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Research and Development of Dual Functional Features of Light-Emitting Diode: Degradation of Atmospheric Fine Particulate Matter and Antimicrobial Efficacy

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Abstract

Light-emitting diode (LED) is a semiconductor light source. LED in biomedical application as photodynamic therapy which induces cell death by the production of cytotoxic reactive oxygen species. Therefore, this principle of cell death can be also utilized to kill bacteria *in vitro*. Moreover, the R&D of the novel functional ability of LED is need as degradation of atmospheric fine particulate matter, $PM_{2.5}$ for LED industry development. Herein, we propose the use of white and blue LED devices at 450 nm wavelength as the powerful light source for *in vitro* killing of *Staphylococcus aureus* and *Pseudomonas aeruginosa*, and degrading atmospheric fine particulate matter, $PM_{2.5}$. Square arranged 48-white and blue LED array was respectively designed as the light source to fit exactly 10 cm culture plate and the degradation assay of $PM_{2.5}$ was also performed. Both *Staphylococcus aureus* and *Pseudomonas aeruginosa* were order from ATCC in this study. Effects of this powerful LED devices on viability of these bacterial species and degradation assay of $PM_{2.5}$ were compared with control samples. Statistical analysis was done using Microsoft Excel Student's *t* test. Results showed that the powerful LED devices against both *Staphylococcus aureus* and *Pseudomonas aeruginosa* was significantly effective compared to control samples *in vitro*. Degradation efficacy of $PM_{2.5}$ was also found after LED lighting. Taken together, the dual functional features, $PM_{2.5}$ degradation and antimicrobial efficacy, of our LED devices were demonstrated in this study. In the future, this powerful LED devices has promising applications in the human and animal life environment and in the biomedical application as disinfection, bacteriostatic, and improvement of air quality.

Abbreviations: LED: Light-Emitting Diode; MRSA: *Methicillin-Resistant Staphylococcus Aureus*; PA: *Pseudomonas Aeruginosa*; ROS: Reactive Oxygen Species; PDI: Photodynamic Inactivation; UV: Ultraviolet

Antimicrobial LED Visible Light is Safer than Ultraviolet Light

Ultraviolet (UV) light has been developed for surface decontamination. However, UV light has some limitations at harmful effects for human and animals [1-2]. Previously, some studies have been demonstrated that the germicidal efficacy of 405 nm light is significantly lower than that of UV light [3-5]. Visible light at 405 nm wavelength can be used at lethal levels to microorganisms without affecting exposed mammalian cells [6-7]. Light-emitting diode (LED) is a cost-effective semiconductor device that produces light within a narrow bandwidth of wavelength through electroluminescence. Recently, LED technology has attention to apply in the area of food production, food preservation, and food safety [8-9]. At present, some researches have been demonstrated that the antimicrobial LED visible light is less antimicrobial efficacy than UV light [7,10]. However, the antimicrobial LED visible light has been recognized as an alternative technology to UV light since it is an environmentally friendly and safe technology for human and animals [7,10]. For this reason, LED technology has recently received attention in the field of microbiology due to its antimicrobial effect.

In particular, many researches have been demonstrated that LEDs with the certain wavelength have antimicrobial effects. *In vitro* lethality of blue light for the bacteria Escherichia coli, aerobic *methicillin-resistant Staphylococcus aureus* (MRSA), and *Pseudomonas aeruginosa* (PA) has also been reported [11-12]. The antimicrobial effect of LED at 400 nm wavelength has been also reported to be effective against Listeria monocytogenes and Salmonella typhimurium [13]. LEDs at 405, 460 and 520 nm wavelength have also demonstrated antibacterial effects against various foodborne pathogens [2,9,14-15]. *Staphylococcus aureus* is a common cause of food poisoning, and some strains of *Staphylococcus aureus* have acquired resistance against a range of antibiotics [16]. Maclean et al. [9] showed that a LED with 405 nm wavelength inactivated 56-90% MRSA in the environment. In addition, De Lucca et al. [17] reported that blue light at 470 nm wavelength effectively inhibits bacterial (*Leuconostoc mesenteroides, Bacillus atrophaeus*, and PA) and fungal (*Penicillium digitatum* and *Fusarium graminearum*) growth.

