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Bilal M. McDowell Bomani, Dan L. Bulzan, Diana I. Centeno-Gomez, and Robert C. Hendricks
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Abstract

The use of biofuels has been gaining in popularity over the past few years because of their ability to reduce the dependence on fossil fuels. As a renewable energy source, biofuels can be a viable option for sustaining long-term energy needs if they are managed efficiently. We investigate past, present, and possible future biofuel alternatives currently being researched and applied around the world. More specifically, we investigate the use of ethanol, cellulosic ethanol, biodiesel (palm oil, algae, and halophytes), and synthetic fuel blends that can potentially be used as fuels for aviation and nonaerospace applications. We also investigate the processing of biomass via gasification, hydrolysis, and anaerobic digestion as a way to extract fuel oil from alternative biofuels sources.

1.0 Introduction

There is worldwide interest in biofuels as a renewable energy source for long-term fuel sustainability because of the predictable depletion of fossil fuels. The world is increasingly accepting the fact that conventional sources of fuel and energy are being rapidly depleted and cannot be renewed. Unlike other renewable energy sources, biomass is a fully renewable resource that can and is used for biofuels, power, chemicals, materials, and other products, and generates virtually no net greenhouse gas. What is needed is a safe, reliable, and efficient method of generating renewable biofuels that can potentially replace or mitigate fossil fuel dependence. We present an overview of the use of several biofuels as well as their advantages, disadvantages, and potential applications within the aviation industry.

While fossil fuels have their origin in ancient biomass, they are not considered biomass by the generally accepted definition because they contain carbon that has been “out” of the carbon cycle for a very long time. Their combustion therefore disturbs the carbon dioxide content in the atmosphere (Ref. 1).

Biomass generally refers to any plant, plant-derived material, or biodegradable waste material that can be used for fuel or industrial production. It does not include such organic material as coal or petroleum and is usually measured by dry weight. Biomass is grown from several plant types including but not limited to corn, poplar, perennial grasses, willow, and sugarcane. Biomass can be converted directly into liquid fuels or biofuels for use as an alternative fuel in cars, trucks, buses, aircraft, and trains. Ethanol and biodiesel are the two most common types of biofuel currently being used as alternative fuel sources today.

Bockris (Ref. 2) predicts that Hubbert’s Peak (the peak of the entire planet’s oil production) will be reached by 2011 and the world economy will be threatened by energy starvation. Demirbas (Ref. 3) reviewed the modern biomass-based transportation fuels such as fuels from Fischer-Tropsch synthesis, bioethanol, fatty acid (m)ethylester, biomethanol, and biohydrogen. Bockris and Demirbas present the basic concepts involved in the thermochemical conversions of biomass fuels and conclude that the reduction of greenhouse-gas pollution during its processing is the main advantage of utilizing biomass energy.

Watkins (Ref. 4) explored how countries are switching to biofuels instead of relying on oil and natural gas. Indonesia, a member of the Organization of Petroleum Exporting Countries, is planning to operate biofuel-fired power plants in 2007. The plants would use palm oil as their main energy source. Malaysia is forecast to export 1 million tons of biofuel next year.

2.0 Types of Biofuels

2.1 Ethanol

Ethanol is an alcohol-based alternative fuel produced by fermenting and distilling starch crops that have been converted into simple sugars. Ethanol has been used as fuel in the United States since at least 1908. Primary feedstocks for this fuel include corn, barley, and wheat. Ethanol can also be made from other products such as grain sorghum (milo), sugar cane, beets, cheese whey, and potatoes. Ethanol is by far the most popular biofuel in use today in the United States of America. It is a high-octane, clean-burning, and renewable fuel. Ethanol is produced at more than 100 facilities across the Nation, most in the Midwest, and then blended into unleaded gasoline in varying percentages. Ethanol is most commonly retailed as E10, the 10 percent blend of ethanol for use in all automobiles. It is also available as E85, the 85 percent ethanol blend for use in flexible fuel vehicles.

Corn, the predominant ethanol feedstock, is converted to ethanol in either a dry or wet milling process. In dry milling operations, liquefied corn starch is produced by heating corn meal with water and enzymes. A second enzyme converts the liquefied starch to sugars, which are fermented by yeast into ethanol and carbon dioxide. Wet milling operations separate the fiber, germ (oil), and protein from the starch before it is fermented into ethanol.

With few exceptions, corn is the primary feedstock for U.S. ethanol production. In the United States, over 95 percent of all ethanol produced comes from corn feedstock.

The production of ethanol from corn is a mature technology that is not likely to see significant reductions in production costs. Substantial cost reductions may be possible if cellulose-based feedstocks (discussed below) are used instead of corn (Ref. 5). The ability to produce ethanol from low-cost biomass will be key to making ethanol competitive with gasoline.

In 2004, 3.4 billion gal of ethanol were produced in the Nation, up from 2.81 billion gal the previous year. By the end of 2005, the ethanol industry reached a capacity of more than 4 billion gal. By the end of 2006, the total capacity reached nearly 5.5 billion gal (Ref. 6). Ethanol producers were predicted to produce the equivalent of 3 percent of U.S. gasoline consumption in 2006.

Concerns are being raised (Ref. 7) on the amount of energy required to grow and convert corn or biomass into ethanol. It is also expected that corn prices will increase significantly and people around the world will suffer as corn-based products become more expensive. Corn prices are increasing because of increasing demand for water to sustain the corn-based crops and the production of ethanol, leading to an increase in the prices of cattle, hogs, poultry, meat, milk, and cheese in the country.

Based on the findings of (Ref. 8), ethanol production using corn grain required 29 percent more fossil energy than the ethanol fuel produced. Ethanol production using switchgrass required 50 percent more fossil energy than the ethanol fuel produced. Ethanol production using wood biomass required 57 percent more fossil energy than the ethanol fuel produced. Biodiesel production using soybean oil required 27 percent more fossil energy than the biodiesel fuel produced. Biodiesel production using sunflower oil required 118 percent more fossil energy than the biodiesel fuel produced.

Ethanol has enjoyed some success as a renewable fuel, primarily as a gasoline volume extender and also as an oxygenate for high-oxygen fuels. A large part of its success has been the Federal ethanol subsidy. However, the U.S. Government ethanol subsidy has expired in 2008, and it is not clear whether ethanol will continue to receive Government support. The lack of Government support might affect ethanol’s ability to compete against crude oil.

