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BIOREFINING OF RENEWABLE RESOURCES – EMERGING OPPORTUNITIES FOR ENGINEERING EDUCATION

Abstract

The society in which we live has developed an insatiable demand for energy and material goods. Historically these needs have primarily been met by utilizing fossil fuels and other non-renewable raw materials. As environmental concerns grow, however, renewable resources are gaining increased attention. This paper examines industrial biorefineries, which are at the leading edge of the development of emerging biobased industries. Biorefineries, similar in concept to traditional petroleum refineries, utilize various conversion technologies to produce multiple products, including fuels, chemicals, industrial products, and electrical power from renewable biomass sources, such as corn stover, residue straw, perennial grasses, legumes, and other materials. Industrial biorefineries are rapidly increasing both in number as well as in capacity throughout this country, and are thus poised to add significantly to the nation's industrial goods and energy supplies in coming years. Therefore it is vital for engineering graduates to understand this developing industry and its fundamental concepts, especially those involved in the Agricultural, Biological, Chemical, Environmental, Food, and Process Engineering disciplines. To adequately prepare engineering students for the opportunities presented by biorefining, it is imperative for engineering programs to address this burgeoning industrial segment. Toward this end, this paper will discuss major biorefinery concepts, specific applications, and curriculum modification and incorporation techniques that can be used to achieve these efforts. The trends discussed here and their implications are critical for educators, because in coming years biorefining will be used to simultaneously meet the needs of our society as well as that of environmental stewardship.

Introduction

As we move into the 21st century, it has become apparent that human societies are over-taxing global resources, and that we are rapidly depleting their finite supplies. This is especially true in the petroleum and petrochemical sectors. Science and technology, however, have progressed to the level that biorenewable materials can now be effectively utilized to produce various manufactured products in their place. Similar to refineries that are used in the petroleum industry, new processing facilities are being designed and constructed to manufacture, from biomass resources, multiple value streams including energy, fuels, chemicals, and various intermediate and finished products. Thus, biomass refineries (known as “biorefineries”) are poised to contribute significantly to the growth and sustainability of the U.S. economy in coming years [1]. Engineering expertise will be required to design, construct, and operate all of the equipment, processes, and facilities for these processing plants. Because biorefineries present many opportunities for the engineering profession, the main objective of this paper is to introduce engineering educators to this new subject so that curricula can be augmented. Toward that end, several essential topics will be discussed, including concepts of biorefineries, the

relevance of these systems to engineering education, resources for educators, and strategies to use the information presented here to bolster current practice in engineering education.

Biorefinery Concepts

In the US, tremendous quantities of biomass are produced annually. It is estimated that between 1.8 and 3.2 billion tons are produced each year, which equates to potential energy production of between 34 and 60 trillion GJ [1]. The main goal of biorefining is to convert the carbohydrates, especially the lignocellulose matrix, that are in these raw product streams into a range of valuable chemicals, chemical intermediates, finished bio-based products, foods, feeds, biofuels, or bioenergy supplies, with minimal waste and emissions. The following discussions will attempt to briefly capture the main concepts of biorefining, as illustrated in Figure 1, but will not be completely exhaustive. More comprehensive treatments can be found in [1, 5-11], to which the reader is referred for more information. Based on these topics, Figure 2 illustrates the major processes and material flows for an example biorefinery. In this example, the core technology is a thermal reactor devoted to sequential, linear biomass fractionation through steam auto-hydrolysis. It produces high purity chemical commodities and has environmental excellence and sound economics. The biorefinery concept is analogous to that of a petroleum refinery, which produces multiple fuels and products from petroleum-based feedstocks. A biorefinery integrates a variety of conversion processes to produce various products such as motor fuels, heat, electricity and chemicals from biomass [12]. By producing multiple products, a biorefinery maximizes the value derived from biomass feedstocks.

