CHAPTER

4

The Biorenewable Resource Base

4.1 Defining the Resource

Biorenewable resources, sometimes referred to as *biomass*, are organic materials of recent biological origin. This definition is deliberately broad with the intent of only excluding fossil fuel resources from the wide variety of organic materials that arise from the biotic environment. Biorenewable resources are generally classified as either *wastes* or *dedicated energy crops*.

A waste is a material that has been traditionally discarded because it has no apparent value or represents a nuisance or even a pollutant to the local environment. Clearly, if so-called wastes from one process were utilized as feedstock in another process, a more appropriate name would be coproducts. For example, oat-processing plants often generate enormous quantities of agricultural residues in the form of hulls that are currently viewed as wastes. If economically converted into process heat, electricity, liquid fuels, or chemicals, they would be considered a coproduct rather than a waste stream. This holistic approach to manufacturing, in which all the outputs from one process become the inputs to other processes, is known as *industrial ecology*. However, the word "wastes" remains a convenient moniker for "low-value coproducts" and will be used in this book.

Dedicated energy crops are plants grown specifically for production of biobased products; that is, for purposes or than food or feed. The term was originally coined to describe woody or herbaceous plants grown for their high yields of lignocellulosic material, which can be burned in a power plant to produce electricity or hydrolyzed to release fermentable sugars suitable for the production of transportation fuels. However, not all dedicated energy crops are grown for fuels and energy (they might be used for production of commodity chemicals or natural fibers), and not all fuels and energy products are derived from lignocellulosic crops (indeed, fuel ethanol is currently produced from corn starch in the United States and sugarcane in Brazil). Thus, the term "dedicated energy crop" is something of a misnomer, but it has wide usage and is understood to mean crops grown specifically as a source of carbon and energy for the manufacture of biobased products.

Biorenewable Resources: Engineering New Products from Agriculture, Second Edition. Robert C. Brown and Tristan R. Brown.

4.2 Waste Materials

Categories of waste materials that qualify as biorenewable resources include agricultural residues, yard waste, municipal solid waste (MSW), food processing waste, manure, and even invasive flora or blighted stands of plants that are harvested as part of an effort to control the contagion. Agricultural residues are simply that part of a crop discarded after harvest such as corn stover (see Figure 4.1), rice hulls, wheat straw, bagasse (fibrous material remaining after the milling of sugarcane), grapevine prunings, and almond shells, to name a few. Yard waste is an urban biomass crop: grass clippings, leaves, and tree trimmings. Invasive flora are plants or microorganisms that spread into non-native habitat. Blighted stands refer to widespread infection of a particular species of plant in an ecosystem.

Municipal solid waste is whatever is thrown out in the garbage, not all of which is suitable as biomass feedstock. In some communities, yard waste may constitute up to 18% of MSW, although a growing number of communities have ordinances against disposal of yard waste with garbage in an effort to conserve landfill space. In communities where yard waste is excluded from MSW, the important components are paper (50%), plastics and other fossil fuel–derived materials (20%), and food wastes (10%). Nonflammable materials (glass and metal) represent 20% of MSW.

Food processing waste is the effluent from a wide variety of industries ranging from breakfast cereal manufacturers to alcohol breweries. These wastes may be dry solids or watery liquids. Sewage represents a source of chemical energy and is often converted into electric power at municipal wastewater treatment plants.

The recent concentration of animals into giant livestock facilities has led to calls to treat animal wastes in a manner similar to that for human wastes. Consequently, many strategies for manure management integrate waste treatment with heat and power generation.

FIG. 4.1 Corn stover.

Invasive flora are plants that have been accidently or sometimes deliberately introduced into a non-native ecosystem where they often thrive because of the absence of natural controls such as herbivores or insects that prey on them. More commonly known as weeds, these plants can quickly dominate an ecosystem causing great damage. Examples are mesquite trees in many semiarid regions of the world and brown kelp along coastal California. Many were deliberately introduced into non-native regions in ill-considered attempts to cultivate them for various commercial purposes. Although invasive species might seem an unlikely supply of biomass, in fact, when they dominate a landscape, harvesting them becomes economically feasible while also helping control their spread. Both mesquite and kelp harvesting have been proposed for just such purposes.

Similarly, blighted stands of plants could be harvested as a supply of biomass as part of an effort to control the contagion. However, this requires local processing of the infected material in a manner that destroys the infectious agent to keep it from spreading, as often occurred in the past when infected trees were harvested and transported to distant sawmills. Thermal processing, as described in Chapter 8, would be particularly effective in destroying infectious agents, whether insects, bacteria, or viruses.

Waste materials share few common traits other than the difficulty of characterizing them because of their variable and complex composition. MSW is the leavings of thousands of households and industries that yield a feedstock that may be easy to process one day and difficult the next. Yard wastes show seasonal variations in quantity and composition: the spring brings high-moisture grass clippings that are replaced by dry leaves in the autumn. Waste streams from food processing plants, on the other hand, may be relatively invariant in composition but contain a wide assortment of complex organic compounds that are not amenable to a single conversion process. Thus, waste biomass presents special problems to engineers who are tasked with converting this sometimes unpredictable feedstock into reliable power or high-quality fuels and chemicals.

The major virtue of waste materials is their low cost. By definition, waste materials have little apparent economic value and often can be acquired for little more than the cost of transporting the material from its point of origin to a processing plant. Increasing costs for solid waste disposal and sewer discharges and restrictions on landfilling certain kinds of wastes allow some wastes to be acquired at negative cost; that is, a biorenewable resource processing plant is paid by a company seeking to dispose of a waste stream. For this reason, many of the most economically attractive opportunities in biorenewable resources involve waste feedstocks. For example, the seed corn industry, which sells seed grown specifically for planting new crops, has an annual waste disposal problem. Seed for which germination cannot be guaranteed after a certain period of storage is taken off the market. This seed cannot be sold for animal feed or even landfilled because the seed is treated with fungicide. Seed corn companies often pay brokers to accept this obsolete seed who, in turn, sell it as an inexpensive fuel for boilers and cement kilns.

As demand for these newfound feedstocks increases, those that generate them come to view themselves as suppliers and may demand payment for their waste stream: a negative feedstock cost becomes a positive one. Such a situation developed in the California biomass power industry during the 1980s. Concerns about air pollution in California led to restrictions on open-field burning of agricultural residues, a practice designed to control infestations of pests. With no means for getting rid of these residues, an enormous reserve of biomass feedstocks was materialized. These feedstocks were so inexpensive that independent power producers recognized that even small, inefficient power plants using these materials as fuel would be profitable. A number of plants were constructed and operated on agricultural residues. Eventually, the plant operators bid up the cost of this once valueless waste material. In the end, many of these plants were closed in part because of the escalating cost of biomass feedstock.

4.3 Dedicated Energy Crops

Dedicated energy crops are terrestrial plants and aquatic species grown specifically for applications other than food or feed. It is important to note that firewood obtained from cutting down an old-growth forest does not constitute a dedicated energy crop. A dedicated energy crop is grown and harvested periodically. Harvesting may occur on an annual basis, as with sugar beets or switchgrass, or on a 5–7-year cycle, as with certain strains of fast-growing trees such as hybrid poplar or willow, or even continuously, as with microalgae. The cycle of growth, harvesting, and regrowth over a relatively short time period assures that the resource is used in a sustainable fashion; that is, the resource will be available for future generations.

Dedicated energy crops can fulfill one or more market niches. In some instances, the whole plant is used as feedstock for production of electricity and/or liquid fuels. Such is the case when trees are grown and harvested specifically as boiler fuel for steam power plants. Another possibility is that a variety of coproducts are coaxed from a single crop. For example, alfalfa has been evaluated for its potential to yield both energy and feed from a single crop. The high-protein leaves would be removed after harvesting and processed into animal feed, while the fibrous stems would be used as fuel in a gasification power plant. The least desirable and most wasteful scenario for dedicated energy crops is extraction of the highest-value portion of the crop for conversion into biobased product and discarding the rest of the plant as waste.

