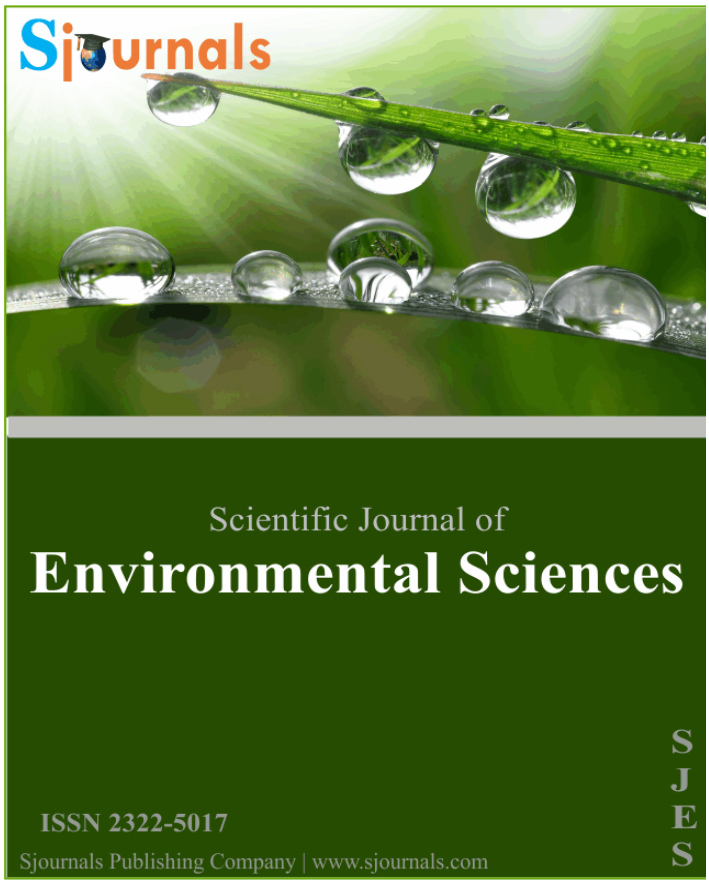

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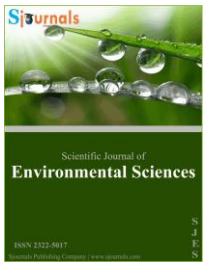

Original article

Comparison of UV-C and UV-C LED germicidal efficiency for potable water use

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ABSTRACT

Ultraviolet (UV) irradiation is a common disinfection option for water treatment. UV irradiation inactivates bacteria, viruses, and protozoa, with the benefits of no taste and odor issues, no known disinfection byproducts (DBPs), no danger of overdosing, relatively fast treatment rates compared to sand filtration. Ultraviolet-light-emitting diode (UV LED) contains no mercury, and its compact size and durable design offer excellent portability. The object of this study was to compare the inactivation efficiency of UV-C and UV-C LED for water disinfection. The collimated-beam system was used for this study. For the microorganisms to be tested, *E. coli* (ATCC 15597), which readily responds to UV light, and *Bacillus subtilis* sp. (ATCC 6633) were used. *E. coli* were 3 log inactivation of UV-C and UV-C LED applied fluence of 18 mJ/cm^2 at pH 7 and *Bacillus subtilis* sp. were 2 log inactivation of UV-C and UV-C LED applied fluence of 40 mJ/cm^2 at pH 7. UV-C LED disinfection was found to have nearly the same level of UV-C disinfection.

1. Introduction

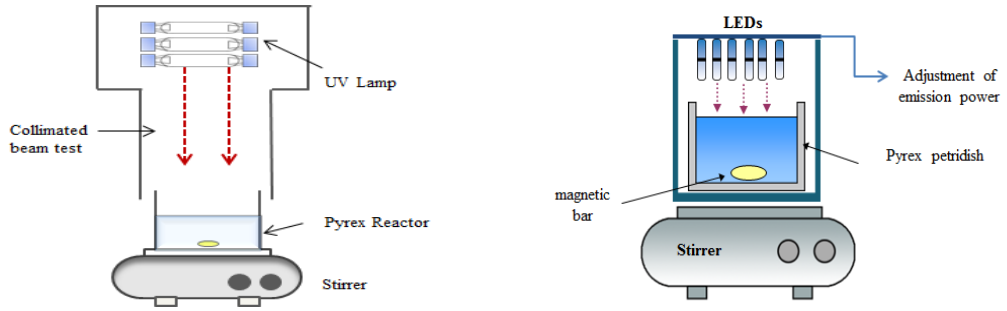
The UV (Ultraviolet) disinfection to disinfect the drinking water has been growing as the textbook method to replace the chlorine disinfection to inactivate the pathogenic microorganisms without generating the side products

