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Industrial-scale bioethanol production from brown algae: Effects of pretreatment processes on plant economics

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HIGHLIGHTS

- Industrial scale ethanol production from brown algae was simulated in Aspen Plus v.8.4.
- Two pretreatment processes named simple and combined pretreatment were considered.
- Developed techno-economic models showed the superiority of simple pretreatment.
- The specific economic parameters were investigated.

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ABSTRACT

Brown algae, considered as the third generation biomass, offer several advantages over lignocellulosic biomass. However, the current high cost of seaweed cultivation hampers the industrialization of macroalgae-based biofuel production. The aim of this study is to determine the maximum dry seaweed price (MDSP) as an upper limit for purchasing price of brown algae at bioethanol plant gates. In addition, a minimum ethanol-selling price (MESP) was calculated by considering the state-of-the-art bioethanol production technology and current brown algae-cultivation costs. A new simple pretreatment process was economically validated and compared with the traditional acid thermal hydrolysis known as combined pretreatment. The processes were simulated at the scales of 80,000 and 400,000 ton/year of dry brown algae using the Aspen Plus v.8.4 software, and techno-economic models were developed based on mass and energy balance. MDSP for the simple and combined processes was calculated as 64.6 and 26 $/ton (80,000 ton/year) and 91.3 and 71.5 $/ton (400,000 ton/year), respectively. In addition, MESP for the simple and combined processes was determined as 2.39 and 2.85 $/gal (80,000 ton/year) and 2.08 and 2.33 $/gal (400,000 ton/year), respectively. These results indicate that the simple pretreatment is economically superior to the combined pretreatment. A comprehensive sensitivity analysis showed that seaweed price had the highest impact on MESP, thereby confirming that the cost-effective large-scale seaweed cultivation is the key to the success of macroalgae-based biofuel production.

1. Introduction

Energy supply is a major economic concern worldwide, and thus, has a strong effect on the government long-term policy and decision-making. Fluctuations in oil prices, gradual depletion of fossil fuel sources, and greenhouse gas emissions have stimulated global efforts in finding sustainable and environmentally friendly alternatives for fossil fuels that can satisfy the ever-growing energy requirements. The potential use of seaweeds as a feedstock for biofuel was first studied in the marine biomass program of the U.S. Department of Energy (DOE) in 1968 [1]. Seaweeds are promising biomass feedstock, because they do not possess any of the major drawbacks associated with first- and second-generation biomasses [1,2]. Preliminary feasibility analysis has recently been conducted in Netherlands [3], U.S.A. [4], and Ireland [5]. Macroalgae has been included in a recent report by the International Energy Agency (IEA) [6] and the U.S. Department of Energy's roadmap for algal biofuels [7]. Pilot plant studies on the development of macroalgae as biofuel feedstock are now underway in Asia and Europe.

An analysis performed for the U.S. Department of Energy (DOE) indicated brown algae productivity of 59 dry ton/ha/year and an ideal ethanol yield from brown algae of 0.254 weight (wt) ethanol/wt dry brown algae [3]. Based on these numbers, an optimum bioethanol productivity of 19,000 L/ha/year was estimated [8]. This value is approximately two and five times higher than that for eth-

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anol production from sugarcane and corn, respectively [9]. Currently, the price of seaweed from naturally cultivated resources is high, and this imposes an immense pressure on the industrialization of biofuel production using seaweeds as raw material. However, modern methods of artificial macroalgae cultivation can be employed for cost reduction and improvement of biomass yield and production efficiency.

Despite numerous experimental studies on ethanol production from brown algae, very few studies have been conducted on the economics of industrial-scale production. Furthermore, simulation studies have not been conducted on industrial-scale ethanol production using brown algae. Reith et al. [3] have estimated the preliminary cost for bioethanol production from 100,000 and 500,000 ton of dry laminaria biomass per year, and, based on these data, Roesijadi et al. [10] have determined the maximum seaweed price (MSP) of \$28/dry ton for a 500,000 ton/year plant. However, as their study was based on optimistic design assumptions for future targets and goals, the maximum feedstock price for bioethanol fermentation is likely to be much higher. One of the objectives of this study was to determine the maximum dry seaweed price (MDSP) bound based on the state-of-the-art bioethanol production technology. MDSP defines an upper limit for brown algae purchase in order to have a competitive final ethanol-selling price compared to those produced from other biomass sources. The calculated MDSP could act as a benchmark biomass price facilitated by artificial cultivation procedures for brown algae production.

Based on a comprehensive study on the state-of-the-art technology for ethanol production from brown algae, two biomass pretreatment approaches were simulated using the Aspen Plus v.8.4 software (Aspen Technology Inc., Cambridge, MA, USA). The results of the simulation were used for calculating accurate capital, operating, and utility costs. Then, techno-economic models were developed for the analysis and economic evaluation of the two approaches. The MDSP was calculated for each process. Later, the minimum ethanol selling price (MESP) was determined based on the current cost of brown algae biomass. Finally, a comprehensive sensitivity analysis of different process parameters was performed to identify the bottlenecks and optimum operating conditions of the two pretreatment methods.