Dedicated energy crops contain significant quantities of one or more of four important energy-rich components: oils, sugars, starches, and lignocellulose (fiber). Crops rich in the first three have historically been grown for food and feed: oils from soybeans, nuts, and grains; sugars from sugar beets, sorghum, and sugarcane; and starches from corn and cereal crops. Oil, sugars, and starches are easily metabolized. On the other hand, lignocellulose is indigestible by humans although certain domesticated animals with specialized digestive tracts are able to break down the polymeric structure of lignocellulose and use it as an energy source. From this discussion, it might appear that the best strategy for developing biomass resources is to grow crops rich in oils, sugars, and starches. However, most terrestrial plants, even those known as “oil crops” or “starch crops,” are mostly lignocellulose, the structural (fibrous) material of plants: hulls, shells, stems, leaves, and roots. If oils, sugars, and starches are harvested and the lignocellulose is left behind as agricultural residue rather than used as fuel or feedstock, a large portion of the biomass crop remains in the field.

Not only should lignocellulose be valued, there is good reason to maximize its production at the expense of lipids and simple carbohydrates if energy production or commodity chemicals are the primary purpose for growing the crop. Research has shown that energy yields (kilojoules per hectare per year) are usually greatest for plants that are mostly “roots and stems”; in other words, plant resources are directed toward the manufacture of lignocellulose rather than oils, sugars, and starches. As a result, there has been a bias toward the development of dedicated energy crops that focus on lignocellulosic biomass, at least for vascular flora (i.e., plants with an internal system for transport of water and nutrients).

Exceptions to this rule-of-thumb are many non-vascular (eukaryote) floras from the phyla *Chlorophyta* (green algae), *Rhodophyta* (red algae), *Phaeophyta* (brown algae, the kelps), and *Bryophyta* (mosses and liverworts) and the prokaryote *Cyanobacteria* (blue-green algae). The term flora is used to avoid confusion in the classification of certain kinds of photosynthetic organisms. At one time, nonvascular flora were considered to be simple plants (kingdom Plantae) but are now classified in the kingdom Protist. Further complicating the nomenclature, blue-green algae were found to be neither plants nor protists but members of the separate kingdom Bacteria.

These non-vascular flora either live as low-growing plants in wet terrestrial environments or as aquatic species. Because non-vascular flora do not require the structural support of vascular terrestrial plants, they do not incorporate lignocellulose into their cell walls. Although they may contain amorphous polysaccharides like starch, lignin is absent. In many unicellular photosynthetic organisms, lipids and protein can be the major constituents of the biomass.

Dedicated energy crops are conveniently divided into three categories: herbaceous energy crops (HEC) and short rotation woody crops (SRWC), both of which represent lignocellulosic-rich vascular plants, and oleaginous (lipid-rich) crops, which includes both oil seed (vascular) plants and non-vascular microalgae and cyanobacteria. Selected feedstocks are described in the following sections and Appendix A.

4.3.1 Herbaceous Energy Crops

Herbaceous crops are plants that have little or no woody tissue. The aboveground growth of these plants usually lives for only a single growing season. However, herbaceous crops include both annuals and perennials. Annuals die at the end of a growing season and must be replanted in the spring. Perennials die each year in temperate climates but reestablish themselves each spring from rootstock. Both annual and perennial HEC are harvested on at least an annual basis, if not more frequently, with yields averaging 5.5–11 Mg/ha/year, with maximum yields between 20 and 40 Mg/ha/year in temperate regions. As with trees, yields can be much higher in tropical and subtropical regions.

Among the many species of herbaceous plants that are potentially suitable as dedicated energy crops, recent development work has focused on grasses because of their high yields of lignocellulose. Grasses are conveniently classified as either thick stemmed or thin stemmed. Thick-stemmed grasses, which include annual and perennial varieties, are indigenous to the tropics. The most familiar examples are sugarcane and energy cane (*Sacharum* spp.), miscanthus (*Miscanthus giganteus*, illustrated in Figure 4.2), and Napier grass (*Pennisetum purpureum*) among the perennials and corn (*Zea mays*) and forage sorghum (sorghum, Sudan grass, and sorghum × Sudan grass, now all classified as *Sorghum bicolor*) among the annuals.

FIG. 4.2 Miscanthus (*Miscanthus giganteus*).

Harvesting of thick-stemmed perennials such as sugarcane is a labor-intensive activity even with mechanized harvesting equipment. Cost-effective harvesting of thick-stemmed perennials as HEC would probably be by forage harvesters followed by storage as silage. The same is true of many of the thick-stemmed annuals although dry corn stalks can be baled readily.

Thin-stemmed grasses include many perennial and annual species. These are conveniently classified as either cool-season grasses, which grow more vigorously in the spring and fall, or warm-season grasses, which grow most actively during the summer. Familiar perennial cool-season grasses include reed canary grass (*Phalaris arundinacea*), Timothy-grass (*Phleum pratense*), and tall fescue (*Festuca arundinacea*). Examples of warm-season grasses are switchgrass (*Panicum virgatum*, illustrated in Figure 4.3), big bluestem (*Andropogon gerardii*), and eastern gamagrass (*Tripsacum dactyloides*).

The thin-stemmed perennials are particularly attractive as HEC because they can be harvested with conventional hay equipment. They are less susceptible to

FIG. 4.3 Switchgrass (*Panicum virgatum*).

lodging (falling over on one another as the plants become tall) than the thick-stemmed grasses. This is important because it allows the plants to be harvested at the end of the growing season when valuable nutrients have translocated to roots. Perennials, as a rule, are more drought resistant than annuals, require less weed control, and are less likely to erode soils. Warm-season, thin-stemmed grasses are the leading candidates for HEC. They are more drought resistant than cool-season grasses and are efficient users of nutrients.

Herbaceous crops more closely resemble hardwoods in their chemical properties than they do softwoods. Their low lignin content makes them relatively easy to delignify, which improves accessibility of the carbohydrate in the lignocellulose, especially for biochemical processing. The hemicellulose contains mostly xylan, which is highly susceptible to acid hydrolysis, compared to the cellulose. As a result, agricultural residues are susceptible to microbial degradation, destroying their processing potential in a matter of days if exposed to the elements. Herbaceous crops have relatively high silica content compared to woody crops, which can present problems during processing.

4.3.2 Short Rotation Woody Crops

Short rotation woody crop is used to describe woody biomass that is fast growing and suitable for use in dedicated feedstock supply systems. Desirable SRWC candidates display rapid juvenile growth, wide site adaptability, and pest and disease resistance. Woody crops grown on a sustainable basis are harvested on a rotation of 3–10 years.

Woody crops include hardwoods and softwoods. Hardwoods are trees classified as angiosperms, which are also known as flowering plants. Examples include willow, oak, and poplar. Hardwoods can resprout from stumps, a process known as coppicing, which reduces their production costs compared to softwoods. Advantages of hardwoods in processing include: high density for many species; relative ease of delignification and accessibility of wood carbohydrates; the presence of hemicellulose high in xylan, which can be removed relatively easily; low content of ash, particularly silica, compared to softwoods and herbaceous crops; and high acetyl content compared to most softwoods and herbaceous crops, which is an advantage in the recovery of acetic acid. Hardwood lignin is less condensed (i.e., lower degree of polymerization) than softwood and contains a greater methoxyl content, which accounts for its preference at one time for the destructive distillation of wood to produce methanol. Hardwood lignin becomes plastic at lower temperatures than for softwood lignin.

