Received: 26 March 2010 Revised: 15 May 2010 Accepted: 18 May 2010 Published online in Wiley Online Library: 25 June 2010

(wileyonlinelibrary.com) DOI 10.1002/jctb.2457

Development of an efficient electroflocculation technology integrated with dispersed-air flotation for harvesting microalgae

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Abstract

BACKGROUND: Various methods, including centrifugation, filtration, electroflocculation, flocculation and flotation, have been developed for harvesting microalgae. However, some economic or technical problems still remain with current methods for algal recovery, such as high capital, energy and running costs, flocculant toxicity or low separation efficiency. Therefore, there is great interest in developing new efficient approaches for harvesting microalgae.

RESULT: An efficient electroflocculation method integrated with dispersed-air flotation has been developed for harvesting *Botryococcus braunii*. The recovery efficiency of *B. braunii* reached 93.6% after 30 min using an electroflocculation process. Microalgae recovery was improved significantly when the electroflocculation process was integrated with dispersed-air flotation; the recovery efficiency of *B. braunii* reached 98.9% after 14 min.

CONCLUSION: The present work demonstrated that electroflocculation integrated with dispersed-air flotation is a promising method suitable for microalgae harvesting. The strategic air supply obviously shortened the algal recovery time in the process of electroflocculation due to facilitating algal aggregation and flotation to the solution surface.

Keywords: algal aggregation; electroflocculation; microalgae recovery; dispersed air flotation

INTRODUCTION

The harvesting of microalgae is very important in various processes such as wastewater treatment with a stabilization or oxidation pond,[1] algal biomass production,[2] drinking water supply and environmental management of inland water.[3,4] Many methods, such as centrifugation, filtration, flocculation and flotation, have been developed for microalgae recovery.[5,6] In order to reduce initial capital investment, energy and running costs, flocculant toxicity, there is still great interest in developing new economic and efficient approaches for harvesting microalgae.[6,7]

Electroflocculation has been used successfully in wastewater treatment and mineral engineering, and is regarded as an alternative to conventional flocculation processes due to its advantages of easy operation, avoidance of chemical usage and no anions such as chloride and sulfate added to the solution.[8–13] Recently, electroflocculation was also employed for microalgae harvesting, and showed obvious advantages over conventional flocculation with chemical reagents.[14–17] Efficiencies of 95% elimination or more were obtained by electroflocculation with different taxonomic groups of algae, while energy consumption only amounted to about 0.3 kWh m^{-3}. As a result, the total cost was 0.11 US$ for separation of 1 m^3 of algal suspension, which was less expensive than other separation processes, such as plate centrifuge (0.80 US$ m^{-3}), sedimentation with flocculants (0.21–0.34 US$ m^{-3}) and flotation with flocculants (0.71–0.84 US$ m^{-3}).[6] During the electroflocculation process, some small micro-bubbles generated from metal anodes were trapped in the algae, bringing the algal aggregates up to the water surface. The air flotation produced in the electroflocculation process was beneficial for algal removal.[18] Dispersed air flotation, as a low cost flotation technique, has been explored for the removal of algae from aqueous solution where surfactants/coagulants were added to form algal aggregates.[19,20] The energy requirement for algal recovery can be very low (3 Wh m^{-3}) in process flotation with flocculants.[21] Therefore, an attractive algal harvesting method may be provided by combining electroflocculation with dispersed-air flotation.

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The objective of this current study is to develop an efficient electroflocculation technology integrated with dispersed-air flotation without surfactant addition for the recovery of the unique colonial green microalgae *Botryococcus braunii*. The key parameters in this integrated process such as power input, air supply strategy and pH were optimized, and the algal aggregate formation was characterized.

MATERIALS AND METHODS

Microalgae source

Botryococcus braunii, obtained from the Culture Collection of Algae, Institute of Hydrobiology, Chinese Academy of Sciences, was grown on modified Chu 13 medium described by Largeau *et al*.[22]. Algal cells were cultured in a 2 L airlift bioreactor and continuously bubbled with air enriched with CO_2 (1 vol %) using a membrane compressor delivering 0.1 vvm. The initial biomass concentration was 0.2 g L^{-1}. The culture was incubated at 25 $\pm$ 1 °C under a light/dark cycle of 16/8 h, with light intensity 35 μmol m^{-2} s^{-1}. After 15 days cultivation, the final microalgae concentration was 1.6 g L^{-1} and the corresponding chlorophyll *a* concentration was 13.8 mg L^{-1}. The pH of the final culture broth was 7.0.

