

# Descriptions of Biorenewable Resources

Descriptions of biorenewable resources come from various sources. A good general reference is: El Bassam, N. (2010) *Handbook of Bioenergy Crops: A Complete Reference to Species, Development and Applications*, Earthscan LLC, Washington, DC.

## Sugar Crops: Sugar Beets



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**Taxonomic Name:** *Beta vulgaris* L.

**Classification:** Cool season, biennial root crop

**Description:** Characterized by large green leaves. Plants flower during spring from autumn plantings. Seed is harvested in June and July to maximize sugar content. Average global yield of 50 Mg/ha. Specific yields can vary from 30 to 70 Mg/ha depending on climate and conditions. Tough and adaptable. Can withstand mechanical abuse, cold, heat, drought, and defoliation. Fertilized often applied to growing crops with nitrogen having greatest influence on root quality and sucrose production. Although large amounts of nitrogen are required for maximum root yield, plant should be nitrogen deficient before harvest to retard use of sucrose for growth. Major diseases caused by variety of viruses, fungi, and bacteria including curly top viral disease, leaf spot, and powdery mildew.

**Natural Ecosystem:** Mediterranean

**Photosynthetic Pathway:** C3

**Cultivation History:** During the Napoleonic wars of the nineteenth century, England attempted a blockade of sugarcane importation to the European continent. In response, Napoleon supported development of the sugar beet industry. Sugar beets grew from being the source of 5% of world sugar in 1840 to 50% by 1890. Since 1920 they have held steady at 40%. The first successful US production was in California in 1870.

**Composition:** Cellulose = 52%, Hemicellulose = 32%, Lignin = 16%

**Ultimate Analysis:** C = 44.5%, H = 5.9%, O = 42.8%, N = 1.84%, S = 0.13%, Cl = 0.053%

**Proximate Analysis:** VM = 82.5, FC = 4.1, Ash = 3.4

**Higher Heating Value:** 17.70 MJ/kg

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*Source of illustration:* Author.

## Sugar Crop: Sugarcane



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**Taxonomic Name:** *Saccharum officinarum* L.

**Classification:** Warm-season, thick-stemmed perennial grass

**Description:** Tropical grass closely resembling bamboo stalks. Requires strong sunlight and abundant water. Can reach heights of 5 m. Holds many positive qualities including high sugar content, low fiber content, good ecological adaptability, and disease resistance. Nutrient requirements vary greatly among different cultivars but typically are high. Through resistance breeding most diseases no longer affect sugarcane. Insecticides may be necessary for pests such as aphids, leafhoppers, and stem borers. Maximum theoretical yields of fresh matter up to 200 Mg/ha.

**Natural Ecosystem:** New Guinea

**Photosynthetic Pathway:** C4

**Cultivation History:** Sugarcane was first cultivated in Polynesia. From there it spread to India. In 510 BC Persia invaded India and found "the reed which gives honey without bees." It was discovered by western Europeans as a result of the Crusades in the eleventh century. In the fifteenth century, European sugar was refined in Venice. In the same century, Columbus sailed to the Americas. It is recorded that in 1493 he took sugarcane plants to grow in the Caribbean. The climate was so advantageous for sugarcane that an industry was quickly established.

**Composition:** (Bagasse) Cellulose = 32–48%, Hemicellulose = 19–24%, Lignin = 23–32%

**Ultimate Analysis:** C = 44.80, H = 5.35, O = 39.55, N = 0.38, S = 0.01, Cl = 0.12

**Proximate Analysis:** VM = 73.78, FC = 14.95, Ash = 11.27

**Higher Heating Value:** 17.33 MJ/kg

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*Source of illustration:* USDA-NRCS PLANTS Database / Hitchcock, A.S. (rev. A. Chase) (1950) *Manual of the Grasses of the United States*. USDA Misc. Publ. No. 200. Washington, DC.

## Sugar Crop: Sweet Sorghum




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**Taxonomic Name:** *Sorghum bicolor* (L.) Moench

**Classification:** Warm season, thick-stemmed annual grass

**Description:** Characterized by a loose, open panicle and slender upper leaves that often droop. Can grow higher than 4 m. Drought resistant and well adapted to a variety of soil types due to extensive root system. Spreads naturally through loose seed dispersion. After frost or under adverse conditions can produce toxic levels of prussic acid. Little or no response to nitrogen fertilization inputs. Very high potassium needs. Yields vary widely, depending on conditions. Can produce over 100 Mg/ha with use of irrigation.

**Natural Ecosystem:** Africa

**Photosynthetic Pathway:** C4

**Cultivation History:** Sorghum was likely first used as food in Ethiopia 5000 years ago. From there it spread through Africa and to India where it was first cultivated 3000 years ago. Grain varieties were brought to America with the slave trade where it was used as a hardy cover crop for livestock or grain production.

**Composition:** Cellulose = 27, Hemicellulose = 25, Lignin = 11

**Ultimate Analysis:** C = 46.8, H = 4.82, O = 39.8, N = 1.35, S = 0.07, Cl = 0.39

**Proximate Analysis:** 6.8% ash

**Higher Heating Value:** 18.322 MJ/kg

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*Source of illustration:* USDA-NRCS PLANTS Database / Hitchcock, A.S. (rev. A. Chase) (1950) *Manual of the Grasses of the United States*. USDA Misc. Publ. No. 200. Washington, DC. *Sorghum halepense* (L.) Pers.

