Research Article

Characterization of a Microalgal UV Mutant for CO₂ Biofixation and Biomass Production

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Received 19 July 2018; Revised 19 October 2018; Accepted 25 November 2018; Published 23 December 2018

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The mutagenesis is an emerging strategy for screening microalgal candidates for CO₂ biofixation and biomass production. In this study, by 96-well microplates-UV mutagenesis, a mutant stemmed from Scenedesmus obliquus was screened and named as SDEC-1M. To characterize SDEC-1M, it was cultivated under air and high level CO₂ (15% v/v), and its parental strain (PS) was considered as control. Growth characterizations showed that SDEC-1M grew best in high level CO₂. It indicated that the mutant had high CO₂ tolerance (HCT) and growth potential under high level CO₂. Richer total carbohydrate content (37.26%) and lipid content (24.80%) demonstrated that, compared to its parental strain, SDEC-1M was apt to synthesize energy storage materials, especially under high CO₂ level. Meanwhile, the highest light conversion efficiency (approximately 18%) was also obtained. Thus, the highest overall biomass productivities were achieved in SDEC-1M under high level CO₂, largely attributed to that the highest productivities of total lipid, total carbohydrate, and crude protein were also achieved in the meantime. By modified UV, therefore, mutagenized SDEC-1M was the better candidate for CO₂ biofixation and biofuel production than its parental strain.

1. Introduction

Energy shortage and climatic change have been greatly focused [1–3]. To solve the problems, the techniques of CO₂ capture and sequestration and clean energy alternative to fossil fuel have been widely applied, among which microalgae is one of the most interesting strategies due to being sustainable, environment-friendly, and noncompetitive with other edible feedstocks [1, 4–10].

Microalgae cultivation via autotrophic system with high level CO₂ is considered as a more viable approach for commercialization due to lower cultivation costs cut by free sunlight and carbon source, high contents of lipid or carbohydrate, acquiring high cell density and sequestering CO₂ [1, 7, 8, 11]. However, the growth of microalgae can also be inhibited by high level CO₂, due to acidified medium [12]. Thus, an ideal candidate should have tolerance for high level CO₂. In previous reports, in addition to the isolation of microalgae from the region affected by atmospheric pollution source [1] and acclimation by bubbled gas with CO₂ gradually increasing [13], screening microalgae with high CO₂ tolerance (HCT) by genetic strategy coupled to high-throughput screening were emerging [3, 4, 13–17]. In consideration of the economic and technological feasibility of genetic manipulations [3, 13, 15], random mutagenesis was more employed to provide microalgae candidates, rather than targeted genetic manipulation [17]. For instance, some mutants with HCT were obtained by chemical [4], nuclear irradiation [13], plasmas [18], and UV mutagenesis [14, 15]. Following mutagenesis, general, surviving mutants should be isolated [4, 15], which means enormous work and risks from invasion of infectious bacteria and algae. According to novel 96-well microplates-UV mutagenesis, each cell was isolated and then mutagenized in a well of 96-well microplates [14].
Since each surviving colony in the closed well was pure strain, luckily, invasion and reisolation were avoided. The novel method can shorten operating time, simplify operation process, and maintain purity of isolated strains [14].

Mutants can access some characteristics which their parental strains do not have, for instance, high biomass productivities [17], high abilities to capture CO$_2$ [4], high light conversion efficiencies ($LCE$) [14, 17, 19], high CO$_2$ requiring (HCR) [14, 20], and high contents of lipid or carbohydrate [14–16]. These genetic characteristics affecting their ability to biofix CO$_2$ and product biomass are key to commercialize microalgae [16]. In view of randomicity of mutagenesis, the above-mentioned characteristics might synchronize. Therefore, it is necessary that the mutants are characterized to test their commercialization potential of the CO$_2$ biofixation and biomass production.

