SUGAR, CANE SUGAR

The term sugar describes the chemical class of carbohydrates (qv) of the general formula $C_n(H_2O)_{n-1}$ or $(CH_2O)_n$ for monosaccharides. Colloquially, sugar is the common name for sucrose, the solid crystalline sweetener for foods and beverages. Sucrose, a disaccharide, is found in most plants, but is in sufficient concentrations for commercial recovery only in sugarcane and sugarbeet plants. Cane sugar is the sugar extracted from sugarcane.

Sugarcaneis a large perennial tropical grass belonging to the tribe *Andropogoneae* of the family *Gramineae* and the genus *Saccharum*. The genera *Saccharum*, *Erianthus* (sect. *Ripidiam*), *Sclerostachya*, and *Narenga*, most cited in regard to the origin of sugarcane, constitute an interbreeding group that, along with three species of *Saccharum* (*S. officinarum* L., *S. barberi* Jeswiet, and *S. sinense* Roxb), were historically used for commercial sugar production. *Saccharum officinarum* is a progenitor of all modern sugarcane varieties. However, the presence of the interbreeding *Saccharum* complex of the three sugar species as well as its wild relatives, *S. spontaneum* L. and *S. robustum* Brandes and Jeswiet ex Grassl, has provided a genetic pool of unparalleled diversity, allowing for the development of thousands of varieties that are adapted to the areas where sugarcane is grown. Most varieties of sugarcane are interspecific hybrids of two or more of the five *Saccharum* species (1).

The sucrose in cane sugar is identical to that in beet sugar; both white refined products are 99.9% sucrose, with water as the principal nonsucrose component. Trace components from the plant indicate the origin of the sugar.

In 1994–1995, 778×10^6 t of sugarcane were grown on 12.6×10^6 ha in the tropical and subtropical areas of the world. Some 73×10^6 t of cane sugar are produced annually (1994) in sugarcane factories, from harvested sugarcane. Of this, about 26×10^6 t is raw sugar (96–99% sucrose basis) for further refining, and the remainder is direct white, also known as plantation white or mill white sugar, of lower purity (sucrose content) than refined sugar, for consumption in the local area of production. Raw cane sugar is shipped to cane sugar refineries, traditionally in areas of high consumption outside the tropics (North America, northern Europe) but increasingly, in recent years, in the tropics where energy is cheap and the market is increasing. Refined white and brown cane sugars, and liquid sugar products, are sold industrially and directly to the consumer around the world. Sugar is one of the purest food substances made. Food-grade sucrose [57-50-1] also ranks as a very pure organic chemical. Food-grade sugar constitutes the world's largest supply of a high purity, naturally occurring chemical compound. However, more than 99% of all crystalline sugar produced is used as food.

1. History

Sugarcane, a sweet reed or grass in its earliest forms, probably originated in New Guinea. It was found throughout Southeast Asia, China, the South Pacific, the Indian subcontinent (where some claim it originated), and the Middle East by the fourth century BC. The soldiers of Alexander the Great (356–323 BC) brought from India to Macedonia a plant that produced "honey without bees," thereby bringing sugarcane to the European continent. Arabic travelers spread sugarcane throughout the Mediterranean area. By the twelfth century, sugarcane had reached Europe, and Venice was the center of sugar trade and refining. Marco Polo reported advanced sugar refining in China toward the end of the thirteenth century. Columbus brought sugarcane to the new world on his second voyage. It spread throughout the Western Hemisphere in the next 200 years, and by about 1750 sugarcane had been introduced throughout the world.

The process for extracting juice from the cane is very old. In antiquity, the canes were undoubtedly sucked or chewed for their sweet taste. Also, in the ancient past in various places the canes were cut and crushed by heavy weights, ground with circular stones or by a heavy roller running on a flat surface, pounded in a mortar with a pestle, or soaked in water to better extract the sweet juice. The term grinding survives to this day as the name of the process for extracting the cane juice, even though the process no longer involves a true grinding. Parallel rolls, which are used in the 1990s, were first used in 1449 in Sicily.

The ancient process for obtaining sugar consisted of boiling the juice until solids formed as the syrup cooled. The product looked like gravel and the Sanskrit word for sugar, *shakkara,* has that alternative meaning. Pliny, who traveled widely in the Roman Empire, wrote in 77 AD that sugar was "white and granular." He noted that Indian sugar was more esteemed than Arabian, and that both were used in medicine. By the fourth century AD, the Egyptians were using lime as a purifying agent and carrying out recrystallization, which is still the main step in refining.

Until a few hundred years ago, sugar was strictly a luxury item. Queen Elizabeth I is credited with putting it on the table in the now familiar sugarbowl, but it was so expensive that it was used only on the tables of royalty. Sugar production reached large volume at a reasonable price only by the eighteenth century.

