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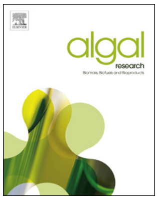

Dynamic modelling of microalgae cultivation process in high rate algal wastewater pond

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ABSTRACT

In this work, a comprehensive dynamic mathematical modelling to simulate the production of microalgae in a high rate algal pond (HRAP) is attempted. A synergetic algal–bacterial system comprising various interrelated biological and chemical system processes is presented. The dynamic behaviour of HRAP system is studied by solving mass balance equations of different components which account light intensity and gas–liquid mass transfer. The model predictions are compared with the previously reported studies in the literature. The influence of kinetic and operating parameters, including the supply of CO_2, the maximum growth rate, pond depth and dilution rates, on the pond performance are evaluated. The sensitivity analysis of important process parameters is also discussed in this study. The developed model, as a tool, can be used to assess the factors that affect the pond performance criteria, including algal productivity and the dynamics of nutrient requirements.

1. Introduction

High rate algal ponds (HRAPs) for the treatment of wastewater obtained from municipal, industrial and agricultural sources are a potential technology to be used in cultivating algal biomass, because there is a growing interest in the development of effective and efficient wastewater treatment methods for domestic and industrial wastes with the concurrent need for alternative sources of energy and water. HRAPs are preferred among stabilization ponds because of its simplicity and economy [1]. HRAPs can serve as a potential nutrient provider for cultivating algae, in addition to wastewater treatment, with the possibility of reducing the cost of sustainable commercial production of biofuels from microalgae. The key characteristic feature of HRAPs is the symbiotic relationship between the photoautotrophic algae and the heterotrophic bacteria. Microalgal growth generates oxygen in the pond systems and thus facilitates dissolved oxygen concentration which in turn is required by aerobic bacteria for both oxidation and nitrification processes. Microalgae also consumes CO_2 produced by the bacteria during the mineralization of pollutants. Integrating wastewater treatment with algal biomass production has the potential to reduce oxygen cost, mitigates CO_2, and enhances nutrient assimilation and stripping processes. These processes stabilize wastes, facilitate the sedimentation process, and promote constructively algal growth coupled with driving the aerobic wastewater treatment synergistically [2]. Thus, the use of algal–bacterium consortia has the potential to increase the economic feasibility and effectiveness of microalgae biomass production. Despite numerous benefits, the lack of knowledge on the design and operational parameters coupled with the management of microalgae–based processes has limited their widespread implementation. This is because of various complex physicochemical and biological processes that determine the efficiency of the pond characterization and the performance in HRAPs. These processes are: nutrient requirements for algae growth; dissolved oxygen that induces bacterial growth and biochemical oxidation of organic matters; pH that controls the rate of distinctive biochemical process; a temperature that controls the rate of biochemical reactions and transformations; light input for photosynthesis and hydraulic behaviour that govern the process of mixing in the pond [3]. To understand the process holistically and improve the efficiency of HRAPs from the standpoint of hydrodynamics through chemical and biological interactions, several studies using modelling approach have been attempted in the literature.

Buhr and Miller [4] have described a process modelling of biochemical interaction and symbiotic relationship of photosynthetic microalgae, and heterotrophic bacteria, and validated the HRAP process experimentally. The hydrodynamics of the system was considered as a series of continuous stirred tank reactors (CSTR) units with recirculation. The growth of both algae and microorganism was described by Monod kinetics. However, the effects of algal respiration and gaseous transformations in the pond are not being considered. Fallowfield et al. [5] have studied the validation of algal pond models to estimate net productivity, oxygen evolution and wastewater treatment capacity. Jupsin et al. [6] have presented a mathematical model of HRAP based on River Water Quality Model (RWQM) that was capable of simulating

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HRAP's operating cycles considering sediment oxygen demand. Grobbelaar et al. [7] have developed algal productivity models in terms of temperature and incident light. Recently, Yang [8] has extended the mathematical models developed by Buhr and Miller [4] to estimate the effect of pH, dissolved oxygen and substrate concentrations on CO_2 supply and utilization. He has considered the growth kinetics, thermodynamics and gas mass transfer, and the absorption of gases such as oxygen and ammonium.

The objective of the present study is to develop a dynamic model for microalgae production in HRAP under different operational conditions. The present model involves the prediction of biomass concentration, dissolved oxygen, total inorganic carbon and total inorganic nitrogen concentrations. The model also considers the effects of sparging CO_2 with congruent sensitivity analysis of some other important parameters. The modelling methods used in this study are mostly drawn from the previous work of Buhr and Miller [4] and Yang [8]. However, there are some differences between this work and the previous literature work [4,8] to build the present model in a simple way. These differences are following. pH limitation in the presented model is considered as the method described by James et al. [9]. This method involves the functional form of the relation between pH and dissolved CO_2 derived from chemical equilibrium theory. CO_2 mass transfer coefficient, k_{lg,CO_2} is calculated as based on the oxygen mass coefficient, k_{lg,O_2} which is considered as a constant value in this work; Yang [8] used gPROMS as process modelling software to solve model equations, whereas, in this work model equations are solved using Matlab tool. The developed model as a tool can be employed to determine the pond performance criteria, including maximum algal productivity and nutrient requirements. Using prediction model, the effect of kinetic and operating parameters, such as supply of CO_2, the maximum growth rate, pond depth and dilution rate, on the pond performance is presented. The sensitivity analysis of some important process parameters is also discussed in this study.

