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Energy input, carbon intensity and cost for ethanol produced from farmed seaweed

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ABSTRACT

Macroalgae, commonly known as seaweed, has received significant interest as a potential source of ethanol because of its fast growth, significant sugar content and successful lab-scale conversion to ethanol. Issues such as energy input in seaweed conversion, lifecycle emissions, global production potential and cost have received limited attention. To address this gap, a well-to-tank model of ethanol production from brown seaweed is developed and applied to the case of ethanol production from *Saccharina latissima* in British Columbia, Canada. Animal feed is proposed as a co-product and co-product credits are estimated. In the case considered, seaweed ethanol is found to have an energy return on invested (EROI) of 1.7 and a carbon intensity (CI) of 10.8 $gCO_2e\ MJ^{-1}$. Ethanol production from conventionally farmed seaweed could cost less than conventional ethanol and be produced on a scale comparable to 1% of global gasoline production. A drying system is required in regions such as British Columbia that require seasonal seaweed storage due to a limited harvest season. The results are significantly influenced by variations in animal feed processing energy, co-product credit value, seaweed composition, the value of seaweed animal feed and the cost of seaweed farming. We find EROI ranges from 0.64 to 26.7, CI from 33 to -41 $gCO_2e\ MJ^{-1}$ and ethanol production is not financially viable without animal feed production in some scenarios.

Contents

Abbreviations: BC, British Columbia; CAD, Canadian dollars; CI, carbon intensity; COP, coefficient of performance; EROI, energy return on energy invested; gCO_2e, GHG emission in grams of carbon dioxide equivalent; GHG, greenhouse gas; GWP, global warming potential

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1. Introduction

Ethanol is a proven transportation biofuel that can reduce GHG emissions with minimal infrastructure change, but its expanded use is limited by current ethanol sources. Corn ethanol production can compete for limited arable land and water resource, driving the “food *vs.* fuel” debate [1], and it requires a significant amount of energy for conversion and fertiliser. Expanding sugarcane ethanol production can contribute to deforestation and wetland destruction [2], and sugarcane grows only in specific climates. Cellulosic biomass has been proposed as feedstock to expanded ethanol production and significant advances have been made in making it a commercial reality [3,4]; however, it is fundamentally difficult to convert cellulosic biomass to ethanol due to the presence of lignin.

Macroalgae or seaweed has generated significant interest as an ethanol source because of its potential to overcome these disadvantages and its promise as a biomass source. Seaweeds lack lignin [5], they have high productivity per unit area [5] and they are currently farmed at large scale [6,7] without the use of fresh water or arable land.

As an ethanol feedstock, seaweed also presents several unique challenges. Seaweed has high water content (75–90%) and high ash content (22–37%) [8] which can result in high costs for drying, transportation and processing. Furthermore, seaweed experiences significant monthly fluctuations in fermentable content [9]. As a result of these fluctuations, brown seaweeds like *Laminaria japonica* and *Saccharina latissima* are only harvested during a one to two month period [10,11]. Because ethanol plants require a year round supply of feedstock to achieve acceptable production costs, compensation mechanisms used in corn and sugarcane ethanol production, like feedstock storage or planting species that mature at different rates, may be required for seaweed ethanol. Although seaweed ethanol has received significant attention in the literature, the effects of these challenges on the overall ethanol production system have not been fully addressed.

The objective of this study is (1) provide a complete model of seaweed ethanol production, (2) estimate seaweed ethanol's well-to-tank energy input and carbon intensity, (3) estimate seaweed ethanol production potential using established seaweed farming methods and (4) perform a financial analysis.

Seaweed biomass can be generated from three sources: natural stocks; near shore farming and offshore farming. Natural stocks provide only 6% of global seaweed harvest and offshore farming is still only experimental, leaving near shore as the dominant form of seaweed production. Near shore farming is labor intensive, and the bulk of farming is done in areas where labor cost is low [8]. The brown seaweed, *Saccharina japonica*, is the most farmed seaweed by mass, accounting for 33% of global near shore farming [6].

Apart from water and ash, all brown seaweeds contain five saccharides (*i.e.* alginate, laminarin, mannitol, cellulose and fucans) as well as proteins and small quantities of lipids [12], as shown in Table 1.

Of these five saccharides, laminarin and mannitol are considered easily fermentable [13], and recent work has shown that alginate fermentation is possible with genetically modified fermenting organisms [5,14]. Several components can be extracted as co-products and sold [6] including, pigment proteins, cellulose, fucans and phenolic compounds from the metabolites, and the whole seaweed mass can be anaerobically digested into methane [15], converted into fertilizer, or made into animal feed. Seaweed fertilizer can act as biostimulant [8], and seaweed ash

Table 1
Components of brown seaweed.

Component[a]	Composition[b]	Index[c]
Alginate	23	1
Laminarin	14	2
Mannitol	12	3
Proteins	12	4
Cellulose	6	5
Fucans	5	6
Lipids	2	7
Ash	24	8
Moisture	88	–

[a] Main components of all brown seaweeds [12].

[b] Typical composition for the Laminaria species [23]. Moisture content is given in wet basis, and the remaining component values are given in percentage of total seaweed solids.

[c] Summation index for Eq. (1).