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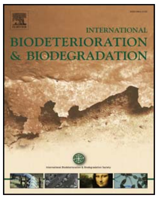

Nutrient removal and community structure of wastewater-borne algal-bacterial consortia grown in raw wastewater with various wavelengths of light

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ABSTRACT

The use of microalgae-bacteria co-culture systems is attractive for wastewater treatment. On the other hand, naturally developed wastewater-borne algal-bacterial consortia growing in real wastewater has rarely been studied and characterized. In this study, wastewater-borne algal-bacterial consortia was grown for photosynthetic oxygen production, nutrient removal, and biodiversity in real wastewater using light-emitting diodes (LEDs) with various wavelengths (blue, green, red, and white light) and intensities (250, 500, 1,000, and 2000 μmol $m^{-2}s^{-1}$). Among the four wavelengths, green light showed the highest tolerance to photoinhibition but the energy efficiency for oxygen production was the lowest. In addition, illumination with red and white lights at 500 μmol $m^{-2}s^{-}$ onto 500 mg TSS L^{-1} appeared to be practical and efficient. In PSBRs operation, the illumination of red and white light resulted in removal ratios of 88.3% and 79.0% for TN, 96.8% and 97.0% for TP, 92.4% and 91.9% for TSS, and an algal biomass productivity of 1.03 and 1.01 g L^{-1} d^{-1}, respectively. The diversity of bacteria was changed by the different wavelength of light, but the dominant species of algae was not changed. These results are expected to provide valuable technical information on algae-based wastewater treatment systems.

1. Introduction

Microalgae have attracted considerable attention in recent years because of their photosynthetic and nutrient-removing capabilities (Shafiee and Topal, 2010). With the growing concerns on microalgae, extensive studies are being conducted to apply microalgae to wastewater treatment (Brennan and Owende, 2010). Microalgae have long been recognized as a cost-effective means of producing O_2 while sequestering CO_2 (Lananan et al., 2014). Currently, WSPs (waste stabilization pond systems), ATS (algal turf scrubber), PBRs (photobioreactors), and HRAPs (high rate algal ponds) have been developed as viable options for microalgae cultivation in wastewater (Christenson and Sims, 2011; Cuellar-Bermudez et al., 2016; Santhanam, 2009). Compared to conventional treatment processes, algae-based treatments can potentially achieve nutrient removal in a less expensive and ecologically-safer manner (Oswald, 2003). On the other hand, to optimize algal biomass production, nutrient removal, and photosynthetic capacity, the growth parameters including temperature, pH, light intensity, and mutual-shading should be properly controlled (Abu-Rezq et al., 1999; Li et al., 2014).

Although natural sunlight is a beneficial light source for microalgae cultivation in terms of energy and economic balances, the varying light intensities under outdoor conditions may inhibit microalgal growth (Ugwu et al., 2007). Therefore, the cultivation of microalgae in the presence of artificial light sources could be a solution to enhance the light intensities, light transmittance, and stability of wavelengths (Yan et al., 2013a). In addition, artificial light sources can enhance the growth of microalgae in the rainy season. In this context, the use of light-emitting diodes (LEDs) might be a better option for microalgae cultivation because they emit specific light ranges and induce high-value biochemical traits for microalgal growth (Schulze et al., 2014). Until now, many studies have focused on the effects of various LED light wavelengths on the growth of microalgae. On the other hand, it is unclear which wavelength is the best for the growth of microalgae.

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Blair et al. (2014) claimed that the most efficient LED wavelength was blue, whereas Yan et al. (2013b) showed that red and white were more efficient than the other wavelengths of light. Why different results were obtained by different groups is unclear. One possibility is that the efficient wavelengths differ according to the algal species. Therefore, it is important to examine the effects of various LED wavelengths on wastewater-borne microalgae.

In case that microalgae are used for wastewater treatment, a pure culture of microalgae is barely maintained in the system (Xu et al., 2009). Instead, bacterial and algal cells grow simultaneously in the reactor. Because most types of wastewater contain a variety of different microorganisms, microalgal systems treating unsterilized wastewater inevitably contain bacteria and microalgae (Saunders et al., 2016). In addition, the turbidity and color of raw wastewater affect the light transmittance. For example, livestock wastewater is difficult to treat in suspended algal systems because of the dark color and turbidity (Gupta et al., 2015). In this case, mutual-shading could influence the light absorption characteristics of the medium significantly.

Although the interactions between bacteria and microalgae are unclear, recent studies have provided technical information for the algal-bacterial consortia system (Maza-Márquez et al., 2014). Karya et al. (2013) reported that 81–85% of the ammonium ions in wastewater were nitrified by the bacteria, rather than being taken up by algae in photobioreactors. In addition, the availability of nitrogen in the reactor affected the uptake of phosphorus (Beuckels et al., 2015), indicating that well-controlled algal-bacterial consortia systems could remove both organic contaminants and nutrients (N and P).

On the other hand, there are few reports dealing with oxygen production, nutrient removal, biodiversity, and mutual-shading simultaneously. In addition, to the best of the authors' knowledge, there are no reports of photosynthesis and nutrient removal in raw wastewater by naturally-developed algal-bacterial consortia illuminated by LED.

In this study, a naturally-developed wastewater-borne algal-bacterial consortia were grown in domestic wastewater. Under these conditions, the effects of the light intensity and wavelength on photosynthetic oxygen production, biodiversity, biomass productivity, and nutrient removal were investigated.