Softwoods are trees classified as gymnosperms, which encompass most trees known as evergreens. Examples include pine, spruce, and cedar. Softwoods are generally fast growing, but their carbohydrate is not as accessible for chemical processing as the carbohydrates in hardwood. Since softwoods have considerable

Fig. 4.4 Hybrid poplar (*Populus nigra*).

value as construction lumber and pulpwood, it is more readily available as waste material in the form of logging and manufacturing residues than are hardwoods. Logging residues, consisting of a high proportion of branches and tops, contain considerable high-density compression wood, which is not easily delignified. Logging residues are more suitable as boiler fuel or other thermochemical treatments than as feedstock for chemical or enzymatic processing.

Development of dedicated feedstock supply systems has focused on several hardwood species, including poplar (*Populus* spp., illustrated in Figure 4.4), willows (*Salix* spp.) silver maple (*Acer saccharinum*), sweetgum (*Liquidambar styraciflua*), sycamore (*Platanus occidentalis*), black locust (*Robinia pseudoacacia*), and eucalyptus. Trees of potential regional importance in the United States include alders (*Alnus* spp.), mesquite (*Prosopis* spp.), and the Chinese tallow (*Sapium sebiferum*).

Hybrid poplar and eucalyptus are most promising for the United States because of high growth rates averaging between 10 and 17 Mg/ha/year, depending upon geographic location, with maximum yields between 15 and 43 Mg/ha/year. In the United States, hybrid poplar has a wider range than eucalyptus, which is limited to southern Florida, California, and Hawaii. Hybrid poplar is also attractive for the ease of propagating it from either stem cuttings or tissue culture.

4.3.3 Oleaginous (Lipid-Rich) Crops

Lipids are a large group of hydrophobic, fat-soluble compounds that include fats, sterols, triglycerides, and waxes. Lipids play several roles in living organisms, including energy storage, cellular structural support as membranes, and intercellular signaling. Storage lipids are particularly important as they are concentrated in discrete lipid bodies, usually as triglycerides although sometimes as fatty waxes, which makes them easier to recover. These storage lipids are distinguished by an absence of charged functionalities and are hence referred to as "neutral lipids." In contrast, "polar lipids" have charged functionalities that allow them to form bilayers that constitute the structure of cell membranes. Polar lipids are difficult to extract and their inorganic contents (phosphorous from phosphates and nitrogen from amides) make them less attractive for fuel synthesis. Vascular plants contain specialized oleaginous plant cells to store neutral lipids in the form of seeds.

Triglycerides, commonly known as vegetable oils, are among the most familiar form of lipids and have been widely used for the production of biodiesel from oil seed crops. Until recently, the potential for significant market penetration of lipid-based biofuels was considered small because of the low productivity of traditional oleaginous crops like soybean and rapeseed, which yield only 450–950 L of biodiesel per hectare. Sunflower, one of the most highly productive vegetable oil crops, only produces 550–1600 L/ha compared to 5800–8700 L of ethanol per hectare of corn crop. Even accounting for the lower energy content of ethanol, the fuel energy obtained per hectare is three to seven times higher for corn ethanol than oilseed biodiesel and even higher for cellulosic biofuels. For this reason, little attention was given to further developing lipid-based fuels until recently.

The drivers for renewed attention to lipid-based fuels are twofold. First, lipids are highly reduced compounds, containing very little oxygen, and in some respects resemble long-chained hydrocarbons found in petroleum-based fuels. As will be subsequently described, lipids can be upgraded in a fashion similar to hydroprocessing of petroleum to yield hydrocarbons that are essentially indistinguishable from gasoline, diesel fuel, and aviation fuel. These so-called "drop-in" biofuels can be directly substituted for petroleum-based fuels without modifying fuel distribution or fuel utilization infrastructure. This is especially important for aviation applications where the hydroscopic (water attracting) properties of ethanol make it unsuitable as aviation fuel. The second driver for renewed interest in lipid-based fuels is the prospect for growing high-yielding lipid feedstocks, sometimes in environments not otherwise suitable for growing food crops. Prominent examples explored below include palm oil, jatropha, salicornia, and microalgae, although there are others.

The oil palm, illustrated in Figure 4.5, is a native of Southeast Asia. It produces a fleshy fruit from which palm oil is derived. The kernel of the palm oil fruit also yields palm kernel oil, which is more saturated than palm oil. The oil palm tree

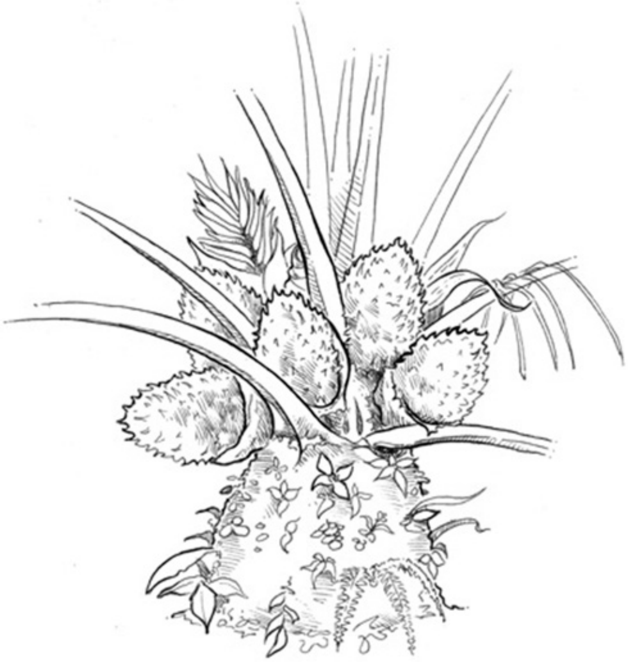

Fig. 4.5 Oil palm (*Elaeis oleifera*).

grows primarily in Malaysia and Indonesia, although equatorial countries in South America and Africa can grow it as well. Its popularity as a crop has grown in recent years both as cooking oil and as lipid feedstock for biodiesel production. The yield of lipids is more than 5600 L/ha, which is nearly 10 times that of soybeans in terms of both energy yield and biofuel yield. This makes it one of the highest-yielding lipid-based feedstocks currently being grown. The oil palm infrastructure is also well developed; palm oil was used in both food and cosmetics for several decades before it became a popular biodiesel feedstock.

Because it grows in tropical countries, concerns have been raised that rainforests will be cleared to allow plantations of oil palm to be grown. Furthermore, its edible nature raises concerns that its use as fuel will compete with food production in developing regions of the world.

Jatropha, illustrated in Figure 4.6, is a genus of hardy bushes and trees originating in the Caribbean and now spread throughout the tropics that produces seeds containing up to 40% triglycerides. Yields for this inedible oil have been reported to be as high as 1400 L/ha. Jatropha oil has been touted as a solution to concerns about fuel crops competing with food crops because it can be grown on marginal and nonarable lands. Oil from jatropha has been successfully hydrotreated to produce jet fuel that has been certified for flight testing.

Fig. 4.6 Jatropha (*Jatropha curcas*).

Jatropha must overcome several challenges before it can be considered a viable biofuel feedstock. Because it has not been domesticated, yields cannot be satisfactorily predicted. These range from an unacceptable 0.1 ton to an impressive 8 tons of seed per hectare. While its ability to grow under poor agricultural conditions is frequently touted, this does not necessarily mean it thrives under such conditions. Additionally, its long-term impact on soil and the environment has yet to be studied. This has also hindered the ability to make accurate estimates of the production costs of jatropha oil. Whereas crops like corn and soybeans have been extensively bred and genetically engineered to develop highly efficient strains, genetic improvement of jatropha to improve its fuel yield is in the very early stages of research.

