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Research Paper

Mathematical modelling of flat plate biofilm photobioreactors with circular and rectangular configurations

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Flat plate photobioreactors (FPPBRs) using bacterial biofilm have gained much recent attention due to operational ease, improved light conversion efficiency and reduction of process cost, particularly in hydrogen production. In this study, two comprehensive mathematical models, one explaining the dynamics of a batch type FPPBR used for the development of biofilm and the other a deterministic model (both temporal and spatial) to predict the performance of a continuous FPPBR using *Rhodopseudomonas* sp. have been developed for both circular and rectangular configurations. The system equations have been solved using MATLAB 2013. From batch studies, the maximum specific growth rate and half saturation constant for the microorganism have been determined to be 0.07 h^{-1} and 1.946 g l^{-1} respectively. An “Instantaneous attachment and proliferation” mechanism has been proposed to explain the behaviour of biofilm right from the early stage of attachment to the reversal from attached to planktonic state. The flow patterns of substrate medium through the biofilm have been generated using COMSOL Multiphysics software. From the perspective of the hydrogen yield, the models predict that the FPPBR geometry plays a crucial role by demonstrating the superior performance of the circular reactor in comparison to the rectangular counterpart. It is expected that the mathematical models developed here will help in the design, scale-up and control of FPPBRs to be used particularly for hydrogen production using suitable microorganisms.

1. Introduction

Photobioreactors (PBRs) have been exclusively used for bioprocesses using phototrophic organisms, namely, algae, cyanobacteria, purple non-sulphur bacteria (PNSB), etc. Stirred tank (Berberoglu, Yin, & Pilon, 2007; Skjanes, Knutsen, Kallqvist, & Lindblad, 2008), tubular (Dasgupta et al., 2010; Molina, Fernandez, Acien, & Chisti, 2001), vertical-column (Eroglu, Aslan, Gündüz, Yücel, & Türker, 1999; Janssen, Tramper, Mur, & Wijffels, 2003; Xu et al., 2002), flat plate (Endres, Roth, & Brück, 2018; Koller, Löwe, Schmid, Mundt, & Weuster-Botz, 2017; Tamburic, Zemichael, Crudge, Maitland,

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Nomenclature

a	Surface area covered by each attached *Rhodopseudomonas* sp. cell (m^2)
C_P	Concentration of product (H_2) (g l^{-1})
C_S	Concentration of substrate (Malic Acid) (g l^{-1})
C_{S0}	Initial concentration of substrate (Malic Acid) (g l^{-1})
C_X	Concentration of biomass (*Rhodopseudomonas* sp.) (g l^{-1})
C_{X0}	Initial concentration of biomass (g l^{-1})
C_{Xb}	Concentration of biomass in the biofilm (g l^{-1})
C_{Xbf}	Concentration of Biomass in the biofilm achieved in the batch reactor (g l^{-1})
d	Diameter of a single *Rhodopseudomonas* sp. cell (μm)
D_e	Effective diffusion coefficient (m^2 s^{-1})
D_k	Knudsen diffusion coefficient (m^2 s^{-1})
ε	Porosity
FPPBR	Flat plate photobioreactor
FPPBBR	Flat plate photo bio-bubble reactor
K_I	Light inhibition constant of cell formation (m^2 W^{-1})
K_{PI}	Light saturation constant of product formation (W m^{-2})
K_{pI}	Light inhibition constant of product formation (m^2 W^{-1})
K_S	Half-substrate saturation constant (g l^{-1})
K_{XI}	Light saturation constant of cell formation (W m^{-2})
N	Cell number concentration (cells μl^{-1})
N_L	Number of biofilm layers
PBR	Photobioreactor
PNSB	Purple non-sulphur bacteria
r	Radial distance from the edge of the circular plate photobioreactor (m)
R	Radius of the circular flat plate photobioreactor (m)
S	Surface area of flat plate photobioreactor (m^2)
σ	Constriction factor
Th	Biofilm thickness (μm)
Th_f	Biofilm thickness achieved in the batch reactor (μm)
τ	Tortuosity
u	Superficial velocity of culture medium (m s^{-1})
μ	Initial specific growth rate (h^{-1})
$\mu_{\max}$	Maximum specific growth rate (h^{-1})
V	Working volume of culture medium (l)
V_a	Volume of abiotic phase (l)
V_b	Volume of biotic phase (l)
x	Axial distance from the edge of the rectangular plate photobioreactor (m)
$Y_{P/X}$	Yield of product in terms of biomass (g [Product] g^{-1} [Biomass])
$Y_{X/S}$	Biomass yield coefficient (g [Biomass] g^{-1} [Substrate])