## Starch Crop: Cassava



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**Taxonomic Name:** *Manihot esculenta*

**Classification:** Perennial woody shrub often grown as an annual of the family Euphorbiaceae

**Description:** Dicotyledon with 1–2 m high shoot system. Consists of palmate leaves along whitish grey to brown colored stems with nodes. Root system has 5–10 tuberous roots and fibrous roots extending down to 2 m depth. Tubers are used for food, animal feed and starch-based products. Leaves are used for other proteins, vitamins and other essential elements. Vegetative propagation by stem cutting is common practice. Fourth most grown crop worldwide from Latin America, Africa to South and Southeast Asia after rice, wheat, and maize. Potential yield can be 40–90 ton/acre.

**Natural Ecosystem:** Lowland tropical crop which cannot withstand cold or frost. Can tolerate prolonged drought—survives by shedding leaves. Can be grown on sandy, poor soils. Yield is sensitive to drought or standing water.

**Photosynthetic Pathway:** Varies between C3 and C4 depending on temperature

**Cultivation History:** Cassava originated in Mexico, Guatemala, and northeastern Brazil. There is evidence that it was grown 5000 years ago in Columbia. It is a true cultigen, a crop unknown in the wild state.

**Composition:** (Root) crude protein 3.5, ether extract 0.8, crude fiber 4.2, ash 4.1, nitrogen free extract 87.4

**Ultimate Analysis:** Not used as boiler fuel

**Proximate Analysis:** Not used as boiler fuel

**Higher Heating Value:** 13.38 MJ/kg

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*Source of illustration:* Author.

## Starch Crop: Maize




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**Taxonomic Name:** *Zea mays* L.

**Classification:** Warm season, annual grass

**Description:** Varies in height from 0.5 to 5 m during flowering. Maturing is 60–330 days after planting. Can grow 1–4 ears per plant, each ear containing 10–1800 kernels. Kernels can be white, yellow, red, blue, or variegated in mottled or striated patterns. Produces from 0.5 to 23.5 Mg/ha. Grown from the 40° latitude S to the 50°N. Dense, fibrous root system. Susceptible to drought, flooding, and frost. Vulnerable to many diseases and pests including various stalk and ear rots, worms, and nematodes. Diseases and pests have been overcome by chemical seed treatment, pesticides, and genetic modification.

**Natural Ecosystem:** Mesoamerica

**Photosynthetic Pathway:** C4

**Cultivation History:** Maize was cultivated in Mexico 4500 years before the Spanish invasion of Central America. The Spanish brought maize back to Europe. Scientists have since developed different types of maize that can grow in many different climates throughout the world.

**Composition:** (Stover) Cellulose = 35%, Hemicellulose = 28%, Lignin = 16–21% (Grain) Starch = 72, Protein = 10, Oil = 5, Fiber = 13

**Ultimate Analysis:** (Cobs) C = 46.58, H = 5.87, O = 45.46, N = 0.47, S = 0.01, Cl = 0.21 (Stover) C = 43.65, H = 5.56, O = 43.31, N = 0.61, S = 0.01, Cl = 0.60

**Proximate Analysis:** (Cobs) VM = 80.1, FC = 18.54, Ash = 1.36 (Stover) VM = 75.17, FC = 19.25, Ash = 5.58

**Higher Heating Value:** (Cobs) 18.77 MJ/kg; (Stover) 17.65 MJ/kg

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*Source of illustration:* USDA-NRCS PLANTS Database / Britton, N.L. and Brown, A. (1913) *Illustrated Flora of the Northern States and Canada*, Vol. 1: 599.

## Inulin Crop: Jerusalem Artichoke



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**Taxonomic Name:** *Helianthus tuberosus* L.

**Classification:** Perennial herb often cultivated as an annual

**Description:** Stems are 1–3 m tall with vegetation similar to a sunflower but perennating from stem tubers. Both crop forage and tubers can be harvested. Production costs and techniques are similar to those for potatoes. Typical yields under normal conditions are 20 Mg/ha. Weed control is not a large issue as the plant shades the ground as it matures.

**Natural Ecosystem:** Native to North America. Has been introduced and become naturalized in all temperate regions in the Northern and Southern Hemispheres.

**Photosynthetic Pathway:** C3

**Cultivation History:** Jerusalem artichoke is grown primarily for the tubers that can be eaten cooked or raw. It was largely cultivated in the northeast United States until the mid-eighteenth century when it was replaced by the potato. Both its foliage and the tuber can be used as energy crops. The tuber contains large amounts of the carbohydrate inulin that can be used in the production of alcohols. It is a high yield crop that makes it attractive for production of ethanol.

**Composition:** Water 80%; Remainder: Inulin 65%, Protein 15%, Fat 1%, Fiber 4%, and Ash 5%

**Ultimate Analysis:** Not used as boiler fuel

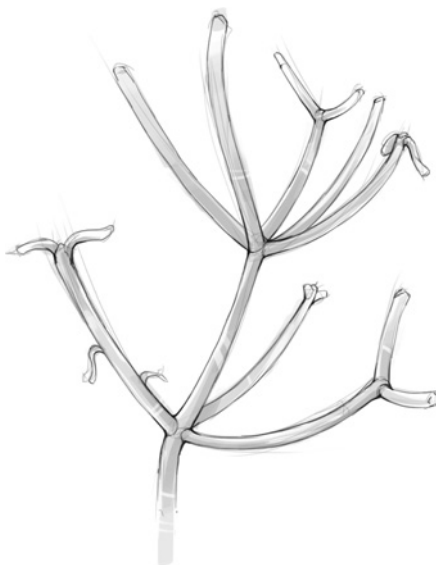
**Proximate Analysis:** Not used as boiler fuel

**Higher Heating Value:** Not used as boiler fuel

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*Source of illustration:* USDA-NRCS PLANTS Database / Britton, N.L. and Brown, A. (1913) *Illustrated Flora of the Northern States and Canada*, Vol. 3: 486.