Electroflocculation

A commercially available power source (Hongbao Electric Co., Ltd., Leqing, Zhejiang, China) was used for the electroflocculation experiments in a 741 mL vessel (L×W×H= 12.8 × 9.9 × 7.3 cm) with wall thickness 4 mm (Fig. 1). The aluminum electrode plate had an area of 5.5 × 7 cm and a thickness of 2 mm. Two aluminum electrode plates were placed in the vessel parallel and vertically. The distance between cathode and anode was kept at 10 cm. A rectangular porous air diffuser, with a range of pore diameters from 16 to 40 μm, was used as a gas sparger at the bottom of the vessel. 600 mL microalgae culture broth was added to this vessel, and each electrode was submerged about 6 cm. Microalgae electroflocculation without gas input was carried out at different levels of input power. Time course for microalgae concentration (as chlorophyll a) was monitored.

Electroflocculation integrated with dispersed air flotation

Electroflocculation integrated with dispersed air flotation at a given input power was tested at a range of flow rates from 0 to 60 mL min^{-1}. The pH value of microalgae culture broth was adjusted to 7 ∼ 12 by adding HCl or NaOH. Time courses for microalgae concentration (as chlorophyll a) and aggregate size (as effective diameter) were determined. All experiments were carried out in triplicate.

Analytical methods

Chlorophyll *a* concentration was determined according to the method described by Lee *et al*.[7] Recovery efficiency (RE) is defined as the ratio of the mass of cells recovered to the total mass of cells.

$$RE = 100\% - (C_t/C_o) \times 100\%$$

where C_t is microalgae concentration (as chlorophyll *a*, mg m^{-3}) in the broth after harvest, C_o is the initial microalgae concentration (as chlorophyll *a*, mg m^{-3}) in the broth.

The algal samples dispersed in petri dishes were observed using an Automatic Colony Analysis System (Shineso Co., Ltd, Hangzhou, Zhejiang, China), and the algal aggregates were recorded by high-resolution CCD camera. Over 100 different aggregates for each sample were measured by the image analysis system which can identify particles down to 10 μm. The data on algal aggregate diameter were analyzed statistically by SPSS (for Windows, standard version 7.5.1 by SPSS Inc. Chicago), and the effective diameter was calculated.

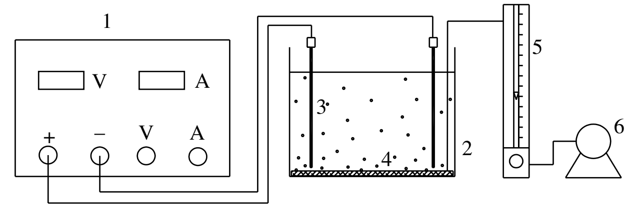

Figure 1. Schematic diagram of electroflocculation integrated with dispersed air flotation (1 DC power supply; 2 electroflocculation vessel; 3 aluminum electrodes; 4 gas sparger; 5 rotameter; 6 air pump).

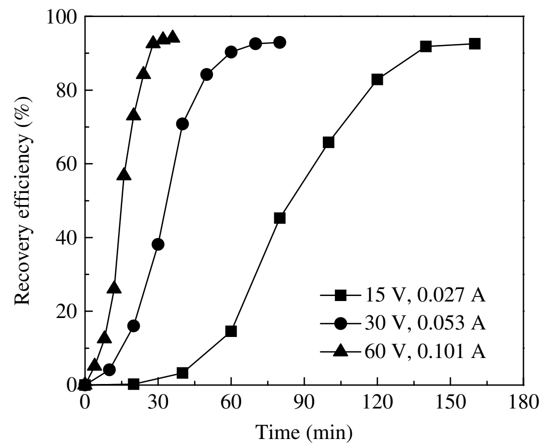

Figure 2. Effect of voltage input on microalgae recovery in the electroflocculation process.

