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Evaluation of a high-moisture stabilization strategy for harvested microalgae blended with herbaceous biomass: Part II — Techno-economic assessment

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ABSTRACT

The seasonal variability in algal biomass production and its susceptibility to rapid degradation increases uncertainty in algal productivity and increases risks to feedstock supply for conversion. During summer months when algal biomass productivity is highest, production could exceed conversion capacity, resulting in delayed processing and risk of biomass degradation. Drying algae for preservation is energy-intensive and can account for over 50% of the total energy demand in algae preprocessing. In comparison, wet stabilization of algae eliminates the need for drying, and blending with herbaceous biomass allows for the utilization of the silage industry's existing harvest, handling, transportation, and storage infrastructure. A storage facility co-located with the algae production and conversion operations was designed in this study to stabilize algal biomass produced in excess of conversion capacity during summer months for use in the winter when algal biomass production is reduced. Techno-economic assessment of ensiling algae and corn stover blends suggest it to be a cost effective approach compared to drying. In a high algal biomass productivity scenario, costs of wet storage ($/liter diesel) were only 65% of the cost of drying. When a reduced algal biomass productivity scenario was considered, the stored blend was able to cost-effectively provide sufficient biomass such that winter production in the algal ponds could cease, meanwhile incurring only 91% of the costs of drying; such an approach would facilitate algal biomass production in northern latitudes. Furthermore, the wet storage approaches require only 8–10% of the total energy consumption and release only 20–25% of the greenhouse gases when compared to a natural-gas based drying approach for microalgae stabilization.

1. Introduction

Algal biomass is an attractive feedstock source for biofuels due to the high productivity potential and ability to use multiple water sources for growth [1]. Based on present productivities and sites where co-location with CO_2 is feasible, the U.S. Department of Energy's 2016 Billion-Ton Report identified resources that could sustain annual biomass production of up to 42 million tonnes of the freshwater algae *Chlorella sorokiniana* or up to 78 million tonnes of the saline strain, *Nannochloropsis salina* [1]. Algal biomass production estimates vary based not only on strain but more importantly based on the seasonal variations that occur based on geographical location, specifically due to shifts in temperature and solar irradiation [2–4].

The U.S. Department of Energy Bioenergy Technologies Office has sponsored the development of design reports describing commercial-scale algae biomass production and conversion facilities to establish cost targets for minimum selling price of fuel produced from algal biomass. Algal biomass production co-located at the conversion facility in open pond systems and subsequent dewatering to 20% solids has been described to establish a production cost target of $541 per tonne of harvested biomass [5]. Two algal biomass conversion pathways have been considered: 1) a thermochemical process, hydrothermal liquefaction (HTL) and upgrading [6] and 2) a biochemical approach, combined algal processing (CAP) [7]. These reports will be subsequently referred to as Design Cases. HTL is a thermochemical conversion process where reactions occur in the liquid state at temperatures between 250 and

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Abbreviations: HTL, hydrothermal liquefaction; CAP, combined algal processing; wb, wet basis; GHG, greenhouse gas; kilowatt, kW; db, dry basis; kilowatt-hour, kWh; TIC, total installed costs; TID, total direct costs; FCI, fixed capital costs; TCI, total capital investment; GREET, The Greenhouse Gases, Regulated Emissions and Energy Use in Transportation Model

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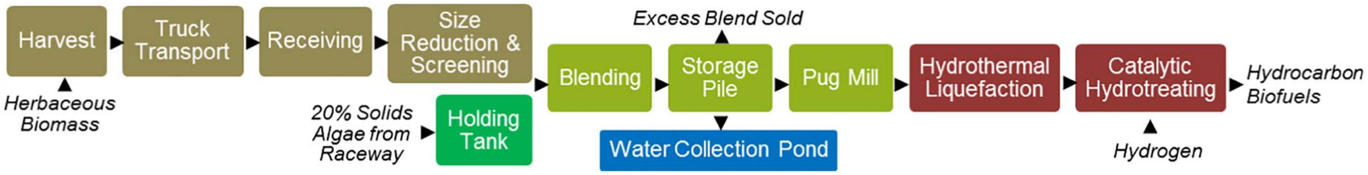

Fig. 1. Flow diagram of unit operations. Herbaceous biomass, harvested from the field and delivered by truck to a receiving area, undergoes preprocessing operations to meet size and ash specifications. Harvested algae (20% solids, db) in excess of conversion capacity is transferred to a holding tank, then mixed with herbaceous biomass and added to a storage pile. Upon retrieval from storage, the blend is reconstituted to 20% solids (db) so that it can be fed into the HTL reactor, followed by catalytic hydrotreating to form hydrocarbon biofuels. Excess blend remaining in the storage pile is sold once capacity in the HTL reactor has been maximized.

380 °C and pressures of 5 to 30 MPa [8,9], and the resulting bio-oil is upgraded through catalytic hydrotreating to produce hydrocarbon fuels. HTL has been documented for multiple feedstock types including algae [9,10], woody biomass [11–13], and herbaceous biomass [11,14,15]. Blends of algae with woody or herbaceous biomass have also been converted into bio-oil through HTL [16]. The biochemical approach to algal conversion, CAP, is similar to approaches used for conversion of herbaceous feedstock in that dilute-acid pretreatment is utilized to make carbohydrates accessible for subsequent fermentation [17]. Upon fermentation of sugars, lipids remaining are upgraded by transesterification or decarboxylation reactions to hydrocarbon fuels [18]. This research article focuses on a hypothetical conversion approach via HTL.

