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Review article

Microalgae for biobutanol production – Technology evaluation and value proposition

Tong Kai Yeong[a,1], Kailin Jiao[b,1], Xianhai Zeng[b,c,*], Lu Lin[b,c], Sharadwata Pan[d], Michael K. Danquah[a,**]

[a] Department of Chemical Engineering, Curtin University, Sarawak, Malaysia
[b] College of Energy, Xiamen University, Xiamen 361102, PR China
[c] Xiamen Key Laboratory of High-valued Conversion Technology of Agricultural Biomass, Xiamen University, Xiamen 361102, PR China
[d] School of Life Sciences Weihenstephan, Technical University of Munich, Freising 85354, Germany

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ABSTRACT

The depletion of petroleum and fossil fuels and the escalating problem of climate change motivate and compel an ongoing effort focusing on the development of renewable energy in the form of biofuels. Biobutanol is one such potent biofuel, attributing to similar characteristics as of gasoline, which manifests in easier public distribution based on the current oil and gas infrastructure. Also, the development of the third-generation biofuels sourced from cultivation of microalgae seems an outright promising prospect for renewable energy sources. This is mainly because of its inherent advantages in comparison to the previous methods of biofuel production from crops and plant waste. However, in spite of the ongoing efforts, the research targeting towards biobutanol production utilizing microalgal resources is insufficient. Working on the strengths of both may provide the much needed boost for the thriving biofuel industry, ultimately aiding to cope with global energy demand and reduce CO_2 emissions. In this review, the design and selection of a complete industrial scale biobutanol production plant, using microalgae as the feedstock, have been proposed. Advances in bioprocess technologies for biobutanol production via fermentation and biobutanol recovery methods are described. In addition, comparative analyses of biobutanol versus petroleum diesel and biodiesel, and strategies for biobutanol cum lipid and methane gas manufacturing are also discussed.

1. Introduction

The wide-spread modernization with an ever-increasing population, the hallmark of 21st Century, continues to strain global energy supplies. As petroleum and fossil fuels steadily deplete with concomitant increase in prices, extensive efforts have been made by the scientific community to search for and/or develop alternative sources of energy. To this end, renewable energy in the form of biofuels is being pioneered to meet the energy demands of the present-day society [1]. The escalating problem of global warming, as an assured consequence of greenhouse gas emissions from fossil fuels/petroleum, is also a prime motivator for this progress.

The development of 3rd generation biofuels sourced from cultivation of microalgae is an encouraging prospect for exploiting renewable energy resources. This is primarily because of the associated characteristic advantages as compared to the earlier approaches of biofuel production from crops (1st generation biofuels) and plant waste (2nd generation biofuels) [2]. In contrast to 1st generation biofuels, clearly, microalgae have no competition with agricultural crops for resource and land space allocation. They possess the capability to grow and thrive in different territories as compared to the region-sensitive crops, with significantly swifter harvest cycles [3]. Compared to 2nd generation biofuel materials, the simple structural characteristics of microalgae make them less recalcitrant as a biomass feedstock with simple and benign processing and conversion technologies [4]. These advantages have allowed microalgae to be a prime source for biomethanol, bioethanol, biohydrogen and bio-syngas production [5].

Biobutanol is conceived as a suitable replacement for conventional fuels due to an ensemble of advantages. As a biofuel, it is more effective than biomethanol or bioethanol, because of its higher energy density and its molecular similarity to gasoline. This indicates that it is more readily usable for the in-place fuel engines: either as a blend with diesel

* Correspondence to: X. Zeng, College of Energy, Xiamen University, Xiamen 361102, PR China.
** Corresponding author.
E-mail addresses: xianhai.zeng@xmu.edu.cn (X. Zeng), mkdanquah@curtin.edu.my (M.K. Danquah).
[1] These authors contributed equally to this work.

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(good inter-solubility), or on its own without any modification [6]. The fact that it possess almost half the heat of vapourization of that of ethanol [7], indicates its superiority over either ethanol or methanol, when it comes to engine initiation at subzero temperatures [3]. Furthermore, it has a lower vapour pressure and lower volatility which facilitates easier storage and transport, and subsequently makes it less prone to problems like pipeline rupture, cavitation and vapour lock [8,9]. Besides being used as a fuel, it also has applications as a solvent in food and pharmaceutical industries [10]. Undoubtedly, it possesses a superior application range over other biofuels [11].

In spite of the admirable benefits associated with microalgae and the notable significance of biobutanol, only a limited number of reported work is focused on the fermentation of microalgae biomass to butanol, and most of the reported studies are only confined to the laboratory stage [12–15] with no commercial scale production reflections or appraisals to create a value proposition. To date, there seems to be lacunae in terms of reasonable research targeting the use of microalgae in large-scale biobutanol production. Current major commercial production of butanol is restricted to the oil and gas industry, as crude oil is processed to manufacture various petroleum products. The process initiates with propene which undergoes hydroformylation reaction, and is reduced with hydrogen to produce a mixture of butanol and iso-butanol [16]. The end product typically has a gas stream containing unreacted propylene, propane, unreacted carbon monoxide and hydrogen, resulting in economic deprivation and environmental pollution [17]. The recent instability over oil prices, the growing concerns over the greenhouse gases, and the depleting oil reserves, all have contributed to the relevance and recent surge in biofuel production [9].