Salicornia, shown in Figure 4.7, is an edible, salt-tolerant plant that grows in salt marshes and on beaches. Long used for glassmaking and soapmaking, its seeds contain high levels of unsaturated oil suitable for biodiesel production. Its main advantage over other lipid feedstocks is its extremely high salt tolerance relative to other agricultural plants, which allows it to grow in saline conditions that would be toxic to other major agricultural crops. Field trials have demonstrated that salicornia can thrive in extreme coastal desert conditions using seawater as its only irrigation source. It has been reported to produce greater yields of seeds and biomass under these conditions than soybeans grown under ideal agricultural conditions. Originally conceived as an alternative to soybeans for chicken feed, salicornia's ability to thrive in marginal, nonagricultural lands makes it attractive as a nonfood biomass feedstock. Furthermore, the ability to irrigate it with seawater

Fig. 4.7 Salicornia (*Salicornia europea*).

provides an opportunity to cultivate dry coastal lands for biofuels production without depleting freshwater sources.

Salicornia faces many challenges similar to those for jatropha. While edible, salicornia has never been domesticated in the same manner as other oleaginous crops, with the result that yields can be attractive but erratic. Furthermore, at roughly 940 L/ha, salicornia's typical yield is far inferior to that reported for jatropha and palm oil (although more than soybeans). There is little data to evaluate the cost of fuel from salicornia.

Microalgae, shown in Figure 4.8, are photosynthetic single-cell microorganisms that grow rapidly under optimal conditions of light and nutrients, producing as much as 100 tons/ha per year of algal biomass containing 5–25% lipid. However, microalgae increase their lipid content when deprived of key growth nutrients such as nitrogen and phosphorus. In this case, lipid content can reach 40–70% although overall biomass productivity generally decreases. As shown in Table 4.1, the potential yield of algae-based fuel is 9800–52 000 L/ha, dwarfing the land

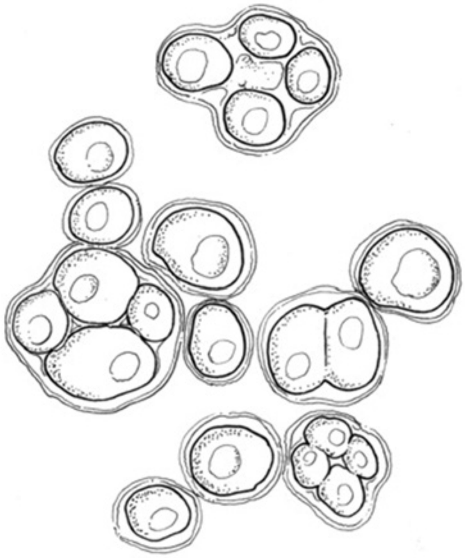

Fig. 4.8 Microphytes.

productivity of biodiesel from sunflower oil and ethanol from cellulosic biomass. Furthermore, algae can be grown on marginal cropland or even within natural bodies of water, allowing it to complement conventional crop production rather than replace it.

The industry faces several hurdles before commercialization. The most formidable is the cost to build the expansive system of ponds or closed reactors that bring together the sunlight, carbon dioxide, water, and nutrients needed to grow microalgae. Open ponds, although little more than concrete or plastic-lined raceways that continuously circulate water and screen out microalgae, are estimated to cost as much as $250 000 per hectare. Photobioreactors are more elaborate closed systems suitable for highly productive pure cultures of microalgae but cost as much as $2.5 million per hectare.

Table 4.1 Comparing biomass yield and fuel productivity for cellulosic and oleaginous feedstocks

Process	Feedstock	Theoretical Fuel Yield (L/ton)	Biomass Production (ton/ha)	Fuel Productivity (L/ha)
Biodiesel	Sunflower	420–520	1.3–3.1	550–1600
Biodiesel	Microalgae	150–420	65.1–124	9800–52 000
Grain ethanol	Corn grain	520	11.2–16.8	5800–8700
Biochemical cellulosic ethanol	Grass	420–470	11.2–44.9	4700–21 000
Thermochemical cellulosic ethanol	Wood	540–670	11.2–44.9	6100–30 000

The major barrier to microalgal fuels is the high cost of microalgal biomass, which at present costs as much as \$1000 per dry metric ton—over 10 times the cost of lignocellulosic biomass. The result is algal fuel that costs \$20–\$75 per gallon. This high cost is largely due to the expense of growing and harvesting microalgae, with feedstock costs being responsible for up to 60% of the cost of algal fuels.

Microalgal biofuels are often touted as a solution to the "food vs. fuel" concern often debated about production of biofuels. Ironically, microalgae could also prove to be an important source of nutrients and dietary protein for direct human consumption or indirectly through its use as animal feed. Microalgae produce large quantities of essential fatty acids (EFAs) such as omega-3, which have been commercially exploited in human nutritional supplements and additives to poultry feed. Algae are also rich in protein that might one day help meet the growing demand for protein around the world although it is not presently palatable as food. Neither are algal fuels a clear solution to land-use concerns. Although microalgae is an aquatic species with potential to be grown in salt marshes or even open oceans, current development focuses on terrestrial systems that would compete with other land uses including irrigated food crops on arid lands that are otherwise fertile.

The harnessing of sunlight and carbon dioxide by plants, protists, and bacteria for growth and production is known as *autotrophic* metabolism. Alternatively, living organisms can obtain essential supplies of energy and carbon from energy-rich organic compounds, a metabolic pathway known as *heterotrophic* metabolism. Many microalgae as well as anaerobic yeasts and fungi can utilize sugars, for example, to accumulate lipids under conditions of nitrogen, phosphate, sulfur, and/or iron deprivation. This eliminates the difficulties of supplying sunlight and carbon dioxide to culture media, reducing capital and operating costs associated with microbial lipid production. However, it does require the production of sugar by conventional agriculture, which reintroduces the issues of competition with food crops.

4.4 Properties of Biomass

Evaluation of biomass resources as potential feedstocks generally requires information about plant composition, heating value, production yields, and bulk density. Compositional information can be reported in terms of organic components, proximate analysis, or ultimate analysis.

Analysis in terms of composition reports the kinds and amounts of plant components including proteins, lipids, sugars, starches, and lignocellulose (fiber). For lignocellulosic crops, engineers are particularly interested in the partitioning among cellulose, hemicellulose, and lignin, while for oleaginous crops the distinction is among carbohydrate, lipids, and protein. Table 4.2 gives the composition of common sugar and starch crops; Table 4.3 includes the composition of several types of

Table 4.2 Composition of starch and sugar crops (dry basis)

Feedstock	Protein (wt%)	Oil (wt%)	Starch (wt%)	Sugar (wt%)	Fiber (wt%)
Corn grain	10	5	72	<1	13
Wheat grain	14	<1	80	<1	5
Jerusalem artichoke	<1	<1	<1	75	25
Sugarcane	<1	<1	<1	50	50
Sweet sorghum	<1	<1	<1	50	50

Source: Wayman, M. and Parekh, S. (1990) *Biotechnology of Biomass Conversion: Fuels and Chemicals from Renewable Resources*. Philadelphia: Open University Press.

dedicated energy crops; Table 4.4 gives the oil content of selected oil seed crops; and Table 4.5 gives the composition of several microalgae species.

Proximate analysis is important in developing thermochemical conversion processes for biomass. Proximate analysis reports the yields (% mass basis) of various products obtained upon heating the material under controlled conditions; these products include moisture, volatile matter, fixed carbon, and ash. Since moisture content of biomass is so variable and can be easily determined by gravimetric methods (weighing, heating at 100°C, and reweighing), the proximate analysis of biomass is commonly reported on a dry basis. Volatile matter is that fraction of biomass that decomposes and escapes as gases upon heating a sample at moderate temperatures (about 400°C) in an inert (nonoxidizing) environment. Knowledge of volatile matter is important in designing burners and gasifiers for biomass. The remaining fraction is a mixture of solid carbon (fixed carbon) and mineral matter (ash), which can be distinguished by further heating the sample in the presence of oxygen: the carbon is converted to carbon dioxide leaving only the ash. Table 4.6 contains the proximate analysis (dry basis) of a wide range of biomass materials.

