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Applications of light-emitting diodes in researches conducted in aquatic environment

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A B S T R A C T

With their good energy efficiency and characteristics that allow the adjustment of light intensity and spectral composition, light emitting diodes (LEDs) have opened up new research prospects for nutrition supply, pollution control as well as energy conversion and conservation. The potentials of LED as an effective light source for studies conducted in aquatic environment such as disinfection, fish behavior, biomass production, and photocatalyst activation have been explored to a greater extent since 1980's. As the third paper of a series that reviews LEDs' applications in scientific researches, this work concentrates in the researches on red, yellow, green, blue, and ultraviolet LEDs' applications published since mid-1990. The review is composed to demonstrate that LEDs are well qualified to succeed its more energy demanding counterparts in the research performed in aquatic environment. In addition, the authors have compiled a table that includes the findings covered in their previous works, which list some common types of LEDs and their respective usages in scientific researches.

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1. Introduction

LEDs are the first light source to make available the true spectral composition control. They permit the modification of

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light intensity and wavelength to match the medical treatment requirements [1]. They can also match to plant photoreceptors to optimize production, as well as to influence plant morphology [2]. As such, the use of LEDs marks great improvements over existing indoor agricultural lighting. Also, LEDs have become the new favorite, following laser and intense pulsed light, in medical treatment and phototherapy.

In addition to a brief development history of LEDs, the previous reviews [1,2] of the researches that use LEDs for indoor plant cultivation and biomedical applications have indicated that the effective wavelengths are centralized in red, blue, and infrared segments for agricultural productions and medical treatments. These reviews have also suggested that the researches about the use of other wavelengths would lead to additional discoveries. To mend the gap that has been left behind from these reviews and to further demonstrate the versatility of LEDs, this paper inspects some researches that use yellow and green light LEDs and examines literatures in the areas of fishery, environmental, biomass productivity, and animal behavior adjustment.

2. Environmental applications

Ultraviolet light (UV) has become a growing alternative to chemicals in drinking water disinfection since UV inactivates chlorine resistant pathogenic organisms without producing known hazardous by-products [3,4]. Mercury lamps have been the primary source of UV radiations for conventional water purification as well as wastewater treatment. Low pressure mercury lamps emit nearly monochromatic UV light at a wavelength of 254 nm [5]. However, besides hazardous mercury contents, mercury vapor lamps are bulky; low shock resistant; energy consuming; and short lived (~4000–10,000 h). Using UV LEDs to perform the same function can eliminate all these disadvantages.

2.1. Disinfection

In addition to causing oxidation and other damages to DNA molecules via preventing their replication and transformation, UV activates the production of reactive intermediates such as hydroxyl radicals from water and organic matters. These radicals oxidize membrane and proteins of microorganisms as well as chemical pollutants such as pesticides [6], endocrine disruptors [7], and polycyclic aromatic hydrocarbons [8]. DNA absorbs UV between 200 and 300 nm [9], with a peak absorption (dependent on the target organisms) around 260–265 nm, which is the most effective germicidal range [10]. At higher wavelength range of 270–280 nm, DNAs' UV curve still displays significant absorption. It is, therefore, safe to say that the wavelengths of reasonable UV sources for water disinfection are between 240 and 280 nm.

Bowker et al. [11] have conducted a research to determine the UV fluence-response of three non-pathogenic microorganisms (*i.e.*, *MS*-2 *coliphage*, *T7 coliphage*, and *Escherichia coli*). They have compared the microbial UV dose responses under 255 and 275 nm LEDs and that under 254 nm low-pressure mercury lamps. The results indicate that (1) the mercury lamps have better *E. coli* and MS-2 inactivation efficiency than the LEDs of both wavelengths, (2) the 275 nm LEDs and the mercury lamps have similar T7 inactivation efficiency, (3) LEDs of the two wavelengths have similar microbial inactivation efficiency on MS-2, and (4) the 275 nm LEDs are more efficient on T7 and *E. coli* than the 255 nm ones. This study indicates that LEDs are suitable for UV disinfection although their low power output makes long exposure times necessary to induce significant results, UV LEDs are appropriate for point-of-use, low flow disinfection applications until their higher power output versions become available.