In this study, we aimed to have microalgal strains for CO$_2$ biofixation and biomass production; Scenedesmus obliquus was mutagenized by 96-well microplates-UV mutagenesis. One competitive potential mutant was screened out. To characterize its growth, biochemical components, and $LCE$, moreover, the mutant and its parental strain were cultivated under air and high level CO$_2$ (15% v/v). After continuous subculture for five generations under 15% CO$_2$, its genetic stability was tested. According to the experimental results, finally, the mutant’s suitability for CO$_2$ fixation and application of its biomass were evaluated.

2. Material and Methods

2.1. Microalgal Strains and Culture Medium. In this study, as a parental strain (PS), one freshwater microalga Scenedesmus obliquus observed dominant in freshwater water systems [27] was obtained from FACHB-Collection of Institute of Hydrobiology, Chinese Academy of Sciences. By 96-well microplates-UV mutagenesis [14], several S. obliquus mutants survived in wells with low pH (4.5) BGII culture medium, and the survival ratio was approximately 3%. The growth status and genetic stabilities of survivors cultivated under 15% (v/v) CO$_2$ were compared and the best-growing and good genetically stable mutant was selected and named as SDEC-1M and employed in this study. The modified SE media (Brosto’s solutions) with 1000 mg L$^{-1}$ of NaNO$_3$ nitrate concentrations [28] were used, which can supply more nitrogen source during the cultivation period. In addition to NaNO$_3$, there are 75 mg of KH$_2$PO$_4$·3H$_2$O, 75 mg of MgSO$_4$·7H$_2$O, 25 mg of CaCl$_2$·2H$_2$O, 175 mg of KH$_2$PO$_4$, 25 mg of NaCl, 5 mg of FeCl$_3$·6H$_2$O, 1 mL of A$_6$ solution, 1 mL of Fe-EDTA, and 40 mL of soil extract in 958 mL of deionized water. IL A$_6$ solution contained 2.86 g of H$_2$BO$_3$, 1.81 g of MnCl$_2$·4H$_2$O, 0.22 g of ZnSO$_4$·7H$_2$O, 10 mg of CuSO$_4$·5H$_2$O, and 39 mg of (NH$_4$)$_6$Mo$_7$O$_{24}$·4H$_2$O. IL Fe-EDTA contained 10 g of Na$_2$EDTA, 0.81 g of FeCl$_3$·6H$_2$O, and 500 mL of 0.1 M HCl. The soil extract was the filtered supernatant from boiled soil solution.

2.2. Culture Conditions. The parental strain cells or mutant cells were cultured in photobioreactors (inside diameter (ID), 120 mm; working height (Hw), 221 mm; working volume ($V_w$, 2.5L)) [22] containing fresh medium. Then, they were kept in a phytotron at 25 ± 1°C. A continuous illumination was provided by a row of fluorescent lamps which were horizontally fixed on the wall at one side of the bottles. The illumination intensities on the photobioreactor surface toward and back to the light source were 47.25 and 2.7 μmol m$^{-2}$s$^{-1}$, respectively, read by a photometer. The initial OD$_{686}$ (optical density at 686 nm) was 0.3 (approximately 73 mg L$^{-1}$ of biomass concentration). During cultivation, deionized water was added to keep working volume. Aeration was carried out by air or high level CO$_2$. Simulating flue gas with high level CO$_2$ (up to 15%, v/v) [10], 15% (v/v) CO$_2$ mixed by air and pure CO$_2$ that were prearranged in industrial cylinders were employed. Using gas flow meters (Sevenstar, Beijing, China), the flow rates were adjusted to 0.2 vvm (volume per minute per volume of mixture, respectively).

2.3. Measurement Methods. Between 680 and 690 nm, Chang and Yang [29] and Akkerman [30] found absorption peaks of microalgal broth and a linear correlation between the biomass concentrations and the optical densities. Thus, the indirect estimation of biomass concentration by optical density (OD) between 680 and 690 nm has been widely used in the microalgal research [2, 14, 28]. The absorption peaks of PS and SDEC-1M were located at 686nm by spectral scanning with a UV-2450 spectrophotometer (SHIMADZU, Japan). OD$_{686}$ and the biomass concentration of PS and SDEC-1M broth diluted in different proportions were determined by a UV-2450 spectrophotometer (SHIMADZU, Japan) and weighing the dry mass, respectively. Then, (1) relating OD$_{686}$ to biomass concentration was established by the linear regression.

$$X = OD_{686} \times 254.1 - 3.182 \quad R^2 = 0.9927 \quad (1)$$

Sample was taken once every day. After proper dilution, the biomass concentrations ($X$, mg L$^{-1}$) of sample were indirectly calculated via (1). pH of the sample was determined using PHS-3C pH meter (Leici, Shanghai, China).