## Oleaginous Crop: Aveloz



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**Taxonomic Name:** *Euphorbia tirucalli* L.

**Classification:** Dioecious, succulent, cactus-like milky tree

**Description:** A perennial with many names including petroleum plant, mole plant, caper spurge, pencil tree, milk bush, and finger tree. Grows with single or multiple trunks that support a tangle of light green, pencil-thick, branches with little sign of leaves. Can reach heights up to 10 m with a 2–3 m spread. Main trunk and branches are woody and brownish. It produces a corrosive white latex sap.

**Natural Ecosystem:** Indigenous to tropical eastern and southern Africa

**Photosynthetic Pathway:** Crassulacean acid metabolism (CAM)

**Cultivation History:** Aveloz was introduced from Africa as a garden plant, but is now naturalized in tropical areas and rainforests in South Africa, Amazon, and Madagascar. Its use as a tribal and herbal medication dates back thousands of years to areas in Brazil, Africa, Malaysia, India, and Peru. In the 1970s, aveloz was touted as a cure for cancer but it was subsequently shown to be an immune system suppressant. The interest for the aveloz as a biorenewable resource came from 1976, when the Nobel Laureate Melvin Calvin suggested that the plant could be the “petroleum plant” due to its production of a hydrocarbon substance. Aveloz has been studied by Petrobras, the Brazilian state petroleum company, as a refinery feedstock.

**Composition:** (Plant) Hydrocarbon = 5.92%, Sugar = 10.21%; (Seed) Oil = 48%

**Ultimate Analysis:** Not available

**Proximate Analysis:** Not available

**Higher Heating Value:** (Oil) 44 MJ/kg; (Hydrocarbon) 42 MJ/kg

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*Source of illustration:* Author.



## Oleaginous Crop: Canola



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**Taxonomic Name:** *Brassica napus* L.

**Classification:** Cool season, bright yellow flowering member of the mustard family

**Description:** Annual with low drought tolerance. Mature plants are 1.5 m tall, non-nitrogen fixing, and propagated by seed. Non-native to the United States.

**Natural Ecosystem:** Cool extremes of temperate zones

**Photosynthetic Pathway:** C3

**Cultivation History:** Canola refers to cultivars of oilseed rape developed in Canada. It was first grown as an emergency war measure on a few acres in 1942. It is bred for low levels of erucic acid. It is widely used for cooking oil, salad oil, and margarine. Canola contains the lowest saturated fat content of all major edible vegetable oils.

**Composition:** (Seeds) Moisture = 8.5%, Protein = 20.4%, Lipid = 42.4%

**Ultimate Analysis:** C = 52.2%, H = 8.06%, O = 35.8%, N = 3.91%, Ash = 5.50%

**Proximate Analysis:** VM = 82.6%, FC = 7.90%, Ash = 5.5%

**Higher Heating Value:** 28.36 MJ/kg

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*Source of illustration:* USDA-NRCS PLANTS Database / Britton, N.L. and Brown, A. (1913) *Illustrated Flora of the Northern States and Canada*, Vol. 2: 193.

## Oleaginous Crop: Chinese Tallow Tree



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**Taxonomic Name:** *Sapium sebiferum*

**Classification:** Tropical hardwood

**Description:** Deciduous tree that can reach 16 m. Matures in 3–5 years. Can be propagated by coppicing.

**Natural Ecosystem:** Eastern Asia

**Photosynthetic Pathway:** C3

**Cultivation History:** The Chinese tallow tree has been cultivated in China for about 1500 years as a seed-oil crop. It has since been established in the outer coastal plains of North and South Carolina, south to Florida, and west to eastern Texas. The wood of the tree can be used as boiler fuel while the seed yields both oil and high-protein meal. The oil is considered superior to linseed oil in its drying and polymerizing properties. The meal can be processed into refined flour suitable for human consumption.

**Composition:** (Fruit) Fatty seed coat = 27–33%, Shell = 36–41%, Kernel = 29–35%. (Outer seed coat) Fat = 55–78%. (Kernel) Fat = 53–64%.

**Ultimate Analysis:** Not available

**Proximate Analysis:** Not available

**Higher Heating Value:** (Wood) 16.8–18.27 MJ/kg

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*Source of illustration:* Author.

## Oleaginous Crop: Jojoba



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**Taxonomic Name:** *Simmondsia chinensis* (Link) Schneid

**Classification:** Perennial, deciduous, evergreen shrub, or small tree

**Description:** Shrub that reaches 4.5 m in height with flat, gray-green, leathery leaves. Deep and extensive root system. Well adapted to withstand desert heat and aridity. Can live under diverse environmental conditions. May live for up to 200 years. During summer, green fruit dries, outer skin shrivels, and peels back, exposing a wrinkled, brown, soft-skinned nut, the size of a small olive. Nuts contain a vegetable oil that is clear and odorless but feels less oily than traditional edible oils. Half the weight of the nut is oil. The oil is a polyunsaturated liquid wax whose only other known source has been the sperm whale. Seeds yield methyl ester instead of the triglycerides of most seeds' oils. The ester does not turn rancid.

**Natural Ecosystem:** Hot, arid and semiarid regions of the southwestern United States (Sonoran Desert)

**Photosynthetic Pathway:** C3

**Cultivation History:** Native Americans extracted the oil from jojoba seeds to treat sores and wounds centuries ago. Jojoba cultivation began in the early 1970s. Average yield of commercial jojoba plantations is approximately 340 kg/ha.

**Composition:** (Seed) Water = 4.45%, Protein = 15%, Fat = 52%, Carbohydrate = 26.85%, Fiber = 3.85%, Ash = 1.5%

**Ultimate Analysis:** C = 81.8%, H = 5.2%, O = 13%

**Proximate Analysis:** Not available

**Higher Heating Value:** (Oil) 42.761 MJ/kg

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*Source of illustration:* Author.