of disinfection (Bohrerova et al., 2006). However, the low pressure or intermediate pressure mercury lamp mostly used for UV disinfection is toxic, consumes high energy, and require often replacement due to the short life. Therefore, development of technology to replace UV has been ongoing, and the UV LED (Ultraviolet Light Emitting Diode) technology has gained the interest (Wang et al., 2005; Vilhunen et al., 2009). Compared to mercury lamps, UV LED is generally smaller and economical, consumes less power, is not toxic and has long life due to the high efficiency. LED does not contain, and its small and solid design has long durability and enables transport. Moreover, it has no warming-up time, consumes low voltage and low energy, has the potential for high energy efficiency, and can reduce the replacement period as the life is extended. Recent studies report that the UV LED technology is also effective in disinfection and show the interest on applying it for water disinfection (Bowker et al., 2011; Wrtele et al., 2011). This study intended to test inactivation of microorganisms using UV and UV LED, apply the leading disinfection models to find the disinfection model that is the most appropriate for UV LED disinfection, and mathematically present the interaction between the given conditions of microorganisms and disinfectants. In addition, it reviewed the applicability of UV LED disinfection of drinking water to replace UV.

2. Materials and methods

2.1. Equipment

Fig. 1 shows the collimated beam device of UV and UV LED system. Collimated-beam UV system was used for UV disinfection. 4 low-pressure UV lamps (Germicidal Lamp (253.7 nm), (4 W, Philips Co.) were used as the light source, and the distance between the reactor and lamp was adjusted to 0.1~0.4 mW/cm^2 (Shin et al., 2001; Cho et al., 2004). For testing, the UV LED module had 6 UV LEDs (UVTOP255, average wavelength 260 nm) laid out side by side, and the distance between the reactor and lamp adjusted to 5 cm so that the vertical light intensity was around 0.004 mW/cm^2. For UV and UV LED disinfection, Pyrex Deep Petri-dish (50 mL, 6 by 3 cm) was used as the reactor, and a magnetic stirrer was used to stir. The light intensity was measured using UV 253.7 Detector (UVX radiometer, UVP Co.).



(a) UV (b) UV LED

Fig. 1. Experimental equipment.

2.2. Culturing microorganism and analysis

E.Coli (ATCC 15597) and *bacillus subtilis* sp. (ATCC 6633) were tested. To generate the *bacillus subtilis* sp., the frozen *B. subtilis* sp. solution was inoculated to the nutrient broth (Difco Co., USA) using platinum loop and cultivated at 37°C. It was then spread to the 1/10 nutrient agar and cultivated for 5~6 days. The induced sporulation was collected and suspended in PBS for cleaning then heat treated at 80°C for 15 minutes. To measure the concentration of *bacillus subtilis* sp., it was spread to the nutrient agar, cultivated at 37°C for 24 hours and then measured in the spread plate method (APHA, 1998). The *bacillus subtilis* sp. was always heat treated, and only the spores were used for experiment (Nakayama et al., 1996). To cultivate and analyze the *E.Coli*, *E.Coli* (ATCC 15597) was inoculated to the 50 mL of tryptic soy broth (Difco Co., USA) and cultivated at 37°C for 18 hours. It was then moved to a 50 mL conical tube and then cleaned in PBS at 1,000×g for 10 minutes. The pellets were suspended in PBS to be used as the culture medium. To measure the concentration, the same method as *bacillus subtilis* sp. was used (Cho et al., 2004). The initial injection concentrations *E.Coli* and *bacillus subtilis* sp. used in the experiment were maintained at 10^6~10^7 CFU/mL.