Potential biomass sources include wastes as well as energy crops. Waste streams include agricultural crop residues (e.g., stover, stalks, leaves, cobs, etc.) which are left after harvest, municipal solid waste (i.e., MSW), especially the paper, food, and other organic waste constituents within the MSW, and food processing wastes. Energy crops, on the other hand, are grown specifically to be used for energy production, as opposed to food or feed. Herbaceous crops, such as sugarcane, Napier grass, sorghum, reed canary grass, fescue, and switchgrass, can be harvested annually, and can yield up to 25 Mg/ha/yr. Short-rotation woody crops, such as poplar, maple, sycamore, and alder, can generally be harvested in 10 years or less, and can yield up to 43 Mg/ha/yr.

To establish a common understanding for subsequent discussions, it is important to delineate uniform terminology. Although precise agreement and consensus in industry has not actually yet been achieved, several key terms and definitions that are essential to understanding biorefining and utilization of biomass can be found in literature [2-4], but will not be discussed further here.

Industrial scale biorefineries have been identified as the most promising route to the creation of a sustainable bio-based economy. All plants are effectively autonomous chemical mini factories, producing sugars and amino acids that are essential for their growth. Plant biomass consists of carbohydrates, lignin, proteins and fats/oils with a variety of minor constituents such as vitamins, dyes, flavors etc. Biorefineries combine essential technologies to transform biological raw materials into a range of industrially useful intermediates and finished products. The biorefinery concept is gaining popularity as a model that will maximize the value of biomass resources in the U. S. Biorefineries will revolutionize the utilization of the nation's vast renewable supply of

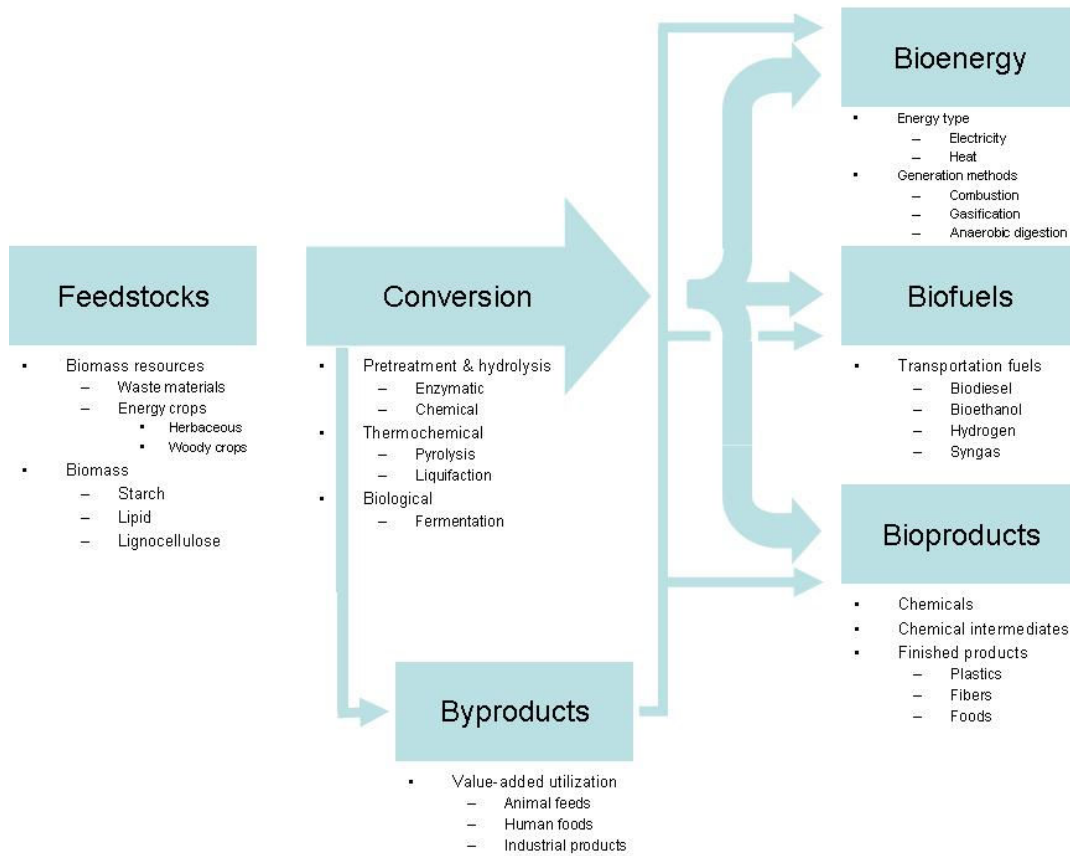


Figure 1. Major concepts associated with biorefineries.

