Renewable and Sustainable Energy Reviews 97 (2018) 233–258

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Model development for the growth of microalgae: A review

Pooya Darvehei[a], Parisa A. Bahri[a,*], Navid R. Moheimani[b]

[a] School of Engineering and Information Technology, Murdoch University, Murdoch 6150, Western Australia, Australia
[b] Algae R & D Centre, Scool of Veterinary and Life Sciences, Murdoch University, Murdoch 6150, Western Australia, Australia

ARTICLE INFO

Keywords:
Modelling
Microalgae
Outdoor cultivation
Growth

ABSTRACT

Despite attracting many attentions in the past decades, microalgal cultivation still faces many challenges for industrialisation. Growth, as one of the most crucial characteristics of a microalgal cultivation system, has been a significant subject for modelling. This paper presents a review of available models in the literature regarding the effect of process parameters such as light, temperature, nutrients, oxygen accumulation, salinity, and pH and carbon, on the growth rate of microalgal cells to understand their application in large-scale microalgal production. The existing models are classified based on the process conditions or parameters they considered in the formulation, and where multiple parameters were included the model was broken into separate functions, and each function was presented in the associated section. The most prominent result of this review is the huge gap between models and their validity for outdoor systems. It seems that to find suitable models for a real condition application, a new pathway is needed where models are developed based on the behaviour of the outdoor cultures in long-term. There are some effects such as adaptation which are difficult to model in short-term modelling while if the long-term approach is used these effects can be considered negligible. These characteristics of outdoor cultivation help in simplification of the models and less struggle in their validation. Moreover, using saline water is an effective way to improve the viability of algal production which requires understanding the relationship between growth and salinity of the medium. Such models are missing in the literature.

1. Introduction

Microalgae are unicellular photosynthetic organisms with multiple beneficial characteristics that can potentially be used to overcome some of today's issues. They have high carbon dioxide fixation rate which can be used in flue gas treatment and the emission rate of this gas [1–3]. They use nutrients such as phosphorus and nitrogen which can be provided from industrial or municipal wastewater, making them a suitable option for waste water treatment [4–6]. Moreover, in case of marine microalgae there is no need for potable water since they can grow in saline water which facilitates the provision of water for large scale cultivation [7]. Another key attribute of microalgae is their low land requirement. They use significantly less area to grow compared to other crops due to their high photosynthetic efficiency per area [8–10]. Microalgae can be cultivated even in non-arable lands; thus, they do not impact agricultural land availability [2,8,11]. In addition to these traits, microalgae are capable of producing multiple valuable products which can be used in various industries such as food, cosmetics, pharmaceutical, etc [3,12–14]. One of the products that have attracted many attentions is biofuel. Algal biofuel is produced from the lipid stored in algal cells [15] which is extracted and converted to biodiesel. High productivity, being renewable, carbon emission mitigation, compatibility of algal biofuel with current diesel engines, and its low pollution are just a few of many advantages of using microalgae as a source of biofuel [3,16–18]. However, production of algal biofuel is still in the research stage and has not been fully commercialised yet [19].

Various systems are common for the algal cultivation of which closed photobioreactors (PBR), and open ponds are used more frequently. While construction and operation of open ponds are easy and relatively inexpensive, they have some disadvantages such as poor illumination and loss of water due to evaporation [20]. Also compared to closed PBRs, open ponds have the high risk of contamination which can directly affect production costs and annual productivity [21].

On the pathway to mass production, many process issues need to be resolved, and the growth and biomass production of algae should be well understood and optimised to make efficient operation and process control viable [22]. An important step for this purpose is mathematical modelling in which the effect of each process condition (temperature, light, etc.) is mathematically related to the key production parameters (growth rate, productivity, etc.) so that the effect of every change in the process conditions can be observed without the necessity to experimentally test the effects separately. Modelling kinetic of algal growth is

* Corresponding author.
E-mail addresses: p.darvehei@murdoch.edu.au (P. Darvehei), P.Bahri@murdoch.edu.au (P.A. Bahri).

https://doi.org/10.1016/j.rser.2018.08.027
Received 21 March 2018; Received in revised form 27 July 2018; Accepted 20 August 2018
1364-0321/

vital for both estimation and optimisation of production parameters and control of process conditions which is of great importance in the industrialisation of algal biofuel production. For a model to be reliable, all the influential process conditions should be included in it which is difficult but crucial to do. Many process conditions influence the growth of microalgae and to control and optimise the industrial production of algal biofuel, an accurate mathematical model is vital. A successful model should include the effects of all parameters and their contribution, and when it is joint with reactor model should be able to predict the performance and productivity of a cultivation system for different operating conditions.

This paper presents a review of the existing models and how their formulations evolved over time to become more accurate. Although all the current models are listed in the tables to show this evolvement; only the most prominent models have been discussed and compared. Finally, the effectiveness of current models for large-scale production is discussed to elaborate a pathway to improve modelling approaches and make the models more applicable in real conditions. While many of these models have been reviewed to see their performance in laboratory scale, the novelty of this study is in two folds: (1) understanding how the current models can be adapted for use in large-scale production of microalgae, and (2) realising the gap in research regarding modelling the simultaneous impact of various factors such as salinity, light, and temperature.