At the end of cultivation (day 7), the microalgae were harvested and the contents of their primary biochemical components were measured. Microalgal pellets were formed by centrifuging microalgal culture at 4000 rpm at -3°C for 10 min and were washed twice with 0.5 M of ammonium formate to desalinate. Then, the microalgal pellets were dried and ground into powder. Higher heating values (HHV) of microalgal powder were determined by an isotherm oxygen bomb calorimeter [31]. Lipids of the microalgae were extracted by solvent, and the total lipid contents were estimated gravimetrically using a modified method [27]. The total carbohydrate contents of the microalgae were measured by the phenol-sulfuric acid method [32]. The crude protein content in the biomass was calculated via (2).

$$\text{Protein content} = \text{Nitrogen content} \times 6.25 \quad (2)$$

where nitrogen content was measured according to the Kjeldahl method [33], and the factor 6.25 is the correlation.
between protein content and nitrogen content reported by previous studies [34, 35].

2.4. Calculations on Important Properties. The maximum biomass concentration (mg L⁻¹) was designated as \( X_{\text{max}} \).

The overall biomass productivity (\( P_{\text{overall}}, \text{mg L}^{-1}\text{d}^{-1} \)) was calculated via (3).

\[
P_{\text{overall}} = \frac{X_{7}X_{0}}{7}
\]

where \( X_{7} \) is the biomass concentration on day 7; \( X_{0} \) is the initial biomass concentration in mg L⁻¹; 7 is the cultured time (d).

Specific growth rate (\( \mu_{t}, \text{d}^{-1} \)) in a day was calculated via (4). The maximum specific growth rate was designated as \( \mu_{\text{max}} \) (d⁻¹).

\[
\mu_{t} = \frac{\ln X_{t} - \ln X_{t-1}}{1}
\]

where \( X_{t} \) and \( X_{t-1} \) were the biomass concentration (mg L⁻¹) on day \( t \) and day \( t-1 \), respectively; 1 was the time (d) gone through from day \( t-1 \) to day \( t \).

The light conversion efficiency (LCE, %) based photosynthetic active radiation was estimated via (5).

\[
LCE = \frac{(\text{HHV} \times P_{\text{overall}} \times V_{w} \times 100)}{[(1 + 1) \times k \times \text{PAR} \times A \times t]}
\]

where the units of HHV, \( P_{\text{overall}} \) and \( V_{w} \) are \( \text{J mg}^{-1} \), \( \text{mg L}^{-1}\text{d}^{-1} \) and \( \text{L} \); \( I^{+} \) and \( I^{-} \) are illumination intensities (mol m⁻²s⁻¹) on the photobioreactor surface toward and back to the light source, respectively; the constant \( k \) that converts illumination intensity to light energy density (W m⁻²) is 218800 J mol⁻¹ photons [36]; the coefficient of photosynthetic active radiation (PAR) is 48% [37]; \( A \) is the irradiated area (m²); \( t \) is 86400 seconds in a day.

Total lipid productivity (\( P_{L}, \text{mg L}^{-1}\text{d}^{-1} \)), total carbohydrate productivity (\( P_{C}, \text{mg L}^{-1}\text{d}^{-1} \)), and crude protein productivity (\( P_{p}, \text{mg L}^{-1}\text{d}^{-1} \)) used to test potential of lipid, carbohydrate, and protein productions were calculated via (6), (7), and (8).

\[
P_{L} = P_{\text{overall}} \times \text{total lipid content}
\]

\[
P_{C} = P_{\text{overall}} \times \text{total carbohydrate content}
\]

\[
P_{p} = P_{\text{overall}} \times \text{crude protein content}
\]

2.5. Statistical Analysis. The differences between parameters of PS and SDEC-1M determined under air and 15% (v/v) \( \text{CO}_{2} \) were assessed using one-way analysis of variance (ANOVA). A difference was considered statistically significant when \( p < 0.05 \). Duncan’s test was performed to detect the statistical significance of differences (\( p > 0.05 \)).

