Production Potential and Logistics of Biomass Feedstocks for Biofuels

Weiping Song, Rachel Apointe and Mingxin Guo

Abstract Intensive biofuel production and utilization require an adequate and sustainable supply of biomass feedstocks. Globally, net terrestrial primary production is estimated at 56×10^{15} g C yr^{-1}, storing 2.2×10^{21} J bioenergy in the annually synthesized biomass. Approximately 8.7% of this primary production can be sustainably used for energy purposes to meet 34% of the current human energy demand. Sustainable bioenergy feedstocks extend to feasible portion of food grains, crop residues, dedicated energy crops, forest debris, animal manures, and domestic organic waste. To transfer biomass feedstocks from the production field to biorefinery plants, an array of unit operations are involved, including harvesting, drying, transportation, densification, storage, and pre-processing. Machineries and equipments have been developed to implement the feedstock logistics. The overall biomass handling cost accounts for 35–50% of the total biomass production budget. Biomass logistics are a critical component in a biofuel production system and an essential part of the bioenergy supply chain. Technological advancement is warranted to improve the efficiency of biomass feedstock logistics.

Keywords Biomass · Biofuel · Feedstock · Harvest · Transportation · Storage · Pre-processing

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1 Introduction

All human activities require energy. The energy is obtained predominantly from food and fuel. Through combustion, the chemical energy stored in fuels is released in heat (thermal energy) and light (radiant energy). The light can be utilized for lighting (e.g., oil lamps), while the heat is used for heating, cooking, powering engines, and running electricity generators.

The energy that drives the Earth system processes (e.g., wind, ocean currents, hydrological cycle, rock weathering, and ecological dynamics) originates from the Sun. Plants absorb solar radiation and grow biomass via photosynthesis, providing food and fuel for human consumption. Before the nineteenth-century wood was the primary fuel for energy to fulfill various domestic purposes (Smil 2010). Wood was burned for heat and light to cook food, illumine night, warm shelters, smelt ores, and treat clay artifacts. Commercial mining and wide use of fossil fuels (coal, petroleum, and natural gas) for energy did not start until the 1800s, when steam engines, gas lights, electric motors, and internal combustion engines were invented during the Industrial Revolution. It was not until 1900 that human consumption of fossil energy exceeded wood energy (Smil 2010). Today, however, fossil fuels are the principal energy sources to power engineering machines, transportation vessels, and electricity generators. The world annual energy consumption reached 5.6×10^{20} J in 2014 (Enerdata 2015), of which >80% was provided by fossil fuels (IEA 2013a). Nevertheless, fossil fuels are nonrenewable and their reserves are limited. At the current consumption rates, the supply of petroleum, natural gas, and coal will only be able to last for another 45, 60, and 120 years, respectively (IEA 2013b). The global energy demand will rise to 6.6×10^{20} J in 2020 and 8.6×10^{20} J in 2040 (EIA 2013), while the fossil fuel supply is dwindling, the world is compelled to develop renewable energy alternatives. Moreover, tremendous amounts of greenhouse gases have been released from fossil fuel consumption into the atmosphere, elevating the atmospheric CO_2 concentration from the pre-industrial level of 280 ppm to the present nearly 400 ppm and causing disastrous climate change effects (IPCC 2013). The incentives for energy independence, security, and climate change mitigation are stimulating international communities to invest in the development and utilization of renewable energies, including solar, wind, hydro, geothermal, and biomass energy. Of these renewable energies, biomass energy (**bioenergy**) draws major and particular development endeavors, primarily due to the extensive availability of biomass, already-existence of biomass production technologies and infrastructures, and biomass being the sole feedstock for renewable liquid transportation fuels. Research has been intensively conducted to develop best technologies for effectively processing biomass materials into solid (e.g., pellets, char), liquid (e.g., bioethanol, biodiesel, pyrolysis bio-oil, and drop-in biofuels), and gaseous (e.g., syngas, biogas) fuels (Guo et al. 2015). Commercial generation of electricity, transportation fuels, and biogas using biomass feedstocks has been practiced in many nations. Production of biomass for fuels, however, competes with food for land, water, and other resources. It is questioned whether sufficient biomass can be produced for biofuels that meet the human energy demand. Also, harvesting, transporting, storing, and pre-processing biomass for biofuel refinery involve a number of biomass preparation steps. Systems thinking becomes essential in establishing the biofuel supply chain starting at biomass production and preparation. This chapter elucidates the global biomass production potential for biofuels and the general logistics of biomass feedstocks.

