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Algae Based Biofuel (ABB): A Review of Novel Technologies

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Abstract

The increasing demand for petroleum based fuels, global warming and environmental pollution has driven the world to search for newer, safer and cleaner sources of fuel. Also, the transportation sector in India is dependent on petroleum and other non-renewable sources of energy. In view of the increased attention to climate change, there is a renewed focus on alternative fuels. Algae have recently received a lot of attention as a new biomass source for the production of renewable energy. Some of the main characteristics which set algae apart from other biomass sources are that algae (can) have a high biomass yield per unit of light and area, can have a high oil or starch content, do not require agricultural land, fresh water is not essential and nutrients can be supplied by wastewater and CO_2 by combustion gas. This paper investigates the ABB production techniques available to holds future promise for developing countries like India.

Keywords- **Biofuel; Algae; Renewable energy; Biomass.**

I. INTRODUCTION

In this paper, we explore each of the primary stages of algae-to-biofuel production and the associated environmental implications. Based on available peer-reviewed journal articles and other scientific publications, news releases, industry workshops, and personal communications with academic experts and entrepreneurs, we have summarized the state of knowledge around the environmental challenges of individual production pathways. The primary stages are categorized as: 1) pathways for algae cultivation; 2) pathways for biomass harvesting; 3) pathways for algal oil extraction; and 4) pathways for oil and residue conversion.

II. PATHWAYS FOR ALGAE CULTIVATION

Algae are an attractive biofuels feedstock compared to other biofuel sources. Their rapid growth rate (doubling in 6–12 hours), high oil content (4–50 percent or greater of nonpolar lipids), biomass harvest (100 percent), and nonseasonal harvest intervals have led to claims of algae biofuel yields that are theoretically orders of magnitude higher than other biofuels feedstock. Nevertheless, the diversity of algal characteristics and lack of scientific and industry consensus have so far made it difficult to forecast the true potential of algae as a fuel feedstock. The purpose of algae cultivation is to grow raw algal biomass for the downstream production of fuel, based on the oil and residual components found in the biomass. In order to flourish, algae need water, carbon dioxide, and essential nutrients, which are collectively referred to as the culture medium; algae cultivation facilities need land or other area to occupy; and, in most cases, algae need light to drive photosynthesis. The varying manners in which water, nutrients, land, and light are supplied and managed for cultivation will have some effect on the environment, especially at the commercial scale. One of the first steps in understanding the potential environmental impact of algae as a mass-produced biofuels feedstock begins with the cultivation process, where algae are grown by a variety of methods. Historically, the two primary classifications for algal cultivation systems are open systems and closed photo-bioreactors. Closed (photosynthetic) cultivation systems can be further subdivided into indoor and outdoor photo-bioreactors. Variations on cultivation systems have also emerged, such as hybrid (combined open and closed) cultivation, heterotrophic cultivation (without light), and integrated biofixation systems. In addition, there are other cultivation systems being implemented and new technologies being explored, including offshore cultivation, aquaculture, and ethanol sweating, which could become viable pathways as the industry develops; however, they are not within the scope of this report. These five pathways—open systems, hybrid systems, closed photobioreactors, heterotrophic fermentation, and integrated biofixation systems—have been selected for discussion because they best represent the myriad approaches currently being researched and implemented for algal biomass production. Although thorough technoeconomic comparisons have not been made among these five pathways and there remain considerable unknowns as to the economics behind each one, this section will provide an overview of the pathways, including system characteristics and core environmental issues as they relate to a scalable biofuels industry.

Open Systems

Open systems, often implemented for their technical simplicity and relative affordability, are the most common method of cultivation today. System Characteristics Open systems are comprised of one or several shallow ponds—preexisting or man-made—that are exposed to the atmosphere, either outdoors or sheltered in greenhouses. They can take a variety of forms such as circular, lagoon, or raceway, the latter of which is the most common open system used for commercial algae cultivation. Modern, commercial-scale open systems are typically designed as high- (growth) rate algal ponds (HRAP) in raceway formation (Figure 1) with a paddle wheel, wave pump, or baffles for circulating water with nutrients, gases, and algae (see Pathway Map A-I). Circular ponds, extensive ponds, and aerated lagoons are also commonly implemented, though not necessarily with the same mixing capabilities. Open pond systems operate in several locations throughout the world. In the United States, there are many examples of established pond systems, such as Earthrise Farms (California), HR Biopetroleum and Cyanotech Corp. (Hawaii), and Green Star Products, Inc. (Montana). Optimal design parameters for large-scale, open pond cultivation have been known for many years. The primary inputs to open pond systems are algae, light, nutrients, and water.

