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A liquid foam-bed photobioreactor for microalgae production

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HIGHLIGHTS

- Proof of principle of a foam-bed photobioreactor for microalgae cultivation.
- A method for continuous foam breaking was established.
- *Chlorella* cultures survive shear stress linked to bubble formation and burst.
- A growth rate of 0.1 h^{-1} was achieved for *Chlorella sorokiniana*.

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ABSTRACT

A novel concept of cultivating microalgae in liquid foam was developed with the intention of reducing biomass production costs. This cost reduction is based on reduced harvesting costs due to high biomass densities, and reduced energy requirements due to improved mass transfer and lower pressure drop in the foam-bed photobioreactor. Foam generation could be controlled by adding foaming agents and employing homogenous gas distribution at the bottom of the photobioreactor. In order to refresh the gas phase entrapped in the bubbles, and ensure sufficient CO_2 for microalgal growth, different foam break-up methods were evaluated. A packed bed filled with large hydrophobic beads resulted in efficient foam break-up at minimal pressure drop. It was shown that microalgae (*Chlorella sorokiniana*) can grow in the liquid channels of liquid foams stabilised by the protein Bovine Serum Albumin, and that the culture can withstand the physical processes of foam formation and foam break-up. An average growth rate of 0.10 h^{-1} was observed. The quantum yield of photosystem II photochemistry remained maximal during the reactor runs, indicating that photosynthesis was not impaired. The results obtained show that cultivation of microalgae in liquid foams is a promising new concept.

1. Introduction

The production of useful substances of algal origin, including specialities for food and aquaculture as well as biofuels and bulk chemicals, requires energy-efficient and economically profitable cultivation systems [1–3]. Many studies highlighted the importance of photobioreactor design and operation as major factors influencing production costs [4–7]. The goal of this study is therefore the development of a novel microalgae cultivation system that could enable economically feasible microalgae cultivation by reducing biomass production costs. The major factors that determine the practical application of photobioreactors is rapid and energy-efficient transfer of carbon dioxide and oxygen [8], the dewatering of the harvested, dilute microalgal cultures [9], and the high energy input for aeration [10]. In this study a foam-bed photobioreactor with high gas holdup was developed since increased gas holdup results in both increased mass transfer and lower pressure drop. In addition, the foam-bed photobioreactor supports increased biomass concentration due to the thin liquid layers between the foam bubbles reducing microalgal self-shading. The concept of growing microalgae in liquid foam-bed photobioreactors is an innovative idea in the field of microalgae cultivation [11].

In a foam-bed reactor small gas bubbles are passed through a thin liquid layer resulting in foam generation. The liquid is either self-foaming or contains a foam stabilising agent. Thus, the culture is composed of a thin liquid layer at the bottom of the reactor with

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a large volume of foam exposed to (sun)light, above it. Due to the continuous gas supply, the generated foam bubbles rise. Simultaneously, the liquid film separating adjacent gas bubbles is continuously draining downwards due to gravity.

This novel concept has several potential advantages over traditional cultivation systems. First, when adopting flat-panel photobioreactors in combination with a liquid foam-bed the light path in the liquid film in the foam over which light absorption takes place is in the order of a few millimetres only. Consequently, the biomass concentration can be increased with an order of magnitude ($\geqslant 10\,g\,L^{-1}$) compared to liquid-filled flat-panel reactors, thereby reducing downstream processing costs with the same factor. Furthermore, a foam-bed reactor only contains a limited water volume (about 5% v/v) resulting in a low pressure drop relative to the height of the photobioreactors. Therefore, the concept might enable energy reduction on gassing due to the low pressure drop present in the reactor. Besides, due to the low pressure drop in the reactor, the carrier capacity of the structure supporting the photobioreactors can be reduced considerably, thereby lowering construction costs of large-scale systems. Also, the high interfacial area created between the gas and water with microalgae contributes to the reduced energy requirement of the foam-bed reactor. The high interfacial area results in a high transfer capacity for both oxygen and carbon dioxide. Finally, the residence time of the gas in the photobioreactor is increased by orders of magnitude since the gas is entrained within the liquid films of the foam. This leads to a much more efficient use of carbon dioxide.

Foam-bed reactors for chemical-physical treatment of gases are known. Owing to the enhanced mass transfer capacity and low pressure drop of these systems, efficient contaminant removal of gas streams is possible. In these reactor systems, components of the gas move from the gas bubbles to the thin liquid films, followed by a chemical reaction in the liquid phase of the foam [12–14]. Foam-bed reactors are also used as bioreactors for contaminant removal from gas streams [15–20]. In these systems the pollutant-degrading microorganisms are grown in the thin liquid films in the foams. The performance of foamed emulsion bioreactors (a type of foam-bed bioreactor, where organic phase emulsion and pollutant-degrading microorganisms are foamed and the resulting gas bubbles contain the pollutant) exceed the performance of any other reactor system for air pollutant control [16]. These reactors rely on high density cultivation of microorganisms in order to reach high removal rates, increased gas-liquid interfacial area provided by the foams, and elimination of clogging problems compared to immobilized beds [16].