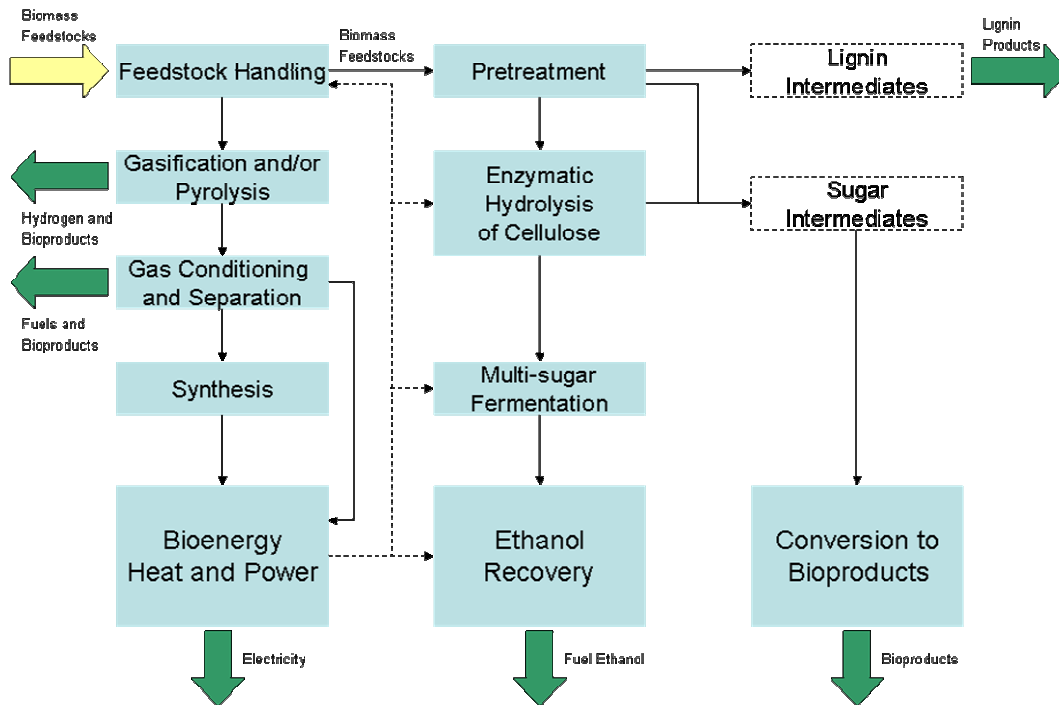


Figure 2. Major processes and material flows for an example biorefinery.

biomass resources. Biorefineries provide two main advantages to production: they will increase the productive utilization of feedstocks and increase returns to scale as additional products are added to the biorefinery's output. Additionally, biorefinery production has the potential to propel bioenergy and biobased products into mainstream markets. The development of biorefineries will have numerous benefits for our society. In addition to increasing the percentage of fuels, chemicals, and manufactured products derived from renewable sources, biorefineries can reduce U. S. dependence on imported oil, reduce greenhouse gas emissions, diversify markets for raw agricultural and forestry products, and enhance rural economies.

The amount of oil imported into the US has been steadily increasing during the last 20 years (Figure 3); the nation is now very much dependent on imported oil, especially for transportation fuels. The increasing cost and potential scarcity of fossil resources are contributing to a growing interest in bioproducts and biofuels. Biomass can potentially be used to diversify our current fossil-energy based systems for fuel, power and products. Diversification can reduce our vulnerability to disruptions in energy supply as well as our dependence on imported energy sources for both fuels and important consumer products. Biomass is carbon-fixing, and represents a way to produce fuels, products and power with a 'net-zero' contribution to global warming. Thus, the biorefinery represents one very viable part of the solution for the imported oil issue. These highly flexible facilities have the potential to manufacture many products that are currently produced from petroleum. Biorefineries could thus help meet demand for both transportation fuels and consumer products, with decreased environmental impacts. Biomass currently supplies over 3% of total energy consumption in United States, mostly through industrial heat and steam production in the paper and pulp industries, electrical generation using forestry products and residues, and municipal solid waste incineration.