## Oleaginous Crop: Rapeseed



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**Taxonomic Name:** *Brassica napus* L.

**Classification:** Warm season or cold season, annual or biennial oil plant depending on cultivar

**Description:** Composed of a deep taproot and a rosette of blue-green leaves with 7–10 lateral shoots. Gold-yellow flowered racemes are located on the ends of the branched stems. Contains approximately 120 long, slender seed pods per plant with 18–20 seeds per pod (2000–3000 seeds per plant). Germinates quickly. Small, round, black seeds. Crop success very sensitive to water levels. Seed yield can reach 3 Mg/ha with 10–12 Mg/ha dry matter straw yield. Common problem weeds include chickweed, foxtail grass, chamomile, and reappearing wheat. Insecticides may be required for pests such as fleas, lice, snails, beetles, and weevils. Fungicide applications may be necessary. Reaches heights of up to 1.5 m. Yields approximately 40% oil.

**Natural Ecosystem:** Mediterranean region

**Photosynthetic Pathway:** C3

**Cultivation History:** Rapeseed remnants have been found in digs from Bronze Age establishments. Large-scale cultivation has been established as far back as the thirteenth century. Rapeseed began to spread to western Europe, Canada, China, India, and the United States following World War II. It is the third largest oil-producing seed behind soybeans and palm.

**Composition:** (Straw) Holocellulose = 75.43, Lignin = 19.34, Ash = 5.23

**Ultimate Analysis:** (Straw) C = 45.2%, H = 5.15%, O = 42.9%, S = 0.14%, N = 0.75%

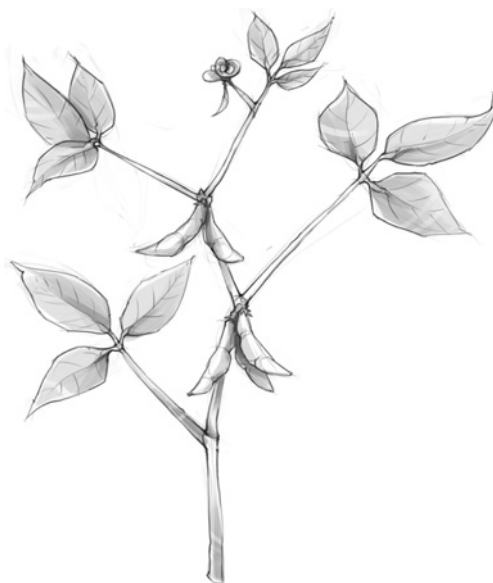
**Proximate Analysis:** (Straw and Stalk) VM = 75.6%, FC = 18.6%, Ash = 5.87%

**Higher Heating Value:** (Straw) 17.64 MJ/kg; (Oil) 39.7 MJ/kg

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*Source of illustration:* Author.

## Oleaginous Crop: Soybean



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**Taxonomic Name:** *Glycine max* (L.) Merr.

**Classification:** Annual, cool season legume. Can be grown as warm-season plant in tropical areas

**Description:** Rapid growing nitrogen producing plant. Grows to a height up to 80 cm. Entire plant covered in hair. Produces a main root with smaller roots branching from it which possess numerous nodules. Bacteria *Bradyrhizobium japonicum* develops in the roots and is responsible for free nitrogen fixation. Leaves usually consist of three leaflets. Numerous small purple or white flowers are found in compact racemes in the leaf axils. Fruit develops in the form of pods with 2–3 seeds usually being found in each pod. Drought strongly affects crop yield. Common diseases include leaf spot, stem canker, and soybean mosaic virus. Insecticides may be necessary for pests such as soya bean moth, Japanese beetle, and nematodes. Yields of up to 3.6 Mg/ha.

**Natural Ecosystem:** China

**Photosynthetic Pathway:** C3

**Cultivation History:** The soybean was domesticated in China over 3000 years ago. The first soybeans arrived in America in the early 1800s as ballast aboard a ship, but soybeans were not harvested in America until 1879 when farmers began to plant soybeans as forage for their livestock. The plants flourished in the hot, humid summer of northeastern North Carolina. In 1904, G.W. Carver discovered that soybeans were a valuable source of protein and oil. Soybeans have been recently genetically modified to produce oil for a number of products including biodiesel fuel, printing inks, paints, soaps, shampoos, and disinfectants.

**Composition:** (Seed) Protein = 40%, Lipid = 20%, Carbohydrates = 35%, Ash = 4.9%

**Ultimate Analysis:** Not available

**Proximate Analysis:** Not available

**Higher Heating Value:** (Oil) 39.6 MJ/kg

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*Source of illustration:* Author.

## Oleaginous Crop: Sunflower



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**Taxonomic Name:** *Helianthus annuus* L.

**Classification:** Warm season, annual broadleaf plant

**Description:** Erect, broadleaf plant. Head is not a single flower but is made up of 1000–2000 individual flowers joined at a common receptacle. Most varieties have rough/hairy oval to heart shaped leaves. Leaves will follow the sun's rays, increasing light interception and photosynthesis. Not highly drought tolerant, but often produces satisfactory results when other crops are damaged during drought. Will grow in a wide range of soil types from sands to clays. Yield increases from N fertilizer rates up to 196 kg/ha have been observed. Heights reaching up to 3.5 m. Head can grow up to 40 cm in diameter with spirally arranged yellow flowers. Strong taproot up to 3 m deep.

