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AREA 5.1 • MICROBIAL WASTE DISPOSAL AND GROUNDWATER REMEDIATION • RESEARCH ARTICLE

Ultraviolet light-emitting diodes in water disinfection

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Abstract
Background, aim, and scope The novel system of ultraviolet light-emitting diodes (UV LEDs) was studied in water disinfection. Conventional UV lamps, like mercury vapor lamp, consume much energy and are considered to be problem waste after use. UV LEDs are energy efficient and free of toxicants. This study showed the suitability of LEDs in disinfection and provided information of the effect of two emitted wavelengths and different test mediums to *Escherichia coli* destruction.
Materials and methods Common laboratory strain of *E. coli* (K12) was used and the effects of two emitted wavelengths (269 and 276 nm) were investigated with two photolytic batch reactors both including ten LEDs. The effects of test medium were examined with ultrapure water, nutrient and water, and nutrient and water with humic acids.
Results Efficiency of reactors was almost the same even though the one emitting higher wavelength had doubled optical power compared to the other. Therefore, the effect of wavelength was evident and the radiation emitted at 269 nm was more powerful. Also, the impact of background was studied and noticed to have only slight deteriorating effect. In the 5-min experiment, the bacterial reduction of three to four log colony-forming units (CFU) per cubic centimeter was achieved, in all cases.
Discussion When turbidity of the test medium was greater, part of the UV radiation was spent on the absorption and reactions with extra substances on liquid. Humic acids can also coat the bacteria reducing the sensitivity of the cells to UV light. The lower wavelength was distinctly more efficient when the optical power is considered, even though the difference of wavelengths was small. The reason presumably is the greater absorption of DNA causing more efficient bacterial breakage.
Conclusions UV LEDs were efficient in *E. coli* destruction, even if LEDs were considered to have rather low optical power. The effect of wavelengths was noticeable but the test medium did not have much impact.
Recommendations and perspectives This study found UV LEDs to be an optimal method for bacterial disinfection. The emitted wavelength was found to be an essential factor when using LEDs; thus, care should be taken in selecting the proper LED for maximum disinfection.

Keywords Disinfection · *E. coli* · Light-emitting diodes · Ultraviolet light · Water treatment

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1 Background, aim, and scope

Ultraviolet (UV)-based water disinfection technology is well known and found to be efficient (Hjinen et al. 2006). UV treatment is not expected to cause any undesired disinfection by-products in contrast to for example conventional chlorination or recently lots of interest in disinfection gained electrochemical oxidation (Polcaro et al. 2007; Jeong et al. 2006). Efficiency of UV systems in disinfection is based on the fact that DNA molecule absorbs UV light which leads to the breakage of DNA and further to fast destruction of bacteria (Soloshenko et al. 2006). The broad absorbance band of DNA has maximum at about 190 and 260 nm. The wavelength mostly used in disinfection is 254 nm, which is the wavelength emitted by mercury vapor lamp (Koivunen and Heinonen-Tanski 2005).

Conventional UV lamps, like mercury vapor lamp, operate at high voltages. Due to high energy demand and toxicity of mercury, other sources of UV light are receiving more interest. Light-emitting diode (LED) is a semiconductor p–n junction device that emits light in a narrow spectrum, produced by a form of electroluminescence (Crawford et al. 2005; Khan 2006; Hu et al. 2006). AlGaN and AlN are materials for deep UV LEDs. LEDs are free of toxicants (e.g., mercury) and consume less energy than traditional lamps, as LED transmits greater amount of energy into light and wastes little energy as heat. Moreover, UV LEDs are hard to break and emit only desirable wavelengths (i.e., 260 nm). The usage of UV LEDs in water treatment is a considerably new method because UV LEDs emitting wavelengths low enough have emerged just recently. LEDs emitting radiation at the wavelengths even as short as 210 nm have been developed (Taniyasu et al. 2006).

The aim of this study was to examine the efficiency of currently marketed UV LEDs in disinfection of water contaminated with *Escherichia coli*. Moreover, the effect of different emitted wavelengths (269 and 276 nm) as well as the impact of the test medium was studied.

2 Materials and methods

2.1 Experimental setup

Two batch reactors using different UV LEDs were prepared with ten similar LEDs in each. TO-39 LEDs were manufactured by Seoul Optodevice Co., Ltd., Korea. Reactors had viewing angle of 120° (low flat) and differed from each other by emitted wavelength, 269 and 276 nm. LEDs were connected electrically and encapsulated in a black plastic tube. In both batch reactors, the UV LED system (diameter 7 cm, height 20 cm) was attached with a clamp 1 cm above the sample in a sterile Petri dish. Magnetic stirrer provided proper mixing. Sample volume was 25 ml. All the tests were conducted at room temperature (23±2°C).

2.2 Radiant flux

According to manufacturer guarantee for UV LEDs, the optical power is not supposed to decrease more than 50% of the initial during 500 h of use. The efficiency of LEDs was monitored throughout the experiments and it remained the same. Radiant flux was measured using integrating sphere (Gigahertz optik/Mitaten Oy) and results as well as other technical information are presented in Table 1. Results are calculated for ten LEDs of each reactor. Measured radiant flux values and information received from manufacturer had some variation probably because of different ways to perform measurements. Reactor emitting higher wavelength gave greater values as expected.