3. Results and Discussion

3.1. Growth Characterizations

3.1.1. Growth Characterization under Air. As shown in Figure 1, PS grew slightly better than SDEC-1M under air. More details were seen in Table 1; no significant differences on \( X_{\text{max}}, \mu_{\text{max}} \) and \( P_{\text{overall}} \) were observed between PS and SDEC-1M under air. Thus, there were no significant changes in growth characteristics of SDEC-1M under air by mutagenesis. Due to randomness of mutagenesis, obviously, SDEC-1M did not attain the high \( \text{CO}_{2} \) requiring (HCR) characteristic closely related to defectiveness in \( \text{CO}_{2} \) concentrating mechanisms (CCMs) [20]. Although it was confirmed that a UV mutant, \( \text{Chlorella vulgaris} \) SDEC-3M obtained by 96-well
microplates-UV mutagenesis, was a HCR mutant [14], this method is not an efficient method for screening HCR algae strains.

3.1.2. Growth Characterization under High Level CO$_2$. Some species in Scenedesmus screened for CO$_2$ fixation were reported [1, 24, 25, 38]. These species generally have two characteristics: survival in low pH medium caused by high level CO$_2$ (high CO$_2$ tolerance) and high CO$_2$ fixation efficiency that exhibits good growing ability [7, 12, 13]. As shown in Figure 1, PS and SDEC-1M both exhibited higher growth rates under 15% (v/v) CO$_2$ and the latter adapted to high level CO$_2$ faster and attained the linear growth phase earlier. More details were seen in Table 1; thus, although there was no significant difference in $\mu_{\text{max}}$ between SDEC-1M and PS under 15% CO$_2$, SDEC-1M maintained a longer logarithmic phase (from day 1 to day 6), and its $X_{\text{max}}$ and $P_{\text{overall}}$ were significantly 33.10% and 47.09% higher than those of PS, respectively. These results demonstrate that longer logarithmic phase can increase the biomass productivity.

3.1.3. Growth Distinction under Air and High Level CO$_2$. As shown in Figure 1, PS or SDEC-1M grew better under 15% CO$_2$ than under air. More details were seen in Table 1; there were no significant differences on their $\mu_{\text{max}}$ between under air and under 15% CO$_2$, while $\mu_{\text{max}}$ occurred at different times. Comparing their performances under air, the $X_{\text{max}}$ and $P_{\text{overall}}$ of PS and SDEC-1M were both significantly higher. It implies that their growth potentials are similar, but the performances under air are poorer. Insufficient carbon source should be the main reason to decrease the metabolism of microalgae under air [7].

3.2. Contents and Productivities of Biochemical Components. Due to their plenty compounds as lipids, carbohydrates, and protein, microalgae have enormous potential for the sustainable production of food, fuels, and other biochemicals [17]. Compounds contents and productivities are essential parameters of evaluation on applied purposes of microalgae biomass [23]. As shown in Figure 2(a), whether under air or 15% CO$_2$, the protein contents in PS were significantly higher than their lipid and carbohydrate contents, which agreed with recent reports, representing 32-58% of protein contents in Scenedesmus sp. [5, 23, 26, 39, 40]. However, in mutant SDEC-1M, the contents of lipid and carbohydrate were significantly higher than in PS, while the protein contents were just the opposite. Thus, carbohydrates became the chief biochemical component in SDEC-1M. Meanwhile, the lipid contents in PS and SDEC-1M under 15% CO$_2$ were both significantly higher than those under air. It agrees with the previous findings that high CO$_2$ stress enhanced lipid production [7, 41]. These results imply that compared to its parental strain, SDEC-1M was apt to synthesize energy storage materials, especially under high CO$_2$ level.

