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Comparative analysis of top-lit bubble column and gas-lift bioreactors for microalgae-sourced biodiesel production

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ABSTRACT

The development of top-lit one-meter deep bioreactors operated as either a gas-lift or bubble column system using air and carbon dioxide enriched air was studied. The goal was high productivity cultivation of algae with elevated lipid levels suitable for conversion into biodiesel. A theoretical energy requirement analysis and a hydrodynamic model were developed to predict liquid circulation velocities in the gas-lift bioreactor, which agreed well with experimental measurements. The influence of operational parameters such as design of bioreactor, gas flow rates and carbon dioxide concentration on the growth and lipid volumetric production of *Scenedesmus dimorphus* was evaluated using factorial design. While biomass productivity was 12% higher in the bubble column bioreactor (68.2 $g_{dw}\ m^{-2}\ day^{-1}$), maximum lipid volumetric production (0.19 $g_{Lipid}\ L^{-1}$) was found in a gas-lift bioreactor sparged with 6% carbon dioxide due to hydrodynamic and light stresses.

1. Introduction

Large-scale microalgal cultivation is typically carried out in open systems such as circular ponds with rotating arms, raceway ponds with paddlewheels, and cascade systems with baffles. They are relatively simple to construct, maintain and operate, but due to light penetration limitations have operating depths of only 15–35 cm [1], which can lead to a large land requirement [2]. This can be a location issue if industrial off-gas is to be considered as a supply of carbon dioxide (CO_2) for enhancing microalgal production [3]. In colder climatic regions, the industrial off-gas can be also utilized as a source of free heat to allow algal cultivation open systems to operate year-round [4].

There have been only a few applications of gas-liquid contacting devices in large-scale shallow open systems with the aim of improving biomass productivity. The placing of porous stones at the bottom of ponds [5] or diffusers at the bottom of single or multiple sumps [6] has been demonstrated to provide higher gas transfer rates. Putt et al. [7] used a bubble column to carbonate the culture before entering the raceway. An airlift-driven design was proposed by Ketheesan and Nirmalakhandan [8] as a means of replacing paddlewheels in raceways. Du et al. [9] showed there was a higher CO_2 injection efficiency with a venturi injector over a conventional diffuser system. A CO_2 supplying device fixed on the bottom of a pond was tested by Su et al. [10] and was shown to enhance CO_2 absorptivity. The shallow depths used in these studies, however, are likely to lead to inefficient use of off-gas due to short gas bubble residence times. This in turn could have an impact on biomass productivity. Raceway ponds should theoretically have production levels of 50–60 $g\ m^{-2}\ day^{-1}$, but in practice productivities of even 10–20 $g\ m^{-2}\ day^{-1}$ are difficult to achieve [11].

While finding sufficient space to locate microalgae cultivation ponds, close to fixed off-gas sources on an industrial site is likely to be a challenge, employing deeper ponds to improve areal productivity could be a possible solution. An option to achieve deeper ponds, smaller footprints and longer gas-liquid transfer times is to use vertical bubble column or gas-lift systems. This approach can improve mass transfer, provide good mixing with low stress and limit algae growth on walls [12]. The use of bubble or gas-lift columns in deep open ponds has not, however, been widely studied and there is little comparative information between the two approaches with respect to their biomass and lipid productivities. Where studies have been reported, there is however, no apparent consistency in the results. Barbosa et al. [13] for example, stated that bubble columns are more efficient for algal growth, whereas other studies showed higher biomass productivity in gas-lift columns. Oncel and Sukan [14] compared the gas-lift photobioreactor with the bubble column photobioreactor and showed a 36% higher growth rate in the gas-lift photobioreactor. In a review conducted