2.3 Experimental procedure

E. coli (K12, obtained from the Hambi collection of University of Helsinki) was used throughout this work. Dried spores were suspended in tryptone–yeast–glucose (TYG) broth and incubated in 37°C for 48 h. Small amounts of the solution (500 μl) were transferred, mixed with 170 μl of glycerol, and stored in −20°C. Before the experiments, the frozen culture was inoculated to TYG agar plate and incubated for 24 h in 37°C. From eight to ten loops of bacterial population was moved to 500 ml of ultrapure or nutrient water to yield the microbial number of approximately 10^7 colony-forming units (CFU) per cubic centimeter. Nutrient water was prepared by adding 2 g of LAB 103 to 500 ml of ultrapure water. In addition, one test was performed diluting 2.2-g model humic acids (from University of Helsinki) to 500 ml of nutrient water to create a background having greater turbidity. Enumeration of spores was performed by spread plate technique with violet red bile agar (LAB 31) at 37°C for 24 h, as CFU per cubic centimeter. Test lasted always 20 to 25 min and a sample was taken in every 5 min. Gram coloring was used to check out the type of bacterial culture. Every experiment was done twice and all the samples were duplicated. All the substances used were from LAB M Ltd. Turbidities were measured with HACH 2100P ISO turbidimeter. Absorbance measurements were done by UV/Vis spectrometer (Perkin Elmer Instruments, Lambda 45).

3 Results

Ultrapure water, nutrient water, and nutrient water with humic acids were studied as a test medium with reactor 2. Turbidities as nephelometric turbidity unit as well as absorbance at wavelengths 269 and 276 nm are presented in Table 2. Destruction of bacteria became somewhat

Table 1 Average of actual wavelengths and radiant flux as well as power inputs of UV LED reactors

Reactor	Emitted wavelength (nm)	Radiant flux from manufacturer (mW)	Radiant flux, measured (mW)	Power input (W)
1	268.6	3.4	5.8	2.7
2	276.1	6.1	11.6	2.7

Table 2 Turbidity and absorbance of different test mediums

Test medium	Turbidity (NTU)	Absorbance at 269 nm	Absorbance at 276 nm
Ultrapure water	0.02	0.00	0.00
Nutrient water	0.35	0.44	0.37
Nutrient water + humic acids	1.45	0.56	0.48

slower when turbidity and absorbances increased. The use of nutrient water also increased the survival of bacteria but despite of that the difference in destruction rates was rather small and can be seen only in long-time exposure (Fig. 1).

Emitted wavelength has an impact to bacteria destruction rate (Soloshenko et al. 2006). It was found that even if the reactor 2 emitting higher wavelength had doubled optical power, the destruction of *E. coli* was almost as fast with reactor 1 (see Fig. 1). In addition, the absorbance of the test medium, nutrient water, was greater at 269 nm compared to 276 nm (see Table 2).

4 Discussion

The minor deteriorating effect of the test medium having higher absorbance is expected to result to some of the emitted light spent to absorption and reactions with humic acids and nutrients. Humic acids also tend to coat the bacteria reducing the sensitivity of the cells to UV light (Cantwell et al. 2008). In treating for example drinking water, this is not a problem because the drinking water has usually low turbidity. The considerable slight effect of test medium containing humic acids on *E. coli* destruction rate is advantageous when disinfection of water having colorful substances or some organics is considered. The thickness of sample layer was low which probably reduced the impact of humic acids.

The lower wavelength was distinctly more efficient when the optical power is considered, even though the difference of the two wavelengths is small. The better efficiency of wavelength 269 nm is presumably caused by the greater DNA absorption and breakage (Soloshenko et al. 2006). By selecting the wavelength accurately, the efficiency of UV treatment can be enhanced and less energy gets wasted. With LEDs, it can be done easily by using the kind of LEDs needed.

5 Conclusions

UV LEDs were efficient in *E. coli* destruction, even if the LEDs were considered to have rather low optical power. Three to four log bacterial reductions were achieved in 5 min in all experiments. The background had no significant effect on efficiency. The difference of two reactors was small, although the 276-nm reactor had doubled radiant flux compared to the 269-nm reactor and the absorbance of the sample solution was greater at 269 nm. Therefore, radiation emitted at the wavelength 269 nm was considered to be much more powerful compared to radiation at 276 nm. Thus, the emitted wavelength seems to be an essential factor in disinfection efficiency.

6 Recommendations and perspectives

Due to the results of *E. coli* destruction, UV LEDs are recommended to be used for disinfection purposes. Accurately selected LEDs emitting certain wavelength with narrow emission band save energy since all the radiation is in the efficient wavelength range. In addition, there are more alternative device structures because of the small size of LEDs. The development of LEDs is ongoing and the efficiency of LEDs is increasing all the time. In future, LEDs emitting different wavelengths have to be tested with multiple test mediums having the maximum absorbance at distinct wavelengths.

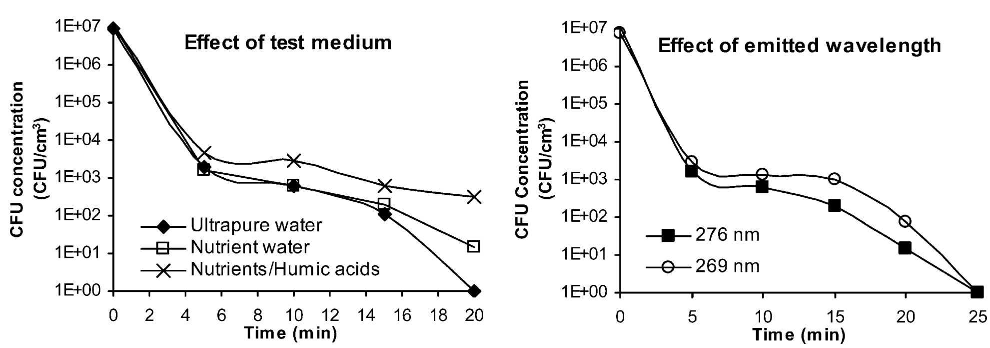

Fig. 1 Effect of test medium and emitted wavelength to *E. coli* destruction

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