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Performance of three microalgal strains in biogas slurry purification and biogas upgrade in response to various mixed light-emitting diode light wavelengths

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HIGHLIGHTS

- N removal could be increased highly using *Scenedesmus obliquus* at red:blue = 7:3.
- CO_2 were removed up to 62%.
- Nutrient removal and biogas upgrading were obtained in the same process.
- *S. obliquus* and *Chlorella vulgaris* achieved the best combined effects.
- The best mixture ratio was red:blue = 7:3 and 5:5.

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ABSTRACT

The three microalgal strains were cultivated, namely, *Chlorella vulgaris*, *Scenedesmus obliquus*, and *Neochloris oleoabundans*, by applying mixed light-emitting diode wavelength treatments to biogas slurry in a photobioreactor bag. This study aims to compare the growth and nutrient removal efficiency of the algae and determine their roles for biogas upgrading. At red:blue = 5:5, *S. obliquus* and *C. vulgaris* efficiently removed COD and TP, respectively. *S. obliquus* demonstrated high N removal efficiency at red:blue = 7:3. The same strain significantly improved removal capacity for all nutrients compared with *C. vulgaris* and *N. oleoabundans*, particularly at red:blue = 5:5, 7:3, and 3:7. For biogas upgrade, CH_4 contents were higher than 75% (v/v) for all strains. The algae exhibited particularly good CH_4 enrichment at red:blue = 7:3, 5:5. Results show that microalgal biomass production offers real opportunities for addressing issues, such as nutrient reduction, CO_2 removal, and biogas enrichment.

1. Introduction

Microalgae have been employed as a new low-cost technology for biogas slurry treatment in areas with adequate sunshine throughout the year. Biogas slurry contains high concentrations of essential nutrients (carbon, nitrogen, and phosphorus) for microalgal growth and can serve as an inexpensive nutrient medium. The utilization of biogas slurry as carbon and nutrients source can enhance microalgal growth reducing costs and environmental impacts (Uggetti et al., 2014). Yang et al. (2008), Bhatnagaret al. (2010) used microalgae to remove nutrients in biogas slurry. They found that this medium can be used to directly culture microalgae and enhance the efficiency of removing nutrients from biogas slurry. Biogas is an environment-friendly fuel, but it must be upgraded before use. The development of innovative low-cost biotechniques for an integral upgrading of biogas via the simultaneous removal of CO_2 and H_2S is mandatory (Serejo et al., 2015). Among the various strategies for CO_2 removal, biological sequestration of CO_2 using photosynthetic microalgae has received considerable attention because the CO_2 fixation capability of microalgae is high given their biomass (Yoo et al., 2010). Some studies have proposed the use of microalgae for ammonium remediation and methane production (Mussgnug et al., 2010). Yan and Zheng (2014) and Zhao et al. (2013) have studied the biomass growth, nutrient recovery, and biogas upgrade of green algae *Chlorella* sp. in a photobioreactor by using light-emitting diodes (LEDs); these groups observed the high removal efficiency (RE) of the organisms for main nutrients and CO_2 and concluded that microalgae may be utilized for biogas slurry treatment and CH_4

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enrichment. The treatment performance of a bioreactor depends on various operational factors that are related to microalgal strain and light condition. System-related factors include LED light wavelengths and intensities, maturity of the nutrient content from the biogas slurry, and CH_4 content (%, v/v).

Light wavelength is an essential parameter that influences microalgal growth during photosynthesis (Richmond, 2003). In general, microalgae use light at the wavelength range of 400–700 nm. The wavelengths absorbed by microalgae differ per species. Green microalgae absorb light energy for photosynthesis, with chlorophylls as the major pigment that absorbs light energy in the range of 450–475 nm and 630–675 nm (Richmond, 2003). Some researchers have reported that microalgal growth differs depending on the light wavelength. Red light (600–700 nm) and blue light (400–500 nm) stimulate microalgal growth, and algal growth rates and biomass differ with light intensity (Das et al., 2011; Cheirsilp and Torpee, 2012). Therefore, blue and red light wavelengths must be selectively provided for microalgal photosynthesis because they are more suitable for microalgal growth than other wavelengths (Ruyters, 1984).

Most previous studies focus on the growth of microalgae and on providing nutrients for growth using biogas slurry (Christenson and Sims, 2011; Yang et al., 2011; Yan and Zheng, 2014). Only a few studies have investigated nutrient treatment in biogas slurry. Data on the treatment of crude biogas from anaerobic digestion with microalgae depending on wavelength and mixing ratios are not comparable because different studies use different microalgal strains, operational conditions, and technologies. The present study aims to achieve comparable data on the growth of different microalgal strains under the same operational conditions. Three strains were cultured in an incubator with a photobioreactor bag containing biogas and biogas slurry from a methane tank at five wavelengths. This set-up allows comparison of growth data as well as the effects of mixed LED light wavelengths on biogas upgrade and biogas slurry. This study also aims to determine the mechanism by which the treatment performance of the three microalgal strains is affected by different mixed wavelength ratios. The optimal mixed ratio of LED light wavelengths is determined by analyzing biogas slurry nutrient removal and CH_4 enrichment. These data are essential for subsequent scale-up treatments of the crude biogas in the framework of a technological process line aimed at addressing the demands of energy and environmental sustainability.