Fig.1: Algae cultivation in open system.

Algae

Open pond systems are typically designed for photoautotrophic monocultures. At a given temperature, most algal species share similar environmental parameters, including abundant light, ample nutrients, and a pH that is characteristic of the growth medium. Most algal species cultivated commercially in open systems (i.e., Chlorella, Spirulina, and Dunaliella), while not necessarily for the purpose of biofuels production, are grown in highly selective, open air environments that remain relatively free of contamination by other algae and protozoa. One of the main disadvantages of open systems is that parameters are harder to control than in closed systems. Management of environmental factors is very important in maintaining pure monocultures in open ponds. Because of a long light path, relatively poor mixing, and low photosynthetic efficiency, which lead to low biomass concentration and volumetric productivity, the algae growing season is largely dependent on location and is limited to warmer months when more light is available. Nevertheless, open ponds are the most common, commercially used algae cultivation systems in operation today. Since the system is open, the culture is vulnerable to contamination. Contamination in open ponds is often described as predation or predominance of unwanted algal species or strains, algal weeds, microbes, or other non-algae organisms. Bacterial and viral diseases (phycodna viruses) could potentially pose an even greater threat to the integrity of large-scale monocultures. Algal culture exposed to contamination can result in decreased quality and yield of the biomass. A sterile environment with controlled parameters, such as temperature, pH, nutrients, and salinity helps produce an algal biomass with maximum desired characteristics such as high density or high oil content. Therefore, only a few species that can grow in such selective environments can be grown in open systems.

Light

Ample light is required as a primary characteristic of any photosynthetic system. Without light, algae will not be able to convert solar radiation into energy for growth. The surface of an open pond has greater photosynthetic efficiency than photobioreactors because the ponds have more surface area, meaning greater access to sunlight. Nevertheless, natural illumination presents many challenges to efficient production of algae, such as climatic, seasonal, regional, and diurnal light and temperature variations, as well as the capacity of algal cells to utilize available natural light. Cloud coverage also redirects irradiation, with an adverse effect on biomass productivity. Mutual shading will influence algal growth rates as well. Paddle wheels help mix algae, balancing their exposure to light. When no mixing occurs, the algae on the water’s surface get too much light, causing photoinhibition (limiting growth), and the algae underneath the surface do not get any light, also preventing growth. In addition, cell division (growth) and lipid accumulation (energy content) in algae are understood to be mutually exclusive. Manipulation of certain biological and/or environmental parameters can help determine which of these characteristics is promoted foremost.

Water

Open systems can utilize many different types of water, including fresh, brackish, alkaline, marine, eutrophic, or mixed waters. The type of water available may dictate the type of cultivation system implemented, the species of algae cultivated, and the nutrients needed. Using low-quality water for algae cultivation has a few significant benefits, which will be touched upon throughout this report. Brackish waters or effluent streams utilized for cultivation may vary in quality based on seasonal environmental conditions and the presence of fertilizers, pesticides, metals, and other waste. Variation in water quality may in turn be detrimental to the quality of biomass produced. For instance, algal biomass cultivated from effluents high in heavy metals (where algae uptake these metals) may not be suitable for converting into animal feed. Management (recovery and disposal) of the metal and chemical byproducts will be important.

III. PATHWAYS FOR BIOMASS HARVESTING

Once an algal culture reaches maturity, the biomass is harvested from the culture medium and dried in preparation for conversion. Biomass harvesting may be one of the more contaminating processes in the production of algae-based biofuels. At this stage, algal biomass from the preceding cultivation system typically carries a high water content and, in most cases, is not suited for conversion to biofuel products until it has undergone some degree of dewatering and drying. There are three systemic components of the harvesting process: biomass recovery, dewatering, and drying. Some pathways employ all three processes, whereas others may only employ one or two of these processes. Biomass Recovery Recovering the algae and disposing or recycling of the process water represent two energy intensive and potentially significant environmental challenges to sustainable algae-based biofuel production. Recovery Techniques and Characteristics There are several techniques for recovering algal biomass, the implementation of which may vary depending on existing pond conditions or PBR design. The most commonly implemented techniques are flocculation, dissolved air flotation, centrifugation, microfiltration, and decantation, each of which is discussed briefly. Additional techniques—discrete sedimentation, membrane filtration, phototactic autoconcentration, tilapia-enhanced sedimentation, tube settling, and ultrasonic separation—may also be considered viable pathways to biomass recovery, but are beyond the scope of this report. Flocculation is a process, often implemented with the help of flocculating agents or flocculants (chemicals of natural or synthetic origin), that causes the coagulation of algal cells into small clumps, known as flocs, allowing for sedimentation and easy extraction from the culture medium. Flocculation is the historically preferred recovery technique for its simplicity and variety of mechanisms, including autoflocculation, bioflocculation, electroflocculation, foam flocculation, inorganic chemical flocculation, ozone flocculation, and polyelectrolyte flocculation. These and other mechanisms of flocculation are familiar to the engineering of waste and water treatment. Bioflocculation, chemical flocculation, and electroflocculation are discussed here to introduce the range of mechanisms and the potential environmental impact of flocculation in general. Bioflocculation—an approach to water treatment that can be traced back 2,000 years.93 It uses naturally occurring, biodegradable polymeric (e.g., Chitosan, sodium alginate) or a microbial (e.g., Pestan) flocculants to coagulate the algal cells.

