inoculated samples were treated with a 278-nm DUV-LED at a 4.5-cm distance between the sample and the DUV-LED PCBs. Ten milliliters of inoculated water sample was placed in a petri dish (50 by 15 mm [internal dimensions]). The sample was mixed continuously with a magnetic stirrer (HY-HS11; Han-yang Science, Seoul, Republic of Korea) to allow even irradiation.

The continuous water treatment system (Fig. 3) consisted of a power supply, a peristaltic pump (JWS600; JenieWell, Seoul, Republic of Korea), and a manufactured quartz pipe (Kum-Kang Quartz, Gyeonggi, Republic of Korea), which was attached with LED modules. The inoculated water sample was transported by the pump through the silicon tubing and treated while flowing. Two to four LED modules that had an output power of 50 mW were attached to the quartz pipe, and the flow rates were adjusted to 0.5, 1, 1.5, or 2 liters per minute (LPM).

**Assessing the generation of injured cells**. After UV treatment of water, 1-ml sample aliquots were 10-fold serially diluted in 9-ml blanks of 0.2% PW, and 0.1 ml of sample or diluent was spread plated onto the selective media described previously to enumerate the three pathogens. All selective agar media were incubated at 37°C for 24 to 48 h, and typical colonies were counted.

**Enumeration of injured cells.** Assessing the generation of injured cells was performed only for media subjected to dose and temperature treatments and for the batch water treatment. The OV method was used to count injured cells of *S. Typhimurium* and *L. monocytogenes* (18). TSA, a nonselective medium, was used to resuscitate injured cells. One-tenth-
milliliter aliquots of appropriate dilutions were spread plated in duplicate, and the plates were incubated at 37°C for 2 h to enable injured cells to recover. The resuscitated media plates were then overlaid with 7 ml of the selective medium XLD for S. Typhimurium or MOX for L. monocytogenes. The solidified plates were incubated at 37°C for an additional 22 h. After incubation, typical black colonies characteristic of either S. Typhimurium or L. monocytogenes were counted. Enumeration of injured E. coli O157:H7 cells was accomplished with SPRAB (19). After incubation at 37°C for 24 h, white colonies characteristic of E. coli O157:H7 were enumerated, and simultaneously, serological confirmation (RIM; E. coli O157:H7 latex agglutination test; Remel, Lenexa, KS, USA) was performed on randomly selected presumptive E. coli O157:H7 colonies.

Statistical analysis. All experiments were replicated three times. All data were analyzed by analysis of variance (ANOVA) using the Statistical Analysis System (SAS Institute, Cary, NC, USA) and Tukey’s multiple-range test to determine if there were significant differences (P < 0.05) in the mean values of microorganism populations.

RESULTS

Emission spectrum of DUV-LEDs. An external view of the LED module is presented in Fig. 4a. The typical spectral irradiance of 275-nm DUV-LEDs was measured with a spectrometer as shown in Fig. 4b. The full width at half maximum (FWHM), defined as the wavelength gap between the output half-peak-intensity values, was 11.3 nm for 275-nm LEDs.

Comparison of properties between DUV-LED and LP-UV lamps. The warm-up time for both DUV-LED and LP-UV lamps was determined by measuring the irradiance intensity over time (0 to 10 min). After 5 min, the intensity of DUV-LEDs decreased by about 5.45%, whereas the intensity of LP-UV lamps increased by about 90.43% (Fig. 5a). Intensity changes relative to temperature presented different patterns between DUV-LED and LP-UV lamps. As the temperature increased, the intensity of the LEDs slightly decreased, while LP-UV lamps showed increasing intensity until they reached peak intensity at around 30°C and then decreased (Fig. 5b).