For the design of a foam-bed reactor, foam formation and foam break-up are fundamental. The properties of the formed foams are dependent on the gas distributer design, as it influences the bubble size of the foam. More specifically, if the gas distributor creates smaller bubbles, more stable and wet foam will be formed [21]. In contrast, larger bubbles will rise faster to the surface and collapse more rapidly [22]. Besides gas distribution, also the gas flow rate and surfactant concentrations play key roles in determining the foam properties.

In order to support maximal microalgae production in a foam-bed photobioreactor, the CO_2 supply must be sufficient. For this reason, the foam bubbles have to be broken in order to refresh the entrapped gas. Ideally, a foam bubble ruptures just before the carbon dioxide is depleted, and/or oxygen builds up to inhibiting levels. For inducing foam break-up, various methods have been reported in literature. The simplest method is spontaneous, self-break-up of the foam [18]. This method is based on natural destabilisation mechanisms, including foam drainage, coalescence, and coarsening. Liquid drainage from the foam is caused by gravity and causes thinning of the liquid films between bubbles. This thinning can lead to film rupture, resulting in coalescence of the neighbouring bubbles. Coarsening takes place due to gas diffusion from the small bubbles to the larger ones, due to the pressure difference inside them. All these processes can result in bubble growth and eventually to foam destabilisation [23].

Another, commonly used method is the use of chemical antifoams or defoamers [12,24–27]. These methods are efficient in destroying and controlling foams, but in several cases they cannot be used. For instance, the antifoaming agents can adsorb to cell surfaces and consequently inhibit growth of the microorganism, they can cause contamination, reduce mass transfer, and exhibit adverse effect on downstream processing of the product (e.g. separation, purification) [28–30]. Foam breaking by mechanical means is free of such problems, however, substantial power is required for the operation of the devices [30]. Mechanical methods are mainly based on shear forces [28], or on centrifugal forces [31], and they include spraying liquid on the foam [16,20,32] or breaking the foam by rotating parts [21,29,33]. Mechanical and ultrasonic vibrations are also often used [28]. Compared to chemical or mechanical foam breaking methods, a foam eliminating net [34] can reduce the operational costs and the contamination of the media can be prevented. Together, these studies highlight the variety of possibilities for foam break-up, which is a crucial factors in establishing and further improving foam-bed reactor systems.

This study aims to develop a liquid foam-bed photobioreactor for microalgal growth with continuous foam formation and foam break-up. For that, optimal foam formation settings were experimentally defined and also an efficient foam break-up method was developed. Furthermore, the possibility of microalgal growth in protein stabilised foams was evaluated. In order to assess whether microalgae are able to withstand the shear stresses involved in foam formation and break-up, the biomass concentration and the quantum yield of photosystem II photosystem were monitored.

2. Materials and methods

2.1. Experimental set-up

The experimental set-up consisted of a foam-bed photobioreactor, a foam breaker column and a recirculation pump (Fig. 1). The foam-bed photobioreactor itself consisted of a flat panel reactor chamber and an adjacent water chamber for temperature control. The reactor had a height of 40 cm, and a width of 20 cm. The reactor had a depth of 2.7 cm and the reactor volume was approximately 2.2 L. The reactor had round edges on the top in order to avoid foam to accumulate and remain there. The reactor plates were made of glass and the reactor fame was made of polyether ether ketone (PEEK). The glass plates were treated with a solution of concentrated sulfuric acid (98 wt%) and hydrogen peroxide solution (30 wt%) in a 3:1 ratio. This solution cleaned the glass surface and rendered it hydrophilic; a contact angle of 12° was reported [35]. The cleaned glass plates were washed with distilled water. The contact of the foam with hydrophilic walls, as opposed to hydrophobic surfaces, had a positive effect on foam stability inside the reactor, enabling faster foam rise and reducing the extent of coalescence at the walls.

The inlet gas was composed of 5.5 v/v% carbon dioxide in nitrogen gas and was supplied with a total flow rate of 614 NmL min^{-1} by mass flow controllers (Brooks Instrument B.V. Model 5850S). This gas was filtered with 0.2 μm filters (Whatman Polyvent 500) prior to entering the reactor. The filtered gas was distributed through a stainless steel gas distributor with small conical holes (30 μm and 100 μm hole diameter on the top and the bottom of the cone, respectively). The gas distributing plate was placed on the bottom of the reactor, enabling bubble formation over 40% of