Mechanisms of LED Light for Antimicrobial Efficacy and $PM_{2.5}$ Degradation

Microbial inactivation via LED technology is commonly referred to as photodynamic inactivation by producing reactive oxygen species (ROS) to kill pathogens. The antimicrobial mechanisms commonly included type I and type II mechanism. Type I mechanism can produce superoxide anion (O_2^-) and hydroxyl radical (•OH). Type II mechanism can excite the triplet oxygen to the reactive singlet oxygen. Due to these ROS generated a number of cytotoxic reactions and caused extensive damage to the cellular components. Absorption of this light results in the production of ROS, including H_2O_2 and singlet oxygen, leading to oxidative damage and cell death [5,18]. Finally, this eventually leads to the bacterial destruction [8,16,19]. Jia et al. [20] and Zhu et al. [21] reported that hot season than cold season can produce a strong oxidative air condition. The positive $PM_{2.5}$-O_3 correlations prevailed for high air temperature samples, while the negative correlations were generally found in cold environments. High O_3 concentrations in a strong oxidative air condition promoted the formation of secondary particles, which could decrease atmospheric $PM_{2.5}$ concentration, which is in a positive correlation between $PM_{2.5}$ and O_3. Hence, whether the mechanism of LED for $PM_{2.5}$ degradation is related with air temperature and O_3? It is needed to further verify.

Application Fields of Antimicrobial LED Visible Light

Photodynamic inactivation (PDI) via the visible light inactivation is a non-thermal photophysical and photochemical reaction that requires visible light [22]. Application of photodynamic inactivation of pathogens are in many fields as food production, food preservation, food safety, and fruit storage [9]. Kim et al. [9] reported that 405 ± 5 nm LED illumination causes photodynamic inactivation of *Salmonella* spp. Photodynamic therapy (PDT) was known as photosensitizers which induces cell death via producing cytotoxic ROS [23]. Blue LED devices are used as a light source which offers various advantages over other light sources (lasers, UV-lamp etc.) as large output, less thermal destruction, easy fabrication, large area illumination, and cost efficiency [24]. Blue LED light can penetrate soft tissue depth of 2-3 mm that can be used in treatment of superficial wound infections [23]. In addition, PDT with LED lamp (630 nm wavelength) is an effective supplement in root canal disinfection [25]. The 405, 460 and 520 nm LEDs proved more effective in inactivating the selected foodborne bacteria (*Lactobacillus plantarum*, *Staphylococcus aureus*, and *Vibrio parahaemolyticus*). The 405 nm LED showed the greatest antibacterial effect at the same level of energy dose [16]. On cancer medicine field, some researches have been previously demonstrated that photodynamic therapy using cancer designed photosensitizers and laser beams has been increasingly used in clinical medicine. The LED light induced cell damage was wavelength-dependent, but not energy-dependent [26-27].

Research and Development of Dual Functional Features of Light-Emitting Diode

According to our previous publication [27], our LED light at 450 nm wavelength can induce highly cytotoxic ability for colon cancer cell lines (HT-29 and CT-26) *in vitro* and significantly suppress the tumor growth in the CT-26-bearing mice *in vivo* [27]. The anti-tumor efficacy of our LED device (450 nm wavelength) may be also utilized to kill bacteria and degrade atmospheric fine particulate matter, $PM_{2.5}$. Both *Staphylococcus aureus* and *Pseudomonas aeruginosa* were ordered from ATCC (https://www.atcc.org/). $PM_{2.5}$ standard sample was order from Sigma-Aldrich (PM2547050). Under the antibacterial assay and the degradation assay of $PM_{2.5}$, these data were showed that our LED device (white

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and blue lights; Figure 1) significantly possessed antibacterial and $PM_{2.5}$ degradation efficacies (Table1 and Figure 2). Compare of blue/white LED light at 15/30 cm of light height and 8 h or 16 h-lighting, white LED light decreased anti-PA efficacy at 15/30 cm of light height following with lighting time increase; blue LED light increased anti-PA efficacy at 15/30 cm of light height following with lighting time increase. On the other hand, both white/blue LED light increased anti-SA efficacy at 15 cm of light height following with lighting time increase. At 30 cm of light height, both white/blue LED light decreased anti-SA efficacy following with lighting time increase (Table 1) (Figures 1 & 2).