Ultimate analysis is simply the (major) elemental composition of the biomass on a gravimetric basis: carbon, hydrogen, oxygen, nitrogen, sulfur, and chlorine

Table 4.3 Composition of lignocellulosic crops (dry basis)

Feedstock	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Other[a] (wt%)
Bagasse	35	25	20	20
Corn stover	53	15	16	16
Corn cobs	32	44	13	11
Wheat straw	38	36	16	10
Wheat chaff	38	36	16	11
SRWC	50	23	22	5
HEC	45	30	15	10
Waste paper	76	13	11	0

Sources: Bull, S.R. (1991) The U.S. Department of Energy Biofuels Research Program. *Energy Sources*, 13, 433–442; Wayman, M. and Parekh, S. (1990) *Biotechnology of Biomass Conversion: Fuels and Chemicals from Renewable Resources*. Philadelphia: Open University Press.[a]Includes proteins, oils, and mineral matter, such as silica and alkali.

Table 4.4 Lipid content of oil seed crops

Feedstock	Oil Content (%)
Castor	45–50
Corn (germ)	48
Cottonseed	18–25
Jatropha	30–40
Jojoba	45–50
Palm kernel	44–65
Oil palm	30–60
Peanut	45–55
Rapeseed	38–46
Soybean	15–20
Sunflower	25–35

Source: Karmakar, A., Karmakar, S., and Mukherjee, S. (2010) Properties of various plants and animals feedstocks for biodiesel production. *Bioresource Technology*, 101, 7201–7210.

along with moisture and ash. Table 4.6 contains the ultimate analysis of several biomass materials on a dry basis. Sometimes this information is presented on a dry, ash-free (daf) basis. This information is very important in performing mass balances on biomass conversion processes. Evident from Table 4.6 is the relatively high oxygen content of biomass (typically 40–45 wt%).

Of course, from ultimate analyses, the molecular formulas can be worked out. In many instances, a generic molecular formula based on 1 mol of carbon is convenient for performing mass balances on a process. For example, cellulose and starch have the generic molecular formula $CH_{1.7}O_{0.83}$, hemicellulose can be represented by $CH_{1.6}O_{0.8}$, and wood is $CH_{1.4}O_{0.66}$.

Table 4.5 Composition of selected microalgae

Feedstock	Protein (%)[a]	Carbohydrate (%)[a]	Lipids (%)[a]
Anabaena cylindrica	43–56	25–30	4–7
Aphanizomenon flos-aquae	62	23	3
Chlamydomonas reinhardtii	48	17	21
Chlorella pyrenoidosa	57	26	2
Chlorella vulgaris	51–58	12–17	14–22
Dunaliella salina	57	32	6
Euglena gracilis	39–61	14–18	14–20
Porphyridium cruentum	28–39	40–57	9–14
Scenedesmus obliquus	50–56	10–17	12–14
Spirogyra spp.	6–20	33–64	11–21
Arthrospira maxima	60–71	13–16	6–7
Spirulina platensis	46–63	8–14	4–9
Synechococcus spp.	63	15	11

Source: Becker, E.W. (2007) Micro-algae as a source of protein. *Biotechnology Advances*, 25, 207–210.[a]Dry cell weight basis.

Table 4.6 Thermochemical properties of selected biomass

Biomass	HHV (dry) (MJ/kg)	Proximate Analysis (wt%, dry)			Ultimate Analysis (wt %, dry basis)						
		Volatile	Ash	Fixed C	C	H	O	N	S	Cl	Ash
Alfalfa straw	18.45	72.60	7.25	20.15	46.76	5.40	40.72	1.00	0.02	0.03	6.07
Almond shells	19.38	73.45	4.81	21.74	44.98	5.97	42.27	1.16	0.02		5.60
Black locust	19.71	80.94	0.80	18.26	50.73	5.71	41.93	0.57	0.01	0.08	0.97
Cedar (western red)	20.56	86.50	0.30	13.20							
Corn cobs	18.77	80.10	1.36	18.54	46.58	5.87	45.46	0.47	0.01	0.21	1.40
Corn stover	17.65	75.17	5.58	19.25	43.65	5.56	43.31	0.61	0.01	0.60	6.26
Corn grain	17.20	86.57	1.27	12.16	44.00	6.11	47.24	1.24	0.14		1.27
Douglas fir	20.37	87.30	0.10	12.60	50.64	6.18	43.00	0.06	0.02		0.01
Food waste	7.59				17.93	2.55	12.85	1.13	0.06	0.38	5.10
Grape vines		80.10	2.20	17.70							
Hemlock (western)	19.89	87.00	0.30	12.70	50.40	5.80	41.40	0.10	0.10		2.20
Maize straw					47.09	5.54	39.79	0.81	0.12		5.77
Manure (cattle, fresh)	17.36				45.40	5.40	31.00	1.00	0.30		15.90
MSW	19.87	76.30	12.00	11.70	47.60	6.00	32.90	1.20	0.30		12.00
Oak bark	19.47				49.70	5.40	39.30	0.20	0.10		5.30
Orchard prunings	19.05	83.30	2.10	14.60	49.20	6.00	43.20	0.25	0.04		1.38
Ponderosa pine	20.02	82.54	0.29	17.17	49.25	5.99	44.36	0.06	0.03	0.01	0.30
Hybrid poplar	19.38	82.32	1.33	16.35	48.45	5.85	43.69	0.47	0.01	0.10	1.43
Redwood (combined)	20.72	79.72	0.36	19.92	50.64	5.98	42.88	0.05	0.03	0.02	0.40
Refuse-derived fuel	17.40				42.50	5.84	27.57	0.77	0.48	0.57	22.17
Rice hulls	16.14	65.47	17.86	16.67	40.96	4.30	35.86	0.40	0.02	0.12	18.34
Rice straw (fresh)	16.28	69.33	13.42	17.25	41.78	4.63	36.57	0.70	0.08	0.34	15.90
Sorghum stalks	15.40				40.00	5.20	40.70	1.40	0.20		12.50
Sudan grass	17.39	72.75	8.65	18.60	44.58	5.35	39.18	1.21	0.08	0.13	9.47
Sugarcane bagasse	17.33	73.78	11.27	14.95	44.80	5.35	39.55	0.38	0.01	0.12	9.79
Switchgrass	18.64	81.36	3.61	15.03	47.45	5.75	42.37	0.74	0.08	0.03	3.50
Vineyard prunings	16.82				48.00	5.70	39.60	0.86	0.08		1.41
Walnut shells	20.18	78.28	0.56	21.16	49.98	5.71	43.35	0.21	0.01	0.03	0.71
Water hyacinth	16.02		22.40		41.10	5.29		1.96	0.41		
Wheat straw	17.51	71.30	8.90	19.80	43.20	5.00	39.40	0.61	0.11	0.28	11.40
White fir	19.95	83.17	0.25	16.58	49.00	5.98	44.75	0.05	0.01	0.01	0.20
Yard waste	16.30	66.04	20.37	13.59	41.54	4.79	31.91	0.85	0.24	0.30	20.37

Heating value is the net enthalpy released upon reacting a particular fuel with oxygen under isothermal conditions (the starting and ending temperatures are the same). If water vapor formed during reaction condenses at the end of the process, the latent enthalpy of condensation contributes to what is known as the higher heating value (HHV). Otherwise, the latent enthalpy does not contribute and the