Largely attributed to significant higher overall biomass productivities, the highest productivities of total lipid ($8.76 \pm 0.47 \text{ mg L}^{-1} \text{ d}^{-1}$), total carbohydrate ($13.16 \pm 0.82 \text{ mg L}^{-1} \text{ d}^{-1}$), and crude protein ($10.14 \pm 0.30 \text{ mg L}^{-1} \text{ d}^{-1}$) all occurred in SDEC-1M under 15% CO$_2$, even though crude protein content was lower. Considering that two strains were harvested in logarithmic phase or linear growth phase, the results imply that biomass productivity plays a leading role in the primary biochemical components production until stationary phase, which agreed with previous reports [2, 6, 42].

3.3. Genetic Stabilities under High Level CO$_2$. In view of the instability of mutagenized strains, especially in continuous subculture, their genetic stability should be tested [18]. Thus, to confirm its stability of biomass product, SDEC-1M, was continuously subcultured under 15% CO$_2$ for five
data indicate the mean ± SD, which was measured from three independent cultures. Data in the same parameter followed by different letters are significantly different by Duncan's test (p < 0.05).

| Strains | Air | 15% (v/v) CO₂ | LCE(%) |
|---------|-----|---------------|--------|
| PS      | 22.03 ± 0.47<sup>a</sup> | 23.1 ± 0.26<sup>b</sup> | 7.2 ± 0.29<sup>a</sup> | 11.54 ± 0.74<sup>b</sup> |
| SDEC-1M | 22.53 ± 0.35<sup>ab</sup> | 24.43 ± 0.59<sup>c</sup> | 6.43 ± 0.62<sup>a</sup> | 17.93 ± 0.62<sup>c</sup> |

As shown in Figure 3, no significant changes were observed on parameters, such as contents of total lipid, total carbohydrate, and crude protein and productivities of overall biomass, total lipid, total carbohydrate, and crude protein in SDEC-1M between the first generation and the fifth generation. The results suggest SDEC-1M is genetically stable from the aspect of biomass production.

3.4. Light Conversion Efficiency (LEC). As shown in Table 2, there was no significant difference in HHV between PS and SDEC-1M under air, and similar results under 15% CO₂. Furthermore, HHV of SDEC-1M was significantly higher than that of PS whether under 15% CO₂ or under air. The results were similar to their growth characterizations. Thus, the highest overall biomass productivity (35.32 ± 1.99 mg L⁻¹ d⁻¹) (Figure 2) or the highest HHV (24.43 ± 0.59 KJ g⁻¹) were both obtained by SDEC-1M under 15% CO₂. As a result, the highest calculated value of LCE (17.93 ± 0.6 %) occurred in SDEC-1M under 15% CO₂.

The higher LCE means more light energy transferred into biomass under same light conditions. Thus, the high overall biomass productivity was obtained in SDEC-1M under 15% CO₂ (Section 3.2). Only photosynthetic active radiation (PAR) is usable radiation fraction (400–700 nm) wavelengths between 400 and 700 nm [43], accounting for 42.3%-45.8% of the total energy from the solar spectrum [44, 45]. Based on PAR, LCEs of most microalgae varied between 4-9% [45], just in which LCEs of PS and SDEC-1M were under air. A few recorded higher LCEs of 21.6% [19] and 14.52% [11] were comparable with those under 15% CO₂ in this study. This result is close to the theoretical upper limit of conversion efficiencies from solar energy to chemical energy (26.7%-29.8%) previously estimated by Brennan and Owende [45] and Robertson et al. [37]. Interestingly, the higher LCEs all were obtained in the cases with additional CO₂ aeration. It shows that CO₂ level is the crucial factor for enhancing biomass production of algal strains with HCT characteristic.