2 Production Potential of Biomass for Biofuels

Biomass is biological material derived from living, or recently living organisms. Biomass contains energy that is originally transformed from solar radiation by plants, algae, and cyanobacteria through photosynthesis. Biomass can be directly combusted for heat and light. Biofuels refer to the biomass and its refined products to be combusted for energy. The utilization of bioenergy in biofuels for different human purposes started from the initial discovery of fire. Even today, nearly 40% (2.6 billion) of the world population relies on firewood to meet its energy requirement (FAO 2013).

The Sun is the primary energy source of the Earth system. It is the solar energy that drives the dynamic processes in the atmosphere, hydrosphere, lithosphere, and biosphere. The average solar energy flux at the top of the Earth's atmosphere is 340 W m^{-2} (Lindsey 2009). On an annual basis 5.5×10^{24} J of solar energy are irradiated to the Earth (surface area 510.1×10^{12} m^2). After reflection and absorption by the atmosphere and the Earth's albedo, 48% of this incoming energy is absorbed by the Earth (Skinner and Murck 2011). At the Earth surface, plants, algae, and cyanobacteria absorb a narrow range of solar radiation (mainly 400–700 nm, accounting for 43% of the overall solar irradiance) and conduct photosynthesis to convert solar energy into chemical energy and store it in the synthesized biomass. The reaction is described as:

$$6CO_2 + 6H_2O + \text{light} \rightarrow (CH_2O)_6 + 6O_2 \tag{1}$$

To convert 1 mol of CO_2 to carbohydrates through photosynthesis, approximately 10,000 kJ of light energy are absorbed but only 470 kJ stored in plant biomass (FAO 1997). The balance is dissipated as heat and long-wavelength radiation. The photosynthetic efficiency—the fraction of light energy converted into chemical energy during photosynthesis—is generally low and influenced by a number of factors, including light intensity, temperature, CO_2 concentration, plant species, and plant growth stage. For a single leaf, the efficiency is typically 5% (maximum 8–9%) of total incident solar irradiance (Bolton and Hall 1991). The photosynthetic efficiency of most plants peaks at 25% of maximum full sunlight; above this light intensity, the efficiency decreases in proportion to the excess radiation absorbed (Ort et al. 2011). At 30 °C and 380 ppm atmospheric CO_2, the maximum photosynthetic efficiency is 4.6% for C3 plants and 6.0% for C4 plants (Zhu et al. 2008). The highest photosynthetic efficiencies observed in the field according to plant growth rates are 3.5% for C3 species and 4.3% for C4 species over a short term. Over a full growing season the figures drop to 2.4% and 3.4%, respectively (Monteith 1977; Piedade et al. 1991; Beale and Long 1995). Intensively cultivated agricultural crops show a photosynthetic efficiency ranging from 1 to 4% and averaging at 3% (Moore et al. 1995). Approximately 39 kJ of energy are fixed per gram biomass carbon via photosynthesis (Klass 1998). Globally, photosynthesis converts ~200 × 10^{15} g C-equivalent CO_2 into biomass each year (FAO 1997). Overall, around 0.3% of the solar energy absorbed by the Earth is stored in biomass through photosynthesis, equivalent to ~7.9 × 10^{21} J/year.

The global gross primary production is estimated at 200 × 10^{15} g C yr^{-1} (FAO 1997). Respiration of the primary producers, however, consumes nearly half of the photosynthesized organic compounds and the inherent energy. The net primary production of the whole Earth is 104.9 × 10^{15} g C yr^{-1}, of which 53.8% is by the terrestrial ecosystem and 46.2% by ocean autotrophic organisms (Field et al. 1998). The annual **terrestrial** primary production amounts 123 (range 107–139) × 10^{15} g C in gross and 56 (range 48–69) × 10^{15} g C in net (Beer et al. 2010). Considering that herbaceous plants typically contain 45% of carbon by dry weight and woody plants 50% of carbon (Chapin et al. 2011), the terrestrial primary production adds approximately 120 × 10^{15} g of dry vegetative biomass each year (Broadmeadow and Matthews 2003). Though different organic compounds vary in energy content, whole plant tissues demonstrate a relatively constant value at 20 kJ g^{-1} of ash-free dry mass (Chapin et al. 2011). The energy density of dry wood ranges from 18 to 22 kJ g^{-1} (Ashton and Cassidy 2007). As such, through photosynthesis 2.2 × 10^{21} J of bioenergy is stored in the annually produced terrestrial plant materials.