Ethanol costs could be reduced dramatically if efforts to produce ethanol from biomass are successful. Biomass feedstocks, including forest residue (wood chips) and agricultural residue (straw, compost, and prairie grass), are abundant and relatively inexpensive, and they are expected to lower the cost of producing ethanol and provide stability to supply and price.

An energy production investigation (Ref. 9) concluded that ethanol production from corn wastes energy and requires a total input of 140 gal of fossil fuels and costs $347 per acre. The conversion of the feedstock into ethanol requires additional energy for the distillation, which concentrates the dilute alcohol solution from the fermented broth into fuel ethanol. The conversion requires 131 000 Btu of energy per gallon of ethanol. A gallon of ethanol has an energy value of 77 000 Btu, and therefore the energy loss is 54 000 Btu/gal of ethanol. The investigation concluded that the United States needs its cropland to produce food and not motor fuel. In addition, the feasibility of replacing any fossil fuel with biomass awaits improved technology.

In contrast, Shapouri et al. (Ref. 10) estimated the net energy balance of corn ethanol utilizing the latest survey of U.S. corn producers and the 2001 U.S. survey of ethanol plants. The major objectives of this report were to improve the quality of data and methodology used in the estimation. These results indicate that corn ethanol has a positive energy balance, even before subtracting the energy allocated to producing byproducts. The net energy balance of corn ethanol adjusted for byproduct credits is 27 729 and 33 196 Btu/gal for wet and dry milling, respectively, and 30 528 Btu/gal for the industry. The study results suggest that corn ethanol is energy efficient, as indicated by an energy output/input ratio of 1.67.

Since conventional ethanol relies on simple sugars, it works best when derived from crops that concentrate starches in their seeds. That is why corn makes a better feedstock than wheat, and sugarcane makes a better feedstock than corn. But the same quality also limits conventional ethanol's efficiency when it comes to mass production since it can only use a relatively small portion of each plant and hence, a lot of biomass goes unused in the process.

Ethanol is commonly used in transportation and agriculture to fuel internal combustion engines. It is typically used as a direct replacement for gasoline or blended with gasoline as an extender and octane booster. One major disadvantage to using ethanol is that vehicle distance is limited by the availability and distribution of ethanol. In addition, ethanol does not ignite under compression and does not mix well with diesel fuel, which limits its use for unmodified aircraft engines. To this end, a recent trend is the use of cellulosic ethanol, which is discussed in the following section.

2.2 Cellulosic Ethanol

Cellulosic ethanol, also called cellanol, is ethanol fuel produced from cellulose. Cellulose is a naturally occurring complex carbohydrate polymer commonly found in plant cell walls. Cellulosic ethanol is chemically identical to ethanol from other sources such as corn or sugar but is available in a great diversity of biomass including waste from urban, agricultural, and forestry sources. Processing cellulosic ethanol differs from ethanol because it requires an extra step called cellulolysis, or the breaking down of cellulose into sugars. It is more difficult to break down cellulose to convert it into usable sugars for ethanol production. However, making ethanol from cellulose dramatically expands the types and amount of available material for ethanol production.

There are at least two cellulosic production methods: the cellulolysis method, which is hydrolysis followed by fermentation of the generated free sugars, and gasification, which is sometimes called systhesis gas fermentation or catalysis (e.g., the Fischer-Tropsch process). It should be noted that neither process generates toxic emissions when it produces ethanol.

Cellulosic ethanol and conventional, grain-based ethanol have identical molecules, but they differ in that conventional fuel ethanol is derived from only a small fraction of biomass feedstock, the edible parts of corn or other feed grains, while cellulose ethanol is made from the nonfood portion of renewable feedstocks, such as cereal straws and corn stover (leaves and stems), or other energy crops. Although the refining process for cellulosic ethanol is more complex than that of corn-based ethanol, cellulosic ethanol yields a greater net energy benefit and results in much lower greenhouse-gas emissions.

Cellulosic ethanol can be produced from a wide variety of cellulosic biomass feedstocks including but not limited to agricultural residues (rice, corn stover, and wheat straw), agricultural wastes (sugar cane, bagasse waste, rice husks, and citrus pulp), forestry and wood wastes (including willow and poplar), municipal solid waste (including paper pulp and saw dust), and energy crops (switchgrass).

Cellulosic biomass is composed of cellulose, hemicellulose, and lignin, with smaller amounts of proteins, lipids (fats, waxes, and oils), and ash. Roughly, two-thirds of the dry mass of cellulosic materials are present as cellulose and hemicellulose. Lignin makes up the bulk of the remaining dry mass.

As with grains, processing cellulosic biomass aims to extract fermentable sugars from the feedstock. The sugars in cellulose and hemicellulose are locked in complex carbohydrates called polysaccharides (long chains of monosaccharides or simple sugars). Separating these complex polymeric structures into fermentable sugars is essential for the efficient and economic production of cellulosic ethanol.

Cellulosic ethanol is attractive because the feedstock is cheap and abundant. Converting it into ethanol requires less fossil fuel, so it can have a bigger impact than corn ethanol on reducing greenhouse-gas emissions. Also, an acre of grasses or other crops grown specifically to make ethanol could produce more than two times the number of gallons of ethanol as an acre of corn, in part because the whole plant can be used instead of just the grain (Ref. 11). Many experts estimate that corn-ethanol producers will run out of land, in part because of competing demand for corn-based food, limiting the total production to about 15 billion gal of fuel. Corn-ethanol plants, both existing and planned, have a capacity of about 11 billion gal.

According to the U.S. Department of Energy, corn-based ethanol provides 26 percent more energy than is required for its production, while cellulosic provides 80 percent more energy. While conventional ethanol reduces greenhouse-gas emissions 10 to 20 percent below gasoline levels, the reductions with cellulosic range from 80 percent below gasoline to completely carbon dioxide neutral. Table I lists advantages and disadvantages of various cellulose feedstocks. Figure 1 shows an ethanol production process.

There are several advantages of cellulosic ethanol over conventional ethanol, and with continued research cellulosic ethanol may have a significant impact in biofuels research as a renewable energy source.

2.3 Biodiesel

Biodiesel refers to any clean-burning alternative fuel produced from domestic, renewable resources. Biodiesel contains no petroleum, but it can be blended at any level with petroleum diesel to create a biodiesel blend. It can be used in compression-ignition (diesel) engines with little or no modifications. Biodiesel is simple to use, biodegradable, nontoxic, and essentially free of sulfur and aromatics.