Table 4.7 Alkali content of biomass

	HHV (MJ/kg)	Ash in Fuel (%)	Alkali in Ash (%)
Hybrid poplar	19.0	1.9	19.8
Pine chips	19.9	0.7	3.0
Tree trimmings	18.9	3.6	16.5
Urban wood waste	19.0	6.0	6.2
White oak	19.0	0.4	31.8
Almond shells	17.6	3.5	21.1
Bagasse—washed	19.1	1.7	12.3
Rice straw	15.1	18.7	13.3
Switchgrass	18.0	10.1	15.1
Wheat straw	18.5	5.1	31.5

Source: Miles, Sr, T.R., Miles, Jr, T.R., Baxter, L., Jenkins, B., and Oden, L. (1995) Alkali deposits found in biomass power plants. *Summary Report*. National Renewable Energy Laboratory, NREL Subcontract TZ-2-11226-1, April 15.

lower heating value (LHV) prevails. These measurements are typically performed in a bomb calorimeter and yield the HHV for the fuel. Table 4.6 reports HHVs for several biomass materials. Heating values of biomass can be conveniently estimated from the percent of carbon in the biomass on a dry basis using the empirical relationship:

$$\text{HHV in MJ/dry kg} = 0.4571 \times (\%\text{C on dry basis}) - 2.70 \tag{4.1}$$

The inorganic constituents of biomass are important to different extents, depending on the conversion process under consideration. No comprehensive information on inorganic constituents will be provided here, although such information can be found in the literature on biomass. However, knowledge of the alkali metal content of biomass (i.e., potassium and sodium) can be very important if the fuel is to be used in combustors. Experience in burning biomass reveals that excessive alkali salts in biomass, which is particularly concentrated in fast-growing biomass, can lead to ash fouling of boiler tubes. Table 4.7 contains information on alkali in ash for selected biomass materials useful in designing biomass combustion systems.

Bulk density is determined by weighing a known volume of biomass that is packed or baled in the form anticipated for its transportation or use. Clearly, solid logs will have higher bulk density than the same wood chipped. Bulk density will be an important determinant of transportation costs and the size of fuel storage and handling equipment. Volumetric energy content is also important in transportation and storage issues. Volumetric energy content, which is simply the enthalpy content of fuel per unit volume, is calculated by multiplying the HHV of a fuel by its bulk density. Table 4.8 compares bulk densities and volumetric energy contents of various liquid and solid fuels. The cost of collecting large quantities of biomass can be significant. Wood or other biomass resources must generally be

Table 4.8 Density and volumetric energy content of various solid and liquid fuels

Fuel	Density (kg/m^3)	Volumetric Energy Content (GJ/m^3)
Ethanol	790	23.5
Methanol	790	17.6
Biodiesel	900	35.6
Pyrolysis oil	1280	10.6
Gasoline	740	35.7
Diesel fuel	850	39.1
Agricultural residues	50–200	0.8–3.6
Hardwood	280–480	5.3–9.1
Softwood	200–340	4–6.8
Baled straw	160–300	2.6–4.9
Bagasse	160	2.8
Rice hulls	130	2.1
Nut shells	64	1.3
Coal	600–900	11–33

Sources: Grohmann, K., Wyman, C.E., and Himmel, M.E. (1992) Potential for fuels from biomass and wastes, in *Emerging Technologies for Material and Chemicals from Biomass* (eds. R.M. Rowell, T.P. Schultz, and R. Narayan), ACS Symposium Series 476, Washington, DC: American Chemical Society; Larson, E.D., Svenningsson, P., and Bjerle, I. (1989) Biomass gasification for gas turbines power generation, in *Electricity: Efficient End-Use and New Generation Technologies and Their Planning Implications* (eds T.B. Johansson, B. Bodlund, and R.H. William). Lund, Sweden: Lund University Press.

produced within a 50-mile radius of the processing plant to be economical, given the high transportation costs and low densities of biomass.

For many applications, including production of paper and composite materials, the length of fibers in biomass is an important property. Fiber lengths for several kinds of agricultural and forestry biomass are listed in Table 4.9. Extraction of plant fibers is discussed in Chapter 10.

Table 4.9 Dimensions of Some Common Lignocellulosic Fibers

	Fiber Dimension (mm)		
Type of Fiber	Length	Average Length	Width
Cotton	10–60	18	0.02
Flax	5–60	25–30	0.012–0.027
Hemp	5–55	20	0.025–0.05
Manila hemp	2.5–12	6	0.025–0.04
Bamboo	1.5–4	2.5	0.025–0.04
Esparto	0.5–2	1.5	0.013
Jute	1.5–5	2	0.02
Corn stalks	1–1.5	–	0.02
Rice straw	0.65–3.48	–	0.005–0.014
Wheat straw	1.5	–	0.015
Deciduous wood	1–1.8	–	0.03
Coniferous wood	3.5–5	–	0.025

Sources: Rowell, R.M. (1992) *Opportunities for Lignocellulosic Materials and Composites*. ACS Symposium Series 476. Washington, DC: American Chemical Society, pp. 12–27; Rowell, R.M., Young, R.A., and Rowell, J.R. (eds) (1997) *Paper and Composites from Agro-Based Resources*. Boca Raton: CRC Press.

4.5 Yields of Biomass

Planning a biomass conversion facility requires estimates of the total amount of land that must be put into production of biomass crops and how far crops must be transported to a facility. Thus, the annual yield of biomass crops (kilograms per hectare) is important information for an engineer working on such a project. Unfortunately, yield information does not lend itself to tabulation, since it depends on so many variables: plant variety, crop management (fertilization and pest control), soil type, landscape, climate, weather, and water drainage. Table 4.10 has been included to give an idea of the kinds of yields that might be expected in various geographical locations for carbohydrate-rich biomass crops that have been widely studied. Site-specific information will require discussions with state extension agents and local agronomists in combination with field trials in advance of detailed plant design.

Yields of agricultural residues, which are rich in lignocellulosic biomass, are conveniently tabulated in terms of residue factors, defined as the ratio of dry weight of residue to the grain weight at field moisture. Thus, the weight of residue available per hectare of crop can be estimated by multiplying the residue factor by the grain yield in kilograms per hectare. Average residue factors are tabulated in Table 4.11.

Yields of lipid (liters per hectare per year) from terrestrial oil crops are tabulated in Table 4.12. These include conventional oil seed crops like soybeans as well as unconventional crops like jatropha and salicornia. Table 4.13 lists biomass productivity (g/m^2/day) for various species of microalgae along with their lipid content and the resulting lipid productivity (L/ha/yr). Of course, these yields

Table 4.10 Nominal annual yields of carbohydrate-rich biomass crops[a]

Biomass Crop	Geographical Location	Annual Yield (kg/ha)
Corn: grain	North America	7000
Corn: cobs	North America	1300
Corn: stover	North America	8400
Jerusalem artichoke: tuber	North America	45 000
Jerusalem artichoke: sugar	North America	6400
Sugarcane: crop	Hawaii	55 000
Sugarcane: sugar	Hawaii	7200
Sugarcane: bagasse (dry)	Hawaii	7200
Sweet sorghum: crop	Midwest	38 000
Sweet sorghum: sugar	Midwest	5300
Sweet sorghum: fiber (dry)	Midwest	4900
Switchgrass	North America	14 000
Hybrid poplar	North America	14 000
Wheat: grain	Canada	2200
Wheat: straw	Canada	6000

Source: Wayman, M. and Parekh, S. (1990) *Biotechnology of Biomass Conversion: Fuels and Chemicals from Renewable Resources*. Philadelphia: Open University Press.[a]Includes moisture content at harvest unless otherwise noted.

