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Review

Algal biofilm reactors for integrated wastewater treatment and biofuel production: A review

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HIGHLIGHTS

- Current algal biofilm reactors are compared with conventional suspended culture systems.
- Algal biofilm reactors and their biomass productivities are comparatively discussed.
- Various support material used for algal biofilm reactors are summarized.
- Current application of algal biofilm reactors to wastewater treatment is also listed.

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ABSTRACT

This review analyzes various algal biofilm reactors used for integrated wastewater treatment and biofuel production to overcome the current challenges for algal biofuel production. Various reactor configurations, support materials and operation strategies of algal biofilm reactors are discussed and compared with conventional suspended culture systems in terms of algal biomass productivity, nutrient removal, biomass harvest and biofuel production. The rotating biofilm reactor among various types of biofilm reactors was found to be a promising option to provide high biomass productivity and efficient utilization of nutrients in wastewater. Some materials such as stainless steel, nylon and natural fibers among various materials were found to be highly effective for supporting microalgal biofilm. To date mainly municipal wastewater has been integrated with algal bioreactors while only a few agricultural wastewater have been used for algal bioreactors due to inhibition of algal growth with high ammonium concentrations in animal manure and poor light delivery with high turbidity of animal manure. Overall, the algal biofilm reactors integrated with wastewater would have great potential for high productivity of algal biomass and efficient wastewater treatment if various conditions are optimized.

Contents

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1. Introduction

Conversion of various biomass to cost-effective biofuels has been considered as a potential solution to replace current use of fossil fuels as fossil fuels become scarce and more expensive [1]. The first-generation feedstock using food crops brought serious competition between food and biofuel [1]. The second-generation biofuel using lignocellulosic biomass can avoid the competition between food and biofuel, but is limited by the high cost associated with pretreatment of lignocellulosic biomass for removal of lignin [2].

Microalgae is a very promising source for biofuel by using efficient photosynthesis for fixation of CO_2. Compared to terrestrial plants, microalgae show faster growth rate, with high efficiency (above 10%) exceeding that of terrestrial plants by a factor of 10–50 [3]. Under unfavorable environmental conditions and in marginal land, microalgae can grow and produce large amounts of lipid, which is used for biodiesel production [4]. In addition, microalgae can use various water sources while recycling nutrients from wastewater streams [5]. Thus, microalgae has distinct advantages such as non-competition with food crops over limited land, high biomass productivity, and high lipid content compared with the feedstock for first and second generation biofuels. In fact, areal productivity of algal biomass is much higher than first and second feedstocks and they also have high lipid content and growth rate [3]. They also require a smaller amount of water and land than first and second feedstocks for biofuels [6]. The possible biofuels from microalgae include biodiesel made from algal lipid content, methane by anaerobic digestion, and bioethanol from algal carbohydrates [7,8]. The remaining biomass can be used as a feed for animals and fish, and it can be used as the materials in bioplastics [9,10].

However, commercial application of microalgal biofuel has been limited by its high operating costs associated with costs for substrate/nutrients, low productivity of algal biomass, and high energy consumption during algal cell harvest. For producing a microalgae biomass, the suspended systems include open and closed types. The open type culture systems like a raceway pond has several disadvantages due to contamination and evaporation problems. Also, it needs large surface area for photosynthesis. Closed bioreactors are not suitable for biofuel production since their operation costs are expensive. No matter what open or closed system, suspended systems consume massive costs for harvesting microalgae cells. Compared with suspended systems, biofilm reactors showed higher algal biomass productivity and easy harvest of algal biomass by scrapping [11].

Besides, algal biofuel production could be integrated with wastewater treatment to lower the overall costs. The Department of Energy's report showed that wastewater treatment should be coupled with the development of microalgae biofuel technologies for economical biofuel production [6]. Current wastewater effluent has high concentration of nitrogen and phosphate which often causes eutrophication and various harmful effects on ecosystems while changing the pH, decreasing dissolved oxygen and causing death of aquatic organisms. While elimination of these nutrient requires a huge amount chemicals and energy [12], adopting microalgae for wastewater treatment can solve the eutrophication problem and treat the water without toxic compounds. Furthermore, wastewater can be nutrients for microalgae to increase microalgae biomass with wastewater treatment. Therefore, research combining microalgae production and wastewater treatment has received increasing attention [11].

Recently, several studies revealed that the biofilm reactors surpassed the suspended reactors in regard to biomass productivity and wastewater treatment efficiency [13–15]. Current studies to develop algal biofilm reactors have included the use of secondary effluent from municipal and agricultural wastewater in various types of bioreactors and substrates [16–18]. Particularly the agricultural wastewater treatment by microalgae sometimes required dilution before treatment since it has high COD, nutrients, turbidity and dark color. Biomass productivity and total biomass are closely related to surface area, reactor design and supports. The porosity and roughness of supporting material can increase the surface area leading to high biomass productivity and wastewater treatment ability. Therefore, this review deals with limitations of current algal biofuel production, and summarizes various biofilm reactors integrated with wastewater treatment as viable solutions to overcome these limitations. Various types of current algal biofilm reactors and support material used for current algal biofilm reactors are comparatively investigated. In addition, algal biomass production combined with treatment of municipal and agricultural wastewater is also discussed.

2. Limitations of current algal bioreactors for biofuel production

Microalgae have distinct advantages such as non-competition with food crops over limited land, high biomass productivity, and high lipid content. Although microalgae have these advantages, the current biofuel from microalgae has not reached competitive prices. Compared to plant oils, microalgal oil is estimated to be 3–4 times more expensive [19]. The limiting factors of biofuel production using microalgae are the cultivation and harvest steps [20]. Cultivation accounts for 40% of the cost and energy in microalgal biofuel production [21]. Major factors that affect cultivation are nutrient supply, land and water availability, gas transfer and exchange, photosynthetically active radiation (PAR) delivery and culture integrity. The harvest step takes 20–30% of the total microalgal biofuel cost [20].

2.1. Types of bioreactors

Most of the current algal bioreactors rely on suspended cultures, which can be categorized into open and closed systems. No matter which type is used, suspended culture systems need huge amount of energy to harvest algal cells and eliminate the water in downstream. The harvest costs also account for 20–30% of algal biofuel production [20]. The open pond culture system can be considered the simplest and most economical method among algae cultivation systems. Several types of open pond system including raceway pond, slope system and circular ponds have been developed [7,22]. The advantage of open system is that the construction and operation cost is cheaper than those of closed system. However, its disadvantages can offset the advantages. The open pond system has low biomass productivity due to several limitations (typical biomass productivity of 4–21 g m^{-2} d^{-1}) [6,23]. The limitations include temperature fluctuation, low CO_2 transfer, limited light transmission and contamination with other organisms such as protozoa [20]. Evaporation is also disadvantageous because it