2. HRAP model development

The schematic algal pond is represented as shown in Fig. 1 to depict the synergetic algal–bacterial system comprising various interrelated biological and chemical processes. Wastewater can be described as a mixture of dissolved oxygen, dissolved inorganic nutrients and biological oxygen demand (BOD). pH of wastewater is an influential parameter that governs the biochemical transformation and substance balance in the reactor. The HRAP model also considers gaseous CO_2 as a carbonaceous source. The assumptions considered in developing the models in this study are: (i) the pond is modelled as completely stirred tank reactors (CSTR); (ii) algal specific growth rate is a function of light intensity, total dissolved CO_2 and total inorganic nitrogen; (iii) exchange of O_2 and CO_2 between the pond and the atmosphere is not included; (iv) evaporative losses are not considered due to lower water loss. It is noted in the literature that other nutrients such as phosphorus and micronutrient are not considered to be the limiting factor because these compounds are usually highly available in wastewater [8,10]. Thus, in the present study, this effect has not been explicitly considered with the assumption that the metabolism of the microbial consortium are not limited or inhibited by these compounds. Also, the ammonia volatilization and the removal of phosphorus by chemical precipitation occurring due to high pH (9–10) and temperature are not considered in the present study.

The model that describes the growth of photosynthetic microalgae in HRAP is a set of nonlinear differential equations derived from mass balance equations for both liquid and gaseous species transformations.

The average light intensity in the pond can be expressed in terms of concentration and depth of the pond (z) at a particular time using the Beer–Lambert's law as [8]

$$I_a = \frac{1}{z}\int_0^z I_0 \exp(-K_e z)\mathrm{d}z \tag{1}$$

where z is the depth of the pond, K_e is the extinction coefficient related to the algal concentration, X_A expressed as a simple linear relationship

$$K_e = K_{e_1} + K_{e_2} X_A \tag{2}$$

here K_{e_1} and K_{e_2} are constants and I_0 is the maximum surface light intensity during the photoperiod (5.00–19.00 h).

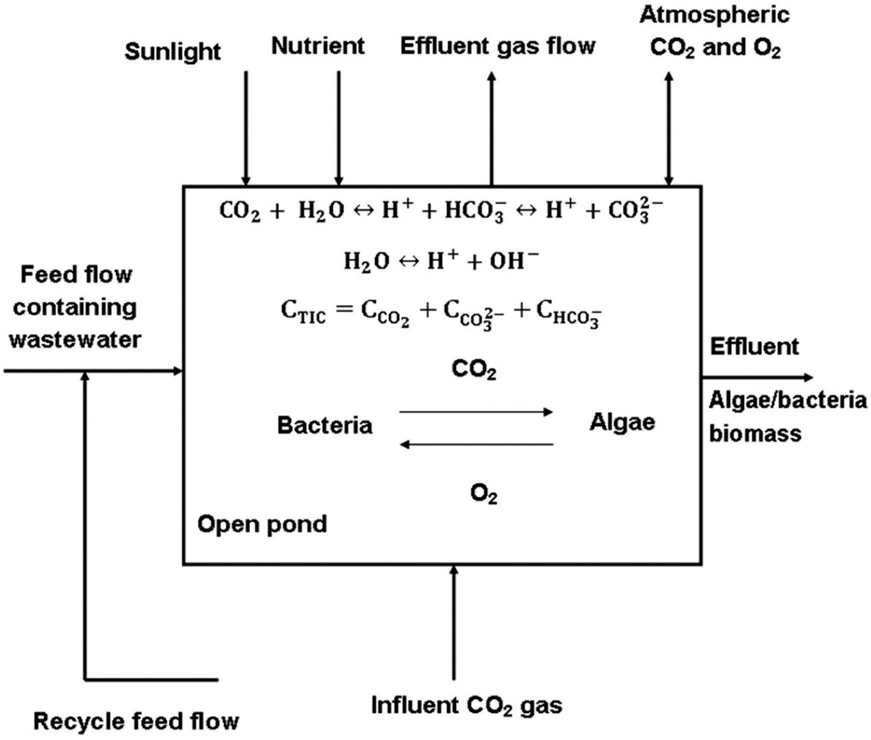

Fig. 1. Schematic diagram of the algal pond system with recirculation [8].

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