Influence of the LED arrangement on the effective area. The intensities at specified distances from DUV-LEDs were measured, and the Petri factor of each point was calculated (Fig. 6). In order to get a collimated beam of UV irradiation, the Petri factor should exceed 0.90. For the 4-corners arrangement, the Petri factor was calculated as 0.48, 0.90, 0.82, and 0.80 at distances of 2, 4, 6, and 8 cm, respectively (Fig. 6a). For other configurations, the Petri factor steadily increased from around 0.5 to 0.9 relative to distance, but all the configurations showed decreasing intensity with increasing distance between the centers of the LEDs and the probe (Fig. 6b). The 4-corners configuration at 4-cm distance had an intensity of 4.41 μW/cm², while the other configurations at 8-cm distance had an intensity of 3.2 μW/cm², yielding the same Petri factor of 0.90.

Bactericidal effect of UV treatment on media. The inactiva-
tion of foodborne pathogens following UV radiation is presented in Table 1. As the UV radiation dose increased from 0 to 1.67 mJ/cm², *E. coli* O157:H7 and *S. Typhimurium* experienced over 6-log-unit reductions and *L. monocytogenes* underwent a >5-log-unit reduction. Only after a dose of 0.34 mJ/cm² did *E. coli* O157:H7 experience a >5-log-unit reduction, and log reductions increased with increasing UV dose. For *S. Typhimurium*, the overall reduction patterns were similar to those of *E. coli* O157:H7. Populations of *S. Typhimurium* were reduced by 2.11 and 6.05 log CFU/ml after UV-C irradiation of 0.17 and 1.67 mJ/cm², respectively. With regard to *L. monocytogenes*, reductions ranged from 0.83 to 5.10 log CFU/ml after UV dosages of 0.17 to 1.67 mJ/cm². For all UV treatments, low numbers of injured cells occurred, but none differed significantly (*P > 0.05*) from the numbers of noninjured cells (Table 1).

**Effect of temperature on UV irradiation.** Table 2 shows the bactericidal effect of 1-min treatment with UV irradiation against the three foodborne bacteria at 0 to 37°C. Log reductions of all three foodborne pathogens increased with increasing temperature. For *E. coli* O157:H7, significant inactivation (*P < 0.05*) was observed at 0°C, which achieved a 5.07-log-unit reduction. As the treatment temperature increased from 0 to 37°C, reduction levels of *E. coli* O157:H7 gradually increased. Reductions of 2.25 to 5.44 log CFU/ml were observed in *S. Typhimurium* after 1 min of UV treatment at 0 to 37°C. Also, treatment at 37°C significantly reduced (*P < 0.05*) levels of *S. Typhimurium* by >5 log units compared to the control. Log reductions of UV-treated *L. monocytogenes* showed significant reduction (*P < 0.05*) compared to the control, but at differing treatment temperatures, irradiated samples were not significantly different (*P > 0.05*).

**Effect of relative humidity on UV irradiation.** Log reductions of *E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes* on media following UV treatment at 30, 60, and 90% RH are presented in Table 3. Only *E. coli* O157:H7 showed a significant reduction (*P < 0.05*) in relation to RH; approximately 0.5-log-unit greater reduction occurred at 90% than at 30 and 60% RH. In the cases of *S. Typhimurium* and *L. monocytogenes*, there were no significant (*P > 0.05*) differences relative to RH.

**Bactericidal effect of UV treatment on a batch water system.** Log reductions (CFU/ml) of *E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes* in 10 ml of water during UV treatment are depicted in Fig. 7. Inactivation levels for all three pathogens were more than 4 log units. Reductions of *E. coli* O157:H7 were 2.42 to 4.85 log units after irradiation with 0.2 to 3 mJ/cm². For *S. Typhimurium*, the overall inactivation pattern was similar to that of *E. coli* O157:H7. Reductions of 0.76 to 4.24 log units were observed after irradiation with 0.2 to 3 mJ/cm². In the case of *L. monocytogenes*, the levels of reduction increased from 0.52 to 4.97 log units as the irradiation dose increased from 0.2 to 2 mJ/cm². The number of injured cells was not significantly different from the number of noninjured cells (*P > 0.05*).