The current world energy demand is ~5.6 × 10^{20} J (Enerdata 2015). Largely, the bioenergy captured each year by land plant biomass production is 3–4 times greater than human energy demands. However, most of the annually added plant biomass is present in remote areas and wildlife habitats. It is not economically viable or ecologically sustainable to harvest and transport the biomass for biofuels. Practically, bioenergy feedstocks refer to crop residues, animal manures, timber and forestry refuses, municipal organic waste, dedicated biomass crops, intentionally cultivated algae, and appropriate portion of starch/sugar/oil-rich food crops. It is projected that future bioenergy feedstock production would use 2.0 billion hectares of accessible land (Dale et al. 2014). Cultivation of dedicated biomass crops on marginal land (e.g., under-utilized land, abandoned land, and land with degraded agricultural soils) and growing algae in artificial bioreactors have been proposed. Worldwide there are approximately 500 million hectares of marginal land available (Tilman et al. 2006). Sustainable biomass feedstock production, however, should not compromise food security, wildlife habitat, or soil conservation. Land clearance or conversion of agricultural land from food to grow bioenergy crops should be avoided. The removal rates of crop and forestry residues should be reasonable to prevent soil erosion or soil fertility deterioration (Woolf et al. 2010). Within these restrictions, Woolf et al. (2010) estimated the global bioenergy feedstock potential was 2.81 × 10^{15} g C yr^{-1} (Table 1), equivalent to 5.0% of the global annual terrestrial net primary production. The energy stored in this amount of biomass is 1.1 × 10^{20} J, matching 20% of the current global energy demand. Estimates by others on the global bioenergy potential

Table 1 Sustainable biomass feedstock availability

Biomass	Global production ($\times 10^{15}$ g yr^{-1})	Scenario	Maximum sustainable potential ($\times 10^{15}$ g C yr^{-1})
Crop residues	Rice: 0.89	Rice husks and 90% of paddy rice straw not used for animal feed	0.28
	Other cereals: 2.60	20% of total straw and stover (45% extraction rate minus animal feed)	0.18
	Sugar cane: 0.31	Sugar cane: Waste bagasse plus 75% of field trash	0.13
Manures	1.74	25% of cattle manure plus 90% of pig and poultry manure	0.19
Biomass crops	1.25	100% of potential production of abandoned, degraded cropland that is not in other use	0.60
Forestry residues	1.90	Firewood plus 44% of difference between reported feelings and extraction	0.64
Agroforestry	1.28	170 Mha of tropical grass pasture converted to silvopasture	0.62
Municipal organic waste	0.52	75% of global yard trimmings and food waste, including 80% of waste sawn wood	0.17
Total			2.81

Data source World Bank (2013), Woolf et al. (2010)

using different methodologies and scenario considerations show a wide range from 0.30 to 13 × 10^{20} J (Haberl et al. 2011; WEC 2013). Dornburg et al. (2010) narrowed the range to 2–5 × 10^{20} J by conducting a sensitivity analysis and incorporating the limiting factors such as water availability, biodiversity, and food demand. The most promising energy crops switchgrass, miscanthus, shrub willow, and hybrid poplar have a typical biomass yield of 12, 20, 11, and 10 dry tons ha^{-1}, respectively (Fuentes and Taliaferro 2002; Pyter et al. 2007; Volk et al. 2011; Sannigrahi et al. 2010). Considering the land availability and the practical biomass yields, the Global Energy Assessment concluded that the global bioenergy potential was 1.6–2.7 × 10^{20} J yr^{-1} (IIASA 2012).

At present, the global biofuel utilization reaches approximately 0.55×10^{20} J yr^{-1} (Haberl et al. 2013). Worldwide, bioenergy provides nearly 14% of the energy demand and counts for 75% of the total renewable energy (IEA 2013c). In 2015, the world bioethanol production was 25.7 billion gallons and biodiesel production was 8.3 billion gallons (RFA 2016; EIA 2016). These biofuels, however, were predominantly from food crops, including corn, sugar cane, wheat, soybean, and canola. If the current food crop portion is included, the global bioenergy potential should reach 30% of the current energy demand. Further considering the selection of new energy crop cultivars with higher biomass yields and the intentional cultivation of algae, the global potential of biomass production for biofuels is reasonably at 4.9 $\times 10^{15}$ g C yr^{-1}, delivering bioenergy 1.9×10^{20} J yr^{-1} and meeting 34% of the current global energy demand (Haberl et al. 2013).