Biodiesel is made through a chemical process called transesterification, where the glycerin is separated from the fat or vegetable oil. The process leaves behind two products: methyl esters (the chemical name for biodiesel) and glycerin (a valuable byproduct usually sold to be used in soaps and other products). Fuel-grade biodiesel must be produced to strict industry specifications (Ref. 13) in order to ensure proper performance. In the United States, biodiesel is the only alternative fuel to have fully completed the health effects testing requirements of the 1990 Clean Air Act Amendments. Biodiesel that meets ASTM D6751 and is legally registered with the Environmental Protection Agency is a legal motor fuel that can be sold and distributed.

Typically, biodiesel refers to a diesel-equivalent, processed fuel derived from biological sources (primarily vegetable oils), which can be used in an unmodified diesel engine. It has physical properties very similar to conventional diesel (Table II). Biodiesel can be produced by a variety of esterification technologies. The oils and fats are filtered and preprocessed to remove water and contaminants. If free fatty acids are present, they can be removed or transformed into biodiesel using special pretreatment technologies. The pretreated oils and fats are then mixed with an alcohol (usually methanol) and a catalyst (usually sodium hydroxide). The oil molecules (triglycerides) are broken apart and reformed into methylesters and glycerol, which are then separated from each other and purified.

TABLE I.—ADVANTAGES AND DISADVANTAGES OF VARIOUS CELLULOSE FEEDSTOCKS
[From Ref. 12.]

Cellulose feedstocks	Advantages	Disadvantages
Agricultural residues (rice, corn stover, and wheat straw)	Probably less costly than most forest residue. It is renewable. New source of revenue (farmers and rural preprocessing industries that may spring up to handle material). Currently, agricultural waste is composted, plowed back into the soil, thrown away, or burned. Potentially higher yields per acre than corn. Potential market for animal feed.	Existing harvest equipment and storage systems are immature. For example, combines are designed to pluck an ear of corn and leave the rest of the corn plant in the field. A new machine is needed to harvest the corn stalk, in addition to the corn kernels. The current high costs for recovering most agricultural residues contribute to preventing their wide use for energy purposes (still more expensive than harvesting corn).
Wood fibers (forestry and wood wastes)	Widely used source of renewable energy—44 percent of the total (in United States). Substantial source of renewable energy. In year 2030, more than 7 percent of the country's energy needs could be met by woody biomass resources. Current infrastructure and natural resources already exist. Reduces sulfur dioxide and nitrogen dioxide in biomass processing versus coal or oil. Use of forest waste helps decrease fire hazards associated with dead wood.	Wood chips could become too expensive to compete. There are competing demands for wood fiber that may drive prices up.
Energy crops (switch grass and miscanthus)	Native to North America. Requires little water or fertilizer to grow. It comes back year after year without planting. Thrives in places unsuitable for most crops. Yields twice as much ethanol per acre than corn. Switchgrass is a "captive energy source." It has no competing use other than energy. Switchgrass helps prevent soil erosion. Broad range of adaptability to poorer soils and drought tolerance, which would allow energy crops to be grown in regions that cannot support large-scale food crop production.	These are perennials that will take 2 to 3 years to get to a full yield. Enzymes needed to break down the cellulose are expensive. Department of Energy and private investors are working diligently to solve this problem.
Municipal waste	Provides a local solution to waste accumulation by allowing managers to dispose of materials with a 30 to 50 mile radius of their generation point. Disposal is safe and permanent, requiring no burning. Producing fuel from municipal solid waste (MSW) provides a viable solution to multiple environmental problems. Establishing MSW-to-ethanol plants in rural communities directly improves economic welfare by creating hundreds of construction jobs and permanent operational positions.	Converting compostable waste to ethanol may divert efforts for recycling paper products. Ideally, however, ethanol production from MSW will only add to the percentage of garbage reused rather than draw away from the material that is currently recycled.