**Bactericidal effect of UV treatment on a continuous water system.** The reduction of *E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes* in a continuous water system during UV irradiation of foodborne pathogens following UV radiation is presented in Table 1. As the UV radiation dose increased from 0 to 1.67 mJ/cm², *E. coli* O157:H7 and *S. Typhimurium* experienced over 6-log-unit reductions and *L. monocytogenes* underwent a >5-log-unit reduction. Only after a dose of 0.34 mJ/cm² did *E. coli* O157:H7 experience a >5-log-unit reduction, and log reductions increased with increasing UV dose. For *S. Typhimurium*, the overall reduction patterns were similar to those of *E. coli* O157:H7.
tion is presented in Table 4. In general, the reduction levels of *E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes* increased with decreasing flow rate and increasing UV light power output. For *E. coli* O157:H7, UV treatment at 100 mW with a flow rate of less than 1.0 LPM, 150 mW with a flow rate under 1.5 LPM, and 200 mW with less than a 2.0-LPM flow rate accomplished greater than 3-log-unit reductions. For *S. Typhimurium*, intensities of 150 mW at a flow rate of 0.5 LPM and 200 mW at less than 1.0 LPM accomplished more than 3-log-unit reductions. For *L. monocytogenes*, the trend of reduction was similar to those of *E. coli* O157:H7 and *S. Typhimurium*. However, only at an intensity of 200 mW with a flow rate of 0.5 LPM did a 3-log-unit reduction of *L. monocytogenes* occur.

**DISCUSSION**

UV irradiation has been used for disinfecting surfaces, air, and water for many years. Also, much research has verified the decontamination efficacy of UV. Caminiti et al. (20) investigated the inactivation efficacy of UV lamps on apple juice. Over 5-log-unit reductions of both *Listeria innocua* and *E. coli* K-12 were achieved at a dosage of 2,660 mJ/cm². Reduction of foodborne pathogens in fresh-cut lettuce by using UV lamps was conducted by Kim et al. (21). Double-sided irradiation for a 10-min treatment with an intensity of 6.80 mW/cm² effected 3- to 4-log-unit reductions of *E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes*.

As one of the nonthermal methods for reducing a broad range of microorganisms, including some pathogens, UV is effective, but safety hazards are associated with its use. LP-UV lamps, which produce UV-A or UV-B at a dosage of 2,660 mJ/cm², have been used in food industry for many years. Also, much research has verified the decontamination efficacy of UV. Caminiti et al. (20) investigated the inactivation efficacy of UV lamps on apple juice. Over 5-log-unit reductions of both *Listeria innocua* and *E. coli* K-12 were achieved at a dosage of 2,660 mJ/cm². Reduction of foodborne pathogens in fresh-cut lettuce by using UV lamps was conducted by Kim et al. (21). Double-sided irradiation for a 10-min treatment with an intensity of 6.80 mW/cm² effected 3- to 4-log-unit reductions of *E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes*.

The data represent means ± standard deviations from three replications. Values followed by the same uppercase letter in the same column are not significantly different (P > 0.05). Means followed by the same lowercase letter in the same row for the same bacterium are not significantly different (P > 0.05).

**TABLE 2** Log reductions of *E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes* on selective media following 1 min of UV-C irradiation at different treatment temperatures

<table>
<thead>
<tr>
<th>Treatment temp (°C)</th>
<th><em>E. coli</em> O157:H7</th>
<th><em>S. Typhimurium</em></th>
<th><em>L. monocytogenes</em></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SMAC</td>
<td>SPRAB</td>
<td>XLD</td>
</tr>
<tr>
<td>0</td>
<td>5.07 ± 0.25 Aa</td>
<td>4.85 ± 0.25 Ba</td>
<td>2.25 ± 0.19 Ba</td>
</tr>
<tr>
<td>4</td>
<td>5.44 ± 0.53 Aa</td>
<td>5.29 ± 0.48 Aa</td>
<td>2.83 ± 0.40 Ba</td>
</tr>
<tr>
<td>15</td>
<td>5.82 ± 0.63 Aa</td>
<td>6.07 ± 0.42 Aa</td>
<td>3.32 ± 0.31 Ba</td>
</tr>
<tr>
<td>25</td>
<td>6.14 ± 0.33 Aa</td>
<td>6.05 ± 0.29 Aa</td>
<td>4.94 ± 0.72 Aa</td>
</tr>
<tr>
<td>37</td>
<td>6.03 ± 0.38 Aa</td>
<td>5.74 ± 0.23 Aa</td>
<td>5.44 ± 0.22 Aa</td>
</tr>
</tbody>
</table>