3 Biomass Feedstock Logistics

3.1 Bioenergy Pathways

To utilize bioenergy, biomass materials can be directly burned or processed into various biofuel products through physical, chemical, biological, and thermal transformations. Similar to fossil fuels, there are solid, liquid, and gaseous biofuels. The biomass materials and conversion technologies vary with different biofuels. All biomass materials, however, require land, water, nutrients, and favorite climate to produce. Furthermore, all biomass materials have to be collected from the field and transported to a processing plant. The steps and efforts (e.g., harvesting, drying, pre-processing, densification, loading, transportation, and storage) involved in moving biomass materials from the production field to a biorefinery plant are termed "biomass logistics" (Fig. 1). At each step, there are distinct engineering and infrastructure constraints that affect costs. Feedstock production and handling costs account for 35–50% of the overall cellulosic ethanol production cost (Hess et al. 2007). Regardless of the logistic costs, the payment at the farm gate for one dry metric ton of cellulosic biomass ranges from $11 to $44 (Hess et al. 2007). It is critical to develop a biomass feedstock supply chain that functions efficiently and cost-effectively.

Dried plant biomass can be directly burned as firewood to release energy. Wood can be chopped into chips or ground and pelletized into pellets. Pelletization of herbaceous biomass is also feasible. Through a chemical reaction "transesterification", vegetable oil and animal fats can be transformed into biodiesel. Starch, sugar, and cellulosic materials are used to produce bioethanol and biobutanol through microbial fermentation. Organic waste, such as animal manure and food waste, is typically used to generate biomethane through anaerobic digestion, a microbial decomposition pathway of organic residues in the absence of air. Pyrolysis and gasification are two thermochemical methods for producing biofuels. Pyrolysis by heating wood chunks without air generates charcoal and bio-oil. Gasification of wood, crop residues, and

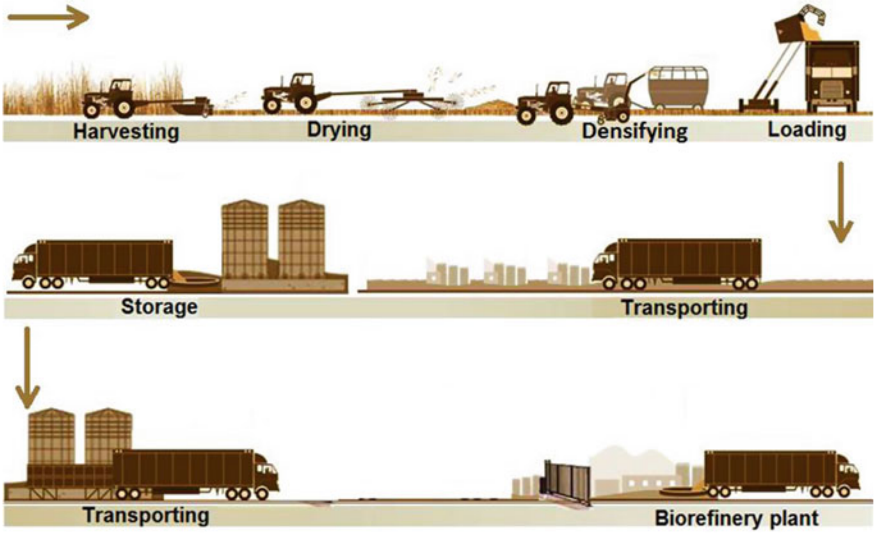

Fig. 1 Logistics of biomass feedstock for biofuels

other lignocellulosic biomaterials at high temperature with controlled O_2 availability produces syngas (a mixture of CO and H_2) and bio-oil (Fig. 2).

3.2 Biomass Harvest and Collection

Crop grains such as corn, soybean, canola, and wheat are usually harvested by a combine (harvester) from the field. The combine automatically reaps, threshes, and winnows the grains from the stover/straw and then collects the grains in a hopper tank or blows the grains into a side-running truck. The grains have to be adequately dry prior to harvesting. Normally, the crops are left in the field until the grain moisture content drops to below 25% for shelling corn, 15% for soybean, 17% for wheat, and 10% for canola (Prairie Grains 2006; ISU Extension 2008; Wiatrak and Frederick 2014). The harvesting costs range from \$85 to \$110 ha^{-1} (UIUC 2008). Crop residues can be collected by shredding, raking, and round baling following grain harvest.

