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Managing variability in algal biomass production through drying and stabilization of feedstock blends

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ABSTRACT

The uncertainty and variability of algal biomass production presents several challenges to the nascent algal biofuel industry, including equipment scaling and feedstock supply. Ideally, on-site processing equipment will be scaled to minimize overall biofuel production costs, which means at times biomass production could exceed down-stream processing capacity due to seasonal variation. Biomass produced in excess of conversion capacity during summer months must be stabilized by some method, such as drying, until needed later in the year. Because of algae's high moisture content and its cohesive nature, drying is challenging. Blending algae with terrestrial biomass may provide a cost-effective method to enable drying and stabilization of algae by reducing moisture content and improving rheological (i.e. flowability) properties. To test the technical feasibility of this approach, bench-scale rotary drum dyers were constructed and tested with blends of algae (*Scenedesmus* sp.), ground pine (2 mm grind), sorghum, corn stover (6 mm), sieved sand, and dried algae. In these studies, blends up to 40% algae exhibited drying behavior similar to that of pine alone, and reached dryness (2% moisture) in half of the time it took to dry algae alone. Thermogravimetric analyses performed on blends and neat blend materials provided drying curves consistent with the bench-scale dryers. Preliminary logistics analysis for production-scale operations were performed to determine cost and availability of feedstock materials for blending as compared to drying algae directly. This analysis indicates that revenue lost due to idle processing capacity had a significant impact on the per gallon gasoline equivalent feedstock cost. The blending approach, described herein, reduced feedstock-related costs, including procurement, drying, and storage by 35% relative to drying algae directly. Our results indicate that blending algae with terrestrial biomass enables the use of rotary dryers and has the potential to improve overall algal biofuel economics.

1. Introduction

The need for sustainable alternatives to petroleum-based fuels has led to increased interest in microalgae as a source of biofuels, due to their high rate of productivity and high lipid content [1,2]. Research into the use of microalgae as a fuel source has focused on every aspect of the process including strain development [3], cultivation [4], harvesting and dewatering [5], and conversion to fuel [6,7]; detailed techno-economic studies have been made to understand how each new technology affects the cost of fuel production [8–12]. A major challenge to the development of economical algal farms is the variability in algal biomass productivity due to seasonal variations in temperature and insolation. In some locations otherwise well suited for algal production (e.g. water, nutrients), large variability between summer and winter production, which can be as high as 10:1, creates a challenge to optimally scale downstream processing equipment [9,11]. Given the high cost of algal biomass production (74% of the final fuel cost [9]), the value of excess biomass must be captured by either scaling conversion facilities to accommodate maximum algal biomass productivity or by preserving excess biomass until conversion capacity becomes available. A recent study on location-dependent scaling of algae biofuel production facilities determined that conversion facilities were economically scaled when their conversion capacity was exceeded 10–30% of the time, highlighting the need for cost-effective approaches to algae preservation [13].

Harvested algal biomass is a high moisture, high nutrient feedstock that begins to degrade almost immediately upon harvest, thereby requiring stabilization if it is not processed within hours of harvest. Algal biomass can suffer dry matter losses up to 20% within a week as a result

Abbreviations: HTL, hydrothermal liquefaction; wb, wet basis; CPVC, chlorinated polyvinyl chloride; PVC, polyvinyl chloride; TGA, thermogravimetric analysis; IAF, integrated assessment framework; BLM, biomass logistics model; BTU, British thermal unit; AFDW, ash-free dry weight; CAP, combined algal processing; gge, gallon gasoline equivalent.

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of respiration and microbial degradation [14]. Reducing moisture content to below 15% is a common preservation strategy for lignocellulosic biomass [15] and is likely to be sufficient for algae biomass preservation. With few exceptions, drying experiments conducted in this study were continued until algae/terrestrial biomass blends reached moisture contents below 10% at which point they were considered stable.

The literature describing algal biomass drying is limited and has primarily focused on preserving *Arthrospira platensis* biomass (spirulina) for the food market. A number of different technologies, such as spray drying, freeze drying and solar drying have been employed to dry spirulina [16–18]. While solar drying was the least costly method employed, it also took the longest time, required a large area of land, and resulted in lower biomass quality [16]. Although spirulina dried by spray drying or lyophilization resulted in high quality biomass, these approaches are considered to be too expensive for algae biofuels applications [16]. There are many other mature drying technologies (e.g. paddle dryer, tray dryer, fluidized bed dryer, etc.) that have not been reported in the literature for their use in drying algae. In this paper, an approach is developed to dry microalgal biomass in a rotary drum dryer. Rotary drum dryers are widely used to dry lignocellulosic biomass because they are highly flexible and capable of drying products with a wide range of moisture contents, particle sizes, and flow properties [19]. This approach to drying algae has also been used in techno-economic models for algae biofuel production [9,11,20].