2. Effective process conditions

In the past century, many studies were conducted to understand the impact of each process parameter on the growth and productivity of algal cultures. The parameters that are discussed in this review are light, temperature, nutrients, pH, salinity, and dissolved oxygen. The effects of these parameters have been studied through many experiments and many models have been suggested, of which a summary of prominent ones can be found here.

2.1. Light

Algae use light as a source of energy for photosynthesis, and therefore it is the most important parameter in the modelling of microalgal growth. Microalgal cells experience three light zones based on the intensity of the light (See Fig. 2): (1) photolimeted, (2) photosaturated, and (3) photoinhibited zone. A common phenomenon inside a turbid media like algae culture is light attenuation, where light intensity decreases as it goes deeper into the media [23] due to absorption of light by cells, and as the photons penetrate into the culture, more of them are absorbed [24]. To show this effect, usually Beer-Lambert Law is used which suggests that light intensity exponentially decreases with depth [25–27].

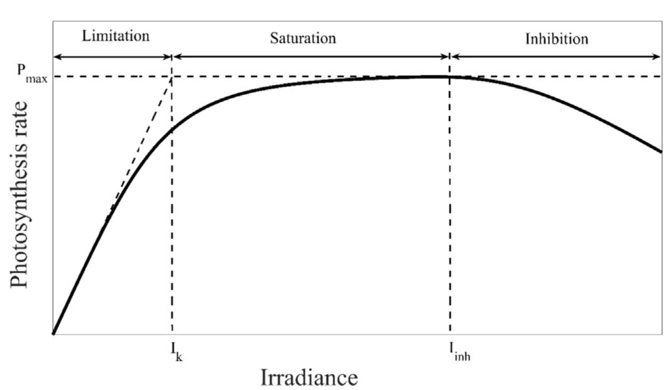

Fig. 1. A schematic of PI curve showing three light regions: (1) light limited, (2) light saturated, and (3) light inhibited.

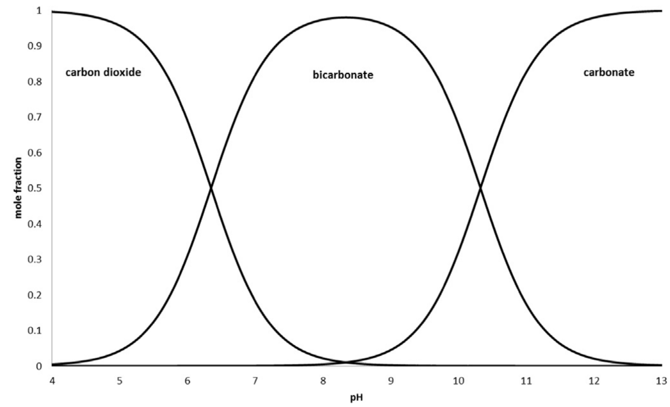

Fig. 2. Distribution of inorganic carbon forms with pH.

$$I = I_0 e^{-kz} \tag{1}$$

Where I is light intensity, I_0 is light intensity entering the media perpendicular to surface, z is depth, and k is attenuation rate. Although this relation is used widely, researchers have used different definitions for k and how it is calculated. Some researchers described it as a linear function of biomass concentration [28] or chlorophyll concentration [29], while others related k to both chlorophyll as well as biomass concentration in the media and even took into account a constant which describes the behaviour of the culture without any cells [25]. Sukenik et al. [30] assumed light attenuation rate to be a linear function of just chlorophyll amount while this dependency varies for different wavelengths. Despite its popularity, Beer-Lambert Law is based on the assumption that light is not scattered in the media which is not correct when it comes to microalgal cultures. Therefore, some researchers proposed models taking into account light scattering in order to overcome this issue [31,32].

Another factor that plays a vital role in the light exposure of algae is hydrodynamics of the culture, and how cells move within the media as when they are closer to the light source, they will be subject to more light and vice versa. This effect is critically important to determine how much light a cell may absorb and from which photosynthesis and growth rate can be calculated. Most attempts in modelling the effect of light focused on equations to describe photosynthesis and light relationship (commonly presented in form of PI curve) [33]. Photosynthesis in this relationship is expressed in various forms such as electron transfer rate (ETR), oxygen evolution, and carbon dioxide consumption, and sometimes is replaced by specific growth rate. Despite the differences between these forms, all result in the same shape of PI curve [22,34,35].

Many models have been suggested in the last few decades, a summary of which can be seen in Table 1, but here we are reviewing the details of the most prominent models. One of the earliest models that can be found in the literature was suggested by Baly [36] and later used by Tamiya [37], reporting that based on their experiments this function had approximately the same shape as their results. This equation is similar to the renowned equation proposed by Monod [38] for effect of substrates on growth of bacteria which is widely used for microalgal growth as well. In this equation, if substrate concentration is replaced by irradiance, it results in Baly and Tamiya's equation. This equation contains two key elements: 1) the maximum specific growth rate (μ_{max}) which indicates the maximum achievable specific growth rate when culture is in light saturated condition, 2) light half-saturation constant (K_I) at which the specific growth rate is half its maximum value. Parameter K_I is often compared to light saturation irradiance (I_k), which is the irradiance that defines light saturated region (Fig. 1). In this model the difference between two parameters are significant as K_I is associated with half the amount of maximum specific growth rate while at I_k the μ almost reaches its maximum value. This difference is