Archer Daniels Midland, in Decatur, IL, for example, has constructed a prototype for an advanced biorefinery. At this site a large corn wet-milling plant produces industrial enzymes, lactic acid, citric acid, amino acids, and bioethanol. The enzymes are used to convert starch to maltodextrins and syrups, and the chemical products are subsequently used in foods, detergents, and bioplastics. The ethanol is used as a solvent and for transportation fuels. Additionally, an on-site cogeneration system provides electricity and steam for the conversion processes [14].

The National Renewable Energy Laboratory (NREL) biorefinery concept (Figure 4) is built on two different "platforms" to promote specific product streams. The "sugar platform" is based on biochemical conversion processes and focuses on the fermentation of sugars extracted from biomass feedstocks. The "syngas platform" is based on thermochemical conversion processes and focuses on the gasification of biomass feedstocks and by-products from conversion processes.

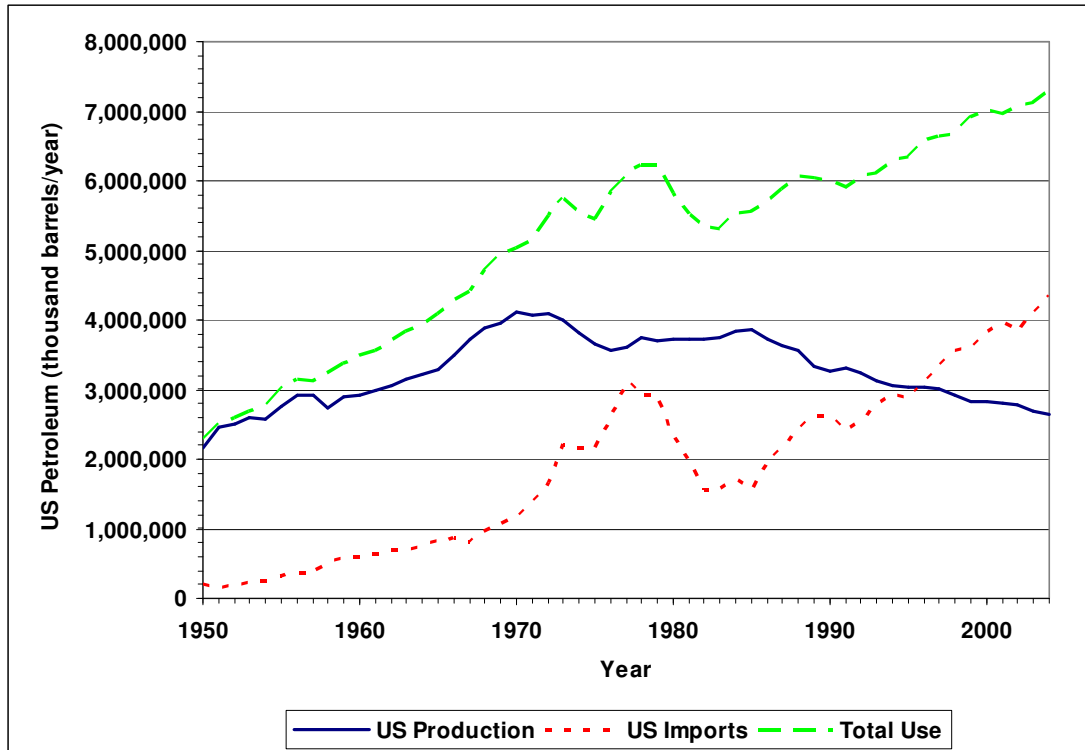


Figure 3. Trends in oil supply and demand [adapted from 13].