**Natural Ecosystem:** North America

**Photosynthetic Pathway:** C3

**Cultivation History:** The wild sunflower was domesticated around 3000 BC for food production. It was taken to Europe around 1500, where improved varieties were developed. It became very popular as a cultivated plant in the eighteenth century when Russians started using it for its oil. The sunflower returned to the United States in the end of the nineteenth century. US acreage increased during the 1970s due to strong European demand for sunflower oil. It was hybridized in the mid-1970s, providing higher yield, oil enhancement, and disease resistance.

**Composition:** (Shell) Cellulose = 48.4%, Hemicellulose = 34.6%, Lignin = 17%

**Ultimate Analysis:** C = 44.2, H = 4.6, N = 0.7, S = 0.1, O = 50.4

**Proximate Analysis:** FC = 13.3, VM = 6.2, Ash = 10.5

**Higher Heating Value:** Shell (18.0 MJ/kg); Seed (15.6 MJ/kg); Oil (39.6 MJ/kg)

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*Source of illustration:* Author.

## Herbaceous Crop: Big Bluestem



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**Taxonomic Name:** *Andropogon gerardii* Vitman

**Classification:** Warm season perennial grass

**Description:** A native prairie grass that grows in clumps, forms a dense sod and can grow to 2.4 m tall. The root system can extend down to 3.7 m making it very drought resistant. It spreads by seed or by rhizomes. Unlike the hollow stems of most grasses, the stems are solid or pithy. The leaves and stem nodes have a bluish cast. The seed heads often occur as three branches giving rise to its common name “turkey foot.”

**Natural Ecosystem:** Its primary natural ecosystem is the North American tallgrass prairie biome, which once extended from southern Manitoba to Texas and from eastern Nebraska to Indiana.

**Photosynthetic Pathway:** C4

**History:** The dominate grass of the tallgrass prairies. A higher stem to leaf ratio makes it more attractive than switchgrass as a potential fiber crop.

**Composition:** Cellulose = 34%, Hemicellulose = 24%, Lignin = 18%

**Ultimate Analysis:** C = 47.4%, H = 5.75%, O = 42.3%, N = 0.74%, S = 0.08%

**Proximate Analysis:** VM = 81.4%, FC = 15%, Ash = 3.6%

**Higher Heating Value:** 18.64 MJ/kg

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*Source of illustration:* USDA-NRCS PLANT Database / Hitchcock, A.S. (rev. A. Chase) (1950) *Manual of the Grasses of the United States*. USDA Misc. Publ. No. 200. Washington, DC.

## Herbaceous Crop: Kenaf



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**Taxonomic Name:** *Hibiscus cannabinus* L.

**Classification:** Warm season, annual

**Description:** Herbaceous plant with a single, straight, unbranched stem. Can grow to heights of about 4–6 m with a 25–50 mm diameter stem. Exhibits rapid growth, reaching full height in 5–7 months. Yields as high as 24 Mg/ha can be obtained with 120 lb of N<sub>2</sub> application. Very sensitive to cold. Requires frequent irrigation in sandy soils. Cannot tolerate waterlogged soils.

**Natural Ecosystem:** Africa

**Photosynthetic Pathway:** C<sub>4</sub>

**Cultivation History:** Kenaf has grown for thousands of years in Africa and was introduced to southern Asia in early 1900. In 1980, kenaf was introduced and researched in the United States. It has the potential to be a renewable source of industrial fiber (mostly for pulp and paper industry) in developed economies.

**Composition:** Cross and bevan cellulose 47–52%, alpha cellulose 31–39%, lignin 7.5–9.5%, pentosans 16–23%, ash 2–5.5% (bast) alpha cellulose 34%, lignin 17.5%, pentosans 19.3%, ash 2.5% (core)

**Ultimate Analysis:** Not available

**Proximate Analysis:** Not available

**Higher Heating Value:** Not available

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*Source of illustration:* Author.



## Herbaceous Crop: Miscanthus



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**Taxonomic Name:** *Miscanthus × giganteus*

**Classification:** Cool season, thick-stemmed perennial grass

**Description:** Deep-rooted (at least 1 m penetration) grass hybrid with heights usually ranging between 2 and 3 m that can attain heights as large as 3.5 m. Lifetime of at least 10–15 years. Sometimes known as “elephant grass.” Naturally occurring sterile species hybrid of the *sinensis* and *sacchariflorus* species. Low nutrient requirements allow growth in a wide variety of soils. Will tolerate dry conditions, but at the cost of yield. Under normal conditions offers high yields ranging from 8 to 15 Mg/ha. Can be harvested annually with a sugarcane harvester.

**Natural Ecosystem:** Southeast Asia

**Photosynthetic Pathway:** C4

**Cultivation History:** While originally from Japan, miscanthus has been propagated by harvesting rhizomes from existing stands and replanting them elsewhere. The sterile nature of this hybrid eliminates the threat of a non-native invasion. Miscanthus is a genus of 14 species widely grown as an ornamental plant because of its attractive inflorescences. Genotypes developed for biomass are selected for delayed flowering and for infertile hybrids to avoid it becoming a weed. *Miscanthus × giganteus* is the cross most commonly used for biomass production.

**Composition:** Cellulose = 46%, Hemicellulose = 29%, Lignin = 15%

**Ultimate Analysis:** C = 45.7, H = 5.70, O = 41.1, N = 0.46, S = 0.11

**Proximate Analysis:** VM = 69.7, FC = 27.7, Ash = 2.60

**Higher Heating Value:** 17.1 MJ/kg

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*Source of illustration:* USDA-NRCS PLANTS Database / Hitchcock, A.S. (rev. A. Chase) (1950) *Manual of the Grasses of the United States*. USDA Misc. Publ. No. 200. Washington, DC.

## Herbaceous Crop: Switchgrass



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**Taxonomic Name:** *Panicum virgatum* L.

