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Microalgal attachment and attached systems for biomass production and wastewater treatment

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ABSTRACT

Microalgae are promising feedstocks for food, feed, fuel, fertilizers, fine chemicals and other value-added products, and are considered of great potential in wastewater treatment. Convenient acquisition of the cultivated microalgal biomass or easy separation of microalgae from the treated effluents, however, are the prerequisites of these applications. Biomass harvesting and dewatering in traditional suspended cultivation systems are costly and energy intensive, since volumes of liquid medium needs to be separated from the obtained diluted microalgal biomass. Attached systems can effectively overcome such limitations by introducing substratum into the liquid medium for microalgae attachment, and the attached biomass with magnitudes higher solid content can be collected via simple and straightforward harvesting methods such as mechanical scraping. As an emerging field with less than ten years of research history, systematic information on microalgae attachment and attached systems for biomass production and wastewater treatment has not been thoroughly reviewed. This review, therefore, analyzed the two-step mechanisms of microalgae attachment, discussed the influencing factors of attached microalgal growth including properties of substratum, properties of microalgal cells, turbulence of liquid medium, frequency of biomass harvesting, etc., and their possible impacts on microalgal biofilm formation and biomass production in attached systems. Classification of attached microalgal systems based on different criteria such as substratum orientation, relative position of microalgal cells and the culturing medium, system scales and culturing medium, was summarized. Performances of attached microalgal systems for biomass production and wastewater treatment were evaluated, with commonly used parameters identified and compared as well. Recommendations for future theoretical research and practical applications were also addressed in the manuscript. This review could offer much useful information on microalgal attachment and attached systems for biomass production and wastewater treatment, and may serve as guidance for future studies in related fields.

1. Introduction

Owing to their fast growth rates as single-celled microorganisms and abundant valuable intracellular components, microalgae have been widely regarded as promising feedstocks for food, feed, fuel, fertilizers, fine chemicals and other value-added products, and because of their higher nutrients demand during biomass growth comparing to hydrophytes and other heterotrophic bacteria, microalgae are considered of great potential in wastewater treatment as well [1–4]. Microalgal cultivation systems are approaches to realize microalgae-based biomass production and wastewater treatment. As traditional means of microalgae cultivation, suspended culturing can be achieved in both open ponds and enclosed photobioreactors, and general biomass concentrations in the above systems are respectively around 0.5 g/L and 2–6 g/L [5–7]. Such low concentrations of microalgae biomass demand energy intensive dewatering and drying for biomass harvest when bioproducts are expected, or when sewage treatment is carried out and effective algae-water separation is required after water purification. Biomass harvest in suspended systems may contribute up to 30% of total cultivation costs [8].

To overcome the issue of biomass harvesting in suspended systems, immobilized cultivation of microalgae by entrapping cells in 3–4 mm

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Fig. 1. Distribution of institutions researched on microalgae attachment and attached cultivation. Larger font sizes correspond to greater numbers of available literature.

natural or synthetic polymeric beads were proposed [9,10]. Compared with suspended systems, easier biomass harvesting could be achieved in immobilized systems by simply separating the microalgae-containing beads from the culturing medium, and better species control can be expected as well. However, the entrapped microalgal cells often undergo longer lag phases in immobilized systems, and may not have access to sufficient light or nutrients, both of which may lead to lower biomass productivity. Leakage of microalgae from entrapment and toxicity of polymeric materials to microalgal cells during long-term cultivation are other shortcomings of immobilized systems [10,11].

As another approach to resolve the limitations of suspended cultivation while preventing new issues such as those in immobilized systems, attached microalgae cultivation has received widespread attention, with institutions researched on microalgae attachment and attached cultivation within the past few years summarized in Fig. 1. Schematic diagrams of suspended, immobilized and attached cultivation are compared in Fig. 2. By introducing substratum into the culturing medium for microalgae attachment, much higher biomass concentration/density can be obtained in attached systems (common solid content of 12–16% vs. up to 0.5% in suspended systems), and the attached biomass can be easily collected via straightforward harvesting methods such as mechanical scraping, which could reduce the energy consumption on biomass harvesting and dewatering by up to 99.7% comparing to open ponds [12–14]. Also different from suspended cultivation, no mixing (e.g. paddle wheels in open ponds) is required in attached systems, leading to much simpler system construction, operation, maintenance, etc., thus lower costs and higher scalability of microalgae cultivation can be expected [15,16]. Compared with immobilized systems where natural or polymeric beads are used for microalgal cell entrapment, attached cultivation is also advantageous in biomass concentration/density and reduced harvesting/dewatering energy demand, meanwhile the cost-intensive cell entrapment process can be perfectly spared, since microalgal biomass "builds-up" on substratum surfaces in attached systems [3,17,18].

In spite of all the above advantages, it has to be noted that, however, because of the relatively short research history (the first publication on using attached system for microalgal biomass production was not available until the year 2010) [19], systematic information on mechanisms of microalgae attachment, influencing factors of attached microalgal growth, classification and evaluation of attached microalgal systems for biomass production and wastewater treatment, and recommendations for future research and application have not been thoroughly reviewed before. In this review, the two-step microalgae attachment mechanisms, namely, initial adhesion and biofilm thickening were analyzed; influencing factors on attached microalgal growth including substratum properties, microalgal cell properties, and other environmental and operational factors were discussed; classification of attached microalgae systems based on different criteria was carried out; evaluating parameters and performances of attached systems for microalgal biomass production and wastewater treatment were respectively summarized; suggestions on future studies in terms of both theoretical research and practical application were also given. This review could offer much useful information on microalgal attachment and attached systems for biomass production and wastewater treatment, and may serve as guidance for future studies in related fields.

2. Mechanisms of microalgae attachment

The process of microalgae attachment generally involves two steps: initial adhesion of microalgal cells on substratum surfaces, and thickening of formed microalgal biofilm (Fig. 3). Primary interactions within the two steps are respectively cell-substratum and cell-cell interactions.