2. Materials and methods

2.1. Induction of algal-bacterial consortia

The wastewater was collected from a domestic wastewater treatment plant located in Yongin, Korea. This wastewater contained 255.5 ± 30.2 mg L^{-1} of BOD (biochemical oxygen demand), 144.4 ± 30.1 mg L^{-1} of SS (suspended solid), 61.4 ± 7.8 mg L^{-1} of TN (total nitrogen), 61.2 ± 7.6 mg L^{-1} of TKN (total Kjeldahl nitrogen), 31.8 ± 3.4 mg L^{-1} of NH_3-N (ammoniacal nitrogen), 0.4 ± 0.4 mg L^{-1} of NO_x^--N (sum of nitrite and nitrate nitrogen), 7.5 ± 0.7 mg L^{-1} of TP (total phosphate), 177.9 ± 24.1 mg L^{-1} of alkalinity as $CaCO_3$. Microalgal cells were not observed in the wastewater.

To induce the algal-bacterial consortia, this wastewater was added to a photo bioreactor with a 12.6L effective volume and irradiated from four sides of the reactor with LED sticks emitting blue, green, red, or white light for 24 h at room temperature. The light intensity was set to 500 μmol $m^{-2}s^{-1}$, imitating bright daylight conditions ($\geq$500 μmol $m^{-2}s^{-1}$) (Long and Hällgren, 1993). From the second day, 25% of the effective volume was drained for 10 min and filled with fresh wastewater for 10 min. The mixed liquor was irradiated at 500 μmol $m^{-2}s^{-1}$ for 1420 min with agitation at 150 rpm. Therefore, the reactors were operated at PSBR (photo-sequencing batch reactor) mode with 10 min of fill, 1420 min of reaction, and 10 min of withdrawal every day.

The algal-bacterial consortia were stabilized at 500 ± 100 mg L^{-1} of TSS and pH 7.2 ± 0.6 after 2 months of cultivation. The grown algal-bacterial consortia were used to analyze the O_2 production, photoinhibition, mutual-shading, species diversity, and nutrient removal.

2.2. Effects of illumination conditions and biomass concentration on oxygen production

To examine the effects of the intensity and wavelength of light on photosynthetic oxygen production, the treated effluent, of which the carbonaceous BOD was removed from a domestic wastewater treatment plant, was fully filled into a BOD bottle (300 mL) and deoxygenated by purging N_2 gas (99.9%, v/v), and this BOD bottle was then inserted with a DO (dissolved oxygen) probe (YSI 5100, Yellow Springs, OH, USA). While being agitated with a magnetic stirring bar at 100 rpm, the bottle was illuminated using LED sticks with various wavelengths of 450–470 nm (blue), 510–540 nm (green), 610–680 nm (red), and 380–760 nm (white). The light intensities were also varied to 250, 500, 1,000, and 2000 μmol $m^{-2}s^{-1}$ using a current controller (CT-300P5, Sungkwang Inc., Korea). Illumination was continued for 60 min. To examine the photoinhibition effects on oxygen production under weak and strong mutual shading conditions, the amount of algal-bacterial consortia with 100 mg TSS L^{-1} and 500 mg TSS L^{-1} were used. The temperature was controlled at 25 ± 1 °C and the DO concentrations were transferred to a computer every 60 s for 70 min, during which illumination was continued for 60 min and turned off for the last 10 min. The experiments were repeated at least three times. To calculate the specific oxygen production rate, the measured DO concentration (photosynthetically produced oxygen in the presence of endogenous respiration of bacteria) was divided by the algal biomass and time during which DO was produced. Microalgal biomass at each reactor was evaluated by assuming that the microalgae contained 1.5% of chlorophyll-a (Raschke, 1993). Although there have been arguments regarding estimations of the microalgae biomass concentration from the concentration of chlorophyll-a, it has been widely accepted that an analysis based on chlorophyll-a is reasonable (Gasol and Duarte, 2000).

2.3. Photo-sequencing batch reactor (PSBR)

Four photo-sequencing batch reactors (PSBRs) were used to examine the effects of the illumination conditions on the biomass productivity and nutrient removal. Each PSBR was made from an acrylic cylinder, 20 cm in diameter and 50 cm in height (total volume of 15.7L, effective volume of 12.6L), and was agitated mechanically at 150 rpm using an impeller (Fig. 1).

Each PSBR was illuminated using two LED sticks emitting blue, green, red, or white light. The light intensity was set to 500 μmol $m^{-2}s^{-1}$ using a current controller. The algal-bacterial consortia (600 ± 30 mg TSS L^{-1}) were suspended in 12.6 L of wastewater

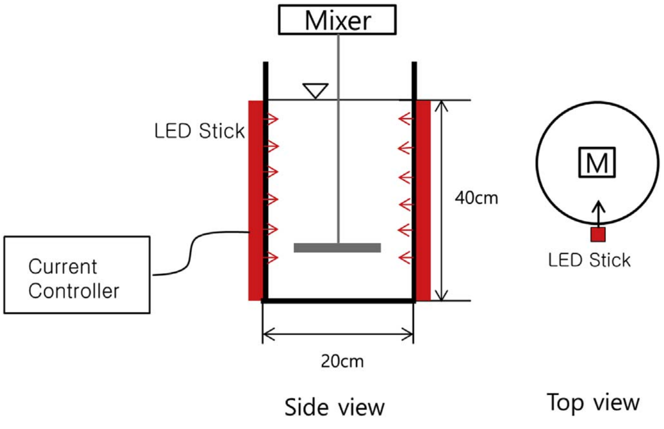

Fig. 1. Schematic diagram of the photo-sequencing batch reactor (PSBR) used in this study.