Table 4.11 Agricultural residue factors for various grain crops

Crop	Residue factor[a]
Barley	1.5
Corn (<95 bushels/acre)	1
Corn (>95 bushels/acre)	1.5
Cotton	1.5
Oats	1.4
Rice	1.5
Rye	1.5
Sorghum	1.5
Soybeans	1.5
Wheat, spring	1.3
Wheat, winter	1.7

Source: Heid, W.J., Jr. (1984). Turning Great Plains crop residues and other products into energy. Agricultural Economic Report No. 523. Washington, DC: US Department of Agriculture.[a]These factors are ratios of dry weight of residue to the grain weight at field moisture.

exclude coproducts of lipid extraction, which are rich in protein and carbohydrate (see Table 4.5).

Manure is a relatively small biomass resource compared to dedicated energy crops or agricultural residues. However, growing concerns about the environmental impact of manure from large concentrations of animals in many modern agricultural operations make manure a potential biomass resource. Manure production rates for various kinds of livestock and poultry are listed in Table 4.14.

4.6 Size of Resource Base

The amount of biomass that could be produced annually in the United States is difficult to estimate. In addition to the uncertainties in estimating yields on

Table 4.12 Lipid yields for selected terrestrial oil crops

Common name	Species	Lipid yield (L/ha)
Castor bean	*Ricinus communis*	1413
Corn (germ)		172
Chinese tallow tree	*Sapium sebiferum*	6300
Jatropha	*Jatropha curcas*	1900
Jojoba		1800
Palm oil	*Elaeis oleifera*	6000
Peanut	*Arachis hypogaea*	1100
Safflower	*Carthamus tinctorius* L.	600
Salicornia	*Salicornia europea*	940
Soybean	*Glycine max*	450
Sunflower	*Helianthus annuus*	950

Source: Karmakar, A., Karmakar, S., and Mukherjee, S. (2010) Properties of various plants and animals feedstocks for biodiesel production. *Bioresource Technology*, 101, 7201–7210.

Table 4.13 Biomass and lipid productivity for selected microalgae species

	High Growth Condition (Optimal Nutrients Supply)			High Lipid Condition (Nutrient Deprived)		
Marine and Freshwater Microalgae Species	Lipid Content (%)	Biomass Productivity ($g/m^2/day$)	Lipid Productivity (L/ha/yr)	Lipid Content (%)	Biomass Productivity ($g/m^2/day$)	Lipid Production (L/ha/yr)
Ankistrodesmus spp.	24	17.4	16 400	31	11.5	14 000
Botryococcus braunii	25	3	2900	75	3	8800
Chlorella emersonii	25	0.97	950	63	0.91	2300
Chlorella vulgaris	5	0.95	190	58	0.57	1300
Chlorella spp.	10	16.5	6500	48	1.6	3000
Nannochloropsis spp.	12	5.3	2500	53	1.9	4000
Nitzschia spp.	16	21.6	13 600	47	8.8	16 300
Phaeodactylum tricornutum	18	21	14 900	57	2.4	5400

Source: Adapted from Mata, T.M., Martins, A.A., and Caetano, N.S. (2010) Microalgae for biodiesel production and other applications: a review. *Renewable and Sustainable Energy Reviews*, 14, 217–232.

the wide diversity of landscapes that could be planted to biomass crops, a variety of social, political, economical, and environmental factors influence decisions on putting land into biomass production. Since these factors are not static, assessments of land available can change with time. It is not surprising that there is a wide opinion on the size of the biomass supply.

Two studies in the 1990s illustrate the divergence of these views. Graham published an analysis of potential biomass supply in 1994 that foresaw 159 million hectares of land suitable for dedicated energy crops. Since "suitable" was defined as lands capable of producing in excess of 11.2 Mg/ha/year of dry biomass, the total supply of biomass was projected to be 1.8 billion Mg of dry biomass. Assuming heating value of 18 MJ/kg, this analysis, which ignores the contribution of agricultural residues to biomass supply, yields 32 billion GJ of energy (note: in the United States, the unit of national energy consumption is the quad, which is 1 quadrillion British Thermal Units (BTU), equal to 1.054 billion GJ). In contrast, a study by Wyman and Goodman a year earlier estimated dedicated energy crops could

Table 4.14 Livestock and poultry manure generation rates

Animal	Manure Production Rate (dry kg/head-day)
Cattle	4.64
Hogs and pigs	0.56
Sheep and lambs	0.76
Chickens	0.040
Turkeys	0.101

Source: Stanford Research Institute (1976) An evaluation of the use of agricultural residues as energy feedstock, Vol. 1. National Science Foundation Report NSF/RANN/SE/GI/18615/FR/76/3. Washington, DC: National Science Foundation.

supply 26–52 billion GJ of energy. They included agricultural residues, forestry residues, and MSWs in their analysis, which contributed another 8 billion GJ of biomass energy, yielding a total annual energy supply from biomass of up to 60 billion GJ. Since energy consumption in the United States is about 98 billion GJ per year, the Graham study suggests that biomass could supply up to 33% of US energy demand while the Wyman and Goodman study places this percentage as high as 60%.

In 2005, the United States Department of Agriculture sponsored a study of biomass supply, including both dedicated crops and agricultural residues. This study concluded that in excess of 1.2 billion tons of dry biomass, representing 25 billion GJ of energy could be produced in a sustainable manner. In 2011, this comprehensive report was updated to include more rigorous production models and in-depth costs analyses. It also included impacts of land-use change and competition among food, feed, and energy crops in the availability of biomass supply at $60 per dry ton. Its baseline case projected 1.1 billion tons of biomass available by 2030 and as much as 1.6 billion tons under a high-yield scenario. Since the 2011 USDA report is the most recent and takes into consideration information from earlier studies, it will be examined here in more detail.

In 2012, the harvested supply of agricultural and forestry resources in the United States used as biomass supply was estimated to be 214 million dry Mg in the form of wood residues and pulping liquors from the forest products industry, urban wood and processing residues, fuel wood, and grains (Table 4.15). About 60% of this came from forestry resources vs. 40% from agricultural resources. With an average heating value of 18 GJ/ton, biomass contributed nearly 4 billion GJ to the nation's energy supply, which is only 4% of the total US consumption. This is a small fraction of what could be produced and harvested in a sustainable fashion.

The land base of the United States encompasses nearly 2263 million acres. About 33% is classified as forest land, 26% as grassland pasture and range, 20% as cropland, 8% special uses (e.g., public facilities), and 13% miscellaneous such as urban areas, swamps, and deserts. The USDA study considered how the first three categories of land could be employed in biomass production, carefully excluding

Table 4.15 Current biomass supply in the United States (2012)

	Biomass Supply (Million dry Mg/yr)
Forest resources	129
Agricultural resources	85
Energy crops	0
Biomass total	214

Source: US Department of Energy (2011) *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge, TN: Oak Ridge National Laboratory. Available on the web at: https://bioenergykdf.net/

inaccessible and environmentally sensitive lands from consideration. It also accounted for use of these lands in the production of conventional forest products and agricultural commodities.

The study included some forward-looking projections on agricultural technology for its baseline analysis including: corn yields increase by a little more than 1% per year, while energy crop yields increase by 1% per year; harvest technology recovers 60% of crop residue for moderate-yield acres and 70% for high-yield acres; no residue is recovered from soybean crops; there is a continuation in current trends toward no-till and reduced tillage methods; up to 63 million acres of cropland and pastureland are shifted into bioenergy crops by 2030 under a farm gate (undelivered) price scenario of $60 per dry ton; and manure from large and medium livestock operations, as classified by the US Environmental Protection Agency, is used for bioenergy.