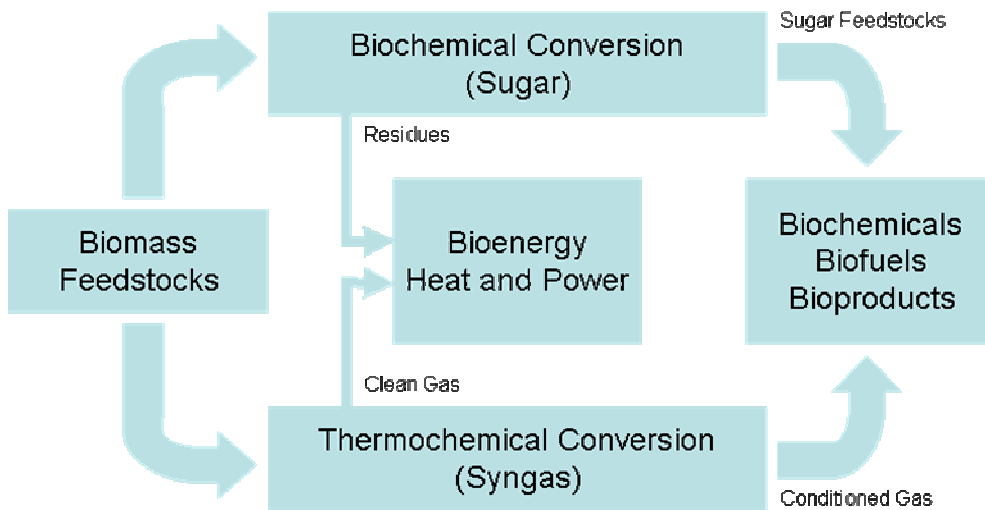


Figure 4. NREL's biorefinery concept [adapted from www.nrel.gov].

Currently there are three major biorefinery concepts being pursued in research and development. The first is the “Whole Crop Biorefinery”, which uses raw materials such as cereal grains or corn [6,7]. The second is the “Green Biorefinery”, which uses green grass, alfalfa, clover, or immature cereal grains [56-61]. The third is the “Lignocellulose Feedstock Biorefinery”, which uses dry raw materials, such as waste or other residue biomass, which generally contains high levels of cellulose, hemicellulose, and lignin. Among the potential large-scale industrial

biorefineries, the Lignocellulose Feedstock (LCF) Biorefinery will most probably be deployed with highest success. The supply of raw materials (e.g., straw, reed, grass, wood, paper-waste etc.) is abundant, and the conversion to various products has progressed, both as replacements of traditional petrochemical-based products as well as other biobased materials.

Lignocellulosic materials consist of three primary chemical fractions, or precursors: a) hemicellulose/polyose, which is predominantly a sugar-polymer of pentoses; b) cellulose, which is a glucose-polymer; and c) lignin, which is a polymer of phenols (Figure 5) [9].

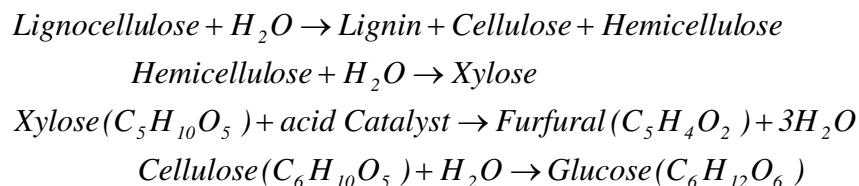


Figure 5. General equations for biomass conversion in an LCF-Biorefinery.

