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Coproduct market analysis and water footprint of simulated commercial algal biorefineries

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ABSTRACT

Algal biorefinery-based integrated industrial sector is getting increased attention in United States as a sustainable way of producing biofuel, high value products and feed ingredients. However, coproduct market analysis and water footprint (WFP) of algal biorefineries need to be studied before large scale deployment and adoption of this strategy. This article highlights the coproduct market and WFP analysis of two simulated algal biorefineries. The market analysis of primary product (biodiesel) and coproducts (algal meal (AM), omega-3 fatty acids (O3FA), glycerin) from these biorefineries showed that there is clear market for AM and O3FA up to certain level, there after diversification for other coproducts is desirable. Challenges include, vigorously finding new market and sectors to integrate the products and coproducts. Hence, comprehensive assessment of coproduct market and coproduct diversification among the biorefinery to meet the local needs and to avoid market glut by excessive production of single coproduct is needed. Our analysis also showed the clear advantages for multiproduct paradigm to attain high operational profit and to sustain initial industry developmental phase with clear return on investment. Our WFP analysis showed that algal biodiesel production requires 23–62 L MJ^{-1} of energy produced and our calculations showed that the energy return on water invested (EROWI) for algal biodiesel at different scenarios ranged between 0.042 and 0.016 MJ. Coproducts market analysis and WFP of algal biorefineries with different production scenarios illustrated the new policy and regulatory needs for the sustainable development of an algal biofuel sector to meet liquid fuel needs.

1. Introduction

The alarm over greenhouse gas (GHG) emission-mediated climate change and depletion of traditional fossil fuel sources has prompted several nations to pass legislation designed to help meet the growing demand for liquid transportation fuel with biofuel. However, there is numerous sustainability challenges associated with large scale deployment of biofuel production. The bioenergy production systems can be highly resource-intensive because of the less-dense energy content of biofuel feedstocks compared to energy-dense fossil fuels which is a primary environmental sustainability challenge. The land required to grow any biomass feedstock for biofuel to meet a large demand is finite [1]. Similarly, water – another finite natural resource – consumption represents a major challenge for future biofuel production, especially terrestrial crops like corn and soybeans [2–4].

Fresh water has become an increasingly scarce resource as cities are buying water rights from farmers to assure water supplies for their citizens. The water footprint for corn ethanol is high, especially for nearly all production west of the Mississippi River in United States where corn fields must be irrigated. Corn requires 3–5.5 acre-feet of water (1 acre-feet is equivalent to 1.23 million liters of water) from rain or irrigation during a growing season [5]. The United States Geological Survey water-use report found that farmers used just over three acre-feet of irrigation for their crops. Farmers in several arid Western states such as Montana, Idaho and Arizona applied an average of over five acre-feet to irrigate crops, while the High Plains averaged about two acre-feet of water [5]. The High Plains get about a third of their water in rain – in wet years. Each acre of irrigated corn consumes three acre-feet – about 3.78 million L of water [6]. The water consumption of irrigated corn was confirmed by interviews and correspondence with corn farmers and water companies. An acre of corn produces about 140 bushels of corn which yields 1324 L of ethanol. Therefore, production of each liter of corn ethanol on irrigated cropland consumes 3000 L of fresh water. Each liter of ethanol made using irrigated corn wastes 45 tons of consumptive use water (water that cannot be recycled and reused). Approximately 70% of water is loss is due to evapo-transpiration, soil percolation and absorption. The remaining 30% becomes surface run-off and ground water recharge

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which may be available for irrigation [7]. Another way to validate ethanol's water footprint uses the USDA ethanol yield per ton of corn, 1276 L, and the FAO approximation that producing one ton of grain requires 1000 tons water. This computation ignores the water cost of the rotation crop; the farm family and refinery water, and yields 40,000 L of water or 42.4 tons of water per liter of ethanol. A typical 190 million L a year ethanol refinery consumes 568 billion L of consumptive use fresh water to grow its feedstock. Nearly all the Western states depend on irrigation for growing crops and have ethanol refineries. California has seven refineries, all using irrigation [8,9]. For corn producers, not only is the corn subsidized but many farmers receive additional subsidies for irrigation water and the power to pump the water. These subsidies move water costs towards zero and lead to tremendous water waste. The water cost alone makes it impossible to produce enough first generation biofuel to offset a large percentage of the total fuel consumption for transportation. Compared to feedstock production, water use in corn-based ethanol plants itself is negligible. For example, in Minnesota the water use efficiency in some of these plants has improved from about 5.8 L of water per liter of ethanol produced in 1998 to 4.2 L of water per liter of ethanol produced in 2005 [10]. These facts tell us the need for developing biofuel feedstocks with less natural resource (land and water) footprint.