2.3. Application of disinfection model

The disinfection model (Eq. 1) is used to quantitatively describe the inactivation of the microorganism in a disinfection process. The Chick-Watson model is generally used, but this study used the Delayed Chick-Watson model which often applied when there is a lag phase (Chick, 1908; Rennecker et al., 1999; Cho et al., 2006).

$$\frac{N}{N_0} = \begin{cases} 0 & if\ \overline{CT} \le \overline{CT_{lag}} \\ \exp(-k(\overline{CT} - \overline{CT_{lag}})) & if\ \overline{CT} > \overline{CT_{lag}} \end{cases} \quad (1)$$

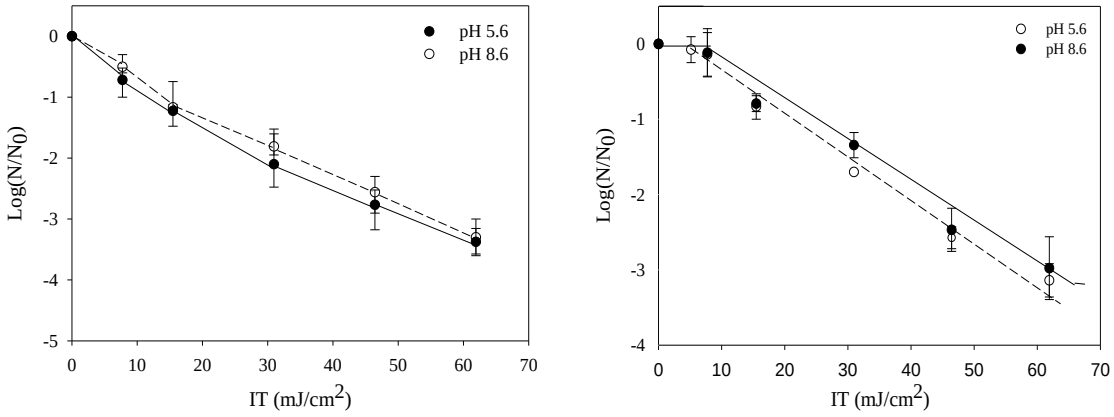
Hear, N=concentration of *bacillus subtilis* sp. (cfu/mL) at time t, N_0 = initial *bacillus subtilis* sp. concentration (cfu/mL), $\bar{C} = \int_0^t C/tdt$ time average disinfectant concentration (mg/L), *k* = inactivation rate constant (L/mg·min), $\overline{CT_{lag}}$ = X segment of the inactivation curve. In a UV disinfection, $\bar{C}$ can be substituted by *I*, and the unit of *k* can be changed from L/mg·min to cm^2/mJ.

3. Results and discussion

3.1. Inactivation rate by UV LED

Fig. 2 (a) shows the result of inactivation of *E.Coli* by UV LED at the conditions of 25°C temperature as well as pH 5.6 and pH 8.6. The test result shows that there was almost no difference of level of inactivation of *E.Coli* by pH. pH is generally known not to affect UV disinfection, and the same result was generated with UV LED (EPA, 2003; Montgomery, 1985). Observation of inactivation of *E.Coli* at the UV LED intensity of around 0.004 mW/ cm^2 showed that the IT (light intensity×inactivation time) value required to achieve 2 log inactivation of colon bacillus was 30 mJ/cm^2.

Fig. 2 (b) shows the result of inactivation of *bacillus subtilis* sp. by UV LED at the conditions of 25°C temperature as well as pH 5.6 and pH 8.6. Like the *E.Coli*, there was almost no difference of level of inactivation of *bacillus subtilis* sp by pH. As other literatures reported, the *bacillus subtilis* sp. had the lag period in UV LED disinfection also. Observation of inactivation of *E.Coli* at the UV LED intensity of around 4.3 μW/ cm^2 for 4 hours until reaction time showed that the IT value required to achieve 2 log inactivation of *E.Coli* was 45 mJ/cm^2.