Bioenergy grasses such as switchgrass are typically cut down and form windrows in the field for drying by a hay swather (a disk cutterbar mower). Annually, a single harvest after plant flowering or after the first frost is recommended (OCES 2010). The cutting and crushing costs are estimated at \$44 ha^{-1} (2013 value; Khanna et al. 2008). The taller grasses such as miscanthus, giant reed, sugar cane, and sweet sorghum are harvested with a forage reaper or a cane harvester (an exact chopper equipped with a big baler). The best time for annually harvesting miscanthus and giant reed is the end of the growing season when the plants become dormant (Pyter et al. 2008). Sugar

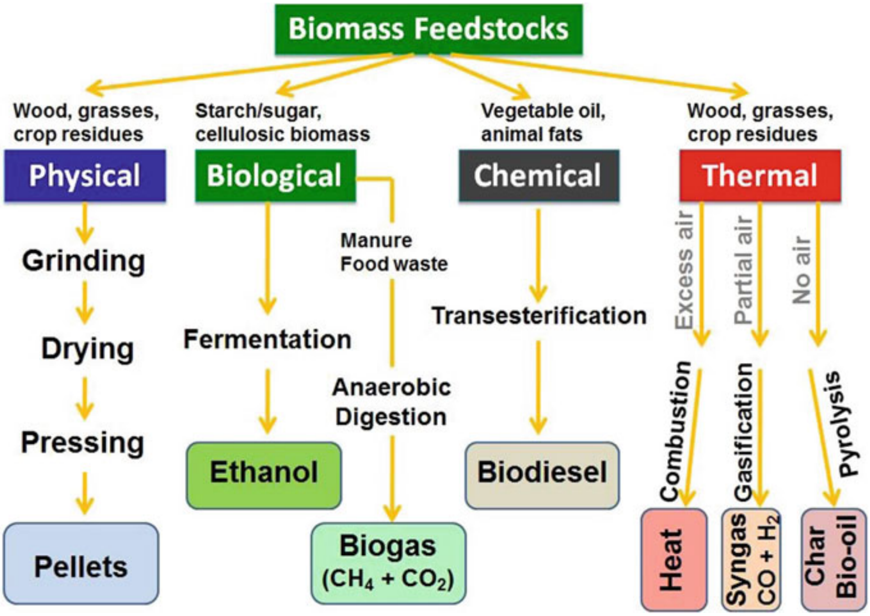

Fig. 2 Common bioenergy pathways from different biomass feedstocks

cane and sweet sorghum are harvested between June and December after 12 months of plant growth at a cost of \$196 ha^{-1} (Salassi and Deliberto 2013).

The woody bioenergy crop shrub willow is harvested every three years after the first coppice. This occurs in November after the leaves fall. The equipment can be a New Holland forage harvester with a willow-cutting head, which cuts willow stems at 10–15 cm above the ground, chops the stems into chips, and blow the chips into an alongside wagon (Abrahamson et al. 2010). Hybrid polar is typically harvested at 6–10 year rotation using standard forest harvesting equipment (e.g., feller bunchers, skidders, forwarders, and chippers). The trees are bunched and chipped (Townsend et al. 2014). If harvested at 2–3 year short rotation, a New Holland forage harvester can be used (Townsend et al. 2014). The harvesting cost is approximately \$250 ha^{-1} (Volk et al. 2012).

Animal manures are collected regularly from animal houses using available tools. Poultry litter is cleaned out of chicken houses once a year. If new bedding is expensive and birds have to be reared on built-up litter, the litter is generally conditioned by annual decaking using a decaking machine, between-flock tilling using a shallow-tine roto-tiller, or between-flock windrowing using a six-blade windrower (Macklin et al. 2008). In case of decaking, litter cakes (fresh manure mixed with bedding materials and spilled feed) are removed and replaced by new bedding (up to 43% of the original volume) (Sistani et al. 2003). Swine manure is typically collected in gutters underneath a slotted shelter floor. The gutters are periodically flushed or drained to an outside lagoon or storage pond. Manure in lots outside the shelter is scraped weekly and stacked in compost piles (EPA 2015). Cattle manure is handled as a solid, semi-solid, or liquid. Solid manure in open lots or in barns collected in gutters behind cows is usually scraped every week and stockpiled in a solid manure storage facility prior to land application. The manure pack in loafing sheds is removed once or twice a year. Manure slurry from open lots or from free stall alleyway and liquid manure from loafing shed are periodically flushed, scraped, or pumped into a storage tank (sump) or an earthen lagoon (EPA 2015).

