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Review of the harvesting and extraction program within the National Alliance for Advanced Biofuels and Bioproducts

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ABSTRACT

Energy-efficient and scalable harvesting and lipid extraction processes must be developed in order for the algal biofuels and bioproducts industry to thrive. The major challenge for harvesting is the handling of large volumes of cultivation water to concentrate low amounts of biomass. For lipid extraction, the major energy and cost drivers are associated with disrupting the algae cell wall and drying the biomass before solvent extraction of the lipids. Here we review the research and development conducted by the Harvesting and Extraction Team during the 3-year National Alliance for Advanced Biofuels and Bioproducts (NAABB) algal consortium project. The harvesting and extraction team investigated five harvesting and three wet extraction technologies at lab bench scale for effectiveness, and conducted a techoeconomic study to evaluate their costs and energy efficiency compared to available baseline technologies. Based on this study, three harvesting technologies were selected for further study at larger scale. The selected harvesting technologies: electrocoagulation, membrane filtration, and ultrasonic harvesting, were evaluated in a field study at minimum scale of 100 L/h. None of the extraction technologies were determined to be ready for scale-up; therefore, an emerging extraction technology (wet solvent extraction) was selected from industry to provide scale-up data and capabilities to produce lipid and lipid-extracted materials for the NAABB program. One specialized extraction/adsorption technology was developed that showed promise for recovering high value co-products from lipid extracts. Overall, the NAABB Harvesting and Extraction Team improved the readiness level of several innovative, energy efficient technologies to integrate with algae production processes and captured valuable lessons learned about scale-up challenges.

1. Introduction

1.1. Preface

Harvesting algae and extracting the lipids are significant cost drivers in the biofuel production process [1–6]. Therefore, the goal of the Harvesting and Extraction task within the National Alliance for Biofuels and Bioproducts (NAABB) was to develop low-energy, low-cost harvesting and extraction technologies that could feed lipids into highly efficient fuel-conversion processes [7].

At the outset of the project, the NAABB leadership team determined that the harvesting and extraction technologies developed in this task must have:

- Low capital expense (CAPEX) and operating expense (OPEX)
- Ease of operation and low maintenance requirements

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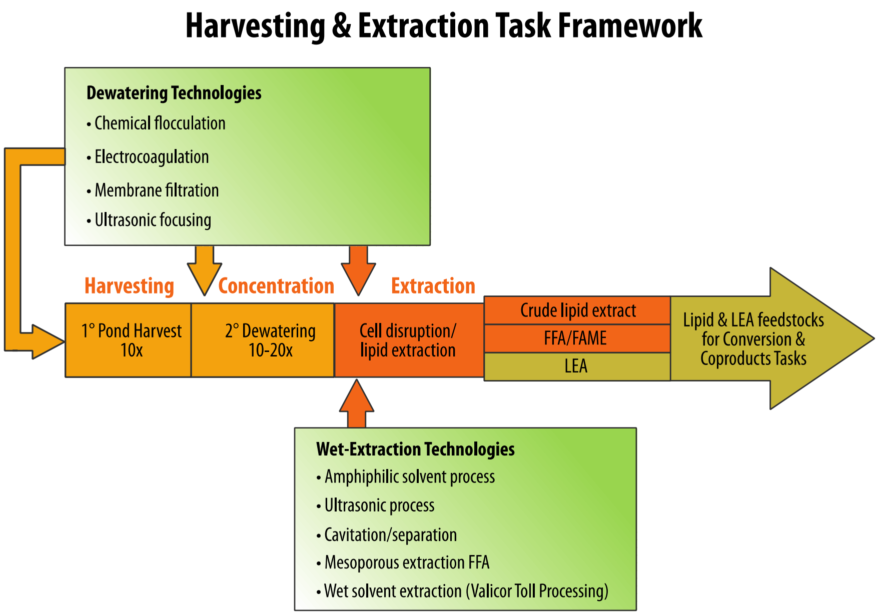

Fig. 1. The NAABB Harvesting and Extraction task framework showing four dewatering technologies to harvest and concentrate the biomass by 10 × and 20 ×, in one or two consecutive steps. This concentrated biomass would then undergo wet-extraction, by one of five technologies developed and tested, to produce key lipid extracts of free fatty acids (FFA), fatty acid methyl esters (FAME), and lipid extracted algae biomass (LEA), that would then go to conversion to fuels and coproduct development processes.

