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Research review paper

Dual purpose microalgae–bacteria-based systems that treat wastewater and produce biodiesel and chemical products within a Biorefinery

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ABSTRACT

Excess greenhouse gas emissions and the concomitant effect on global warming have become significant environmental, social and economic threats. In this context, the development of renewable, carbon-neutral and economically feasible biofuels is a driving force for innovation worldwide. A lot of effort has been put into developing biodiesel from microalgae. However, there are still a number of technological, market and policy barriers that are serious obstacles to the economic feasibility and competitiveness of such biofuels. Conversely, there are also a number of business opportunities if the production of such alternative biofuel becomes part of a larger integrated system following the Biorefinery strategy. In this case, other biofuels and chemical products of high added value are produced, contributing to an overall enhancement of the economic viability of the whole integrated system. Additionally, dual purpose microalgae–bacteria-based systems for treating wastewater and production of biofuels and chemical products significantly contribute to a substantial saving in the overall cost of microalgae biomass production. These types of systems could help to improve the competitiveness of biodiesel production from microalgae, according to some recent Life Cycle Analysis studies. Furthermore, they do not compete for fresh water resources for agricultural purposes and add value to treating the wastewater itself. This work reviews the most recent and relevant information about these types of dual purpose systems. Several aspects related to the treatment of municipal and animal wastewater with simultaneous recovery of microalgae with potential for biodiesel production are discussed. The use of pre-treated waste or anaerobic effluents from digested waste as nutrient additives for weak wastewater is reviewed. Isolation and screening of microalgae/cyanobacteria or their consortia from various wastewater streams, and studies related to population dynamics in mixed cultures, are highlighted as very relevant fields of research. The species selection may depend on various factors, such as the biomass and lipid productivity of each strain, the characteristics of the wastewater, the original habitat of the strain and the climatic conditions in the treatment plant, among others. Some alternative technologies aimed at harvesting biomass at a low cost, such as cell immobilization, biofilm formation, flocculation and bio-flocculation, are also reviewed. Finally, a Biorefinery design is presented that integrates the treatment of municipal wastewater with the recovery of oleaginous microalgae, together with the use of seawater supplemented with anaerobically digested piggery waste for cultivating *Arthrospira* (*Spirulina*) and producing biogas, biodiesel, hydrogen and other high added value products. Such strategies offer new opportunities for the cost-effective and competitive production of biofuels along with valuable non-fuel products.

Contents

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1. Introduction

1.1. The strategy of producing biodiesel from microalgae

The International Panel on Climate Change has concluded that our planet's sustainability relies heavily on our capacity to generate enough renewable clean energy to satisfy future generations' demands (IPCC, 2007). Thus, many current sustainability issues, such as greenhouse gas emissions, climate change, fossil fuel depletion and energy security, can be mitigated (Subhadra, 2010). However, there are many practical challenges associated with the large-scale production of renewable energy. The primary constraint in future energy scenarios is the land and water resources required to harvest, grow or process the potential feedstock (Subhadra, 2011).

Using oleaginous microalgae to produce biodiesel has several advantages for producing renewable energy, making it the most promising biofuel option. Among the most important advantages are: a) oleaginous microalgae have an oil yield much higher than that of oleaginous plants; b) this biofuel has a small ecologic footprint because it requires less surface area compared to conventional crops; c) some oleaginous microalgae can be cultivated in seawater or brackish water (Table 1). Additionally, the fresh water species can be cultivated in municipal wastewater, avoiding competition for fresh water that is used to irrigate crops; d) microalgae are excellent at capturing CO_2, fixing 183 tons per every 100 tons of produced biomass; and e) biodiesel from microalgae is one of the very few biofuels with negative CO_2 emissions (-183 kg CO_2 MJ^{-1}) (Chisti, 2007, 2008).

Furthermore, there have been substantial efforts worldwide to produce renewable biofuels, resulting in an overwhelming amount of information in this field. Some recent reviews have offered an in-depth discussion of several issues within this topic (A. Singh et al., 2011; Greenwell et al., 2010; Lee, 2011; Loera-Quezada and Olguín, 2010; Mata et al., 2010; McGinn et al., 2011; Norsker et al., 2011; Park et al., 2011; Schenk et al., 2008; Singh and Olsen, 2011; Wijffels et al., 2010) and are therefore outside the scope of this review.

In addition to the interest expressed by academic and government entities in renewable energy technologies, private entities have also been created to explore these alternative strategies (Christenson and Sims, 2011). However, significant obstacles (Lam and Lee, 2012; Singh and Gu, 2010; Tredici, 2010) still need to be overcome before microalgae–based biofuel production becomes cost-effective and can impact the world's supply of transport fuel. Several recommendations have been made recently to overcome the economic constraints of microalgae production on a large scale. Among the most relevant

Table 1
Oil content and lipid productivity of some microalgae species (Loera-Quezada and Olguín, 2010).

Species	Oil content (% dry weight)	Lipid productivity ($mg\ L^{-1}\ d^{-1}$)	Reference
Parietochloris incisa (f)	60[a]	N.R.	Solovchenko et al. (2008)
Nannochloropsis sp. (m)	60[a]	204	Rodolfi et al. (2009)
Neochloris oleoabundans (f)	56[a]	13.22	Gouveia et al. (2009)
Chlorella vulgaris (f)	~42[a]	12.77	Widjaja et al. (2009)
Crypthecodinium cohnii (m)	41.14[a]	82	Mendoza et al. (2008)
Scenedesmus obliquus (f)	43[b]	N.R.	Mandal and Mallick (2009)
Neochloris oleoabundans (f)	38[c]	133	Li et al. (2008)
Nannochloropsis sp. (m)	28.7[c]	90	Gouveia and Oliveira (2009)
Chlorella vulgaris (f)	27[c]	127.2	Francisco et al. (2010)
Nannochloropsis oculata (m)	30.7[c]	151	Chiu et al. (2009)
Dunaliella (m)	67[c]	33.5	Takagi et al. (2006)
Choricystis minor (f)	21.3[c]	82	Mazzuca-Sobczuka and Chisti (2010)
Chlorella protothecoides (f)	50.3[d]	N.R.	Xiong et al. (2008)
Chlorella vulgaris (f)	21[d]	54	Liang et al. (2009)
Scenedesmus rubescens (m)	73[e]	N.R.	Matsunaga et al. (2009)

(f) = freshwater; (m) = marine; N.R. = not reported.
[a] Cultured under nitrogen starvation.
[b] Cultured under nitrogen deficiency.
[c] Cultured with nutrient sufficiency.
[d] Heterotrophic culture.
[e] Nutrient starvation.