Biomass streams generally cannot be utilized directly as bioenergy, biofuels, or bioproducts; they typically must undergo conversion operations in order to be successfully used. The key objective of biomass conversion is to improve the relatively poor characteristics of the material as a fuel or material precursor. The poor characteristics of fresh biomass when compared to fossil fuels can include: 1) modest thermal content; 2) high moisture content, which can inhibit combustion, thereby causing significant energy loss; 3) low bulk density of biomass, which leads to the use of relatively large equipment for handling, storage and burning; and 4) biomass is generally not homogeneous and free flowing, which can create problems in conveying, pumping, metering, storing, and feeding to end-use equipment. Conversion of biomass into chemicals or intermediates is usually accomplished via several manufacturing steps, including pre-treatment and hydrolysis, fermentation, and distillation. Additionally, thermochemical conversion technologies, such as pyrolysis and liquefaction, also appear promising. Pre-treatment, such as grinding, and acid, enzymatic, or steam explosion hydrolysis are used to generate available sugars from lignocellulosic materials, and thus make the biomass suitable for subsequent fermentation. Fermentation is an operation where microorganisms digest the carbohydrates, especially sugars and starches, in the biomass matrix, and produce various substances, depending on the specific organisms, biomass stream, and operational conditions implemented. Potential fermentation products include ethanol, butanediol, aliphatic acid, lactic acid and succinic acid. Additionally, distillation can be used subsequent to fermentation to separate various water-soluble compounds. More information regarding industrial fermentation of biomass can be found in [15-18]. Thermochemical conversion includes pyrolysis, where the biomass is heated in the absence of oxygen to produce a bio-oil along with residual solids (i.e., char), and various gases (such as methane, carbon monoxide, and carbon dioxide), and liquefaction, where the biomass is converted at moderate temperatures and pressures into a liquid state. The products produced via thermochemical conversion contain high concentrations of organic compounds, and thus are useful as a concentrated source for further utilization. More information regarding thermochemical conversion of biomass can be found in [19-25].

Converted biomass can then be transformed into energy, primarily in the form of heat or electric power (e.g., stationary generation). Generally it is only the lignocellulosic components of the

biomass that are used to produce energy, though, as the other constituents are typically utilized in other value-added products such as biofuels and bio-based products, including chemicals and polymers. Combustion, gasification, and anaerobic digestion are three techniques that are commonly used to generate bioenergy. Combustion, which essentially is the conversion of biomass into heat, can be accomplished in grate-fired, suspension, and fluidized bed combustors, furnaces, and boilers. More information regarding combustion of biomass can be found in [26-28]. Gasification, which is the conversion of biomass into flammable gas using an atmosphere which is deficient in oxygen, can be accomplished in updraft, downdraft, or fluidized bed gasifiers. More information regarding gasification can be found in [29-32]. Anaerobic digestion, which is the decomposition and conversion of biomass using microbes into flammable gas, can be accomplished in batch-fed, intermittently-fed, and continuously-fed digesters. More information regarding anaerobic digestion can be found in [33-40]. The gas produced by gasifiers and anaerobic digesters can then be combusted and used to drive electric generation turbines.

Converted biomass can also be processed into liquid fuels that are used to power transportation vehicles. Biofuels, which are renewable sources of energy, can help meet increasing energy needs, and are produced from various biomass sources including residue straw, corn stover, perennial grasses and legumes, and other agricultural and biological materials. At the moment, the most heavily utilized is corn grain, because corn starch can be readily fermented into ethanol on an industrial scale. Although directly tied to the market value of the grain itself, industrial ethanol production from corn is readily accomplished at a relatively low cost vis-à-vis other biomass sources. In coming years, however, due to rapid technological advances, the hydrolysis and conversion of other lignocellulosic materials is expected to become cost-competitive as this industry matures [41]. More information regarding the production of bioethanol can be found in [42-45]. Currently, bioethanol is the biofuel with greatest use in the US, but biodiesel is also poised to significantly contribute to the nation's energy supply in coming years. Biodiesel is produced by converting triglycerides into methyl or ethyl esters via chemical modification. Soybean, sunflower, safflower, cottonseed, and other oil seed crops are targeted for production of commercial triglycerides for biodiesel production. More information regarding the production of biodiesel can be found in [46-48].