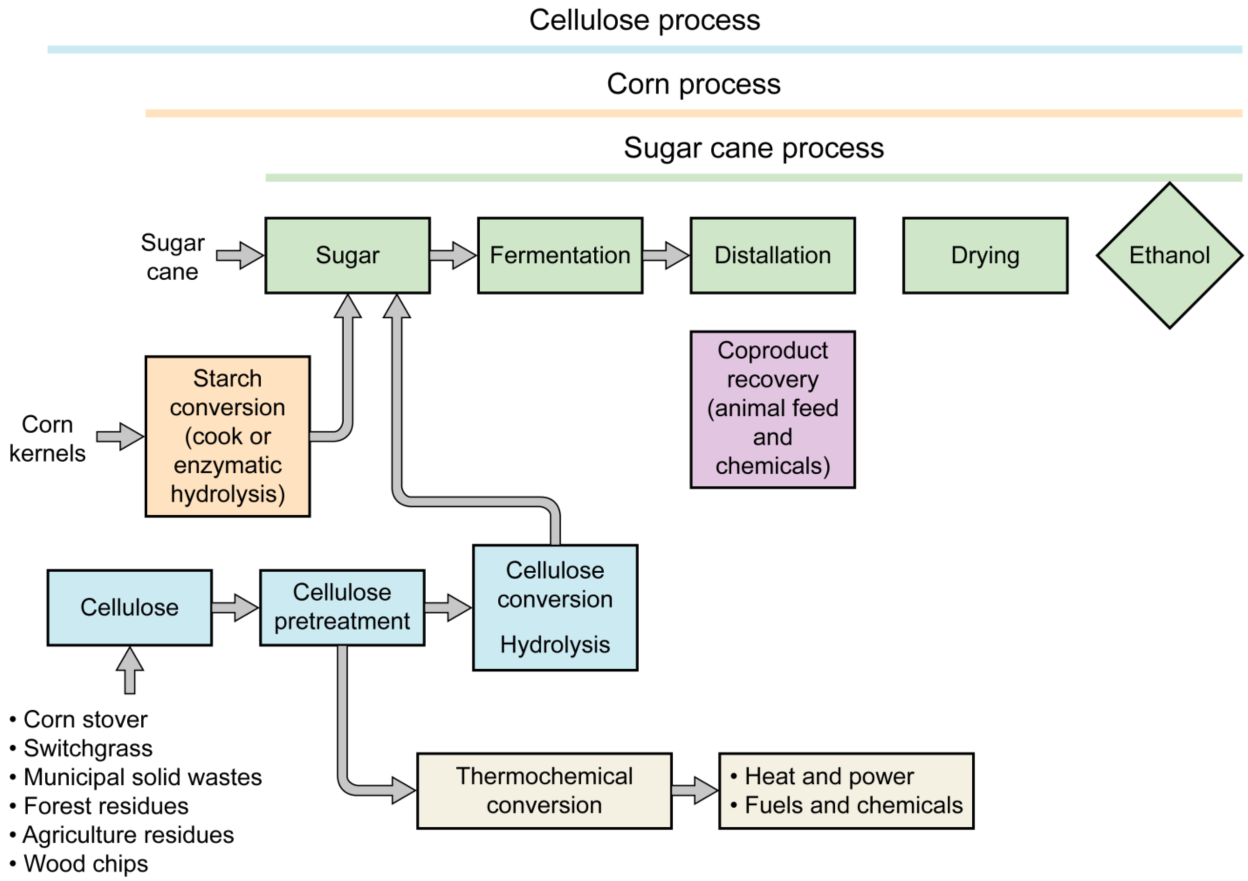

Figure 1.—Ethanol production flowchart (Ref. 12).

TABLE II.—PHYSICAL PROPERTIES OF BIODIESEL
[From Ref. 14.]

Specific gravity	0.87 to 0.89
Kinematic viscosity at 40 °C	3.7 to 5.8
Cetane number	46 to 70
Higher heating value, Btu/lb	16 928 to 17 996
Sulfur, wt%	0 to 0.0024
Cloud point, °C	–11 to 16
Pour point, °C	–15 to 13
Iodine number	60 to 135
Lower heating value, Btu/lb	15 700 to 16 735

According to Hill et al. (Ref. 15), biodiesel production is highly efficient, generating 93 percent more energy than is required to make it. They also found that biodiesel reduces greenhouse-gas emissions by 41 percent compared with fossil fuels.

Biodiesel is almost always mixed with conventional diesel by fuel distributors because of its higher cost, engine compatibility issues, and cold weather operation concerns. The most common blends are B2, B5, and B20 (2, 5, and 20 percent biodiesel, respectively). Pure 100 percent biodiesel (B100) can also be used unblended as a fuel in some diesel engines. The environmental benefits of using biodiesel scales with the percent of biodiesel contained in the blend. B20 can be more broadly applied to existing engines with little or no modification.

Biodiesel feedstock plants utilize photosynthesis to convert solar energy into chemical energy. The stored chemical energy is released when it is burned, therefore plants can offer a sustainable oil source for biodiesel production. Using biodiesel in a conventional diesel engine substantially reduces emissions of unburned hydrocarbons, carbon monoxide, sulfates, polycyclic aromatic hydrocarbons, nitrated polycyclic aromatic hydrocarbons, and particulate matter. Most of the carbon dioxide emitted when burning biodiesel is simply recycling what was absorbed during plant growth, so the net production of greenhouse gases is small. Biodiesel typically produces about 60 percent less net CO_2 emissions than petroleum-based diesel fuel since it is produced from atmospheric carbon dioxide via photosynthesis in plants. There are a variety of oils that can be used to produce biodiesel such as rapeseed and soybean oil, which account for approximately 90 percent of all fuel stocks. Other crops include mustard, flax, sunflower, canola, palm oil, hemp, jatropha, and algae. Waste vegetable oil, animal fats (tallow, lard, yellow grease, chicken fat, and fish oil), and sewage are also used for biodiesel production. Thermal depolymerization, a new process that reduces almost any hydrocarbon-based feedstock, including non-oil-based feedstocks into light crude oil can be used to produce biodiesel.

Worldwide production of vegetable oil and animal fat is not yet sufficient to replace liquid fossil fuel use. According to the U.S. Environmental Protection Agency, restaurants in the United States produce about 300 million U.S. gal (0.001 km^3) of waste cooking oil annually. The estimated transportation fuel and home heating oil used in the United States is about 230 billion U.S. gal (0.87 km^3) (Ref. 16). Waste vegetable oil and animal fats would not be enough to meet this demand. In the United States, estimated production of vegetable oil for all uses is about 24 billion lb (11 million tons) or 3 billion U.S. gal (0.011 km^3). The estimated production of animal fat is 12 billion lb (5.3 million tons).

The use of biodiesel decreases the solid carbon fraction of particulate matter (since the oxygen in biodiesel enables more complete combustion to carbon dioxide) and reduces the sulfate fraction (biodiesel contains less than 15 ppm sulfur), while the soluble, or hydrocarbon, fraction stays the same or increases. Therefore, biodiesel works well with emission control technologies such as diesel oxidation catalysts (which reduce the soluble fraction of diesel particulate but not the solid carbon fraction).

Emissions of nitrogen oxides increase with the concentration of biodiesel in the fuel and the increase is roughly 2 percent for B20. Some biodiesel produces more nitrogen oxides than others, and some additives have shown promise in reducing the increases. One disadvantage of using biodiesel for the aviation industry is its freezing point. Biodiesel from corn feedstock, vegetable oil, and animal fats freezes at –20 °F, which is well above typical fuel temperatures used in jet airplanes. Other disadvantages to using biodiesel are its cloud point, gel point, and thermal stability. Fuel storage is also a major concern since biodiesel degrades sufficiently over time in storage.

2.3.1 Biodiesel From Palm Oil

The palm fruit is the source of both palm oil (extracted from palm fruit) and palm kernel oil (extracted from the fruit seeds). Palm oil contains a high amount of beta-carotene and is used as cooking oil, making margarine, as well as a component (edible vegetable oil) of many processed foods. Palm oil is a form of edible vegetable oil obtained from the fruit of the palm tree. According to the U.S. Department of Agriculture (Ref. 17) 28 million metric tons of palm oil were produced worldwide in 2004, and it is on pace to surpass soybean oil as the most widely produced vegetable oil in the world.

Demand for palm oil is rising and is expected to climb further, particularly for use as a biodiesel fuel. The demand for palm oil usage is forecast to double by 2020 (Ref. 18). To achieve that production increase, 1160 new square miles will have to be planted every year for 20 years. Malaysia, where the palm tree has been grown since the 1870s, and Indonesia account for 85 percent of the world's production of palm oil. Indonesia has 26 300 square miles of forest land officially allocated for new palm oil plantations while Malaysia has almost 3000 square miles more than that. The expected thousands of square miles of new plantings on the islands of Sumatra and Borneo have the potential to eliminate the remaining orangutans, rhinos, and tigers. The environmental impact of the growth and further development of palm oil plantations is a serious threat that cannot be accurately predicted because of the amount of political pressure on palm oil countries.

