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Algae Technology

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INTRODUCTION

In the algae industry, there are three specific areas of interest currently receiving significant attention:

1. Algae organism research and genetic modification
2. Algae production systems
3. Product Isolation, i.e., algae harvesting, dewatering and product extraction

In the area of organismal research, this report delves into the area of bioprospecting, industry partnerships, such as Synthetic Genomics partnership with ExxonMobil, as well as other industry developments surrounding strain development.

In the area of production systems, this report assesses developments in various types of cultivation systems such as open ponds, closed photobioreactors, heterotrophic "sugar-fermentation-to-lipids" type systems, as well as hybrids of the three afore mentioned systems are investigated.

Economics are presented and compared for commercial scale systems lipid production via open pond, closed photobioreactor, and heterotrophic systems, as well as ethanol production from algae in a photobioreactor.

In the area of product isolation, developments in harvesting, dewatering, algae lysing, and product extraction are investigated. Included and informing the analysis is data and perspectives from key leading algae developers such as Algenol, Joule, OriginOil, PetroAlgae, Solazyme, and Solix, among others.

This report also opines on some of the various options for downstream conversion of algae products into end-use products both currently being targeted by algae developers such as FAME biodiesel, HVO renewable diesel, HVO renewable jet, ethanol to ethylene, as well as other routes to downstream products that are not currently being developed.

MICROALGAE BIOLOGY

Microalgae are extremely fast-growing organisms. They can double their biomass in as little as two hours. In fact, algae are the fastest growing plants on the planet. They do require water, but this does not have to be potable water or even fresh water, as algae processes can produce clean fresh water as a byproduct. They can and are grown in brackish water and waste water streams. Some algae are halophytes that thrive in high salinity environments, such as in inland salt lakes or wetlands with evaporating seawater. The differently-colored ponds (purple-through-green) seen from the air in Southeast San Francisco Bay in the United States, for example, are the result of different algae living in various concentrations among these solar-evaporative salt ponds.

At this time, there are over 200 companies focusing on algae for the production of various products, and a significant number of these are targeting biofuels. The simplest way to categorize these and the most significant difference between most of these companies is in their

approach to growing and harvesting the algae. Additionally, a subset of the algae industry has emerged to serve the algae producers (e.g., *Algae Venture Systems'* AVS Dewatering Technology).

The term "algae" (singular, alga) encompasses many different groups of living organisms. Algae have been commonly regarded as simple plants. Others, such as blue-green algae or cyanobacteria, are more closely related to bacteria in character, though they have the ability to photosynthesize. Algae have been part of the pattern of life on earth since primeval periods and range from small, single-celled organisms (microalgae) to much larger, multi-cellular organisms (macroalgae) that are related to plants, but without a vascular system, roots, steams, leaves, or embryos (fruits and seeds). Collectively micro and macroalgae are mainly aquatic and are the primary producers in the aquatic food chains. Some of the macro forms are fairly complex with differentiated forms, such as giant kelp, which are algal species that grow in underwater "forests" and can be nearly 60 meters (200 feet) long.

Microalgae have been the predominant focus of biofuels and biochemical research. This report is concerned only with microalgae, which are microscopic, though they can be single-celled, colonial, or multi-cellular.

This section of the reports discusses:

- The Cellular Biology of Algae

  Photosynthesis and Lipid/Hydrocarbon Accumulation are the focus of the discussion.

- Biotechnology Development Goals

  Biotechnological developments are essential to the successful commercialization of algal biofuels. Capital and operating costs must be reduced dramatically to produce biofuels at a competitive price as compared with petroleum fuels.

GROWING AND CULTURING SYSTEMS

Many of the large oil and chemical companies have taken a position on algae. These include BP, Chevron, ConocoPhillips, Dow, ExxonMobil, GE, Marathon, Pemex, Shell, UOP, Valero etc.

Aviation interests of many types (aircraft, jet engines, airlines, military, etc.,) also have shown interest in and various types of sponsorship of algae fuel development.