Converted biomass can also be manufactured into many different bio-based products. Using biomaterials in the manufacture of various industrial products, such as bio-based chemicals, fibers, and biopolymers, are prime targets for utilization. This includes finished products as well as intermediates which are ready for further manufacture. At the moment, several important chemicals are currently manufactured from various biomass sources, including mannitol, sorbitol, xylitol, gluconic acid, lactic acid, and furfural. Moreover, several additional chemicals and materials should be commercially-viable in the foreseeable future, including polyhydroxybutyrate, acetylated wood, bio-based polymers, hydroxyacetaldehyde, levoglucosan, and levulinic acid. More information regarding the production of bio-based chemicals can be found in [1, 37, 49-52]. Moreover, conversion of fibers into various products has been successfully advanced and highly utilized over the years in the pulp, paper, and textile industries. Fibers are, however, increasingly being used to develop novel biocomposite materials and plastic reinforcements. Traditional plastics manufacturing operations, such as compression and injection molding, as well as extrusion processing, have been shown to be quite successful in

developing these products. More information regarding production of biomaterials can be found in [53-55].

Relevance to Engineering Education

Although it exists at the intersection of multiple sciences, including chemistry, biochemistry, microbiology, enzymology, and biology, the topic of biorefineries is very germane to the engineering discipline. For example, equipment, processes, and unit operations must be designed; these systems must be optimized; and they must be examined via modelling and simulation. Furthermore, facilities to house and service these processes, as well as human-machine interfaces, must be designed and constructed. Thus, engineering is fundamental to the successful design and deployment of these operations. Specific engineering areas that will be vital to these efforts include Agricultural, Biological, Biochemical, Bioprocess, Chemical, Industrial, Manufacturing, Mechanical, and Structural.

Resources for Educators

Biorefinery information is currently quite dispersed; no single comprehensive literature source exists. For instructors who are interested in incorporating individual, specific modules into existing engineering coursework at appropriate locations during the semester, as well as those who may design and implement entire courses devoted to biorefining, supporting teaching materials are critical to success. Therefore, a thorough listing of recent textbooks, current online publications and websites has been compiled and is provided below in Table 1.

Table 1. Biorefining resources for educators.

Books

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- A Vision for Bioenergy: Growing an Integrated Industry Growing an Industry: Overview of DOE's Bioenergy Activities and Proposed Plan of Action.
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- Biobased Industrial Products: Research and Commercialization Priorities. 1999.
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bioenergy.gov/pdfs/MYTP%20FY%202002%20v13.pdf](http://www.bioproducts-bioenergy.gov/pdfs/MYTP%20FY%202002%20v13.pdf)
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American Soybean Association. www.oilseeds.org/asa/
Association for the Advancement of Industrial Crops. <http://www.aaic.org/>
Bioenergy Australia. www.bioenergyaustralia.org
Bioenergy Information Network. Oak Ridge National Laboratory. bioenergy.ornl.gov/
Biomass Research & Development Initiative. www.bioproducts-bioenergy.gov/. National Biomass Initiative. U.S. Departments of Energy and Agriculture (USDA and DOE)
Biomass Resource Information Clearinghouse. www.rrdec.nrel.gov/biomass
Canadian Renewable Energy Network (CAREN). Bioenergy. www.canren.gc.ca/bio
Carbohydrate Economy Clearinghouse. <http://www.ilsr.org/>
CNE (China New Energy). Biomass. Overview. www.newenergy.org.cn/english/biomass
Corn Refiners Association. www.corn.org
EUBIA (European Biomass Industry Association). www.eubia.org/
Energy Efficiency and Renewable Energy Network. www.eren.doe.gov
EREC. European Renewable Energy Council. www.erec-renewables.org
IEA Bioenergy. International Collaboration in Bioenergy. www.ieabioenergy.com/
Industrial Agricultural Products Center. <http://ianrwww.unl.edu/ianr/iapc/research.htm>
National Biofuels Program Website. www.ott.doe.gov/biofuels
National Corn Growers Association. www.ncga.com
National Energy Foundation, United Kingdom. The Greenenergy website. www.nef.org.uk/greenenergy
National Renewable Energy Laboratory (NREL). Biomass Research. www.nrel.gov/biomass/
New Uses Council. www.newuses.org
Office of the Biomass Program Official Website. <http://www.bioproducts-bioenergy.gov/>
Regional Biomass Energy Program Websites. www.rrdec.nrel.gov/biomass/doe/rbep/
U.S. Department of Energy. Energy Efficiency and Renewable Energy. Biomass Program. www.eere.energy.gov/biomass/
U.S. Department of Energy. Energy Efficiency and Renewable Energy. www.eere.energy.gov/RE/bioenergy.html