An independent study commissioned by the Malaysian government in 2006 has shown that palm oil requires an input of only 30 to 40 percent of fossil fuel energy to produce a given amount of energy compared with an input of up to 60 percent fossil fuel energy in the process of making biofuels from maize, rapeseed, or soybeans.

2.3.2 Biodiesel From Algae

While a number of biofeedstocks are currently being used for ethanol and biodiesel production, algae has emerged as one of the most promising sources—especially for biodiesel. The yields of oil from algae are orders of magnitude higher than those for traditional oilseeds. As a comparison, a single acre of algae ponds can produce 15 000 gal of biodiesel, an acre of soybeans produces up to 50 gal of biodiesel per acre, an acre of jatropha produces up to 200 gal per acre, coconuts produce just under 300 gal per acre, and palm oil produces up to 650 gal of biodiesel per acre (Ref. 16). Table III lists the gallons of oil per acre per year for corn, soybeans, safflower, sunflower, rapeseed, palm oil, and microalgae.

TABLE III.—ANNUAL YIELDS OF OIL PER ACRE OF VARIOUS BIOFUEL FEEDSTOCKS
[From Refs. 16 and 19.]

Feedstock	Yield, gal
Corn	18
Soybeans	48 to 50
Safflower	83
Sunflower	102
Rapeseed	127
Jatropha	200
Coconut	300
Palm	635
Microalgae	5000 to 15 000

Algae can be grown in sewage and next to power-plant smokestacks, where they digest pollutants. Although research into algal oil as a source for biodiesel is not new, the current oil crisis and fast depleting fossil oil reserves have made it more imperative for organizations and countries to invest more time and efforts into research on suitable renewable feedstock such as algae. Berzin (Ref. 20) has developed a method of capturing carbon dioxide from smokestack emissions using algae and turning the result into biodiesel, ethanol, and even a coal substitute. His process, based on technology he developed for NASA in the late 1990s, captures more than 40 percent of emitted CO_2 (on sunny days, up to 80 percent) along with over 80 percent of NOx emissions. In turn, it produces biodiesel at rates per acre that could make a full conversion to biofuel for transportation readily achievable. Berzin calculates that just one 1000-MW power plant using his system could produce more than 40 million gal of biodiesel and 50 million gal of ethanol per year.

Bullock (Ref. 21) conducted a 6-month test in a small plant to demonstrate GreenFuel Technologies Corporation’s process that uses microalgae in a photobioreactor to sequester carbon dioxide from furnace gases. The pilot plant used gases from the Hazelwood Power Station, an Australian brown-coal-fired electric power plant, in tubular photobioreactors to grow microalgae.

According to the U.S. Department of Energy, most current research into efficient algal-oil production is being done in the private sector. The per unit area yield of oil from algae is estimated to be from 5000 to 20 000 gallons per acre, per year; which is 7 to 31 times greater than the next best crop, palm oil (635 gal).

Algal oil can be processed into biodiesel as easily as oil derived from land-based crops. The difficulties in efficient biodiesel production from algae lie not in the extraction of the oil, but in finding an algae strain with a significant lipid content and fast growth rate that is not too difficult to harvest. Open-pond systems have not been considered feasible for the cultivation of algae with high oil content. This is due to the algae not being able to withstand wide variations in temperature and pH as well as competition from invasive algae and bacteria. Algae species with lower oil content, not having to divert their energies away from growth, have an easier time in the harsher conditions of an open system.

Research into algae for the mass production of oil is mainly focused on microalgae capable of photosynthesis that are less than 2 mm in diameter as opposed to macroalgae (seaweed). This preference towards microalgae is due largely to its less complex structure, fast growth rate, and high oil content (for some species). Some commercial interests into large-scale algae-cultivation systems are looking to tie into existing infrastructures, such as coal power plants or sewage treatment facilities. This approach not only provides the raw materials for the system, such as carbon dioxide and nutrients, but it changes those wastes into resources.

2.3.3 Biodiesel From Halophytes

By definition, a halophyte is any plant, especially a seed plant, that is able to grow in habitats excessively rich in salts, such as salt marshes, sea coasts, saline or alkaline semi-deserts, and steppes. These plants have special physiological adaptations that enable them to absorb water from soils and from seawater, which have solute concentrations that nonhalophytes could not tolerate. Some halophytes are actually succulents, with a high water-storage capacity (Ref. 22). Less than 2 percent of plant species are halophytes. The majority of plant species are glycophytes, which are damaged easily by salinity (Ref. 23).

Naturally occurring saline environments in the Middle East provided necessary selection pressure for the evolution of highly salt-tolerant plants, to primarily be used for grazing. Approximately 211 halophytic species from 29 plant families are recorded in the Middle East; in comparison, the world flora lists some 885 species of halophytic angiosperms from 250 genera. Indigenous and exotic halophytes constitute an untapped genetic resource that can be used in developing crops under saline conditions. These wild plants, if domesticated, can utilize saline water and soil resources for sustainable agricultural production. Their seeds, fruits, roots, tubers, or foliage can be used directly or indirectly as human food.

A minimum of 50 species of seed-bearing halophytes are potential sources of grain and oil; these include halophytes with seed quality comparable to, or better than, that of wheat and species with seeds that are rich in energy, protein, and fat content. Other halophytes are candidates as tuber-, vegetable-, or fodder-producing crops. A number of fruit-producing halophytes can be used as rootstocks or grafts to produce economic fruit yields using saline water and soil resources. Salt-tolerant trees and shrubs constitute a rich source of energy known as fuelwood. In addition, genetic resources have been identified among the halophytes as sources for pulp, fiber, gums, oils, resins, bioactive derivatives, and as landscape and ornamental plants.

One of the most important contributions of halophytes towards sustainable farming systems in the Middle East is their potential as fodder grasses, legumes, shrubs, and trees. Long-term sustainability of farming systems based on these halophytes depends on the economic value of inputs and outputs, their environmental impact, future food needs, economics, the extent to which freshwater ecosystems are withheld from further agricultural development, and development of agronomic practices appropriate for new farming systems (Ref. 24).