The drying behavior of a material in a rotary drum dryer is highly dependent on the flow properties of the material, and rotary driers are generally less effective for sludges than free-flowing materials. Algae slurries at 20% solids (wet basis (wb)) exhibit flow behavior that more closely resembles that of sludges than free-flowing materials, so it is anticipated that modifications to the dryer or algal slurry will be needed for efficient drying. Sludge-like materials are often characterized as "sticky", meaning that they have a tendency to agglomerate and adhere to contact surfaces. The cohesive and adhesive tendency of sludges limits the air-solids contact area and also limits heat and mass transfer within the material [21]. Due to mass transfer limitations, sludge-like materials undergo drying at the material surface more quickly relative to the interior, forming an outer crust that further interferes with removing moisture from the interior [22,23]. Several industries have overcome this challenge through blending their sludges with dry material. Arjone et al. mixed an olive oil waste product, which has similarities to a 20% solids algae slurry, with previously dried waste to reduce the moisture content and prevent agglomeration [24]. Industrial drying equipment manufacturers recommend blending sludges with dry product to reduce moisture content and to obtain compatible rheological properties [25]. Blending algae with terrestrial biomass provides an opportunity to reduce the starting moisture content and improve the physical properties (e.g. flowability) of the blend, which decreases drying costs using a rotary drum dryer. The final algae/terrestrial biomass blended product can be shelf stable and compatible with hydrothermal liquefaction (HTL) conversion or other conversion technologies or end uses, with both pine and algae contributing to the final product yield.

This paper assesses the technical and economic feasibility of blending algae with terrestrial biomass prior to drying. The technical feasibility is determined by evaluating the drying characteristics of algae blended with terrestrial biomass (pine or other lignocellulosic biomass) at ratios ranging from 20 to 80% algae (dry matter basis) in a bench-top rotary drum dryer. The improved flowability and reduced starting moisture content of algae blended with other materials is anticipated to enhance drying rates and reduce the cost of drying. The economic feasibility is evaluated through logistical analysis by assessing the quantities of terrestrial biomass needed for blending and determining the relative costs of bringing the two feedstocks together to create the blend. The feedstock-related costs from two alternate scenarios of managing algal biomass produced in excess of processing capacity are evaluated. The base case scenario involves drying excess algae directly, while the second considers drying algae as a blend with pine. Although the blending approach is developed with HTL as the focal conversion technology, adaptations are discussed that would produce dried algae using a rotary drum dryer compatible with other algae fuel conversion pathways, such as lipid extraction and upgrading [26].

2. Materials and methods

2.1. Materials

Two sources of algae biomass were used in completing this research. *Scenedesmus dimorphus* algal biomass was provided by Prof. Bruce Bugbee, Utah State University. Briefly, microalgal biomass was cultivated in vertical flat plate photobioreactors (5 cm pathlength) until reaching stationary phase. *S. dimorphus* was cultivated in Bristol media [27] The biomass was harvested and dewatered to 28.5% solids (wb) by a combination of crossflow filtration and centrifugation, then frozen until needed. *Scenedesmus* sp. was provided by the Arizona Center for Algae Technology and Innovation (AzCATI, Arizona State University, Mesa, AZ) as frozen paste with a solids content of 16.6% (wb). The algae biomass was thawed at 4 °C prior to use and was used either without modification or blended with terrestrial biomass or sand. Loblolly pine ground to 2 mm (top size) with a Wiley Mill (model 4, Thomas, Swedesboro, NJ) and dried to a moisture content of 6.3% moisture (wb), unless otherwise noted. For experiments examining the drying behavior of wet pine, water was added to the ground pine and moisture was allowed to equilibrate at 4 °C for 24 h before use. Single pass, 6 mm grind sorghum was used fresh (78.5% moisture, wb) or dry (6.5% moisture, wb) for blending with algae. Additionally, corn stover (6 mm grind) was also used fresh (46.6% moisture, wb) or dry (8% moisture, wb). The sand used in some experiments was obtained from a local building supply store.

2.2. Biomass blending

Algae and pine were blended together in ratios ranging from 20 to 80% algae on a dry mass basis. Wet algae (71.5% moisture), which had consistency similar to tomato paste, was added to 2 mm grind pine (6.3% moisture) in varying ratios to achieve targeted algae/pine blends (e.g. 50% algae, 50% pine on a dry mass basis). Algae and pine were blended together using a grout mixer paddle and a cordless power drill in a clean 5 gal pail. Moisture content of each blend was determined gravimetrically after incubation at 105 °C for at least 24 h. Blends with algae and other blend materials (sorghum, corn stover, sand, and dry algae) were achieved in a similar manner.

2.3. Shear test

Specific shear strength and unconfined yield strength measurements were performed for ground pine (2 mm top size) that had been rehydrated to 59% moisture and for blends of algae biomass and ground pine (2 mm top size, 6% moisture, wb) consisting of 30%, 40%, and 50% algae. Shear tests were conducted in accordance with ASTM D6773–08 using an automated Schulze ring shear instrument (Dietmar Schulze Schüttgutmesstechnick, Wolfenbüttel, Germany), and a size S shear cell (outer diameter of 6 cm and inner diameter of 3 cm). Briefly, each material was subjected four times to the same preshear compression stress (σ_{pre}) while varying the shear compression stress (σ_{shear}) each time to obtain a yield locus [28]. Three or more yield locus curves obtained using different values of preshear compression stress (σ_{pre}) were used to construct a flowability curve.

2.4. Bench-scale drum dryer

A simple bench-scale rotary drum dryer was utilized to assess the technical feasibility of drying algae blends. The dryer was constructed of a six inch diameter CPVC nipple and two six inch PVC caps. The