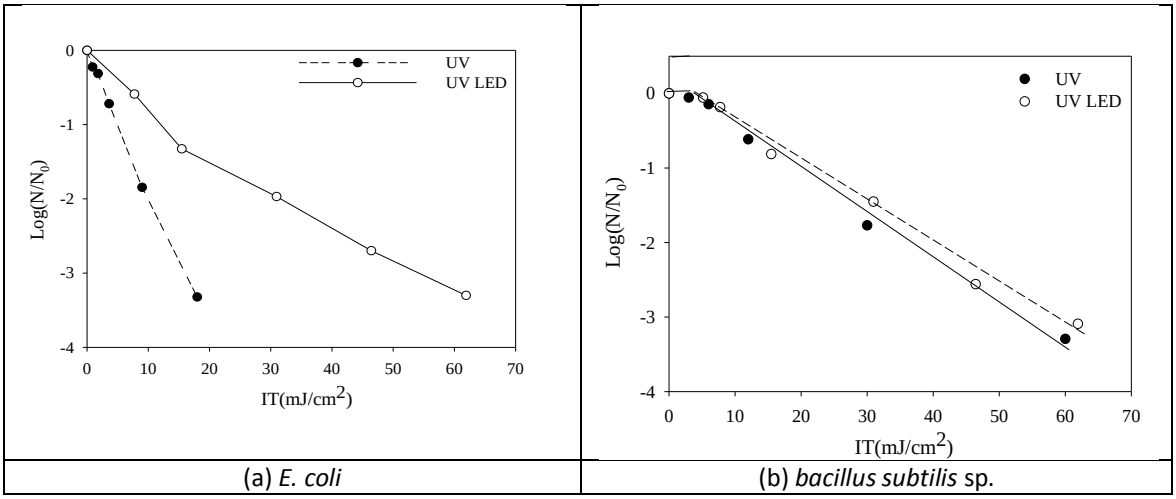
(a) *E. coli* (b) *bacillus subtilis* sp.

Fig. 2. Inactivation response of *E. coli* and *bacillus subtilis* sp. in deionized water for 260 nm UV LEDs (pH 5.6 and 8.6).

3.2. Comparison of inactivation rate of UV LED and UV

Fig. 3 show the result of inactivation of colon bacillus and *bacillus subtilis* sp. by UV LED and UV at 25°C temperature and pH 7. As shown in Fig. 3 (a), the comparison of inactivation of *E.Coli* by UV LED and UV showed that the IT in UV LED was around 30 mJ/cm^2 at 2 log inactivation while IT in UV was around 8 mJ/cm^2 at 2 log inactivation. For *E.Coli*, the UV LED disinfection inactivated more slowly than UV. Although there was a difference of IT value, the test result was similar to other studies (Bowker et al., 2011). Since *E.Coli* can be greatly inactivated even with very small stimulation when it is damaged by disinfection, the great inactivation of *E.Coli* in UV LED was

also expected, but UV LED required more IT than UV. Fig. 3 (b) shows that the *bacillus subtilis* sp. was inactivated in the similar level in both UV LED and UV. It showed 2 log inactivation at the IT value of around 40 mJ/cm^2. Moreover, it had a clear lag period up to the IT value of around 5 mJ/cm^2 in both UV LED and UV. In the case of *bacillus subtilis* sp., the inactivation rate was equally high in both UV and UV LED at the same IT value.



(a) *E. coli* (b) *bacillus subtilis* sp.

Fig. 3. Inactivation response of *E. coli* and *bacillus subtilis* sp. in deionised water for by UV and UV LEDs (pH 7).

3.3. Application of UV LED disinfection model

Bacillus subtilis sp. had clear lag period in UV LED disinfection. As the *bacillus subtilis* sp. has the surface structure with strong resistance similar to the surface structure of cyst and oocyst, the damage on the surface structure may not affect the *bacillus subtilis* sp. at all, and it is not directly damaged by disinfection thus does not become inactivated. In the case of *E.Coli*, it can be inactivated even with small stimulation if it is damaged by disinfection. Therefore, different disinfection model must be applied to different microorganism. In the case of the *bacillus subtilis* sp., the modified delayed Chick-Watson model described its characteristics well and showed the similar result as other studies in UV LED disinfection (Jung et al., 2008; Cho et al., 2006). In UV LED disinfection, both *E.Coli* and *bacillus subtilis* sp. had the lag period, and the slope of lag period and inactivation were confirmed.

4. Conclusion

Following conclusions were obtained from the experiment of inactivation of *E.Coli* and *bacillus subtilis* sp. with UV LED and UV.

1) At pH 7, the *E.Coli* had the inactivation of around 3 log at the IT value of around 18 mJ/cm^2 in UV LED and UV disinfection, and the *bacillus subtilis* sp. had the inactivation of around 2 log at the IT value of around 40 mJ/cm^2. The UV LED disinfection showed the similar inactivation rate as the UV disinfection.

2) Review of applying UV LED to disinfect the drinking water indicated that the UV LED disinfection can substitute UV disinfection at the wavelength of 260 nm.

3) For the *bacillus subtilis* sp., the modified delayed Chick-Watson model represented the UV LED disinfection well.

4) It is expected that the levels of microorganism disinfection control and operation with UV LED can be determined by calculating the lag period and inactivation velocity values using a disinfection model.

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