**Classification:** Warm season, thin-stemmed perennial grass

**Description:** Deep-rooted bunch grass that grows as tall as 2.5 m. Natural prairie grass that is drought resistant. Demand for nitrogen is low due to deep rooting and storage of nutrients in rhizomes. Once established, need for pesticides are low. High yielding, as much as 10 Mg/ha. Can be distinguished from other warm-season grasses by a white patch of hair at the point where the leaf attaches to the stem. Stem is round and usually has a reddish tint.

**Natural Ecosystem:** North to Central America

**Photosynthetic Pathway:** C4

**Cultivation History:** Switchgrass was one of the main species forming the North American grass prairies before the coming of the plow. It is valued as a soil stabilization plant, and is used as a windbreak in crop fields. It was selected by the US DOE as an early candidate among prospective dedicated energy crops and has been used in demonstrations of biomass power.

**Composition:** Cellulose = 43%, Hemicellulose = 36%, Lignin = 22%

**Ultimate Analysis:** C = 47.2, H = 5.79, O = 41.2, N = 0.62, S = 0.10

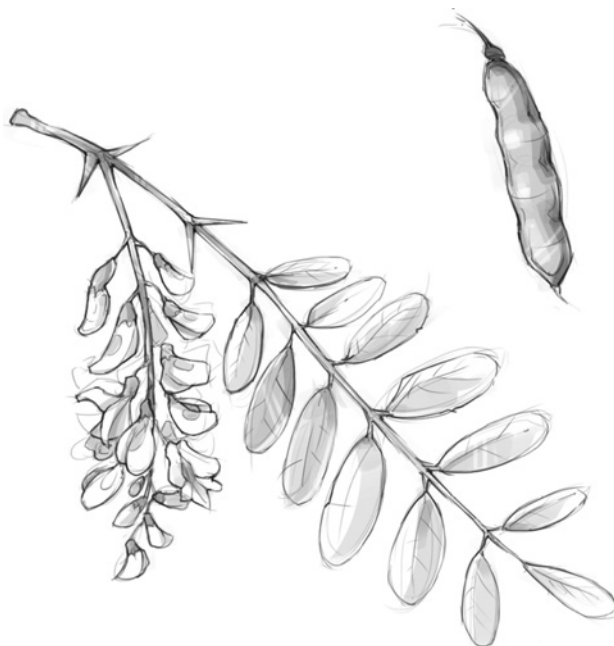
**Proximate Analysis:** VM = 80.3, FC = 14.6, Ash = 5.1

**Higher Heating Value:** 18.4 MJ/kg

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*Source of illustration:* USDA-NRCS PLANTS Database / Hitchcock, A.S. (rev. A. Chase) (1950) *Manual of the Grasses of the United States*. USDA Misc. Publ. No. 200. Washington, DC.

## Woody Crop: Black Locust



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**Taxonomic Name:** *Robinia pseudoacacia* L.

**Classification:** Perennial, leguminous hardwood

**Description:** Rapid growing, nitrogen-fixing tree that tolerates low fertility sites and yields 6–14 Mg/ha. When mature, this perennial can reach 35 m in height and 1 m in diameter. It regenerates from root sprouts or coppice, but is intolerant to shade. Attributes include wide climatic adaptation, resistance to drought stress and decay fungi, and high genetic variation. Its dense (690 kg/m<sup>3</sup>) wood is extremely durable, though plagued by stem borer, *Megacyllene robiniae*.

**Natural Ecosystem:** Cool, temperate regions of eastern United States

**Photosynthetic Pathway:** C3

**Cultivation History:** In early US history, houses were built on posts of black locust. Later it was used for erosion control, land reclamation after strip-mining, and timber production on abandoned farmlands. Potential includes use as a fiber or energy crop. Though native to eastern United States, it is now being developed and cultivated throughout the world.

**Composition:** Cellulose = 45%, Hemicellulose = 19%, Lignin = 29%

**Ultimate Analysis:** C = 50.7, H = 5.71, O = 41.9, N = 0.57, S = 0.01

**Proximate Analysis:** VM = 80.9%, FC = 18.3%, Ash = 0.80%

**Higher Heating Value:** 19.87 MJ/kg

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*Source of illustration:* Author.

## Woody Biomass: Eucalyptus




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**Taxonomic Name:** *Eucalyptus globulus* Labill

**Classification:** Myrtaceae, perennial fast growing tree

**Description:** Rapid growing tree, up to 25 m in its first 20 years. Actively grows in all but summer season. Tree can grow in a variety of soil types in areas with mild weather conditions and high moisture content. Cannot tolerate cold, frost, drought, or harsh winds. Secretes fragrant, sticky gum containing antibacterial properties, increasing pest resistance. Deters growth of non-eucalyptus plants. Prefers to grow in dense stands. Mean annual yield for California estimated at 270 ft<sup>3</sup>/acre. Planting density at over 10 000 plants/ha.

**Natural Ecosystem:** Native to Australia, introduced to California and other countries

**Photosynthetic Pathway:** C3

**Cultivation History:** The Tasmanian blue gum was first discovered and described in 1792 in Tasmania. It was introduced to California in 1856. It is one of the world's most valuable windbreak trees because of its wind firmness and the unpalatable nature of its seedlings to grazing animals. It is used as fuel wood in many countries and leaves little ash. Its bark is often used for pulpwood. Essential oils can be extracted from its leaves, and honey can be produced from its flowers. It has potential as industrial fuel wood.

**Composition:** Glucose 59.5%, Xylose 17.8%, Galactose 5.4%, Mannose 2.8%, Rhamnose 0.8%

**Ultimate Analysis:** C = 50.4, H = 6.0, N = 0.17, S = 0.08, Cl = 0.02, O = 43.3

**Proximate Analysis:** VM = 81.42, FC = 17.82, Ash = 0.76

**Higher Heating Value:** 19.1 MJ/kg

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*Source of illustration:* Author.