RESULTS AND DISCUSSION

Microalgae recovery in electroflocculation process

The time course for microalgae recovery at various voltages ranging from 15 V to 60 V (corresponding to current intensities of 0.027 A to 0.101A) are shown in Fig. 2. The microalgae recovery efficiency reached over 90% at all electrical powers tested. The electroflocculation time was shortened significantly when the voltage was increased. Similar results was also observed in some previous studies on algal electroflocculation.[6,18] The amount of flocculants dissolved into the solution from the electrode is correlated with the current intensity in a certain time.[9] As a result, higher electrical power produced more flocculants to enhance algal flocculation.[18]

Microalgae recovery in electroflocculation process integrated with dispersed air flotation

Since flotation exhibited a positive effect during the electroflocculation process,[17,18] electroflocculation was integrated with dispersed air flotation for microalgae recovery at 60 V (0.101 A). As shown in Fig. 3, the microalgae recovery efficiency in the integrated process increased more rapidly than that in the electroflocculation process alone at the beginning period of algal

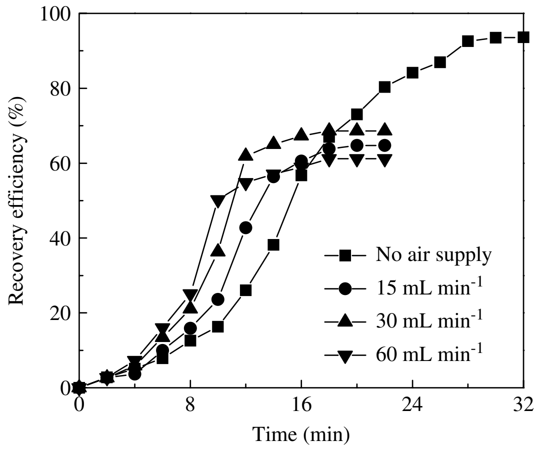

Figure 3. Effect of gas flow rate on microalgae recovery in the electroflocculation process integrated with dispersed air flotation (60 V, 0.101 A).

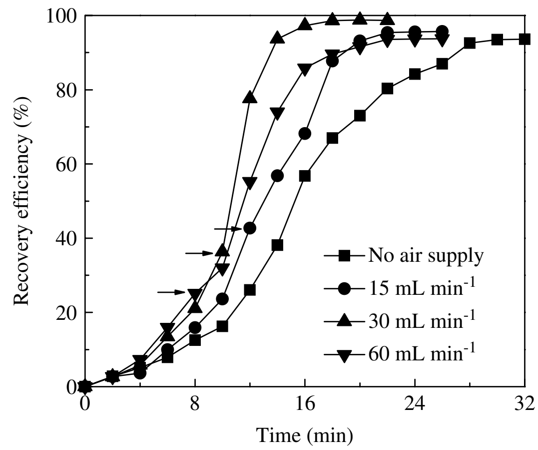

Figure 5. Effect of different air supply strategies on microalgae recovery in the electroflocculation process integrated with dispersed air flotation (60 V, 0.101 A; arrows indicate the time on air supply stop).

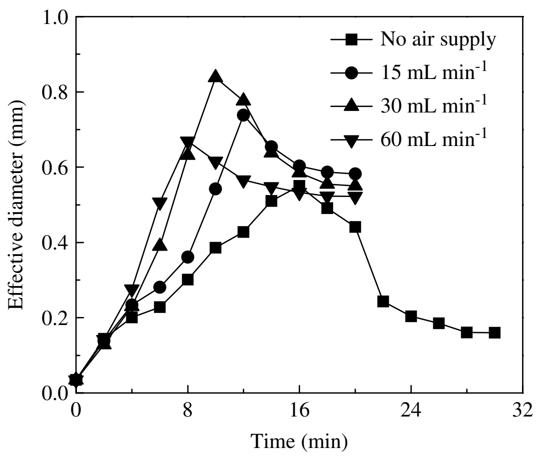

Figure 4. Effect of gas flow rate on aggregate size in the electroflocculation process integrated with dispersed air flotation (60 V, 0.101 A).

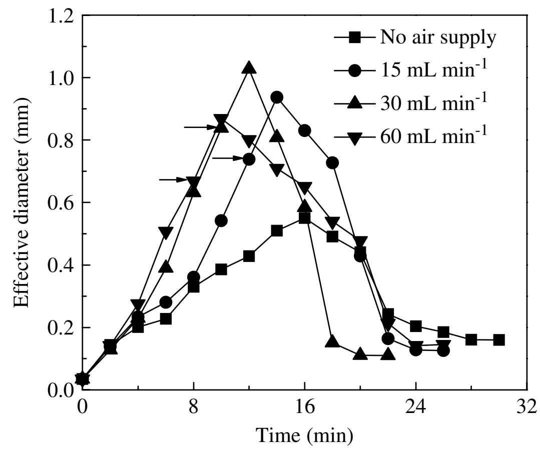

Figure 6. Effect of different air supply strategies on aggregate size in the electroflocculation process integrated with dispersed air flotation (60 V, 0.101 A; arrows indicate the time on air supply stop).

recovery, and reached a maximum without further increase after 18 min for all air flow rates tested. However, the algal recovery efficiency in the electroflocculation process increased gradually, and reached 93.6% after 30 min. The water content of the resulting flocs was 99.0%.

