Robert M. Kerr Food & Agricultural Products Center

FOOD TECHNOLOGY FACT SHEET

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Downstream Processing of Algal Cultures

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Introduction

In fact sheets (FAPC-191 and FAPC-192), principles of photosynthetic microalgae growth and photobioreactor designs are discussed. This fact sheet will cover downstream processing of microalgae cultures, which involves the following steps: 1) cell harvesting, 2) drying and 3) biomass processing (i.e. extraction, conversion and refining of the crude product).

Cell Harvesting

In general, biomass is separated from the growth medium when microalgae cells reach the stationary phase of their growth. The highest biomass concentration in the culture medium would vary from 0.1 to 3 g/L (rarely up to 5 g/L) depending on the reactor type, algae strain and the growth conditions. Microalgae harvesting is a very challenging process because of the very small size of the cells (1-30 micron) and dilute culture biomass concentration, which requires handling of large volumes of water.

Microfiltration and settling methods are not very efficient for separating algal biomass from the culture medium because of the small size and low specific gravity of the cells. Microfiltration is a simple and relatively inexpensive process. The filter pore size is critically important for efficient filtration. Small algae cells pass through large pores resulting in biomass loss. When a filtration medium with small pore size is used, cells get trapped in the pores fouling the filtration medium; consequently, reducing the permeate flow rate and process efficiency. Therefore, filter medium pore size needs to be optimized for specific applications.

Centrifugation of the culture results in efficient biomass recovery. Nonetheless, the capital and operating costs of the centrifuges are high. Flocculation of the cells prior to filtration, centrifugation or settling is a common practice to improve biomass recovery. Chemical additives such as alum, lime, cellulose, salts, polyacrylamide polymers, surfactants, chitosan and other synthetic fibers have been examined as flocculants.

Adjustment of the pH of the culture medium is an effective method for cell flocculation. An acid or base solution is used for pH adjustment. Electroflocculation and electrocoagulation methods, which are based on the manipulation of the electric field in the culture medium, eliminate the need for chemical additives. Various combinations of flocculation and other separation techniques can be used to improve biomass recovery (i.e. flocculation + settling, flocculation + microfiltration or flocculation + air flotation).

The other harvesting technologies that have been examined for algal biomass recovery include: 1) growing microalgae on immobilized substrates, which can be easily removed from the culture medium, 2) ultrasound induced aggregation followed by sedimentation, 3) bio-harvesting where microalgae are grown with higher organisms such as shrimp and fish and harvested together, and 4) bio-flocculation where algae are co-cultured with another organism that promotes sedimentation. For example, an algae strain, *Skeletonema*, was used to form flocs of *Nannochloropsis*, another microalgae strain.

Microalgae harvesting costs can be substantial at 2-3 percent of the total system capital cost. The most efficient flocculation technique and processing parameters for a given operation will depend on the algae strain, cell concentration, pH and chemical composition of the medium. Cost, environmental impact and scalability of the flocculation process, the effect of the residual flocculants in the harvested biomass on downstream processing, and quality of the water effluent for recycling and disposal are very important factors that need to be evaluated while choosing a flocculation technique.

Drying

Drying algal biomass may preserve its chemical integrity, enhance shelf life, reduce shipping and transportation costs, and prevent microbial growth during storage and handling, consequently, eliminating contamination by other microorganisms. Furthermore, some of the downstream processes may require low moisture biomass (i.e. oil extraction).

The traditional techniques such as spray drying, freeze-drying, solar drying and convective hot air drying have been used to dry algal biomass. Biomass is exposed to high heat for an extended time during drum drying to produce a product in flake form. Spray drying is efficient, but may rupture the cells during the high pressure atomization of the culture and cause product degradation because of the high temperature in the dryer. Spray drying produces a product in powder form. It is difficult to maintain the quality of the biomass during open sun drying. Besides contamination issues, the slow drying rate due to low temperature may lead to biomass degradation and microbial growth. A closed solar device generating a high temperature in the dryer could lead to a high drying rate and may produce a good quality dry biomass. Freeze drying minimizes biomass degradation, but it is an expensive batch process. Selection of a suitable drying technique for a given application will depend on the type of the product to be produced from the algal biomass. The cost of the drying process can be 2-3 percent of the total system's capital cost.