3.3 Drying Biomass

Fresh biomass generally contains 60–70% of moisture. It has to be dried for transportation and storage convenience. The moisture requirements for crop grains in the marketplace are below 15% for corn, 14% for soybean, 13% for wheat, and 8% for canola. The cost for reducing corn from the moisture 25% to 14% using a propane-powered grain dryer is \$17.3 ton^{-1} (OSU Extension 2011).

At cutting in October, switchgrass typically contains 50% of water (wet basis). The moisture content is required to reduce to below 18% prior to baling. Switchgrass is commonly conditioned upon cutting by passing through two rollers to crush the plant stems, dried in the field in windrows for 3–7 days with occasional raking the swaths, and baled (Sokhansanj et al. 2009). The cost is roughly \$11 ha^{-1} for raking/swathing (Khanna et al. 2008). Miscanthus and giant reed have to be dried to below 20% moisture content prior to storage. If harvested in the spring (e.g., March–April), the plant materials can be baled directly. The plants harvested in November are commonly chopped and mechanically ventilated for drying at a cost of \$15 ton^{-1}. Chopped materials reduced their moisture from 60 to 17.5% under 21,500 m^3 air h^{-1} ventilation for 91 h (Kristensen 2003). Sugar canes and sweet sorghum canes are immediately transported to sugar mills and crushed to extract juice after field harvesting. No drying is necessary.

Greenwood contains moisture up to 65%. It should be seasoned in a well-ventilated place for at least 6 months to bring its moisture content to below 20% prior to use. Fresh wood chips are commonly dried using a mechanical drying conveyor, in which heated or ambient air is forced through stockpiles of wood chips. The latent heat of water evaporation is 2470 MJ ton^{-1} of water, but dryers require 1.4–2.0 times more energy to drive away the same amount of water from wood chips due to low energy efficiency. The drying cost is ~\$2.0 ton^{-1} of dry matter per % moisture reduction (or \$200 to remove 1 ton of water; Price 2011).

Animal manures do not require drying if used in anaerobic digestion for biogas. If used as feedstocks in pyrolysis and gasification, drying is necessary. Solid manures can be naturally dried in a thin layer. Mechanical drying by passing through a heater to raise the temperature to 80–110 °C is also practiced. Manure slurries can be conditioned with polymers, dewatered using belt filter presses, and dried to below 20% moisture by heating. According to the energy consumption, \$100 is needed

Fig. 3 Baling switchgrass (left) and bundling forest slashes (right)

to remove 1 ton of water from moist manure (Price 2011). If labor and equipment wearing are considered, the drying cost may reach \$200 ton^{-1} of water removed.

3.4 Pre-processing and Densification of Biomass

Plant materials collected from the field are bulky (e.g., density < 60 kg m^{-3}). Densification is generally needed to facilitate transportation. Baling air-dry switchgrass, crop residues, and other herbaceous plant materials into round (1.2–1.8 m in diameter and 1.2–1.8 m in length) or rectangular (0.9–1.2 m in height and width and 1.8–2.4 m in length) bales using a hay baler increases the density to 650 kg m^{-3} (Fig. 3). The cost is approximately \$140 ha^{-1} (Khanna et al. 2008). Densification of forest debris is usually carried out by compressing thinnings and slashes into bundles (3 m by 60–80 cm, density ~380 kg m^{-3}) using a biomass bundler (Solomon and Luzadis 2009). The bundling cost is \$46.5 dry ton^{-1} (Harrill 2010). Slash bundles can be stockpiled in the field or under a shed for natural drying.

Pelletization is another method for biomass densification, applicable to wood, bioenergy grasses, crop residues, and animal manures. Pellets are made by grinding dry plant materials into fine particles through a hammer mill and subsequently compressing the particles through 6–8 mm holes in the die of a pelletizer. The pellets are 2–3 cm in length, possessing a low moisture content in the range of 5–10% and a high packing density at around 650 kg m^{-3}. Pellets show advantages in biomass storage, bunker transfer, and long-distance transport. However, the pelletization cost is high, up to \$50–130 ton^{-1} (Pirraglia et al. 2010; Qian and McDow 2013).