Exploiting the scope of renewable energy exploration and environmental protection, several past studies have reviewed the importance of microalgae as a crucial source of biofuel production [4,5,18,19], and the processes and economics of biobutanol production [6,9]. Contextually, the current study will lay a comprehensive review of the potential application of microalgae cultivation to propose an industrialized biobutanol production process. A general approach to the proposed process flow diagram (PFD) of a biobutanol production plant would be classified into two distinct platforms: the first focuses on biomass production from microalgae; while the second focuses on biobutanol production via anaerobic fermentation (Fig. 1).

2. Microalgae feedstock production

2.1. Selection of microalgae with implemented bioengineering

The most desirable choice of microalgae would be the one with an inherently high starch content and productivity. This would be supplemented by nutrient limitation in order to encourage enhanced carbohydrate concentrations in the microalgae. Carbohydrates, which exist mostly as cellulose within the cell wall or as starch in plastids, are the major products of photosynthesis and carbon fixation in the Calvin cycle [20,21]. The absence of any lignin or hemicellulose contents lends precedent to its ease of fermentation in sizeable quantities. The composition of carbohydrates varies between different species of microalgae. Ideally, a strain with the highest concentration of convertible sugars from the cell wall and starch storage, should be selected. Past analyses have shown a list of microalgae strains with their carbohydrate contents [20]. Particularly, *Tetraselmis subcordiformis*, *Chlorella* sp. AE10, *Chlorella vulgaris*, *Chlorella reinhardtii* and *Scenedesmus obliquus* have demonstrated a high carbohydrate content (Table 1) [22–38]. Of these, *C. vulgaris* is notable for its high growth rate and high temperature tolerance in vitro [39]. Indeed, *C. vulgaris* has been used as a satisfactory feedstock for testing biobutanol fermentation in the laboratory [12,15].

2.2. Algae cultivation

Algae can be grown either in open pond systems or closed photobioreactors (PBRs). Prospects and limitations of algae cultivation systems have been evaluated and widely reported [40,41]. Open ponds are generally cheaper and easier to construct, but are susceptible to contaminations that can affect the quantity and quality of biomass and biochemical production capacity. Quality control can be ensured through the use of closed PBR systems. PBR systems minimize contamination with a better control of flow hydrodynamics and bioreaction conditions depending on the type. Hence, an efficient PBR cultivation process for maximizing algae biomass cultivation is dependent on successful implementation in an industrial-scale process, one that is energy efficient and economically feasible. Vertical column and flat-plate PBRs represent the two most viable options for algae cultivation [40–43]. While the vertical column PBRs are inherently batch systems, the flat-plate PBRs are continuous systems with easier construction methodology and lower operating costs. For instance, a combination of

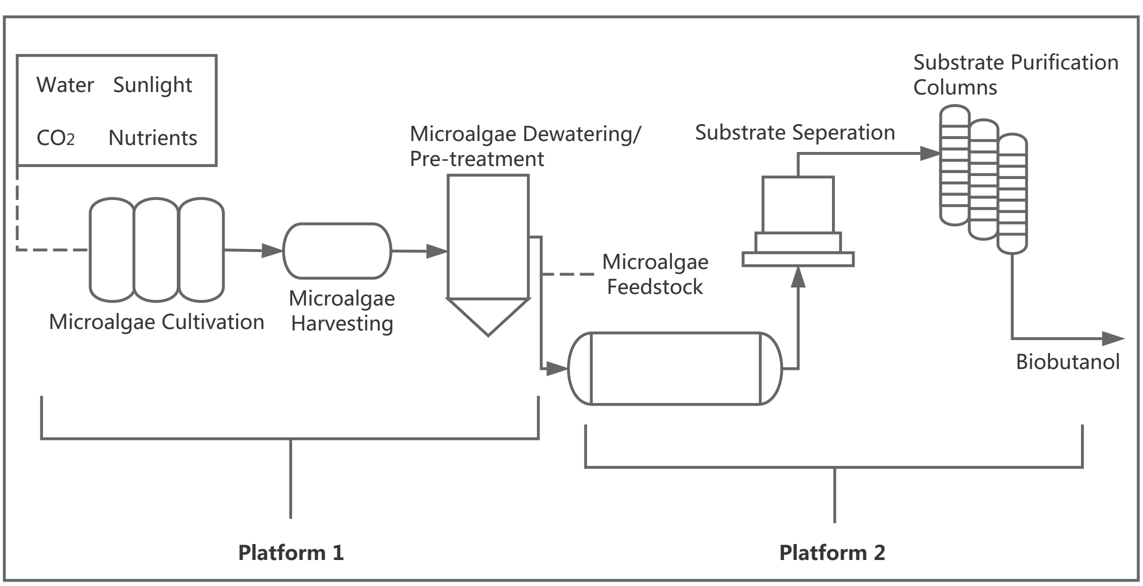

Fig. 1. Simplified process flow diagram of the proposed biobutanol production plant.