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Nomenclature

A_b	free area between riser and downcomer, m^2
A_d	cross-sectional area of downcomer, m^2
A_r	cross-sectional area of riser, m^2
A_t	total area of bioreactor, m^2
C	DO concentration at time t, mg L^{-1}
C^*	DO saturation concentration, mg L^{-1}
C_b	dry weight of biomass, g_{dw} L^{-1}
D_i	internal diameter, m
D_o	column diameter, m
D_L	oxygen diffusivity in water, m^2 s^{-1}
d_H	hydraulic diameter, m
d_B	mean bubble diameter, m
f	Darcy friction factor, –
g	gravitational acceleration, m s^{-2}
h_L	unaerated height, m
h_d	aerated height m
h_r	height of riser, m
K_B	friction loss coefficient, –
k_La	volumetric mass transfer coefficient, s^{-1}
L_c	length of circulation loop, m
P_a	areal productivity, g_{dw} m^{-2} day^{-1}
P_v	volumetric productivity, g_{dw} L^{-1} day^{-1}
P_L	volumetric lipid production, g_{Lipid} L^{-1}
P_G	power input due to aeration, W
t_c	circulation time, s
U_G	superficial gas velocity, m s^{-1}
U_{Gd}	superficial gas velocity in downcomer, m s^{-1}
U_{Gr}	superficial gas velocity in riser, m s^{-1}
U_{Ld}	superficial liquid velocity in downcomer, m s^{-1}
U_{Lr}	superficial liquid velocity in riser, m s^{-1}
U_b	mean bubble rise velocity, m s^{-1}
V_L	average liquid circulation velocity, m s^{-1}
V_d	actual liquid velocity in downcomer, m s^{-1}
V_r	actual liquid velocity in riser, m s^{-1}
V_t	total volume, m^3
W_i	energy input, W
W_{Rr}	energy loss due to wakes behind the bubbles in riser, W
W_{Dd}	energy loss due to stagnant gas in downcomer, W
W_{Fr}	energy loss due to friction in riser, W
W_{Fd}	energy loss due to friction in downcomer, W
W_B	energy loss due to fluid turn-around at the bottom of bioreactor, W
X_1	gas flow rate, L min^{-1}
X_2	CO_2 concentration (%), –
X_3	design of bioreactor, –
Y	response, –
Ψ	relationship between gas transfer and hold-up, s^{-1}
β_0	independent coefficient, –
β_{ij}	linear coefficient, –
ε	overall gas hold-up, –
ε_d	gas hold-up in downcomer, –
ε_r	gas hold-up in riser, –
μ	specific growth rate, day^{-1}
ρ_L	culture density, kg m^{-3}
ρ_G	density of mixture of air and CO_2, kg m^{-3}

by Ugwu et al. [15] on mass cultivation of algae in bioreactors, it was illustrated that the gas-lift photobioreactors had the highest biomass productivity. Kumar and Das [16] also reported approximately 43% higher biomass production in the gas-lift bioreactor compared to the bubble column.

The production of algal lipids that can be used as a feedstock for conversion into biodiesel [17] has been shown to be influenced by the growing conditions. Cakmak et al. [18] for example, showed an increase in total neutral lipids in response to nutrient starvation. Cultivation under a low pH environment also resulted in high lipid content of *Scenedesmus* sp. isolated from abandoned mine site water bodies [19]. Xin et al. [20] studied the growth and lipid accumulation properties of *Scenedesmus* sp. under a temperature range of 10–30 °C. Light stress due to flashing light induced microalgal lipid synthesis [21]. Xia et al. [22] investigated the effect of CO_2 content in a range of 5–15% on lipid productivity of *Chlorella* sp. and found maximal productivities at 10% CO_2. Mixing stress due to an increased gas liquid ratio has been demonstrated to have a positive effect on growth and lipid formation of algal cells [23].

This study is a systematic comparative analysis of top-lit bubble column and gas-lift bioreactors with regards to microalgae productivity using enhanced CO_2 levels and tanks deeper than those currently most commonly used for mass production. The differences in mixing patterns of bubble and gas-lift columns, as well as CO_2 concentration, lighting and hydrodynamic conditions are examined in terms of not only algal biomass productivity, but also the productivity of lipids suitable for conversion into biodiesel.

2. Material and methods

In this section, the microalgae species, growth medium and bioreactor configurations used in this study are explained. The hydrodynamic characterization and energy dissipation models as well as the biomass and lipid evaluation methods are also described.

2.1. Microalgae selection and growth medium

The green microalgae *Scenedesmus dimorphus* was used in this work. It was obtained from the University of Texas, Austin collection (1237 UTEX collection) and inoculums grown in freshwater Bold's Basal growth medium [24] at 25 °C.

A pre-culture was then produced in covered 180 L glass tanks ($120 \times 30 \times 50$ cm) under fluorescent light of approximately 60 μmol m^{-2} s^{-1} on a 12 h light/dark photoperiod. The temperature was 22 ± 2 °C, and they were continuously agitated with bubbling air and fed Bold's Basal growth medium every three weeks.

2.2. The bioreactor set-up

The bioreactors used were a bubble column and a concentric gas-lift column which had a sparged draft tube with an internal diameter (D_i) of 0.13 m and height of 0.8 m (Fig. 1). They were made from 5 mm thick, transparent Plexiglas with a diameter (D_o) of 0.2 m. The columns had side ports at 0.05 m and 0.5 m from the base for taking samples. The ratio of cross sectional area of riser to downcomer was 0.83 for the gas-lift reactor. The draft tube was located 0.05 m from the bottom. The working volume was 0.03 m^3 at 1 m depth. Air mixed with carbon dioxide to achieve a 6% CO_2 mix content was sparged through a 0.10 m diameter ceramic sparger with a mean pore size of 15 μm (Refractron Technologies Corp., NY, USA). The flow rate was controlled by using rotameters (Omega Engineering Ltd., QC, Canada).

The outside of the bioreactors were covered with a layer of black plastic sheet on top of a layer of white plastic sheet to block