3.5 Biomass Transportation

Crop grains are mostly transported from the production site to a storage facility by trucks. From a storage silo, grains are shipped in bulk containers or cargo bags by trucks, barges, and railroad to end uses and export markets. Depending on the distance, the transportation costs by truck, rail, and ocean average at \$11, \$15, \$30 ton^{-1}, respectively (USDA 2012).

Switchgrass and crop residues are usually transported in bales by hauling trucks. The transportation cost is approximately \$0.20 (ton mile)$^{-1}$ (Purdue Extension 2008). A mechanical loader is required to upload the bales onto trucks. This operation costs additionally \$65 ha^{-1} (Khanna et al. 2008). Biomass chips and pellets are typically transported by trucks/self-unloading trailers, barges, and railroad. The related costs are \$0.20, \$0.10, \$0.05 (ton mile)$^{-1}$, respectively (Short 2009).

Transportation of solid manure is generally realized by hauling trucks, while manure slurry by 3000–9000 gallon tank spreaders. Including lagoon agitation and pumping, liquid manure transportation costs reach \$12 (kgal mile)$^{-1}$ (Hadrich et al. 2010).

3.6 Biomass Storage

Normal operation of a biorefinery requires a substantial amount of biomass feedstocks to be safely stored on a year-around basis. One option is to transport biomass to a central location and subsequently dispatch it to conversion facilities. While in a depot, the biomaterials can be ground into powders for minimal pre-processing or further treated and pelletized.

Crop grains are normally stored in grain silos. Grain elevators are used to load grains into silos. A delivery auger is installed at the bottom of silos to unload grains. Grains in silos are continuously aerated to maintain an optimal temperature and humidity environment for quality storage. The overall storage cost is estimated at \$7 ton^{-1} for 6 months (Hofstrand and Edwards 2009). During the silo storage, however, grains usually decrease their weight by 1.3% due to moisture reduction (shrinkage) (Hofstrand and Wisner 2009).

Biomass bales can be stockpiled outdoor on graveled surfaces and covered by plastic film. Indoor storage in enclosed buildings is generally more expensive (e.g., \$17 ton^{-1} for 12 months; Duffy 2008), yet the extra costs can be partially offset by reductions in storage losses and feedstock quality degradation. Trials in Texas showed that 5–13% of the original weight of switchgrass round bales was lost during 6–12 months outdoor storage; the loss was 0–2% for indoor storage (Sanderson et al. 1997).

Wood chips should be stored under a shelter (e.g., a shed) or outdoor with a water-proof cover. Uncovered open storage is discouraged. Wood chips may lose significantly in dry matter weight and energy value during storage (White et al. 1983). Covered storage of pre-dried wood chips is economical for bioenergy recovery (Purdue Extension 2011). To minimize wood chip deterioration during storage, torrefaction of the material may be employed. Torrefaction is to heat wood at 240–300 °C in the absence of air for partial pyrolysis. The treatment can reduce wood chips by 20% in dry mass and consequently 10% in heating value, but results in a dry, hydrophobic, sterile, and stabilized product.

3.7 Biomass Pre-processing

Before dispatched from a depot or processed at a biorefinery, biomass needs to be pre-treated for feedstock quality and effective biofuel conversion. The pre-processing operations may extend to one or several of the following: cleaning, grinding, heating, steam cooking, and conditioning (Fig. 4). For example, corn and canola seeds need to be cleaned to remove dirt, dust, weed seeds, leaf debris, and any other foreign materials. The cleaning is typically achieved using a grain cleaner by screening, vibration, aspiration, or purging. Grinding into fine particles is a minimal pre-processing requirement for all biomaterials before biofuel refining.

Lignocellulosic materials, especially straw, stover, and other herbaceous biomass, tend to form loose, dusty pellets. To increase pellet durability and reduce percent fines, chemical binders are generally added upon pelletization, undesirable for biofuel refinery. Through physiochemical pre-processing to partially break down cellulose, hemicellulose, and lignin into smaller amorphous molecules, however, the compression and compaction characteristics of lignocellulosic materials can be improved. Pre-treatments such as steam explosion and acid or alkaline hydrolysis significantly