2. Methods

2.1. Microalgal strains and culture conditions

Three strains of Chlorophyceae known for their productivity and their high biogas tolerance were selected as candidates for sustainable energy production and nutrient removal. All strains were obtained from stock cultures in Dr. Yuhong Liu's laboratory and confirmed as highly biogas tolerant and fast growing (Li, 2012; Li et al., 2013).

The strains were preserved in BG11 medium (Rippka et al., 1979). The culture conditions were as follows: cool-white LED light with a photosynthetic photon flux density (PPFD) of 100 μ mol m^{-2} s^{-1}, temperature of 25 ± 0.5 °C, and light–dark cycle of 12 h light:12 h dark; and artificial intermittent shaking thrice a day (8:00 AM, 2:00 PM, and 8:00 PM).

2.2. Growth medium

The growth medium was obtained from an anaerobic digester in Jiaxing, Zhejiang Province, China. The biogas was pretreated via chemical absorption to decrease the H_2S concentration to <50 ppm (v/v) (Chung et al., 2006). The biogas slurry was treated using an ultraviolet sterilizer (KCJ-10 W, Konche Water Treatment Co., Ltd., PR China) for 2 min and then filtered using a glass microfiber filter (GF/C, Whatman, USA) to prevent interference from other sediments and microorganisms. Table 1 lists the characteristics of biogas slurry and crude biogas before and after pretreatments.

2.3. Experimental procedure

A photobioreactor bag contained 20 L of crude biogas and 4 L of biogas slurry culture (the initial dry weight of the microalgae was 0.058 ± 0.002 g L^{-1} across all samples). During treatment, all of the photobioreactor bags were placed in an illuminating incubator (SPX-400I-G, Boxun Industry & Commerce Co., Ltd., PR China) equipped with LEDs as a light source. Temperature was maintained at 25 ± 0.5 °C, and light with a photosynthetic PPFD of 200 μmol m^{-2} s^{-1} was used. Light intensity was classified into four monochrome LED light wavelengths (monochrome green, blue, red, and white LED) and five mixed LED light wavelengths treatments (red:blue = 9:1; 7:3; 5:5; 3:7, 9:1). Blue light (400–500 nm, with a peak at 450 nm) and red light (600–700 nm, with a peak at 670 nm) were used. The optimal mixture of LED light wavelengths was determined by evaluating biogas slurry nutrient REs and CH_4 contents (%, v/v). The experiment was performed for 6 d, all the experiments were carried out in duplicate, and average values are reported as results. The cultures were not maintained in a strictly sterile environment; as such, the biomass may include other microorganisms such as bacteria and fungi.

Table 1
Characteristics of biogas slurry and biogas.

Parameter	Before pretreatment	After pretreatment
pH	6.79 ± 0.18	6.84 ± 0.11
DIC (mgL^{-1})	954.32 ± 30.14	939.43 ± 25.36
COD (mgL^{-1})	1038.15 ± 35.74	1013.87 ± 29.48
TN (mgL^{-1})	325.32 ± 27.18	308.75 ± 21.51
TP (mgL^{-1})	10.48 ± 1.45	9.93 ± 1.27
CH_4 (%, V/V)	–	61.32 ± 5.74
CO_2 (%, V/V)	–	34.45 ± 3.48
H_2O (%, V/V)	–	3.65 ± 0.39
O_2 (%, V/V)	–	0.62 ± 0.05
H_2S (%, V/V)	–	<0.005

Table 2
Growth rates and mean daily productivity of *C. vulgaris*, *S. obliquus* and *N. oleoabundans* under different wavelength mixing ratios treatments.

	C. vulgaris	*S. obliquus*	*N. oleoabundans*
Parameter	Growth rate (d^{-1})		
Green	0.167 ± 0.05	0.172 ± 0.04	0.134 ± 0.06
Blue	0.174 ± 0.04	0.187 ± 0.06	0.158 ± 0.05
Red	0.213 ± 0.06	0.241 ± 0.07	0.179 ± 0.04
White	0.267 ± 0.05	0.282 ± 0.08	0.216 ± 0.06
Red (9):blue (1)	0.315 ± 0.09	0.396 ± 0.09	0.269 ± 0.07
Red (7):blue (3)	0.321 ± 0.08	0.423 ± 0.08	0.298 ± 0.06
Red (5):blue (5)	0.363 ± 0.09	0.451 ± 0.09	0.327 ± 0.08
Red (3):blue (7)	0.298 ± 0.07	0.358 ± 0.08	0.271 ± 0.06
Red (1):blue (9)	0.276 ± 0.08	0.315 ± 0.07	0.259 ± 0.03
	Mean daily productivity (gL^{-1} d^{-1})		
Green	0.020 ± 0.003	0.021 ± 0.002	0.014 ± 0.001
Blue	0.023 ± 0.002	0.025 ± 0.003	0.019 ± 0.003
Red	0.032 ± 0.004	0.041 ± 0.005	0.023 ± 0.002
White	0.053 ± 0.009	0.059 ± 0.004	0.034 ± 0.003
Red (9):blue (1)	0.072 ± 0.007	0.135 ± 0.009	0.050 ± 0.004
Red (7):blue (3)	0.079 ± 0.008	0.171 ± 0.012	0.066 ± 0.006
Red (5):blue (5)	0.112 ± 0.009	0.217 ± 0.016	0.086 ± 0.007
Red (3):blue (7)	0.067 ± 0.006	0.108 ± 0.010	0.054 ± 0.003
Red (1):blue (9)	0.059 ± 0.008	0.079 ± 0.007	0.051 ± 0.004