* The data represent means ± standard deviations from three replications. Values followed by the same letters within the same column are not significantly different (P > 0.05). Means followed by the same lowercase letter in the same row for the same bacterium are not significantly different (P > 0.05).
at low temperatures, particularly *L. monocytogenes*, which is one of the major foodborne pathogens known to grow under refrigeration (25). For inactivating these bacteria, DUV-LEDs may therefore be more appropriate than LP lamps.

Log reductions of all three pathogens showed a tendency to increase as the applied UV energy increased. *L. monocytogenes*, a Gram-positive bacterium, had more resistance to UV radiation than Gram-negative bacteria, such as *E. coli* O157:H7 and *S. Typhimurium*. This added resistance may be due to the thick peptidoglycan wall that surrounds the cytoplasmic membrane in Gram-positive bacteria, whereas Gram-negative bacteria possess only an external membrane (26). Many research studies investigating the sanitization of foodborne pathogens in various foods report that *L. monocytogenes* is considered to be one of the most UV-resistant bacteria (27, 28, 29).

Most of the UV-related studies have focused on the storage temperature following UV treatment (30, 31). Along with storage temperature, treatment temperature is one of the key factors. In the present study, the treatment temperature had a profound effect on inactivation of *E. coli* O157:H7 and *S. Typhimurium*. When the temperature increased from 0 to 37°C, log reductions of both pathogens increased. However, *S. Typhimurium* produced significant numbers of injured cells when the treatment temperatures exceeded 4°C, whereas *E. coli* O157:H7 and *L. monocytogenes* experienced no formation of injured cells regardless of the treatment temperature. A related study showed that about 60.73 to 93.14% of *S. Typhimurium* cells on cherry tomatoes became injured following UV lamp irradiation at 2 to 10 kJ/m² (32). However, the selective action of sodium desoxycholate in XLD for *Salmonella* is so powerful that actual live (noninjured) cell populations have a tendency to be underestimated. Therefore, injured cells of *S. Typhimurium* are assumed to be less prevalent and thus less important.

Although DUV-LEDs emit a higher intensity of radiation at lower temperatures, the inactivation effect showed the opposite results. The enhanced inactivation at higher temperatures might be explained by phase transition of the phospholipid molecules that are found in the cell membrane (33). Thayer and Boyd (34) stated that the level of inactivation of bacteria by gamma radiation was directly related to chemical reactions at treatment tempera-

![FIG 7](https://www.asm.org/aem/2016/82/1/aem16010101.01.jpg)
TABLE 4 Reductions in levels of *E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes* in a continuous water system following UV-C irradiation at various flow rates and intensities