Conversion facilities require a consistent source of feedstock in order to operate at designed capacity and fuel production levels. Seasonal variation in algae production is a challenge for algae conversion facilities and has been considered in the conversion Design Cases, such that the conversion facility is sized at approximately 65% of the maximum algae production levels and drying and long-term storage is used to preserve a fraction of biomass produced in the summer for winter utilization. Drying is a common method for stabilizing biomass by reducing moisture contents substantially to below 15–20% wet basis (wb), which is generally considered safe from microbial degradation [19]. The use of rotary drum dryers, the costs of which are detailed in the Design Cases, have recently been shown to be ineffective for drying 20% solids algal biomass [20], and adaptive methods are necessary for more effective drying. Long-term storage of the dried algae is required between summer and winter months, yet advanced storage solutions including refrigeration may be necessary for preservation in hot, humid climates such as the Gulf Coast.

Conversion of algal biomass to fuels previously required drying algae prior to lipid extraction; however, drying wet microalgal paste from 80% (wb) moisture to less than 10% (wb) is energy intensive and unsustainable. In the context of lipid extraction, Delrue et al. concluded that thermal methods of drying must be avoided and the extent of drying should be limited as much as possible [21]. Drying followed by lipid extraction also has tremendous sustainability implications, where as much as 90% of the processing energetics can be dedicated to lipid extraction and recovery [22]. Wet conversion methods, such as HTL and CAP, have subsequently been developed and optimized, and drying now is only considered when long term storage is necessary [6,7,18,23].

Wet storage is an alternative to drying that is frequently used in the forage industry for stabilizing high-moisture biomass through ensiling; commonly stored biomass types include grasses, whole corn plants (i.e. corn silage), and sorghum [24]. The ensiling of macroalgae has gained recent attention as a preservation strategy in order to provide a stable biomass source for conversion given seasonal variations in availability [25–27]. However, the preservation of microalgae through ensiling has not been documented except for at low concentrations of microalgae (less than 2.5%) blended with herbaceous biomass for biogas production or improvement of protein content in animal feed [28,29]. Blending microalgae with herbaceous biomass provides an opportunity to take advantage of the rheological properties of herbaceous biomass such that the existing infrastructure of the silage industry, including low-cost drive-over piles for storage, can be utilized. This article explores high-moisture stabilization of algae with corn stover to manage algal biomass productivity variation due to seasonality in order to maximize conversion throughput. Proof-of-principle experiments investigating the stability of freshly-harvested microalgae stored alone or blended with corn stover have been demonstrated in Part I of this study. Results show that both feedstocks were successfully preserved in anaerobic, acidic conditions for 30 days with low dry matter loss. Building on these promising experimental results, a techno-economic assessment was performed in the current Part II to assess how wet storage may provide a feedstock stabilization option at an HTL conversion facility, and resulting costs as well as the sustainability metrics of energy consumption and greenhouse gas (GHG) release were evaluated to compare wet storage scenarios with a drying scenario.

2. Material and methods

2.1. Conceptual design of centralized preprocessing and storage facility

A centralized preprocessing and storage facility was designed that stores a blend of algae and corn stover onsite at an algal biomass farm and co-located conversion facility. Fig. 1 provides a flow diagram for the receiving, blending, storage, and formatting operations undertaken at the storage facility as well as delivery of the feedstock to an HTL conversion facility. Briefly, an on-site storage facility receives corn stover over a 90 day period in the summer, removes soil contamination, reduces the particle size, and then blends it with harvested, dewatered algal biomass. A storage pile containing roughly 65% (wb) moisture is then constructed and stored for 3–6 months until utilization in the fall and winter. At that time, the stored blend is recovered from the pile and reconstituted to 20% solids, and is then available for conversion via HTL followed by catalytic upgrading to transportation fuel. Techno-economic assessment was performed to determine the annual costs of the centralized preprocessing and storage facility, and assumptions on fuel yield through HTL were used to determine how the approach might influence resulting fuel cost.

2.2. Feedstock supply scenarios

Two algae production profiles were chosen for investigation: 1) a 3:1 summer to winter variation in growth from ponds totaling 2025 ha (4 ha individual ponds [30]) as detailed by Davis et al. [5], and 2) a 5:1 summer to winter variation in growth from ponds totaling 405 ha (4 ha individual ponds) with production levels as detailed in Davis et al. and Jones et al. with one exception: an algae farm totaling 405 ha of pond surface was considered as opposed to a collection of ten 405 ha pond modules as listed in the designs [6,7]. Drying and dry storage of biomass produced in excess of conversion capacity are described in the above referenced reports and are compared to the three wet storage scenarios described in Fig. 2. In all these scenarios, algal biomass produced in excess of conversion capacity is blended with corn stover in order to provide sufficient biomass to meet maximum conversion capacity year-round. However, in the 5:1 wet B scenario, ample stored

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