Economic sustainability of biofuel operation is another major issue [1,11]. With much of the existing technologies still not in a position to commercially produce biofuel at a price competitive with fossil fuel, one of the other major challenges facing the biofuel sector is to attain high productivity while reducing capital and operating costs. If biofuel alone is the product, the profit or return on investment is comparatively low for biofuel based farming, which is a major economic sustainability issue from an investment perspective on using bioenergy feedstock. Further, the recent political division on ethanol subsidies in countries like US tells us the need in future for operational profit without substantial governmental support (e.g. subsidies, tax exemptions).

Recently, more and more studies are showing the benefits of algal biomass as a next generation advanced biofuel feedstock for sustainable biofuel production [11,12]. Algal biomass production offers several advantages over conventional terrestrial biofuel feedstocks. Algae offer significantly higher biomass and lipid yields per acre per year, economic use and recovery of waste nutrients, use of non-potable water such as saline, brackish, industrial or municipal waste water, productive use of non-crop lands (desert, arid and semi-arid land) and capture of CO_2 from power-plant flue gas, cement or other manufacturing plants, breweries or other carbon sources [11,12]. Further, without the need for herbicides and pesticides [13], algae appear to be a high potential feedstock for biofuel production that could potentially avoid pollution problems associated with terrestrial feedstocks. Algal biofuel do not compete directly with agricultural food production because algae do not require fertile cropland and consume negligible amounts of sweet water. Algal biofuel may use 40–1600 L of water for each liter of fuel depending on the systems employed [4]. However, the value of this water changes dramatically if algal production can be designed to use treated waste water or to lower the salt concentration in brackish or brine water. These positive sustainability indices have attracted substantial research investments from federal government, private investors and energy industries into this sector to develop this technology as a next generation biofuel feedstock [11,12].The Southwestern US is particularly poised to be ideal for the algal biofuel industry due to the availability of optimal natural resources for a diversified algal biofuel industry in this region [11,12,14].

Similar to other biofuel technologies, one of the main challenges facing the algal biofuel sector is to attain return on investment in a reasonable time frame [1]. Business models show that if algal farmers produce biofuel alone, the profit or return on investment is comparatively low for two reasons. First, biofuel remain a commodity and farmers cannot add value other than produce a higher energy fuel such as JP-8 jet fuel rather than diesel. Second, most business models show only 20–40% of the algal biomass contains lipids which can be extracted for biofuel. The remaining 60–80% of the algal biomass offers substantial value in a wide range of coproducts. Algal biomass provides many valuable coproducts from the same biomass such as organic pigments, nutraceuticals, omega-3 fatty acids (O3FA), reactive proteins, algal meal (AM) and advanced compounds. This multiproduct paradigm aligns with the biorefinery model used by the multiproduct crude oil refineries [1]. An algal biorefinery model has been suggested for the nascent algal industry to accelerate its maturation into a vital business sector. A biorefinery scenario may produce one low-volume but high-value chemical or nutraceutical products and a low-value, but high-volume liquid transportation fuel such as biodiesel or bioethanol [15–17]. By producing multiple products, the biorefinery takes advantage of the various components of biomass raw material and their intermediates, therefore maximizing the value derived from the biomass feedstock. As some of these coproducts, such as O3FA and recombinant proteins, have high demand and market value, adopting this approach can be a viable option for the algal biofuel sector to attain financial sustainability [18,19]. An integrated algal biorefinery industrial ecology can also provide numerous sustainable deliverables to the society such as carbon capture and sequestration as well as wastewater remediation [1,20].The projected algal biomass-based biofuel production is on such a large scale that there is an increasing concern that coproducts produced by algal biorefineries may quickly saturate the market. Market saturation would affect the price elasticity and significantly diminish the market value of these products. Sustained markets for algal coproducts are required to develop biorefinery-coproduct paradigm. The "coproduct market glut" is one of the reasons why integrated biorefineries are not being currently considered for commercial level demonstration plants. The growing algal biorefinery industry needs to assess the present and future markets for various algal coproducts.

As unsustainable water use in biofuel production is projected to cause irreversible consequences in water resources in some regions [2–4], the actual use of water in commercial algal biorefineries also needs to be determined before large scale demonstration or commercial deployment of this concept. This paper addresses these two major sustainability issues -coproduct market and water footprint (WFP) – by simulating two model biorefineries with the main objective of determining the volumetric outflow and market of coproducts from integrated biorefineries. Further, the water footprint analyses for the biomass generation of these biorefineries at different biomass production rates were also included in the study.

2. Methodology

2.1. Unit operational and processing assumptions for two biorefineries

Two simulated algal biorefinery plants (plants A and B) with the biomass processing capacity of 2×10^5 tons per year were considered for this study. The plant A is projected to produce ~49.1 million liter per year (L yr^{-1}) biodiesel as the primary product along with AM and glycerin as the coproducts. Plant B is projected to produce ~37.8 million L yr^{-1} biodiesel plus O3FA, AM and glycerin as coproducts. The various assumptions on production and processing characteristics for both plants are listed in Table 1. The basic processing of unit biomass (1000 kg), processing steps and efficiencies