Glenn et al. (Ref. 25) have tested the feasibility of using seawater agriculture to grow halophytes and found that it works well in desert or sandy soil environments. The most promising halophyte they have found thus far is Salicornia bigelovii, which is a leafless salt-marsh plant that colonized new areas of mud flat. Their seeds contain 30 percent oil and 35 percent protein (very similar to other oilseed crops) and the salt content is less than 3 percent.

Yensen (Ref. 22) believes that most new halophyte crops will be used inland based on the fact that most halophytes have significantly increased productivity at lower salinities. There is more than 300 times as much land already salinized and many inland areas already have canals, fields, farms, and infrastructure as well as people needing food, but have no crops. New halophyte crops such as NyPa Forage and NyPa Grain (NyPa Australia Ltd.) have the potential for utilizing salt-ruined land, stabilizing soil from wind and water erosion, providing pasturage, and helping less advantaged populations to feed themselves.

A number of halophytes have already been utilized by indigenous populations along maritime coastlines who understood how to make use of many plants growing in mangroves and saltmarshes. The plants were used from the places where they grew naturally. These places include areas where tidal action washes seawater over land and in delta areas where seawater and river water clash together and create large, fertile marsh areas. This is where halophyte farming can be extremely beneficial.

Halophytes are gaining in popularity today because of the steady increase of the salinity in irrigation systems in Mediterranean and subtropical desert countries where the increasing population reaches the limits of freshwater availability. One of the most urgent global problems is finding enough water and land to support the world’s food needs. The United Nations Food and Agriculture Organization estimates that an additional 200 million hectares (494.2 million acres) of new cropland will be needed over the next 30 years just to feed the burgeoning populations of the tropics and subtropics. However, only 93 million hectares are available in these nations for farms to expand but much of that land is forested, which poses an environmental concern.

2.4 Synthetic Fuel

Synthetic fuel (synfuel) is any liquid fuel obtained from coal, natural gas, or biomass. It can sometimes refer to fuels derived from other solids such as oil shale, tar sane, or waste from plastics. Depending on the initial feedstock, the process of producing synfuel can be referred to as coal-to-liquids, gas-to-liquids, or biomass-to-liquids. The most common process is the Fischer-Tropsch systhesis, which was used on a large scale in Germany during World War II. An intermediate step in the production of synthetic fuel is often syngas, which is a stoichiometric mixture of carbon monoxide and hydrogen and is sometimes directly used as an industrial fuel.

Sasol, a South-African-based company, is the leading company in the commercialization of synthetic fuel. They currently operate the world’s only commercial coal-to-liquids facility at Secunda, with a capacity of 150 000 barrels a day (Ref. 26). Other companies that have developed coal-to-liquids or gas-to-liquids processes include Shell, Exxon, Statoil, Rentech, and Syntroleum. Worldwide commercial gas-to-liquids plant capacity is 60 000 barrels per day (Ref. 27) including plants in South Africa, Malaysia, and New Zealand.

The U.S. Department of Energy projects that domestic consumption of synthetic fuel made from coal and natural gas will rise to 3.7 million barrels per day in 2030 based on a price of $57 per barrel of high-sulfur crude (Ref. 27). For synthetic fuels to be competitive with petroleum-based fuels without Government subsidies, crude oil would have to be at a relatively high price. They offer the potential to supplement or replace petroleum-based fuels if oil prices continue to rise or stay above a cost of $100 per barrel for the long term. Synthetic fuels are primarily produced in the United States because of government subsides but are a proven technology that can offer the potential to solve the energy crises due to the depletion of crude oil.

3.0 Processing of Biomass

Although we have investigated the energy production potential of several types of biofuels in this report, the processing of biomass is the most significant step in getting energy out of renewable energy sources. Although biomass is a renewable fuel source, it is part of the carbon cycle and is often called a “carbon netural” fuel. By way of photosynthesis, carbon from the atmosphere is converted into biological matter, and then goes back into the atmosphere or soil via decay or combustion. This process happens over a relatively short timescale and plant matter used as a fuel can be constantly replaced by planting for new growth, effectively resulting in zero “net” carbon emissions. It is commonly accepted that the amount of carbon stored in biomass is approximately 50 percent of the biomass by weight (Ref. 28). Cellulose, hemicellulose, and lignin are the three main components of the bulk of biomass and are listed in Figure 2.

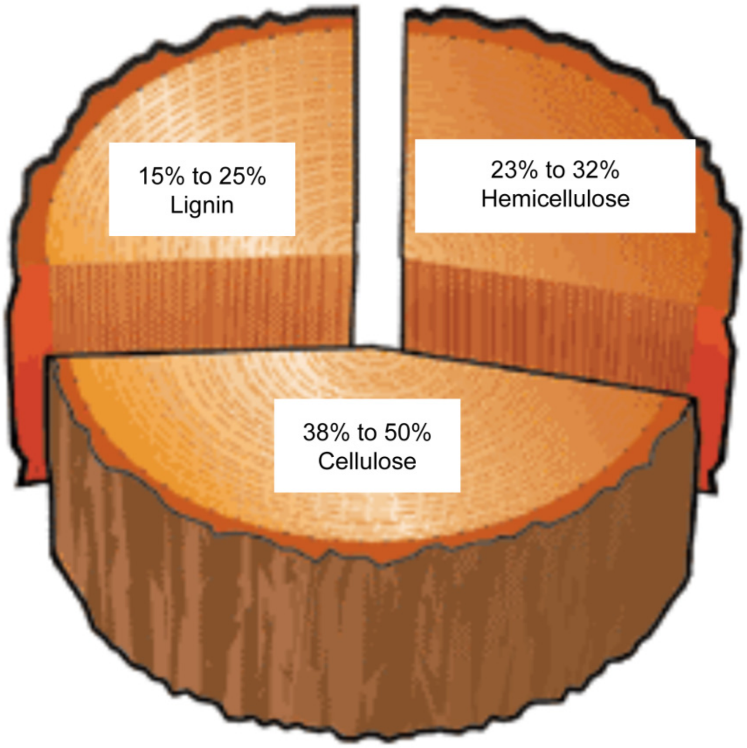

Figure 2.—Three main components of the great bulk of biomass resources (Ref. 29).