Biomass Processing

Algal biomass can be used to produce a diverse range of products such as food, nutritional compounds, omega-3 fatty acids, animal feed, organic fertilizers, biodegradable plastics, recombinant proteins, pigments, medicines, pharmaceuticals, vaccines and fuels including jet fuel, aviation gas, biodiesel, gasoline and bioethanol. Conversion of biomass to an end product can be achieved via selective conversion of individual biomass components. For instance, cellulose in algal biomass can be converted to intermediate platform chemicals. Then, these chemicals are reacted to produce a final product. This may require separation of cellulose, or the compound of interest, from the other cell components prior to conversion. An alternative process could utilize whole cells for conversion. Utilization of whole cells rather than isolated compounds (extracted and purified) may reduce the number of unit operations needed for a conversion process. Conversion efficiency may decline due to the complex nature of the whole cell matrix, potential side reactions, and limited mass and energy transfer due to the presence of the other cell components in the reaction medium. The end product, then, needs to be separated from the reaction mixture including the cell debris after the conversion. As such, biodiesel can be produced in situ by using the whole cells rich in oil. Alternatively, oil is extracted from the cells using a solvent; cell debris and solvent are removed, and oil is refined before extracted oil is converted to biodiesel.

Chemical, biological or thermochemical pathways can be utilized for converting algal biomass to fuels and other products. Thermal processes use heat for the conversion. Torrefaction, pyrolysis and gasification are some of the thermal processes used for biomass conversion.

Torrefaction of biomass, is a milder form of pyrolysis that is performed at temperatures typically ranging between 200 and 320 degrees Celsius. Torrefaction leads to a dry product with no biological activity. During torrefaction, the biomass properties are changed to obtain a higher quality fuel for combustion and gasification applications.

Pyrolysis is a thermochemical decomposition that takes place at elevated temperatures (higher than 200–300 degrees Celsius or 390–570 degrees Fahrenheit) in the absence of oxygen or any halogen. The pyrolysis can be carried out with or without a catalyst. Fast pyrolysis, which is performed at about 500 degrees Celsius and very high heating and heat transfer rates, requires a finely ground dry biomass feed of typically less than 3 mm particle size and short hot vapor residence times, less than 2 seconds, to minimize secondary reactions. Bio-oil obtained by condensation of the pyrolysis gas needs to be refined to obtain the final product of interest.

Gasification also requires dry biomass and converts it into carbon monoxide, hydrogen and carbon dioxide at high temperatures (higher than 700 degrees Celsius), without combustion in the presence of a controlled amount of oxygen and/or steam. The resulting gas mixture is called syngas or producer gas. Syngas may be burned directly in gas engines, used to produce methanol and hydrogen, or converted into synthetic fuel or chemicals. Many of the conversion processes such as syngas to methanol, olefins (ethylene and propylene), and other similar chemical or fuel processes are based on the methods developed for coal (i.e. the Fischer-Tropsch synthesis).

Hydrothermal liquefaction (HTL) is a thermal process that utilizes pressurized water to convert whole, wet algae to a liquid that can be further refined into fuels or other products. First, algae culture is dewatered to about 20 percent solid content (percent by weight). Then, the liquefaction takes place in a reactor at high temperature and pressure. Four phases, which include oil, solid, aqueous and gas, are produced during the process. The oil can be hydrotreated to produce diesel. The aqueous phase is catalytically treated to recover the carbon content and allow water to recycle back into the ponds. Process off gas may be used to generate hydrogen, heat and/or power.

Biochemical conversion processes make use of the enzymes of bacteria and other microorganisms to break down biomass. In most cases, microorganisms are also used to perform the conversion process: a) anaerobic digestion, b) fermentation and c) composting. In general, biochemical processes are carried out under mild conditions that may minimize the formation of by-products and preserve other potentially valuable co-products such as proteins, carotenoids and vitamins. Biochemical conversion processes may potentially eliminate some of the algal biomass pretreatment steps (i.e. drying and extraction).