Table 4.16 summarizes the findings of the USDA study, which projects 1.1 billion Mg of dry biomass could be harvested annually in the United States by 2030 under an assumed farm gate price of $60 per dry ton. Forestry resources, in the form of fuel wood, milling residues, urban wood residue, logging residues, and wood recovered from forest thinning (for forest fire control) could yield 328 million Mg of dry wood per year or 30% of the total. Agricultural resources, in the form of crop residues, dedicated energy crops, grains for biofuels, processing residues, and manure, could yield 768 million Mg of dry biomass per year. Agricultural biomass and wastes (mostly crop residues) and dedicated energy crops each represent 37% of the total biomass supply. A more optimistic analysis, based on faster gains in crop yields over two decades, suggests that US biomass supply could be as high as 1.6 billion Mg.

Assuming an average heating value of 18 MJ/kg, the base case of 1.1 billion Mg of biomass represents 19.3 billion GJ of energy, or 20% of the total US energy consumption. Calculating the potential for biorenewable resources to replace imported petroleum resources is difficult because, as will become apparent

Table 4.16 Projected biomass supply in the United States (2030)[a]

	Biomass Supply (million dry Mg/yr)
Forest resources currently used	226
Forest biomass and waste resource potential	102
Agricultural resources currently used	103
Agricultural biomass and waste resource potential	265
Energy crops	400
Biomass total	1094

Source: US Department of Energy (2011) *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge, TN: Oak Ridge National Laboratory, Available on the web at: https://bioenergykdf.net/

[a] Includes projections for resources currently used and biomass and waste resource potential that would be available at $60/dry ton.

Table 4.17 Annual livestock and poultry manure generation in the United States

Animal	Population (10^6)	Production (10^6 dry ton)	Heating Value (GJ/dry ton)	Energy potential (10^9 GJ)
Cattle	92.6	157	15.73	2.47
Hogs and pigs	64.9	13.3	16.99	0.226
Sheep and goats	8.5	2.5	17.82	0.0446
Chickens	8660	126	13.53	1.70
Turkeys	246	9.7	13.49	0.131
Total	–	–	–	4.57

Sources: Overview of U.S. Livestock, Poultry, and Aquaculture Production in 2010, Animal and Plant Health Inspection Service, U.S. Department of Agriculture, Washington, DC. Available on the web at: http://www.aphis.usda.gov/animal_health/nahms/; manure production rates calculated from Table 3.16; heating values obtained from Stanford Research Institute (1976) An evaluation of the use of agricultural residues as energy feedstock, Vol. 1. National Science Foundation Report NSF/RANN/SE/GI/18615/FR/76/3. Washington, DC: National Science Foundation.

in subsequent chapters, a kilogram of cellulose is not equivalent to a kilogram of hydrocarbon in generating the fuels and chemicals to which we are accustomed. However, even accounting for the lower conversion efficiency of biomass into transportation fuels compared to petroleum, biorenewable resources have the potential for replacing one-third of the 37 billion GJ of petroleum consumed in the United States in 2011.

Table 4.17 separately considers the energy potential of livestock manure in the United States. The total energy potential is 4.6 billion GJ, with 54% and 37%, coming from cattle and chickens, respectively. However, manure is often highly diluted in water and sometimes difficult to recover, reducing its attractiveness as a chemical and energy resource. Changes in the way that manure is collected and stored would be required in some instances.

World supply of biomass is estimated in Table 4.18. China and India together could produce as much as 1.7 billion dry Mg of biomass, while Latin America could produce 1.5 billion dry Mg. Europe, with its high-density population, has

Table 4.18 Projection of world supply of biomass (2030)

Region	Land Cultivated in Energy Crops (Acres, Millions)	Biomass Supply (Billions dry Mg/yr)
USA (2005 USDA study)	74	1.1
USA (2011 USDA study)	63	1.4
Australia	–	<0.004
China and India	212	1.7
Europe	62–222	0.4–1.5
Latin America	299	1.5

Source: Bauen, A., Berndes, G., Junginger, M., Londo, M., Vuille, F., Ball, R., Bole, T., Chudziak, C., Faaij, A., Mozaffarian, H. (2009) *Bioenergy – A Sustainable and Reliable Energy Source – A Review of Status and Prospects,* IEA Bioenergy: ExCo: 2009:06IEA, 107 pp. Available on the web at: http://www.ieabioenergy.com/LibItem.aspx?id=6479 less potential to grow biomass although it could be in the range of 0.4–1.5 billion dry Mg. Although Africa is not included in this table, it also has large biomass potential if modern agricultural policies and practices were widely adopted in sub-Saharan regions of the continent. In fact, some studies suggest that the tropical parts of the world could become net exporters of bioenergy through sustainable agriculture.

Further Reading

Lignocellulosic Crops

Hendee, J.C., Dawson, C.P., and Sharpe, W.F. (2012) *Introduction to Forests and Renewable Resources.* Long Grove, IL: Waveland Press.

Kole, C., Joshi, C.P., and Shonnard, D.R. (eds) (2012) *Handbook of Bioenergy Crop Plants*. Boca Raton, FL: CRC Press.

Lewandowskia, I., Scurlockb, J.M.O., Lindvallc, E., and Christoud, M. (2003) The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. *Biomass and Bioenergy*, 25, 335–361.

Nasir, El Bassam (ed.) (2010) *Handbook of Bioenergy Crops: A Complete Reference to Species, Development and Applications.* London: Earthscan.

Oleaginous Crops

Hu, Q., Sommerfeld, M., Jarvis, E., Ghirardi, M., Posewitz, M., Seibert, M., and Darzins, A. (2008) Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. *Plant Journal*, 54(4), 621–639.

Murphy, D.J. (2005) *Plant Lipids: Biology, Utilisation and Manipulation*. Oxford: Blackwell Publishing Ltd.

Sheehan, J., Dunahay, T., Benemann, J., and Roessler, P. (1998) A look back at the U.S. Department of Energy's Aquatic Species program, National Renewable Energy Laboratory, NREL/TP-580-24190, July. Available on the web at: www.nrel.gov/biomass/pdfs/24190.pdf (accessed September 22, 2013).

Properties of Biomass

Rowell, R.M., Schultz, T.P., and Narayan, R., (eds) (1992) *Emerging Technologies for Material and Chemicals from Biomass*. ACS Symposium Series 476. Washington, DC: American Chemical Society.

Rowell, R.M., Young, R.A., and Rowell, J.R. (1997) *Paper and Composites from Agro-Based Resources.* Boca Raton: CRC Press.

Sjostrom, E. (1993) *Wood Chemistry: Fundamentals and Applications*, 2nd edn. San Diego: Academic Press.

Yields of Biomass

Halford, N. G., and Karp, A. (2011) *Energy crops*, Cambridge: Royal Society of Chemistry, Cambridge.

Wayman, M. and Parekh, S. (1990). *Biotechnology of Biomass Conversion: Fuels and Chemicals from Renewable Resources*, Philadelphia: Open University Press, Philadelphia.

Size of Resource Base

Bauen, A., Berndes, G., Junginger, M., Londo, M., Vuille, F., Ball, R., Bole, T., Chudziak, C., Faaij, A., and Mozaffarian, H. (2009) Bioenergy—A sustainable and reliable energy source—a review of status and prospects. IEA Bioenergy: ExCo: 2009:06IEA. 107 pp. Available on the web at: http://www.ieabioenergy.com/LibItem.aspx?id=6479 (accessed September 22, 2013).

Perlack, R.D., Wright, L.L., Turhollow, A.F., Graham, R.L., Stokes, B.J., and Erbach, D.C. (2005) Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Department of Energy Technical Report GO-102995-2135.

US Department of Energy (2011) *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge, TN: Oak Ridge National Laboratory. Available on the web at: http://www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf (accessed September 22, 2013).