The production of biomass is a growing industry with advances being made every year as pressure for sustainable nonfossil fuels increases. Biomass has surpassed hydroelectric power as the largest domestic source of renewable energy. Biomass currently supplies over 3 percent of the U.S. total energy consumption primarily through industrial heat and steam production by the pulp and paper industry and electrical generation with forest industry residues and municipal solid waste (Ref. 30).

A new industry is emerging around the production of bioenergy and bio-based products. Facilities that integrate biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass are called biorefineries and are very similar in concept to petroleum refineries. These refineries concentrate specifically on refining biomass feedstock (agricultural and forestry crops and residues and municipal and process wastes) into chemicals, fuels, pressboards, biocomposites, and other valuable products.

The commercial refining of biomass (biorefining) from trees or agricultural residues is fast approaching because of advances made in acidic and enzymatic hydrolysis of the cellulose component of biomass and in some newer processes for biomass refining. By producing multiple products, a biorefinery can take advantage of the difference in biomass components and maximize the value derived from biomass feedstocks (Ref. 31). Figure 3 lists an example of the conceptual activities of a biorefinery.

A new UOP/Eni Ecofining process technology called green diesel has been developed by UOP LLC that produces green diesel from vegetable oil. This process utilizes catalytic saturation, hydrodeoxygenation, decarboxylation, and hydroisomerization reactions to produce an isoparaffin-rich diesel fuel from renewable feedstock containing triglycerides and fatty acids such as soybean, palm, and rapeseed oils. The resultant biofuel product has a high cetane value and is compatible for blending with the standard mix of petroleum-derived diesel fuels, which can provide added value to the refiner. They conclude that green diesel has the potential to displace more petroleum resources per energy content in the fuel when compared with biodiesel (Ref. 33).

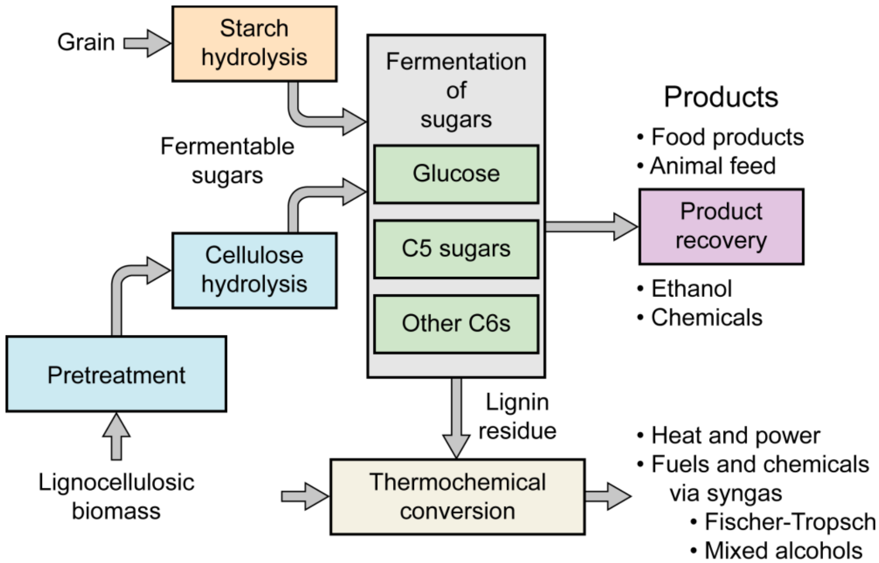

Figure 3.—Conceptual example of processing of biomass at biorefinery (Ref. 32).

Gorden and Polle (Ref. 34) describe a process to significantly increase bioproductivity in algal photobioreactors by integrating photonics with biotechnologies. This is achieved by customizing the photonic temporal, spectral, and intensity characteristics with pulsed light-emitting diodes, which produce rapid light-dark algae exposure cycles. The result is a higher yield from a technique that is adaptable to existing photobioreactors.

The technologies used for the processing of biomass primarily consist of gasification, hydrolysis, and anaerobic digestion and these techniques are briefly described below.

3.1 Gasification

Gasification is a process that uses heat, pressure, and steam to convert materials directly into a gas composed primarily of carbon monoxide and hydrogen. When biomass is heated with no oxygen or only about one-third the oxygen needed for efficient combustion, it typically gasifies (pyrolyzes) to a mixture of carbon monoxide and hydrogen called synthesis gas.

Typical raw materials used in gasification are coal, petroleum-based materials, and organic materials. The feedstock is prepared and fed, in either dry or slurried form, into a sealed reactor chamber called a gasifier. The feedstock is subjected to high heat, pressure, and either an oxygen-rich or oxygen-starved environment within the gasifier. The three primary products from gasification are hydrocarbon gases (syngas), hydrocarbon liquids (oils), and char (ash).

Syngas (synthesis gas) burns more efficiently and cleanly than the solid biomass from which it was made. Syngas also mixes more readily with chemical catalysts than solid fuels, which can greatly enhance its ability to be converted to other fuels needed for transportation. The Fischer-Tropsch process converts syngas to liquid fuels needed for transportation. A variety of other catalytic processes can turn syngas into a myriad of chemicals or other potential fuels or products.

3.2 Hydrolysis

Hydrolysis is a chemical decomposition process that uses water to split chemical bonds of substances. There are two types of hydrolysis: acid and enzymatic. Feedstocks that may be appropriate for acid or enzymatic hydrolysis typically are plant-based materials containing cellulose. These include forest material and sawmill residue, agricultural residue, urban waste, and waste paper.

All plants have structural components composed of lignocellulosic fibers, which in turn comprise three major fractions: cellulose, hemicellulose, and lignin. Cellulose and hemicellulose are chains of sugar molecules that can be broken down chemically or biologically into the component sugars. The sugars are then fermented using yeast or bacteria to produce ethanol, which is then distilled to a higher concentration for final use. Lignin binds cellulose and hemicellulose together and cannot be broken down to form sugars. At this point, the most cost-effective use for lignins is as a fuel for biomass-to-energy facilities.

Sugars can also be converted to levulinic acid and citric acid. Levulinic acid is a versatile chemical that is a precursor to other specialty chemicals, fuels and fuel additives, herbicides, and pesticides. The largest application for citric acid is in the beverage industry, which accounts for about 45 percent of the market for this product. Citric acid is also used in a wide variety of candies, frozen foods, and processed cheeses and as a preservative in canned goods, meats, jellies, and preserves.