- Ease of integration with cultivation facilities to limit pumping and power requirements
- Compatibility with a broad range of algal species
- Ability to recycle water
- Low environmental impact, i.e., low or no hazardous chemical or solvent use
- Minimum energy requirements that reduce the carbon footprint
- Downstream compatibility, e.g., nothing be added that negatively affects later processing or quality.
- Feasibility of affordable scale-up and good performance at large scale

A significant technical challenge for harvesting algae is that algal cells make up only about 0.1% of the total culture volume in a typical outdoor pond. Photobioreactors (PBRs) can produce higher density cultures, but still have < 1% cell densities. This highly dilute system presents the challenge of needing to collect a very small fraction of the total volume for downstream processing. As expected, there are significant energy (and therefore cost) penalties for pumping such large volumes of water. Centrifugation is the industry state of the art for harvesting algae for the production of high-value products. While time-tested and effective, centrifugation has high capital costs, is energy intensive, and can require significant maintenance. Standard centrifuges cannot be deployed directly at the pond, so algal water must be pumped from the pond to the centrifuge station for harvesting.

Therefore, our team aimed to develop methods for harvesting algae that reduce the energy penalty of this step, leading to significant reductions in costs and taking the industry closer to cost-competitive values for a gallon of algae-based oil. We hypothesized that the exploration of a portfolio of innovative methods would provide a path forward for cost-effective algae harvesting. Some methods employed off-the-shelf technology, while at least one method was largely conceptual at the start of the project. In each case, the team demonstrated that algae harvesting could be achieved with these technologies at costs that we projected to be significantly below the baseline case of traditional centrifugation.

Once the algae are harvested, there are two main pathways available for making a fuel or a bioproduct from the concentrated algae [8]. A conventional pathway is to extract and separate the oil from the cells. This process typically entails drying the algae, treating it with solvent, removing the liquid fraction from the remaining biomass leaving behind lipid extracted algae (LEA), and distilling the solvent from the oil. This crude oil is then sent for conversion to fuel, and the LEA can be used as a co-product. In NAABB, the focus of the Harvesting and Extraction Team was on the lipid extraction pathway, and LEA was evaluated as an animal feed co-product by the Co-Products Team. In another pathway, the harvested, whole wet algae can be directly converted to oil via a hydrothermal liquefaction (HTL) process [9]. The resulting oil can then be upgraded to a fuel. The HTL pathway was studied in the NAABB Fuel Conversion Team [7].

There are a number of challenges associated with the lipid-extraction step in the algal biofuels value chain. First, in order for the solvent to effectively remove the oil, the algae must be very dry, and drying is a costly and energy-intensive process. Simple air-drying may be incomplete and may result in spoilage of the algae, which may damage the quality of the products. Second, any cell debris (for example, with high N or S content) or solvent that carries through to the conversion process may affect the quality of the resulting fuel or co-products. Thus, an additional objective of this team was to explore effective and inexpensive wet extraction technologies. Again, a portfolio of innovative lipid extraction technologies was assessed, resulting in an improved understanding of the extraction requirements.

Much of the research reported here was initially described in the NAABB Final Report [7]. It is reviewed here with the benefit of additional time to fully analyze the data and publish more detailed descriptions of the experimental work.

1.2. Approach

The National Alliance for Advanced Biofuels and Bioproducts (NAABB) Harvesting and Extraction Team comprised physicists, engineers, chemists, and biologists from national laboratories, universities, and industry, who had strong track records of developing novel technologies. Our approach focused on minimizing the energy consumption of each technology, while maximizing the yield of product (as shown in Fig. 1).

In this project, harvesting was defined broadly as a 10–20 × dewatering/cell concentration process that may include one or more steps. Likewise, extraction was broadly defined to include cell disruption and recovery of lipids and lipid-extracted biomass from the dewatered, cell-concentrated feedstock in one or more steps. In order to do this, the Harvesting and Extraction Team began the NAABB program effort evaluating five harvesting technologies and four lipid extraction technologies. The initial goal was to develop proofs of concept and