Curriculum Infusion Techniques

Within the context of engineering, an untapped, but growing need for biorefinery education currently presents an opportunity to infuse undergraduate curricula with cutting-edge science that depends, to a large measure, upon the design and implementation of engineering concepts. To adequately cover the extensive range of topics relevant to this proposal, the authors recommend a full-semester stand-alone course dedicated to biorefining and bioprocessing. Table 2 presents core topics for such a course which, in conjunction with the other topics discussed in this paper, could easily be converted into a syllabus.

Table 2. Potential biorefining course topics.

Section	Topic
1	INTRODUCTION Definitions, brief history of bioprocessing, etc.
2	FUNDAMENTAL CONCEPTS IN BIOBASED PRODUCTS Review of organic chemistry concepts, plant material biology and chemistry.
3	BIOMASS RESOURCE BASE AND PRODUCTION National production statistics, properties, yields, size, etc.
4	PROCESSING BIOMASS INTO BIO-BASED PRODUCTS AND ENERGY Bioenergy, industrial products, fibers, etc. Conversion techniques.
5	PROCESSING BIOMASS INTO CHEMICALS AND FUELS Chemicals, fuels, etc. Chemical conversion, thermo-mechanical conversion, thermo-chemical conversion, biological conversion, etc.
6	MANUFACTURE OF BIO-BASED PRODUCTS; ECONOMIC ANALYSIS OF BIOPROCESSES Manufacturing processes, process economics, capital and operational expenditures.
7	ENVIRONMENTAL IMPACTS OF BIOPROCESSES Industrial regulations, industrial ecology concepts.

Moreover, the development of this type of course could logically provide a basis for an engineering program to offer a minor in biorefining and/or bioprocessing. This would, however, require additional supporting courses, such as those listed in Table 3.

Table 3. Potential biorefining/bioprocessing minor.

Sequence	Supporting Courses
1	Biology
2	Inorganic Chemistry
3	Organic Chemistry
4	Biochemistry/Biotechnology
5	Plant Science/Biology
6	Microbiology
7	Biorefining/Bioprocessing

Currently, one of the only collegiate biorefinery courses is under development at the University of Idaho, in the Department of Biological and Agricultural Engineering (<http://www.webpages.uidaho.edu/~bhe/biorefinery/index.html>). Even though the course structure differs from that discussed in Table 2 somewhat, it does appear to cover very similar topics, especially the fundamental concepts discussed here.

Understandably, not all academic programs will be able to accommodate this addition with all other programmatic requirements currently in place. Therefore, it is beneficial to examine other mechanisms for incorporating biorefinery instruction, either as individual topics, components, or units that can be used as specific learning modules, into existing coursework. Many approaches have been found to be quite successful vis-à-vis augmenting engineering instruction by inserting additional materials into mainstream instruction [62]. Addressing engineering ethics is a prime example. Some avenues that have been shown to work well include integrating focused components (theory as well as case study analyses) into specific technical courses [63-67], examining issues during technical problem solving in specific technical courses [68], issues and topics for review during capstone experiences [69-70], specific components in coursework dedicated to professionalism [71-72], topical seminars [73], as well as integration throughout the entire curriculum [74-76]. Ultimately, the inclusion of biorefinery concepts in undergraduate engineering education will be dependent upon individual faculty interest and implementation, and will be primarily influenced by the creativity of the instructor.

Conclusions

This paper has been intended to introduce engineering educators to the emerging field of biorefining. Essential definitions and concepts have been discussed, as have the relevance to engineering education and curriculum infusion techniques. Although it is not completely comprehensive in nature, many references have been included, so educators should find this a useful resource base from which to work.

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