3.3 Anaerobic Digestion

Anaerobic digestion is the bacterial breakdown of organic materials in the absence of oxygen. This biological process produces a gas called biogas that is primarily composed of methane and carbon dioxide. This gas is produced from feedstocks such as sewage sludge, livestock manure, and wet organic materials. There are three steps used in anaerobic decomposition: (1) the decomposition of plant or animal matter by bacteria into molecules such as sugar, (2) the conversion of decomposed matter to organic acids, and (3) the organic acid conversion to methane gas. Cellulose and hemicellulose, two of the three main components of the great bulk of biomass resources, are polymers of sugars and can be broken down in this way to those component sugars for fermentation or for processing to ethanol and other valuable fuels and chemicals.

Anaerobic processes can occur naturally or in a controlled environment such as a biogas plant. In controlled environments, organic materials such as sewage sludge and other relatively wet organic materials, along with various types of bacteria, are put in an airtight container called a digester where the process occurs. Depending on the waste feedstock and the system design, biogas is typically 55 to 75 percent pure methane.

4.0 Biomass Supply

According to the U.S. Department of Agriculture, the potential biomass annual supply could be as much as 1.4 billion dry tons per year (dT/yr), and this resource is large and relatively untapped (Ref. 35). It comprises mainly agricultural residues (~1 billion dT/yr) and forestry residues (~0.4 billion dT/yr). As an energy feedstock, biomass could be used to displace a large amount of imported foreign oil (~1 to 2 billion barrels per year), and therefore it represents a very large domestic renewable energy reserve. Approximately 70 to 100 billion gal per year of ethanol could be produced from this biomass resource without having to plant a single energy crop. This is about 100 times the current ethanol production capacity in the United States. The 1.4 billion dT/yr of biomass resource potential comprises approximately 1 billion dT/yr of agricultural residues and 0.4 billion dT/yr of potential forestry residues. Other sources of biomass feedstock that could also be utilized in the near term include urban wood waste, mill residues, and new dedicated energy crops (Ref. 35).

5.0 Biofuel Uses in the Aviation Industry

The temperature, viscosity, and opacity (clear/clean) requirements for aviation-grade fuel have been the most difficult challenge for biofuels. One such fuel that has been successful is aviation-grade ethanol. Aviation-grade ethanol (AGE–85) is a high-performance, 85-percent-ethanol blended fuel for use in any reciprocating engine aircraft. AGE–85 is beginning to replace 100 octane low-lead aviation gasoline, which has been the standard leaded gasoline for aviation since World War II. AGE–85 offers a substantial improvement in performance for these aircraft, producing at least 12 percent more horsepower and torque at typical cruising power. Lower operating temperatures are also achieved, with engines tending to run 50 to 100 °C cooler than with current fuel. Because AGE–85 fuel causes considerably less buildup of combustion byproducts in the engine, the time between engine overhauls is greater, and maintenance costs are lower.

Daggett et al. (Ref. 36) provide an excellent overview of alternative fuels and their feasibility for use in the aviations industry. They considered bioderived fuels, methanol, ethanol, liquid natural gas, liquid hydrogen, and synthetic fuels for their potential to replace or supplement conventional jet fuels. They point out that synthetic fuel made from coal, natural gas, or other hydrocarbon feedstock shows significant promise as a fuel that could be easily integrated into present and future aircraft with little or no modification to current aircraft designs. Alternatives, such as biofuel, and in the longer term hydrogen, have good potential but presently appear to be better suited for use in ground transportation.

CFM International (Ref. 37) has successfully performed an initial test of a CFM56–7B engine using an ester-type biofuel. The CFM56–7B is the exclusive engine for the Boeing next-generation single-aisle airliner: 737–600/–700/–800/–900. The thrust ranges from 18 500 to 27 300 lb. The biofuel used for this test was a 30 percent vegetable oil methyl ester blended with 70 percent conventional Jet-A1 fuel. This test was designed to check the operation of a jet engine using a fuel made from biomass, without making any technical changes to the engine. With this type of biofuel, the target is a net reduction of 20 percent in CO_2 emissions compared with current fuels.

The U.S. Defense Department has been directed to explore a wide range of energy alternatives and fuel efficiency efforts in a bid to reduce the military's reliance on oil to power its aircraft, ground vehicles, and nonnuclear ships. The Defense Advanced Research Projects Agency (DARPA) is interested in proposals for research and development efforts to develop a process that efficiently produces a surrogate for petroleum-based military jet fuel (JP–8) from oil-rich crops produced by either agriculture or aquaculture (including but not limited to plants, algae, fungi, and bacteria) and which ultimately can be an affordable alternative to petroleum-derived JP–8. Current commercial processes for producing biodiesel yield a fuel that is unsuitable for military applications, which require higher energy density and a wide operating temperature range. There are several research institutions and companies collaborating on this effort.

Summary and Conclusion

Finding a viable source of renewable energy is a global task. We presented several biofuel alternatives to using fossil fuels. The use of corn for ethanol production shows promise for local farmers as well as the automotive industry, but the technology is quite mature and growth is not expected for traditional ethanol. However, cellulosic ethanol is gaining interest for its ability to utilize more biomass from plants than ethanol. Biodiesel has shown promise but demand far exceeds current capacity. Biodiesel from algae has the potential to generate orders of magnitude more fuel than any other method, and it should be researched so that an ideal algae species or strain can be identified and utilized for efficient biofuel production. Biodiesel from halophytes also show great promise because of their ability to serve not only as a fuel source, but a food source as well.

Synthetic oil and hydrogen also show promise for the future as we look for efficient, safe, and affordable biofuels as a replacement for fossil fuels.

We plan to investigate the feasibility of using halophytes as well as marine algae for use as biofuels for the aviation industry with the hope that we will provide some insight and guidance into the large-scale research and development of renewable energy sources in the future.

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14. ABSTRACT
The use of biofuels has been gaining in popularity over the past few years because of their ability to reduce the dependence on fossil fuels. As a renewable energy source, biofuels can be a viable option for sustaining long-term energy needs if they are managed efficiently. We investigate past, present, and possible future biofuel alternatives currently being researched and applied around the world. More specifically, we investigate the use of ethanol, cellulosic ethanol, biodiesel (palm oil, algae, and halophytes), and synthetic fuel blends that can potentially be used as fuels for aviation and nonaerospace applications. We also investigate the processing of biomass via gasification, hydrolysis, and anaerobic digestion as a way to extract fuel oil from alternative biofuels sources.

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