There are four basic types of growing systems:

- **Open Pond** – Open pond systems, as the name suggests, are ponds that are open to the environment. These include circular ponds, as well as the oblong shaped "raceway ponds"
- **PBRs** – PBRs (Photobioreactors) are systems that are closed from the outside environment, and are usually encased in a transparent medium [plastic or glass, though glass can be prohibitively expensive for such an application, alternatively light may be introduced within the PBR (e.g., LED lights)] that allows the algae access to light, while preventing organism escape, foreign attack, and gas escape

- **Hybrid Systems –** Hybrid systems are a combination of PBRs and open ponds. Typically cultures are started in a PBR system, and then used to inoculate the open ponds
- **Heterotrophic Systems** – Heterotrophic systems are also called 'sugar-fed' systems. These algae do not utilize sunlight and carbon dioxide to grow and produce products; instead they are fed sugar and utilized in a system that is analogous to fermentation

A fifth option being explored is the harvest of existing wild algae blooms.

This section of the report discusses growing and cultures systems, includign commercial timelines, open pond, PBR, hybrid, heterotrophic, and other systems.

Among the critical factors, such as suitable land and climate and sustainable water resources, that will attribute to the success of algae-to-biofuels technologies is the availability and affordability of CO_2. CO_2 is vital to algae cultivation as the microorganism uses photosynthesis to convert CO_2 and sunlight into biomass and energy storage chemicals so as to grow and be sustainable. Research has shown that enhanced CO_2 concentration can dramatically improve algae yields. Integrating CO_2 sources with algae growth systems is discussed in the report.

HARVESTING AND PRODUCT EXTRACTION

Once algae have been grown, in order to extract a useful product, the cells must be concentrated, and the water removed. This applies to most of the technologies, granted that they are pursuing the oil fraction of the cell (although *OriginOil* claims the ability to excrete products into a separate phase excluding them, and *Algenol* claims the ability to excrete their product ethanol into the vapor phase, and to strip with air, excluding them as well). Following this, the individual membranes of each of the cells in culture must be broken to release the oils held within the cell.

This section of the report discusses harvesting and product extraction in some depth, including a discussion on product quality, and an overview on diversity of approaches.

PROCESS ECONOMICS

Cost of production estimates have developed for:

- Production of Algae Oil by PBR Process (Brazil, China, U.S. bases)
- Production of Algae Oil by Open Pond Process (Brazil, China, U.S.bases)
- Production of Algae Oil by Heterotrophic Algae (Brazil, Thailand, U.S., Western Europe bases)

Various sensitivity analysis have also been carried out (i.e., effect of variation in capital investment required and effect of carbon credits on algae oil cost of production).

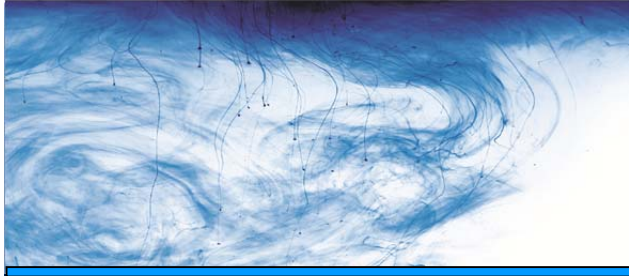
Ethanol is a good fuel to supplement or substitute for petro-gasoline. However, it has a number of issues ranging from performance characteristics to production costs. It is the only major biologically-derived fuel being used as a substitute for petroleum gasoline in the world today, but there is concern over global limits on the availability of feedstocks. Nexant foresees the

commercialization of several second generation biofuel products and processes that augment or supplant grain and sugar ethanol as a substitute for gasoline over the next decade, and/or utilize lipids other than by transesterification, alongside the development of third generation biofuels.

Algae as a producer of ethanol, or as providing feedstock for ethanol production is a concept that is yet to be commercialized, but companies are experimenting with the idea.

- A cost of production estimate for ethanol production has been analyzed in this section via the Algenol process for generating ethanol (Brazil, China, and U.S. bases).

The cost of production tables given in this report include a breakdown of the cost of production in terms of raw materials, utilities consumed (electrical energy, cooling water, fuel etc.), direct and allocated fixed costs, by unit consumption and per metric ton and annually, as well as contribution of depreciation to arrive at a cost estimate. Capital costs are broken down according to inside battery limits (ISBL), outside battery limits (OSBL), other project costs, and working capital.



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