Würtele et al. [12] have investigated the suitability of GaN-based UV LEDs for water disinfection and concluded that these LEDs provide a promising alternative for decentralized and mobile water disinfection systems. After evaluating the performance characteristics of the LEDs under various water treatment requirements, these researchers designed a module with LEDs of 269 nm and 282 nm and use it with *Bacillus subtilis* spores for bioanalytical testing. The results indicate that UV LEDs effectively inactivate the test organism during both static and flow-through tests in varying water qualities. First flow-through tests demonstrated a linear correlation between inactivation and fluence. For the same fluence, the 269 nm LEDs attained a higher inactivation level than their 282 nm counterparts. The study also shows that the 282 nm LEDs' higher photon flux tends to compensate their lower inactivation level.

Chevremont et al. [13] have investigated the efficiency of UV-A (315–400 nm) and UV-C (100–280 nm) LEDs on bacteria inactivation using bioindicators of fecal pollution in wastewaters. Among four parameters (*i.e.*, pH, bacterial density, exposure time, and wavelength) tested on simple bacterial cultures, the wavelength and the exposure time factors tend to trigger more significant responses. The combined wavelengths of 280/365 nm and 280/405 nm have the best bactericidal effect. No bacterial reactivation has been identified after 60 s of exposure. In another experiment [14], this group of researchers have studied the efficiency of UV-A and UV-C radiations on bacterial and chemical indicators. Through monitoring the endurance of fecal bioindicators in wastewaters as well as the oxidation of conventional organic matter and the aromatic pollutant, they have found that combining UV-A and UV-C results in better microbial reduction comparing to a single bandwidth. The combination of the two oxidizes up to 37% of creatinines and phenols. Such efficiency is comparable to what achievable with the use of photocatalyst like anatase titanium dioxide (TiO_2). A more recent study of photoactivated disinfection (PAD) using LED [15] has shown a reduction of the microbe colony-forming unit (CFU) counts in saline by 1.42 $\log_{10}$ after 30 s and by 1.99 $\log_{10}$ after 60 s compared with negative controls.

2.2. Photocatalyst activation

Fujishima and Honda [16] discovered the photocatalytic activity of TiO_2 when they used UV to irradiate TiO_2 electrode to split H_2O for H_2. With a 3.2 eV band gap, TiO_2 can generate electron–hole (e^-–h^+) pairs and become a highly active photocatalyst when irradiated with UV. The e^- (a strong reducing agent) in conductive band can react with O_2 to produce O^{2-} ($O_2+4e^- \rightarrow 2O^{2-}$). The h^+ (a strong oxidizing agent) in valence band can pull the charges from H_2O to produce OH^- ($2H_2O \rightarrow 2OH^- + H_2 + 2h^+$). These free radical species can attack organic molecules via radical addition, hydrogen abstraction, or electron transfer [17] and thereby efficiently degrade organic materials [18]. H_2O_2 is also generated during the photocatalytic process [19,20]. UV LEDs in combination with H_2O_2 are promising for wastewater treatment via photodegradation of aqueous phenols and other organic compounds [21]. Researches in the field of TiO_2 applications using UV have been abundant [22–26] as UV is able to match the 3.2 eV band gap of TiO_2. Considering UV's hazard to the human eyes, however, strategies have been developed to adapt TiO_2 to visible light.

Cheng et al. [27] have used blue LED activated TiO_2/Fe_3O_4 particles to evaluate the photocatalytic activity efficiency of the particles. The result indicates that blue LED is a feasible light source to activate the photocatalytic effects of TiO_2/Fe_3O_4 in both freshwater and seawater. The particles activated by the energy-saving blue LEDs are fully capable of disinfecting marine fish pathogen in seawater. Compared to UV, blue LED has the advantage of the same effect with less harm to human eyes. Lu et al. [28] have shown that TiO_2/magnetic Fe_3O_4/floating fly-ash cenospheres