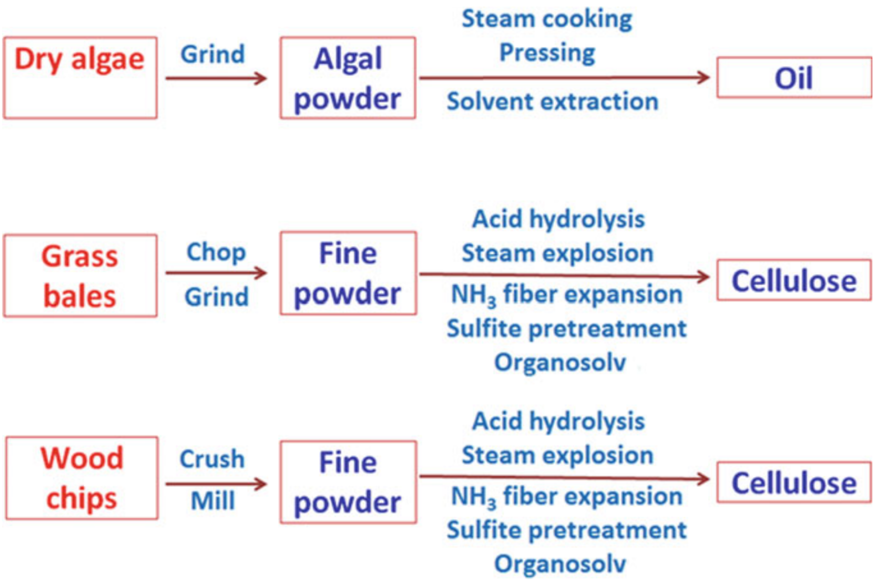

Fig. 4 Common pre-processing operations of algal, grassy, and woody biomass for biodiesel and bioenthanol production

increase the cohesiveness of lignocellulosic materials and their readiness for simple sugars (Chen et al. 2004). Steam explosion is to heat biomaterials with hot steam at 180–230 °C and high pressure for 2–10 min and then flash the cooker to atmospheric pressure. Water inside the substrate rapidly vaporizes, expands, and disintegrates the biomass (Zimbardi et al. 1999). Acids, alkalis, and oxidizing agents can pre-treat lignocellulosic materials for facilitating lignin removal and (hemi)cellulose digestibility. Dilute H_2SO_4, ammonium hydroxide, sodium sulfite, ozone, and other chemical agents are widely tested to disrupt lignin and loosen cellulose structure (Tabil et al. 2011). To separate lignin from cellulose without structural disruption, the technique organosolv fractionation is being developed in which biomass is treated with ethanol at 160–200 °C and 5–30 bars for 20–120 min prior to enzymatic hydrolysis (Huijgen et al. 2010). These essential pre-pretreatments, however, incur additional costs to biofuel production.

4 Summary and Conclusions

Bioenergy originates from solar radiation. Through photosynthesis, plants absorb solar energy and store it in biomass. Globally, net terrestrial primary production is estimated at 56×10^{15} g C yr^{-1}, adding 2.2×10^{21} J of bioenergy to the Earth system. Due to limitations from land availability, wildlife protection, and soil conservation, approximately 8.7% of the primary production can be practically used as biofuels in a sustainable manner, meeting 34% of the current human energy demand. Bioenergy feedstocks include feasible portion of food grains, crop residues, dedicated energy crops, forest debris, animal manures, and domestic organic waste. The biomass feedstocks can be converted into solid, liquid, and gaseous biofuels through physical, chemical, biological, and thermal pathways. A number of unit operations are involved in moving biomass feedstocks from the production field to a biorefinery plant, including harvesting, drying, transportation, densification, storage, and preprocessing. In addition to field production, handling biomass materials also requires a variety of machineries and infrastructures. The costs involved in biomass logistics range from 35 to 50% of the overall biomass production budget. It is critical to consider biomass logistics in designing bioenergy refining systems. Technological advancement is urgently needed to improve the efficiency of biomass feedstock logistics.

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Review Questions

1. Briefly describe the energy budget of the Earth system.
2. Define photosynthesis efficiency. What is the photosynthesis efficiency of intensively cultivated crops?
3. Globally, how much solar energy is captured by plants, algae, and cyanobacteria through photosynthesis each year?
4. What is the net annual primary production of terrestrial plants?
5. What is the global sustainable bioenergy production potential? Is this figure significant in the current global energy demand?
6. What biomass materials are identified as bioenergy feedstocks?
7. What are biomass logistics? Name the typical operations of biomass logistics.
8. Explain the general logistics of switchgrass production for bioethanol.
9. What equipment is commonly used for collecting and densifying woody biomass in the field?
10. What techniques have been tested to pre-process lignocellulosic materials for bioethanol generation?

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References

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