2. Seaweed

Seaweed can be a promising bioethanol feedstock because of its fast growth rate, high biomass yield, and superior productivity in comparison to terrestrial crops. A high yield of seaweed is facilitated by lower energy requirements for the production of supporting tissues in the marine environment compared to terrestrial conditions. They are capable of absorbing nutrients over their entire surface area [11] and can save energy due to zero requirements for internal nutrient transport [12]. Growing in the ocean, seaweed does not depend on land availability or fertilizers and irrigation for growth support, which eliminates economic concerns regarding scarcity of fertile land required for food supply. Another advantage of brown algae compared to terrestrial biomass sources is the paucity of lignin-type materials resistant to biochemical conversion during biofuel production.

Seaweed price (i.e., seaweed production cost) is an important factor in the economics of biofuel production plants since the price of a final product is directly related to seaweed price. Although seaweed can be cultivated naturally and artificially, a significant variation exists in the production costs between the two due to the different production practices. Currently, ~90% of the ~1.6 million tons of total dry seaweed harvested worldwide is derived from cultivated sources [4]. Macroalgae cultivation can be performed by offshore and near-shore farming. An extensive discussion of the available technology and methods for cultivation, harvesting, and processing seaweed can be found in the study by McHugh [13]. In the offshore (ocean) farms, seaweed is grown and harvested from submerged supporting lines and buoyancy-control structures covering thousands of hectares and lying 10–30 m below the ocean surface. The plants achieve high growth yields using the unlimited supply of water in the ocean, dissolved carbon dioxide in surface water, and nutrients either upwelled from nutrient-rich ocean water (from 150 to 300 m) or recycled from processing effluents [14]. However, the offshore cultivation method has many operational difficulties, which makes it hard to employ. In contrast, the near shore cultivation methods are expected to have improved economics due to the ease of operation and access. Important examples of the near-shore cultivation systems include *Macrocystis* and *Laminaria*/*Gracilaria* multicrop farming, rope and tidal flat farms, and terrestrial and floating cultivation. Seaweed production costs and respective yields for different seaweed cultivation systems shown in Table 1 indicate that the production cost decreases with the increase of seaweed yield per unit area. The higher cost of the *Gracilaria*/*Laminaria* rope farm is likely a result of a more distant offshore location compared to the other farms.

Table 1
Seaweed yields and production costs of different cultivation systems [14].

System	Yield		Production cost	
	$\frac{\text{ton daf}^{a}}{\text{ha year}}$	$\frac{\text{ton dry}}{\text{ha year}}$	$\frac{\$}{\text{ton daf}^{a}}$	$\frac{\$}{\text{ton dry}}$
Macrocystis, nearshore	50	83	42	25
	34	57	67	40
Gracilaria/laminaria rope farm (offshore)	45	59	147	112
	11	14	538	409
Gracilaria/ulva, tidal flat farm	23	30	28	21
	11	14	44	33
Sargassum, floating cultivation	45	66	37	25
	22	32	73	50

3. Brown algae

Brown algae (class Phaeophyceae) farming is a growing industry worldwide. Brown algae represent the first largest seaweed source with the yearly production of 9.72 million tons (dry weight) in 2004; in comparison, red algae, which are at the second place, produce 3.99 million tons (dry weight) of biomass [4]. The main carbohydrates synthesized by brown algae include laminarin, cellulose, mannitol, alginic acid, and fucoidan. Laminarin $(C_6H_{10}O_5)_n$ is a β-1,3-linked glucan that also contains mannitol. Cellulose, which has the same chemical composition as laminarin $(C_6H_{10}O_5)_n$ represents a linear chain of β(1 → 4)-linked D-glucose units. Mannitol is a sugar alcohol with the chemical formula $C_6H_{14}O_6$. Alginic acid $(C_6H_8O_6)_n$, an anionic polysaccharide composed of mannuronic and guluronic acids, is widely distributed in the cell walls of brown algae. Fucoidan is a sulfated fucan that contains other sugars, such as galactose, xylose, and uronic acid; it mainly consists of sulfated L-fucose, which can be easily extracted from the cell wall of brown algae by hot water [15] or acid solution [16]. The molecular structure of fucoidan differs depending on the algal species [15,17], extraction process [18], season of harvest, and local climatic conditions [16,19]. Although brown algal fucoidans are complex and heterogeneous, recent structural analyses have revealed the presence of ordered repetitive fucoidan units in several species [20]. Unlike microalgae which have high lipid content (up to 50% dry weight) [21,22], lipids in macroalgae typically constitute <5% of the total dry weight [23]. Therefore, biofuel production from seaweed depends on the conversion of carbohydrates