As shown in Fig. 4, the algal aggregate size increased to a peak value and then declined to a constant level during electroflocculation with/without dispersed air flotation. The decline of aggregate size was due to the formation of surface-floated flocs resulted from these algal aggregates. The aggregate size increased more quickly and was bigger in the integrated recovery process than in the electroflocculation process. The dispersed air flotation quickened the formation of algal aggregates and up-floated flocs at the beginning of this recovery process. However, the shear stress and/or turbulence caused by the continuously dispersed air also broke the up-floated flocs into algal aggregates, which were observed to re-suspend in the algal culture broth.[18] As a result, the maximum recovery efficiency of microalgae in the integrated recovery process was lower than that in the electroflocculation process, where the algal aggregates and up-floated flocs were formed gradually without disturbance from the continuous air supply.

In order to avoid the disturbance from the continuous air supply in the integrated recovery process, the dispersed air flotation was stopped once the aggregate size reached the peak value. As shown in Fig. 5, the microalgae recovery efficiency reached 95.4%, 98.6% and 93.6% respectively when the air was supplied at 15 mL min^{-1} for 12 min, 30 mL min^{-1} for 10 min and 60 mL min^{-1} for 8 min. The algal recovery time in the strategic recovery process shortened significantly in comparison with electroflocculation without dispersed air flotation.

As shown in Fig. 6, the maximal algal aggregate size in the strategic recovery process reached 1.03 mm which is bigger than that (0.77 mm) in the integrated recovery process with continuous air supply. After the air flow was cut off, the algal aggregate size still increased and easily formed into up-floated flocs, which were beneficial to algal recovery. As a result, the algal aggregate size decreased quickly to a constant level close to the initial size, and the microalgae recovery efficiency reached a maximum of 98.6% in the strategic recovery process after 18 min.

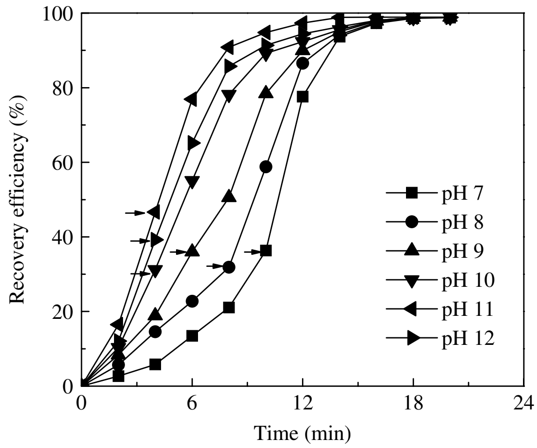

Figure 7. Effect of pH on microalgae recovery in the electroflocculation process integrated with dispersed air flotation with the optimized air supply strategies (60 V, 0.101 A; arrows indicate the time on air supply stop).

Effect of pH on microalgae recovery

The pH value is one of the important parameters in the flocculation process of algal biomass, and a 90% recovery efficiency of *B. braunii* was achieved by a flocculation method with pH adjustment and flocculant addition after 2 weeks of incubation.[7] As shown in Fig. 7, the algal recovery time decreased with increase of pH from 7 to 11 in the strategic recovery process. At the optimal pH of 11, the recovery efficiency reached 98.9% after 14 min. The algal recovery efficiency decreased at a pH value of 12 because of algal lysis.[14]

CONCLUSIONS

Electroflocculation integrated with dispersed air flotation has been developed successfully for microalgae recovery. The strategic air supply in the integrated recovery process was beneficial to the formation of large algal aggregates, which tended to rise easily to the liquid surface to become surface-floated flocs. This integrated recovery technology has great potential for saving time associated with improved algal harvesting.

ACKNOWLEDGEMENTS

This work is supported financially by National Basic Research Program (973 Program) of China (No.2007CB714301) and the Knowledge Innovation Program of the Chinese Academy of Sciences (No. YZ200947 & KSCX2-YW-R-2).

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