<table>
<thead>
<tr>
<th>Bacterium</th>
<th>Flow rate (LPM)</th>
<th>Log [log_{10} (n_{0}/n)] (%) reduction by treatment at:</th>
<th>100 mW</th>
<th>150 mW</th>
<th>200 mW</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>E. coli</em> O157:H7</td>
<td>2.0</td>
<td>1.97 ± 0.32 (98.93) Cb</td>
<td>3.68</td>
<td>3.63</td>
<td>3.93</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2.36 ± 0.12 (99.56) Cb</td>
<td>4.06</td>
<td>4.06</td>
<td>4.06</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>3.24 ± 0.32 (99.94) Cb</td>
<td>4.90</td>
<td>4.90</td>
<td>4.90</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>4.69 ± 0.40 (&gt;99.99) Ab</td>
<td>6.38</td>
<td>6.38</td>
<td>6.38</td>
</tr>
<tr>
<td><em>S. Typhimurium</em></td>
<td>2.0</td>
<td>1.20 ± 0.17 (93.74) Ca</td>
<td>1.85</td>
<td>1.85</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>1.40 ± 0.19 (96.05) BCB</td>
<td>2.27</td>
<td>2.27</td>
<td>2.27</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>1.87 ± 0.29 (98.66) Bb</td>
<td>3.06</td>
<td>3.06</td>
<td>3.06</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>2.87 ± 0.25 (99.86) Ab</td>
<td>5.81</td>
<td>5.81</td>
<td>5.81</td>
</tr>
<tr>
<td><em>L. monocytogenes</em></td>
<td>2.0</td>
<td>0.42 ± 0.14 (62.27) Ba</td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>0.58 ± 0.23 (73.56) Ba</td>
<td>1.19</td>
<td>1.19</td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0.63 ± 0.15 (76.56) Bb</td>
<td>1.49</td>
<td>1.49</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1.48 ± 0.17 (96.69) Ab</td>
<td>3.47</td>
<td>3.47</td>
<td>3.47</td>
</tr>
</tbody>
</table>

* The data represent means ± standard deviations from three replications. Means followed by the same uppercase letter in the same column are not significantly different (P > 0.05). Means followed by the same lowercase letter in the same row are not significantly different (P > 0.05). \( n_{0} \), number of bacteria before irradiation (time zero); \( n \), number of bacteria after irradiation.

tures, Rather than a direct effect of irradiation, cellular inactivation is due to interactions with radiolytic products of water. This phenomenon can be understood in the context of temperature-dependent UV radiation because of photochemical reactions that can occur as a direct result of UV radiation energy (35). Also, the fluidity of the cell membrane increases with heating, making the affected cells more sensitive to UV exposure (36). On the other hand, the UV treatment temperature did not affect the reduction rate of *L. monocytogenes* because of its characteristics as a Gram-positive bacterium mentioned above.

DUV-LEDs applied to a batch water system inactivated foodborne pathogens effectively without generating injured cells. In 2009, Lakretz et al. (37) investigated the inactivation efficacy of medium-pressure (MP) UV lamps in a static solution system. The MP lamps generating polychromatic light were filtered with band-pass filters to select the desired peak wavelength. *Pseudomonas aeruginosa* in phosphate-buffered saline (PBS) was inactivated by 2.5 to 3.5 log units at various wavelengths, which induced a lower fluidity of affected cells more sensitive to UV exposure (36). On the other hand, the UV treatment temperature did not affect the reduction rate of *L. monocytogenes* because of its characteristics as a Gram-positive bacterium mentioned above.

DUV-LEDs have advantages over LP-UV lamps. DUV-LED use led to effective inactivation of *E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes* both on medium surfaces and in water systems under various conditions with minimal generation of injured cells. Furthermore, to date, this is the first report of the direct application of DUV-LED technology for the inactivation of foodborne pathogens. In addition, water treatment by DUV-LEDs in large capacities and at high flow rates has not been previously reported. DUV-LEDs could be a very promising alternative technology for UV irradiation in the field of controlling foodborne pathogens. Moreover, application of this technology to actual food samples and comparison of disinfection effectiveness between types of UV lamps must be studied in the future.

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6. Bintsis T, Tzanetaki EL, Robinson RK. 2000. Existing and potential characteristics of DUV-LEDs, such as fast-stabilizing intensity and insensitivity to temperature, should be regarded as great advantages over LP-UV lamps. DUV-LED use led to effective inactivation of *E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes* both on medium surfaces and in water systems under various conditions with minimal generation of injured cells. Furthermore, to date, this is the first report of the direct application of DUV-LED technology for the inactivation of foodborne pathogens. In addition, water treatment by DUV-LEDs in large capacities and at high flow rates has not been previously reported. DUV-LEDs could be a very promising alternative technology for UV irradiation in the field of controlling foodborne pathogens. Moreover, application of this technology to actual food samples and comparison of disinfection effectiveness between types of UV lamps must be studied in the future.