Biodiesel production can be performed by simultaneous enzymatic hydrolysis, esterification and transesterification of whole algae or algal oil extracts. Application of multiple enzyme cocktails to whole algae enables simultaneous or sequential production of lipid and fermentable sugar-based products.

An algal biomass conversion process, which is still under investigation, includes the following steps: a) biomass pretreatment, b) bioconversion and c) refining. First, algal biomass (20 percent solids by weight) is combined with steam and treated with dilute sulfuric acid catalyst at a high temperature for a short time to hydrolyze the glucan carbohydrates to monomeric sugars and make the remaining biomass more amenable to lipid extraction. The pH of the treated slurry is raised to about 5 by adding ammonia prior to fermentation. The treated biomass is cooled and brought back to 20 percent solid content and then inoculated with the fermenting organism *Saccharomyces cerevisiae*. For this process enzymatic hydrolysis is not required because the biomass is already acid hydrolyzed in the previous step. Fermentation proceeds in batch mode for about 1.5 days and converts most of the sugars (primarily the hexose sugars glucose and mannose) to ethanol. The resulting dilute ethanol broth is distilled to near azeotropic concentration and then purified to 99.5 percent. The slurry containing all residual solids can be used for lipid extraction using hexane. The micelle, crude oil + hexane, from the extraction process is routed to a stripping column to recover the solvent, hexane. The desolventized crude oil needs to be refined to remove polar lipids and other impurities before conversion to other products. The purified oil consisting primarily of fatty acid based lipids can be hydrotreated to produce a product, which is suitable as a diesel blend stock and a small amount of naphtha as a co-product. The oil can also be converted to biodiesel by chemical or enzymatic transesterification reaction.

Carbon dioxide generated during the fermentation process can be recycled to upstream algal cultivation ponds. The aqueous phase from the entire process can be routed to anaerobic digestion for biogas production and/or recycled to the process after treatment. The digester's effluent water and solid cake contain nitrogen and phosphorus nutrients that can be used as fertilizer.

Conclusions

The systems for algal biomass production as aquaculture feed have been around since the 1950s. In the U.S. there are several companies marketing microalgae based dietary supplements and high-value specialty products such as oils. Most of the microalgae to biofuel, bioproduct or chemical production processes discussed in this fact sheet are still at developmental stage. The process economics rather than the technological issues appear to be the main hurdle for commercial utilization of algal biomass as feedstock for diverse range of products to replace fossil fuels or nonrenewable feedstock.

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Bringing the University to You!

The Cooperative Extension Service is the largest, most successful informal educational organization in the world. It is a nationwide system funded and guided by a partnership of federal, state, and local governments that delivers information to help people help themselves through the land-grant university system.

Extension carries out programs in the broad categories of agriculture, natural resources and environment; home economics; 4-H and other youth; and community resource development. Extension staff members live and work among the people they serve to help stimulate and educate Americans to plan ahead and cope with their problems.

Some characteristics of Cooperative Extension are:

- The federal, state, and local governments cooperatively share in its financial support and program direction.
- It is administered by the land-grant university as designated by the state legislature through an Extension director.
- Extension programs are nonpolitical, objective, and based on factual information.
- It provides practical, problem-oriented education for people of all ages. It is designated to take the knowledge of the university to those persons who do not or cannot participate in the formal classroom instruction of the university.
- It utilizes research from university, government, and other sources to help people make their own decisions.
- More than a million volunteers help multiply the impact of the Extension professional staff.
- It dispenses no funds to the public.
- It is not a regulatory agency, but it does inform people of regulations and of their options in meeting them.
- Local programs are developed and carried out in full recognition of national problems and goals.
- The Extension staff educates people through personal contacts, meetings, demonstrations, and the mass media.
- Extension has the built-in flexibility to adjust its programs and subject matter to meet new needs. Activities shift from year to year as citizen groups and Extension workers close to the problems advise changes.