IV. PATHWAYS FOR ALGAE OIL EXTRACTION

In recent years, many calculations for theoretical oil yields from algae have been made. The biomass generated from algal growth and cell division is known to reach oil contents of up to 80 percent, making algal biomass an appealing candidate for biofuel feedstock. Although the actual oil content (2–80 percent), measured in gallons/acre/year, will depend on many parameters, there is certainly a scientific basis allowing projection of potential yields that are orders of magnitude larger than current biofuel technologies. However, while there is a range of practical and theoretical oil yield estimates publicly available, in this section we identify the technologies and environmental impacts associated with extracting oil from the algal cells, and oil yields will only be referred to in terms of technological efficiencies. At this stage in the biofuel production process, the percent yield of total available oil from the biomass will depend on the efficiency of the extraction method used. In some instances, technologies may be favored for their superior performance (e.g., chemical extraction) over less efficient technologies (e.g., mechanical extraction), despite higher environmental costs. Depending on the desired fuel product, algae will undergo a variety of treatments to manipulate the oil and residue. This section discusses methods for extracting algal oil for conversion to biodiesel. Algal oil is typically extracted by mechanical, chemical, or electrical means, whereas bio-oil is extracted with the use of chemicals and high temperatures. This difference is important because each pretreatment yields either algal oil or bio-oil, two chemically distinct feedstocks possibly with differing environmental implications which are subsequently converted to different fuel products. The next section will discuss oil and residue conversion pathways, including pretreatments for biooil. Extraction Techniques and Characteristics Oil extraction from algal biomass yields algal oil (triglycerides or TAG lipids) and residue (carbohydrates, proteins, nutrients, ash). Algal oil extraction can be achieved via a number of techniques such as mechanical expulsion, solvent extraction, or supercritical fluid extraction. Osmotic shock and sonication are less common methods and are only discussed briefly. Mechanical Expulsion Mechanical technologies for extracting algal oil include the screw press, extruder and expander, and pulverization in a mortar. In the mechanical expulsion process, oil is expelled from dried algal cells by one or more of these methods Machines that combine these technologies for increased extraction efficiencies are also available. Process inputs are basic electricity to power the machinery. Possible innovations could help overcome the inefficiencies of mechanical technologies, including genetically modifying algal strains to have weaker cell walls that can be broken under lower pressures or low-heat pretreatment. A combination of mechanical expulsion and chemical solvents also holds the potential to increase efficacy of the extraction process. Breaking the cells under the high pressure of a mechanical press may cause the fusion of lipid droplets with cellular membrane material that leads to a loss of oil. When mechanical methods are paired with hexane solvent extraction, this “lost” oil can be recovered. Solvent Extraction Hexane (or chloroform) is a relatively inexpensive chemical commonly used in oil extraction from soybeans and other plants and is now being explored for its efficiency in expelling oil from algal cells. Hexane solvent extraction mixes hexane with the algal biomass. The oil dissolves in the hexane and the biomass can be filtered out from the medium through distillation. Although this process can be used effectively in isolation, coupled with press expulsion these two processes are capable of extracting most of the total available algal oil. Supercritical Fluid Extraction In the supercritical fluid extraction process, oil is extracted from the algal cells with a solvent, such as methanol or liquefied CO_2, and heated under pressure up to or above its critical point. The process has the efficiency and ability to isolate oil components leading to the extraction of almost 100 percent of the oils. The liquefaction of a solvent for supercritical extraction is often an energy-intensive process. The temperature and pressure (critical point) at which the fluid liquefies vary depending on the type of solvent used (Table 3), which would determine respective energy inputs. Osmotic Shock Osmotic shock is the sudden reduction in the movement or concentration of water across the algal cell membrane. The stress from the rapid change in movement, created by the addition of high concentrations of a solute or other additive (e.g., salt, substrates, neutral polymers such as polyethylene glycol, dextran) causes the cells to rupture, releasing the oil. Sonication uses an ultrasonic reactor (sonicator) to make acoustic shock waves and liquid jets that induce algal cell walls to break and release their contents into the medium without the use of toxic solvents. Environmental Impacts of Extraction Environmental issues concerning sustainable oil extraction include recalcitrant biomass residue, chemical solvents, and energy demand. Recalcitrant Biomass Residue After the main portion of the biomass is separated into oil, protein, and starch, there will be a portion left over consisting mostly of metals, salts, lignin, and other recalcitrant matter that will need to be managed. The environmental implications of the processing, such as via anaerobic digestion or disposal of recalcitrant biomass, will need to be considered for commercial-scale systems. Chemicals Because of the inefficiencies of mechanical expulsion technologies (where up to 10–25 percent of the oil can be lost), stronger consideration may sometimes be given to chemical extractions, such as supercritical fluid extraction, to provide an improved yield. The specific solvent used (e.g., CO_2, methanol, hexane), if any, will determine the environmental impact of the extraction process. Since volatile chemical solvents have inherent health and safety problems as well as environmental toxicity, the feasibility of storage, handling, and disposal may have additional implications. For example, the hexane extraction process can cause lethal explosions in laboratory and commercial settings.