## Woody Crop: Hybrid Poplar



**Taxonomic Name:** *Populus* × *canadensis* Moench 'I-45/51'

(*Populus deltoides* × *Populus nigra*)

**Classification:** Hardwood

**Description:** Grows very rapidly, reaching a height of 6.5 m in 7–8 years. Crown shape varies with different clones, but generally is very loose, providing little winter protection. Short lived under arid conditions (20–25 years) while under moist conditions may reach 20–24 m and survive 50–60 years. Roots are shallow and may spread 15–20 m.

**Natural Ecosystem:** Widely distributed in Northern Hemisphere

**Photosynthetic Pathway:** C3

**Cultivation History:** Early French explorers in North America brought home eastern cottonwood (*Populus deltoides*), which crossed naturally with poplars in Europe (*P. nigra*). Hand-pollinated poplar hybrids were first produced in Britain in 1912, and many European countries established plantations after the World War II, in response to shortages of timber. Since 1979, the task of improving hybrid poplar as an energy crop has been conducted in the United States. Research has focused on reducing costs by improving yields, increasing pest and disease resistance, and developing efficient management systems.

**Composition:** Cellulose = 39%, Hemicellulose = 17%, Lignin = 25%

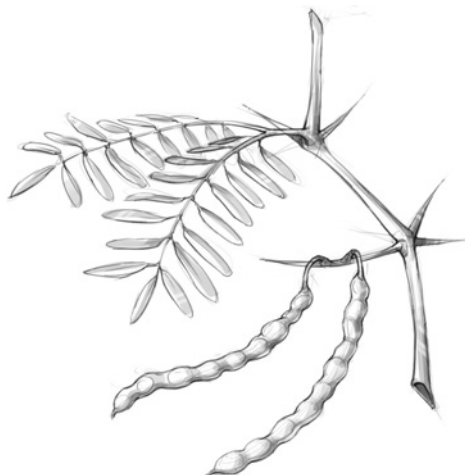
**Ultimate Analysis:** C = 49.75, H = 5.52, O = 42.42, N = 0.52, S = 0.03

**Proximate Analysis:** VM = 78.7, FC = 19.96, Ash = 2.03

**Higher Heating Value:** 8384 BTU/lb

*Source of illustration:* USDA Natural Resource and Conservation Service PLANTS Database. *Populus nigra* L. <http://plants.usda.gov/>

## Woody Crop: Mesquite



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**Taxonomic Name:** *Prosopis glandulosa* Torr.

**Classification:** Small to medium sized hardwood tree

**Description:** Commonly called honey mesquite. Tall shrub or tree growing 3–9 m in height. Foliage is deciduous, and wood is very dense at above 0.7 SG. Propagates aggressively through rhizomes, and also deposits nitrogen in the ground (legume). Tolerates annual precipitation as low as 30 cm and as high as 200 cm and annual temperatures of 18–21°C. Ranked in the “unfailing” class of perennial crops because of the ability to produce fruit independent of annual precipitation trends. Root system has been observed to reach depths of up to 50 m, allowing for high drought resistance.

**Natural Ecosystem:** Grows in southern North America, central and southern South America, sub-Saharan Africa, and regions of the Middle East. Natural ecosystem is semi-arid to arid desert.

**Photosynthetic Pathway:** C3

**Cultivation History:** Mesquite was a key resource of indigenous people due to its drought resistance, providing food, alcohol drink, fuel, medicine, and fertilizer. In more recent years it has been considered more a nuisance, but is still used for firewood, fence posts, and woodworking.

**Composition:** Cellulose = 42%, Hemicellulose = 38%, Lignin = 18%

**Ultimate Analysis:** Not available

**Proximate Analysis:** Not available

**Higher Heating Value:** 20 MJ/kg

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*Source of illustration:* Author.

## Woody Crop: Willow



**Taxonomic Name:** *Salix* sp.

**Classification:** Hardwood

**Description:** Most are compact shrubs with numerous thick branches and grow to heights between 0.3 and 4 m. Some are true trees that reach 15–20 m (*S. fragilis* and *S. alba*). Some species build leaves before blossoms in spring. Shrubs normally have extensive root system. *S. viminalis* (L.) and *S. dasyclados* (Wimm.) are cultivated on biomass plantations for use as energy sources. Very dependent on water availability. Weed control necessary during the first year of establishment. Average application of 60–80 kg/ha N, 10 kg/ha P, and 35 kg/ha K suitable after first year. May be attacked by numerous insects but none cause serious problems. Diseases are more of problem but can be controlled. Considerable damage may be caused by mice and deer during establishment phase. Can produce first yield in three years.

**Natural Ecosystem:** Common across many continents and grows in many climates

**Photosynthetic Pathway:** C3

**Cultivation History:** Willow is a prominent candidate for plantations of short-rotation woody crops in northern climates, especially the basket willow (*Salix viminalis*). Several large field trials have been performed in the state of New York and northern Europe. Grown in short rotations (3–5 years) and harvested when 5–7 m in height. Regenerates from stump and roots, allowing 6–10 rotations before replanting.