3.5. Characteristics Comparison with Other Algae Strains. The main characteristics represented the growth potential and conversion efficiency of SDEC-1M and other algae strains were shown in Table 3. By comparison, it is found that the contents of lipid, carbohydrate, and protein of SDEC-1M were comparable with those of S. obliquus parental strain (PS) and mutant (SDEC-1M) under air and 15% (v/v) CO₂. The higher overall biomass productivity (35.32 ± 1.99 mg L⁻¹ d⁻¹) (Figure 2) or the highest HHV (24.43 ± 0.59 KJ g⁻¹) were both obtained by SDEC-1M under 15% CO₂. As a result, the highest calculated value of LCE (17.93 ± 0.6 %) occurred in SDEC-1M under 15% CO₂.

S. obliquus SDEC-1M with genetic stability was obtained after UV mutagenesis and was cultivated under air and
Table 3: Comparison between characterizations of SDEC-1M and other algae strains.

| Strain                     | Lipid content (%) | Carbohydrate content (%) | Protein content (%) | HHV (kJ g⁻¹) | LCE (%) | Reference |
|----------------------------|-------------------|--------------------------|---------------------|--------------|---------|-----------|
| SDEC-1M                    | 24.80             | 37.26                    | 28.74               | 24.43        | 17.93   | This study|
| *Chlorella protothecoides* | -                 | -                        | -                   | 21.1         | -       | [21]      |
| *Chlorella sp.*            | 33.6              | -                        | -                   | -            | -       | [22]      |
| *Chlorella vulgaris*       | 32.7              | -                        | -                   | -            | -       | [2]       |
| *Chlorella vulgaris*       | 19.15             | 42.48                    | -                   | 22.1         | 14.52   | [14]      |
| *Cladophora fracta*       | -                 | -                        | -                   | -            | -       | [21]      |
| *Phaeodactylum tricornutum*| -                 | -                        | -                   | -            | -       | [19]      |
| Scenedesmus bajacalifornicus BBKLP-07 | 25.81 | 26.19 | 32.89 | - | - | [1]⁺ |
| Scenedesmus dimorphus      | 12                | 53.7                     | 17.4                | -            | -       | [23]      |
| Scenedesmus obliquus       | 19.80             | 25.39                    | 31.26               | -            | -       | [2]       |
| Scenedesmus obliquus       | 27.5              | -                        | -                   | -            | -       | [24]      |
| Scenedesmus obliquus       | -                 | -                        | -                   | 22.9         | -       | [25]      |
| Scenedesmus sp.            | 21                | 38                       | 23                  | -            | -       | [5]       |
| Scenedesmus sp.            | 25.4              | -                        | 49.97               | -            | -       | [26]⁺      |

a: the optimal value under different conditions.
b: unit is 10⁶ cell/mL.

15% CO₂, with its parental strain used as control. SDEC-1M got the best growth performance and the highest LCE (17.93 %) under 15% CO₂, which confirms its high CO₂ tolerance and high CO₂ fixation efficiency. Meanwhile, the highest total carbohydrate and lipid contents (37.26% and 24.80 %, respectively) and productivity (13.16 and 8.76 mg L⁻¹d⁻¹, respectively) were obtained. These results confirmed SDEC-1M’s ability to convert more efficiently light into energy storage materials. Compared to its parental strain, therefore, SDEC-1M is a more suitable candidate for CO₂ fixation and biomass production, especially biofuel production, which mitigates the global warming and energy shortage.

Abbreviations List

UV: Ultraviolet
PS: Parental strain
HCT: High CO₂ tolerance
LCE: Light conversion efficiencies
HCR: High CO₂ requiring
OD: Optical density
HHV: Higher heating values
PAR: Photosynthetic active radiation
ANOVA: Analysis of variance.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The financial assistance for this investigation was gratefully provided by National Key Research and Development Planning of China (2017YFF0209903), Key Research and Development Planning of Shandong Province (2016GSF117014 and 2016GSF117018), Shandong Province Water Conservancy Research and Technology Extension Project (SDLKY201812), Science and Technology Plans of Ministry of Housing and Urban-Rural Development of the People’s Republic of China (UDC2017031512), and the Innovation Team of the Co-Innovation Center for Green Building of Shandong Province in Shandong Jianzhu University.

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