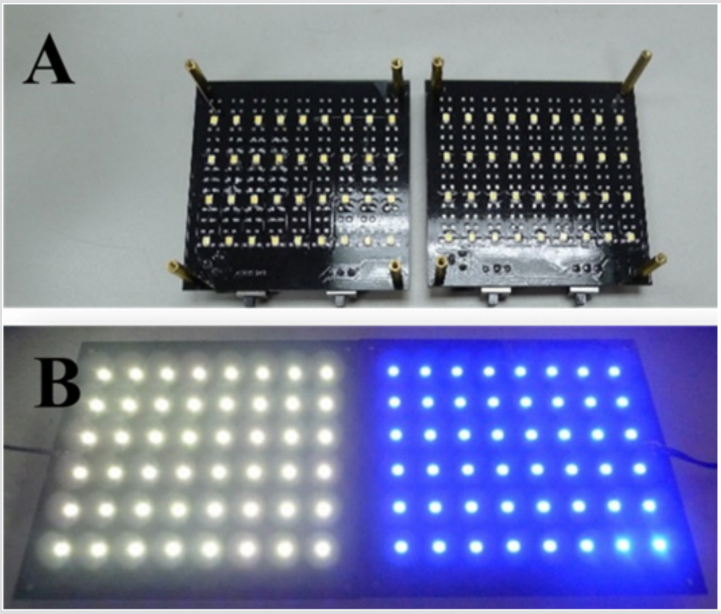

Figure 1: LED device
(A) Appearance of LED device. (B) White and blue visible light.

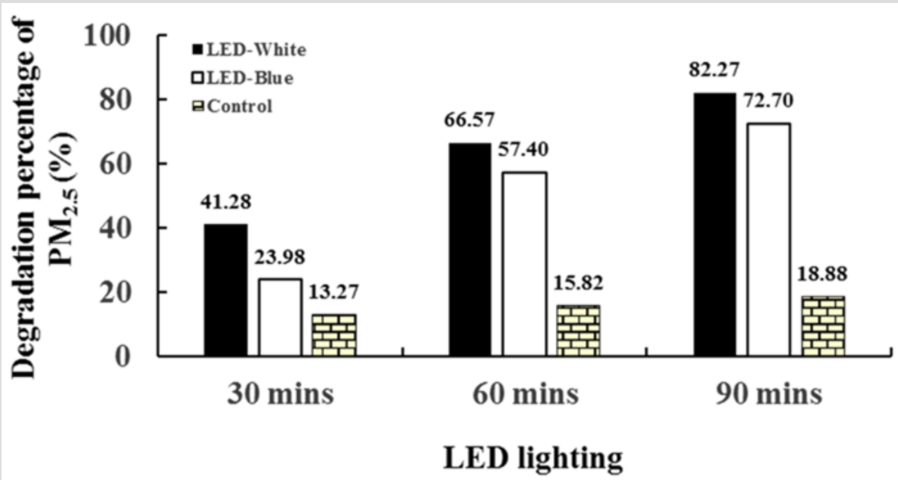

Figure 2: Degradation of $PM_{2.5}$ by LED device (White and blue visible light at 450 nm wavelength).

Table 1: Antibacterial efficacy of our LED device (Blue and white light at 450 nm wavelength).

Lighting Height/Lighting Time	LED Light Color	Illuminance (lux)	Antibacterial Efficacy (%)	
			PA	SA
15 cm/8 h	QT-White	23,200	47.47	17.00
	QT-Blue	956	85.57	40.74
30 cm/8 h	QT-White	8,828	89.08	39.90
	QT-Blue	462	48.45	24.34
15 cm/16 h	QT-White	23,200	40.14	21.21
	QT-Blue	956	88.89	41.18

30 cm/16 h	QT-White	8,828	46.99	28.83
	QT-Blue	462	53.70	20.59

Abbreviation: Light-emitting diode (LED); *Pseudomonas aeruginosa* (PA); Quantum (QT); *Staphylococcus aureus* (SA)

Conclusion

The dual functional features, degradation of atmospheric fine particulate matter, $PM_{2.5}$ and antimicrobial efficacy, in our LED device were first demonstrated in this study. In the future, this powerful LED devices have the promising applications in the human and animal life environment and biomedical application to serve as disinfection, bacteriostatic, and improvement of air pollutions.

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