& Hellgardt, 2011) and flat plate photo bio-bubble reactor (FPPBBR) (Pradhan, Bhattacharjee, Mitra, Bhattacharya, & Chowdhury, 2015) types are some of the usually practised configurations of PBRs. In PBR design, the proper distribution and conversion efficiency of light are key factors besides other conventional reactor design criteria, namely, uniform stirring, availability of high surface area for interphase transfer of substrates and metabolites etc. From the literature review, it is evident that tubular and vertical column PBRs suffer from problems regarding scale up (Molina et al., 2001) and small illumination area (Miron, Gomez, Camacho, Molina, & Chisti, 1999) respectively. On the other hand, Flat plate photobioreactors (FPPBRs) have been reported to offer better control and acceptable photosynthetic efficiency (Hu, Gutermann, & Richmond, 1996; Richmond, 2000) due to their high surface to volume ratio (Akkerman, Janssen, Rocha, & Wijffels, 2002) and shorter light penetration length; they are also a cheaper alternative than the aforementioned configurations (Lehr & Posten, 2009). Along with the use of suspended culture, researchers have also used attached biofilms in FPPBRs. Through the employment of biofilm, cost incurred in the downstream processing, i.e., the separation of biomass from the products and unconverted substrate existing in the extracellular medium, is reduced (Gross & Wen, 2014; Irving & Allen, 2011). Attached biofilms in FPPBRs have been widely employed for harvesting microalgae (Christenson & Sims, 2012; Genin, Aitchison, & Allen, 2015; Gross & Wen, 2014; Johnson & Wen, 2010; Li, Suwanate, & Visvanathan, 2017; Liu et al., 2013; Ozkan, Kinney, Katz, & Berberoglu, 2012; Tao et al., 2017; Zhuang, Hu, Wu, Wang, & Zhang, 2014). Mathematical models for the microalgal FPBRs using biofilm have also been reported from the perspective of growth kinetics (He et al., 2016; Kandilian, Tsao, & Pilon, 2014; Koller et al., 2017; Li et al., 2017) and trajectories of particles and flow using a computational fluid dynamics (CFD) approach (Zhang et al., 2013). Several studies on FPPBRs using biofilms of photoheterotrophic bacteria have also been reported (Adessi, Torzillo, Baccetti, & De Philippis, 2012; Kernan, Chow, Christianson, & Huang, 2015; Wu, Hay, Kong, Juan, & Jahim, 2012). Among different solid matrices used for the development of phototrophic bacterial biofilm, the performance of transparent glass plates (Tsygankov, Hirata, Miyake, Asada, & Miyake, 1994; Zagrodnik, Seifert, Stodolny, & Laniecki, 2015; Zagrodnik, Thiel, Seifert, Włodarczak, & Łaniecki, 2013) appears interesting. This type of reactor design facilitates the uniform distribution of light and can reduce the chance of detachment of biofilm from the solid matrix. As reported by Zagrodnik et al. (2013) the yield of product (biohydrogen) obtained from this configuration is higher than that obtained using tubular reactors using immobilised forms of the same bacterial strains (Eroglu et al., 1999). However, the research studies on the semi-continuous and continuous FPPBRs using the glass plates (Zagrodnik et al., 2015; Zagrodnik et al., 2013) have been conducted only on laboratory-scale using 200 ml and 230 ml reactors respectively. Although it is understandable that the mathematical modelling can play a vital role for scaling-up to larger reactors and control of reactors on any scale, no such effort for FPPBRs using glass plates has been reported. It has