V. PATHWAYS FOR OIL AND RESIDUE

Conversion to Biofuels

Once the biomass is separated into raw algal oil and residue, the energy content of the two components can be thermally or biologically transformed to liquid or gaseous fuels or solid coproducts. Conversion pathways include transesterification, fermentation, anaerobic digestion, gasification, pyrolysis, liquefaction, and hydroprocessing. These pathways are discussed below according to whether the technology is biochemical or thermochemical. Industry may categorize these technologies in a different manner; however, the goal of this section is not so much to define pathways (e.g., pretreatment vs. conversion) as to identify major environmental issues associated with them. These conversion pathways are nearly identical to those for converting first- and second-generation biofuel feedstocks; hence, this section does not focus on differentiating the conversion of algal biomass from other feedstocks. The descriptions are kept brief the nuances of each conversion system are generally excluded—while greater emphasis is put on environmental benefits, concerns, and unknowns in the event such a technique is applied to an algae biofuel production pathway. These descriptions are meant to provide the reader only with a general understanding of the range of processes being explored by algae biofuel producers and the relationship between the conversion process and preceding (upstream) processes in a production pathway. An overview of potential bioproducts is also presented to provide context for this discussion about oil and residue conversion pathways. Conversion Pathways Depending on the condition or quality of the biomass and the intended fuel application, a range of conversion pathways could be pursued. Bio-oil is chemically distinct from algal oil and must therefore be converted to biofuel under different conditions. When biomass is pretreated thermochemically, via pyrolysis or liquefaction, it produces intermediate products bio-oil and residue. Once the biomass is separated into oil and residue (nutrients, proteins, carbohydrates, ash), transesterification can convert algal oil to biodiesel; hydroprocessing can convert algal oil and bio-oil to green or renewable biofuels; and much of the residue can be biochemically or thermochemically converted to a gaseous fuel or a solid, nutrient-rich bioproduct. Biofuel Products Conversion processes are of varying efficiency depending on reaction temperature, pressure, heating rate, and catalyst type, as well as algal species and quality of biomass—theoretically converting algal biomass (or components of biomass) into several possible biofuels and coproducts. There are essentially two categories of biofuels being produced today i.e. hydrocarbons and oxygenates. Hydrocarbon Biofuels Hydrocarbons are fuels such as gasoline, diesel, and jet fuel that do not contain oxygen. Bioderived hydrocarbon fuels are products of thermochemically converted algal oil or biooil and are sometimes referred to as green or renewable gasoline, diesel, and jet fuels. Fuel properties will differ based on biomass origin, fuel type, and country specifications. One of the foremost qualities of hydrocarbon biofuels is that they are drop-in replacements for existing petroleum-based transportation fuels. Other hydrocarbon fuels include methane (CH_4), ethane (C_2H_6), and propane (C_3H_8).

VI. CONCLUSION

Algal biomass holds the potential to meet a significant portion of our global fuel demand, and with 320 billion gallons of motor fuel consumed every year worldwide the potential demand for cleaner, renewable algae biofuels is enormous.

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