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Recent trends in the mass cultivation of algae in raceway ponds

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ABSTRACT

Algal technology has potential to combat the global energy crisis, malnutrition, and production of several value added products useful for the mankind. The cost effective cultivation system is the basis to realize this goal. Microalgal production in raceway ponds seems to be most promising, especially in the large scale. Several environmental (location of the cultivation system, rainfall, solar radiation, etc.), engineering (pond depth, CO_2 delivery system, methods of mixing, power consumption, etc.), and biological (light, pH, oxygen accumulation, salinity, Algal predators etc.) parameters affect the biomass productivity in the open pond system. Vertical mixing is an important criteria influencing the algal growth compared to axial mixing as it determines the frequency by which cell will travel from bottom (dark zone) to surface (light zone) of the open pond. Therefore, different research works on the various designs of raceway ponds were mostly focused towards enhancing the vertical mixing (e.g. Design of bend and surface geometry, engineering flow field, etc.) and CO_2 residence time (e.g. Closed, sump, airlift driven raceway ponds etc.). The present study summarizes the current state of knowledge for the biomass production in raceway ponds.

Contents

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1. Introduction

Currently, the world is facing many challenges: global warming, malnutrition, increasing energy demand are some of them. Algal technology is an emerging field, which has potential to combat these problems. Microalgae transform gaseous CO_2 into their cellular components such as carbohydrates, lipids, and proteins in a process called photosynthesis. In this way, microalgae help in mitigating the effect of global warming by capturing the CO_2 from the earth's atmosphere [1,2]. Microalgal biomass is rich in protein, and many value-added products having nutraceutical, cosmetic and pharmaceutical importance [3–5]. These are the sources of Bioenergy such as biohydrogen, biodiesel, bioethanol, biogas etc. [1,3–5]. In microalgae, energy condenses in the form of either starch or triacyglycerides (TAGs) as lipid droplet. Lipids of microalgae can be further converted into biodiesel by transesterification.

Microalgae is superior in terms of biomass and biodiesel yield compared to terrestrial energy crops. Biomass productivity of energy crops such as soybeans, corn, switch grass is ~3 Mt ha^{-1} $year^{-1}$, ~9 Mt ha^{-1} $year^{-1}$, and ~10–13 Mt ha^{-1} $year^{-1}$, respectively [6]. Therefore, cultivation of energy crops is less attractive compared to biomass productivity of microalgae: ~50–70 Mt ha^{-1} $year^{-1}$ in open ponds and ~150 Mt ha^{-1} $year^{-1}$ in photobioreactors [6]. Algal lipid production rates per unit area are several orders of magnitude higher than the conventional biofuels feedstocks [7]. For example, potential oil production from the rapeseed grown in U.K is ~1.5 t ha^{-1}, which is much lower than the microalgae-derived biodiesel of magnitude ~40 t ha^{-1} in a large scale open pond [6]. In addition, algal biofuel has a higher heating value of 41 K J Kg^{-1} [8].

Algal cultivation is one of the technological thrust areas, which has a huge market potential for biodiesel as well as other valuable biochemicals. An estimation by Chisti calculates that energy consumed during algal cultivation is nearly 28% of the total biodiesel production cost from microalgae [9]. Open ponds and closed photobioreactors (PBRs) are used for the algal biomass production. Both of them have their own advantages and disadvantages. Photobioreactors have merits of having significantly higher volumetric algal productivities (0.2–3.8 g L^{-1} d^{-1}) compared to those of raceway ponds (0.12–0.48 g L^{-1} d^{-1}) [10,11]. Closed PBRs prolong the gas retention time and improve the mass transfer efficiency. For example, airlift reactors have advantages such as high volumetric mass transfer rate of CO_2, efficient mixing, light/dark cycle, light utilization etc. In addition, closed PBRs offer greater control over process parameters.

Closed PBRs also have several disadvantages, which limit their use for commercial scale. The gas exchange requirement limits PBR scale-up to 100 m^2 compared to 10,000 m^2 in case of open ponds [12]. The operation and cleaning of thousands of individual PBRs are laborious, costly, and time consuming. The cost of commercial PBR is 100 times higher than open ponds. The water and energy consumption, total actual area occupied by the PBR, and the problem of long term resistance to contamination are other disadvantages of PBR [12]. Algatechologies, Israel is the probably only commercially successful company, operating modular array of tubular PBR of 300 km long, and occupying 10 acres of desert land (http://www.algatech.com/technology.asp). This company grows *Haematococcus pluvialis* for the production of astaxanthin. The company claims stable climatic condition with high sunlight intensity make them ideally positioned for the algal cultivation.

The mass production of microalgae was started in the early 1950s using *Chlorella* sp. in Japan. Oswald coined the term high rate algal ponds (HRAPs) for the open and shallow raceway design having a large scale recirculating system [13]. Since then, raceway ponds are being utilized mostly for algal cultivation and wastewater treatment [14]. Generally the four major open systems can be used for the algal cultivation: shallow big ponds, tanks, circular ponds, and raceway ponds (RWPs). Each of them has its own characteristic features. The choice of the open cultivation system depends upon types of algal species, local climatic conditions, and the cost of lands and water [15]. Open ponds preference is due to their small capital investment, free solar energy, and the low energy required for mixing, which may be order of as low as 4 W m^{-3} [3,16].

Today, most of the large scale algal biomass production facility is based on RWPs and this accounts for nearly 95% of the total worldwide algal production [3]. For example, high value products such as astaxanthin has been produced in raceway ponds of 20,000 L capacity [17]. In fact, RWPs use the simplest form of algal cultivation [18]. Raceway pond was found better compared to circular pond [19]. On the basis of the cost of production, average lipid production cost in open ponds (12.73 USD per gallon) is significantly lower compared to that of photobioreactor (31.61 USD per gallon) [20]. This indicates the financial feasibility of lipid production in open ponds. Further, Stephenson et al. conducted the life cycle assessment (LCA) and concluded that the global warming potential (GWP) for algal based biodiesel obtained from RWPs is nearly 80% lower than the fossil-derived diesel [21]. Contrary to this, GWP was significantly higher for the biodiesel obtained from an airlift photobioreactor compared to fossil-derived diesel [6]. A comparative evaluation of the performance of open pond and photobioreactor has been shown in Table 1.

Raceway ponds are intended to cultivate selected microalgae growing only in selected environments [18]. Some of the microalgae and cyanobacteria generally cultivated in RWPs are *Nannochloropsis* sp., *Chlorella* sp., *Tetraselmis* sp., *Arthrospira platensis, Dunaliella salina, Scenedesmus* sp., *Haematococcus pluvialis, Anabaena* sp., *Phaeodactylum tricornotum, Micractinium* sp., *Actinastrum* sp. etc [3,16,22]. Some of them can make large settleable colonies and bio-floccs helpful in harvesting by gravity sedimentation [22]. Land cost in Australia is cheaper than the USA and Israel. Therefore, an Australian company, Betatene Ltd. produces *D. salina* in very large ponds (up to 250 ha) having no facility for mixing [15]. However, USA and Israel based companies generally use well mixed RWPs for the cultivation of microalgae such as *Dunaliella* sp. CO_2 addition in RWPs is necessary to achieve high cell density. However, maintaining high alkaline condition in open ponds is sufficient for the cultivation of *Spirulina* sp. In Trebon, Czech Republic, algal cell density as high as 10 g L^{-1} is also reported in open air system, but having less than 1 cm culture depth [15].

The commercial scale biodiesel production by microalgae is possible by minimizing the cultivation cost near to $0.25 per kg of