**Composition:**

**Ultimate Analysis:** C = 47.7%, H = 5.72%, O = 46.2%, N = 0.43%, S = 0.03%, Cl = 0.01%

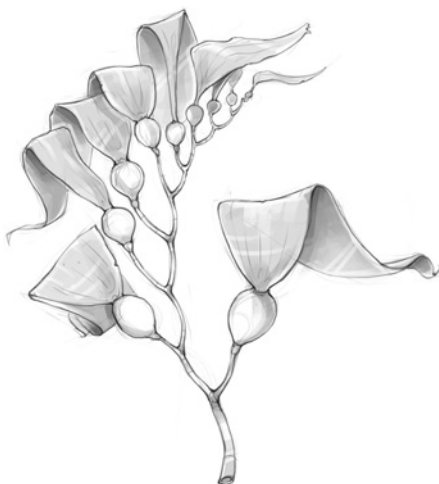
**Proximate Analysis:** FC = 12.4%, VM = 76.5%, Ash = 0.85%, Moisture = 10.2%

**Higher Heating Value:** 19.2 MJ/kg

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*Source of illustration:* Britton, N.L. and Brown, A. (1913) *An Illustrated Flora of the Northern United States, Canada and the British Possessions*, 3 vols. New York: Charles Scribner's Sons.

## Aquatic Species: Giant Brown Kelp



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**Taxonomic Name:** *Macrocystis pyrifera*

**Classification:** Eukaryota, cold season, perennial kelp

**Description:** May reach 45.7 m long and grow in waters 6–20 m deep. Largest of the Pacific kelps. Can grow more than 45 cm per day. Usually grows in beds called forests. Buoyed up by many small, gas-filled bulbs. Attaches to rocks on the ocean floor by means of a large holdfast.

**Natural Ecosystem:** Alaska to Baja California

**Photosynthetic Pathway:** C3

**Cultivation History:** Giant brown kelp was originally used as a fertilizer, then later in the manufacture of gunpowder and as animal feed. Much of today's harvest is used to produce chemicals for the manufacture of medicines, plastics, beauty aids, paper, clothing, and processed foods.

**Composition:** 5–25% mannitol, 12–20% algin, 56–82% cellulose

**Ultimate Analysis:** C = 27.8%, H = 3.77%, O = 23.7%, N = 4.6%, S = 1.1%

**Proximate Analysis:** 57.9% volatiles, 42.1% ash

**Higher Heating Value:** 10.75 MJ/kg

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*Source of illustration:* Author.



## Aquatic Species: Common Water Hyacinth



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**Taxonomic Name:** *Eichhornia crassipes*

**Classification:** Tropical/sub-tropical obligate flowering perennial

**Description:** Floating, aquatic plant. Height ranges from a few centimeters to nearly a meter tall. Long feathery roots. Rounded, leathery leaves attached to bulbous spongy petioles that are sometimes inflated for buoyancy. Multiplies quickly by runners (stolon) from primary plant. Can produce up to 248 secondary plants in 90 days under ideal conditions. Linked plants form thick mats. Can bloom and produce seeds but runners are primary method for multiplication.

**Natural Ecosystem:** Located in freshwater rivers, ponds, streams, ditches around the world in temperate climates.

**Photosynthetic Pathway:** C3

**Cultivation History:** The water hyacinth originated in Latin America. It is believed it was introduced to Africa in the nineteenth century as a pond decoration. It was reportedly brought to the United States in 1884 at an exposition in New Orleans. It is considered one of the most aggressive plants in the world with more than 50 countries listing it as a weed.

**Composition:** Cellulose = 29.3%, Hemicellulose = 33.2%, Lignin = 4.79%, Other = 4.79%

**Ultimate Analysis:** C = 41.1%, H = 5.3%, O = 51.2%, N = 1.96%, S = 0.41%

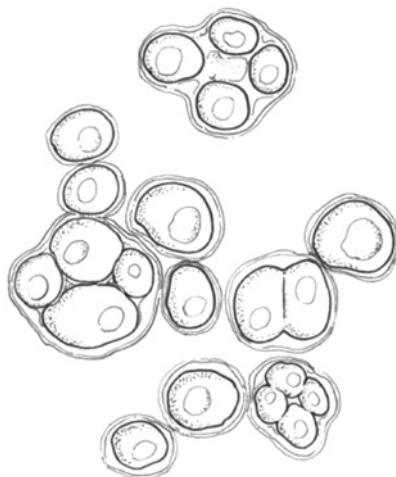
**Proximate Analysis:** Not available

**Higher Heating Value:** 16.02 MJ/kg

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*Source of illustration:* Author.

## Aquatic Species: Microalgae



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**Taxonomic Name:** Various (thousands of strains have been analyzed)

**Classification:** Nonvascular flora, Kingdom Protist, Phyla Chlorophyta

**Description:** Found in both freshwater and marine systems. Depending on species, size ranges from a few to several hundred micrometers. Can exist individually, although many harvestable species grow in chains or groups. Can be phototrophic, heterotrophic, or mixotrophic. Yield a variety of carotenoids, antioxidants, enzymes, polymers, and lipids. Lipids yield estimated to be as high as 15 000 gallons/acre/year, depending on species and cultivation conditions.

**Natural Ecosystem:** Freshwater and marine systems. Prefer warmer climates, although some species can grow in closed bioreactors.

**Photosynthetic Pathway:** C3

**Cultivation History:** Microalgae naturally occurs in aquatic systems. Initially grown in small-scale raceway pond systems located in California and Hawaii by the US government in the 1980s. Small-scale raceway ponds and closed bioreactors now exist in several locations globally, while larger ponds are under construction in the southwest United States and Mexico.

**Composition:** Depends on species, but up to 50% oil, remainder protein, carbohydrate, ash

**Ultimate Analysis:** C = 43%, H = 7%, N = 6%, O = 28%

**Proximate Analysis:** 67% volatiles, 12% fixed carbon, 16% ash

**Higher Heating Value:** 17 MJ/kg

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*Source of illustration:* Brown, R. and Brown, T. (2012) *Why Are We Producing Biofuels?* Brownia, LLC.