The development of the sugar industry from the sixteenth century onward is closely associated with slavery, which supplied the large amount of labor used at the time. Owing to the low cost of labor and the high price for sugar, many fortunes were made. The abolition of slavery at various times in different countries between 1761 and 1865 profoundly affected the sugar industry. Upon freeing of the slaves, sugar production fell drastically in many producing areas.

The first use of steam power as a replacement for the animal or human power that drove the cane mills occurred in Jamaica in 1768. This first attempt worked only a short time, but steam drive was used successfully a few years later in Cuba. Steam drive for the mills soon spread throughout the world. The use of steam instead of direct firing was soon applied to the evaporating of the cane juice.

Probably the most essential piece of equipment in the modern process is the vacuum pan, invented by Howard (U.K.) in 1813. This accomplishes the evaporation of water at a low temperature and lessens the thermal destruction of sucrose. The bone-char process for decolorization dates from 1820. The other essential piece of equipment is the centrifuge, which was developed by Weston in 1852 and applied to sugar in 1867 in Hawaii. This machine reduces the time for draining the molasses from the sugar crystals from weeks to minutes by applying a force of several orders of magnitude greater than gravity. It is to the everlasting credit of the cane-sugar industry that the greatest energy saver of all time was developed in this industry: the multiple-effect evaporator invented by Norbert Rillieux of Louisiana. The 1846 patents of Rillieux describe every detail of the process. This system is used universally by every industry that has to evaporate water.

The manufacture of sugar was early understood to be an energy-intensive process. Cuba was essentially deforested to obtain the wood that fueled the evaporation of water from the cane juice. When the forests were gone, the bagasse burner was developed to use the dry cane pulp, called bagasse, for fuel. Bagasse was no longer a waste product; its minimal value is the cost of its replacement as fuel.

The principal analytical methods were developed in the mid-nineteenth century: the polariscope by Ventzke in 1842, the Brix hydrometer in 1854, Fehling's method for reducing sugars, and Clerget's method for sucrose in 1846.

Sugar loaves were for centuries the traditional form in which sugar reached the market. These were formed by pouring the mixture of crystals and syrup into a mold. The molds were kept in the hot room to facilitate the draining of the syrup, either through the porous mold or through a hole in the bottom. With a little cooling or drying, the crystals stuck together, forming a convenient marketable loaf of sugar. The sugar

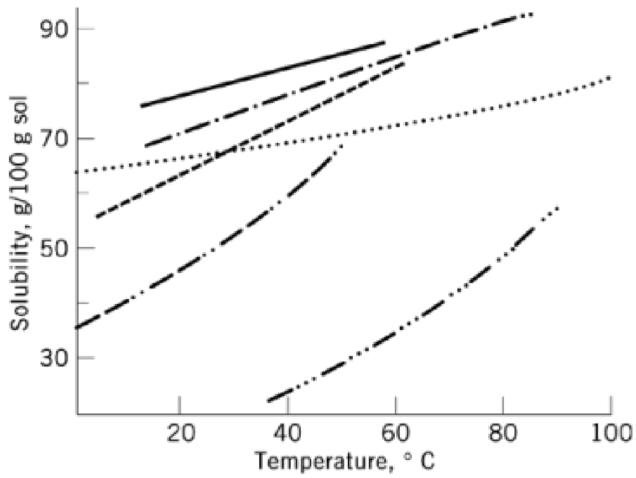

Fig. 1. Solubility of some sugars, where (____) represents fructose; (_._), sorbitol; (_), xylitol; (....), sucrose; (_.._), glucose; (_...._), lactose.

loaves required no packaging and were broken up by the user as needed. Only a very small amount of sugar now reaches the market in this form. A few loaves are made in Europe for advertising purposes.

2. Physical and Chemical Properties

Cane sugar is generally available in one of two forms: crystalline solid or aqueous solution, and occasionally in an amorphous or microcrystalline glassy form. Microcrystalline is here defined as crystals too small to show structure on x-ray diffraction. The melting point of sucrose (anhydrous) is usually stated as 186°C, although, because this property depends on the purity of the sucrose crystal, values up to 192°C have been reported. Sucrose crystallizes as an anhydrous, monoclinic crystal, belonging to space group $P2_1$ (2).

The specific rotation in water is $[\alpha]_D^{20} = +66.529°$ (26 g pure sucrose made to 100 cm^3 with water). This property is the basis for measurement of sucrose concentration in aqueous solution by polarimetry. 100°Z indicates 100% sucrose on solids.

Among physical properties of cane sugar that are most important for its use in foods are bulk density, dielectric constant, osmotic pressure, solubility, vapor pressure, and other colligative properties, and viscosity (3). Bulk density, important for cane sugar as an ingredient in dry mixes, is listed in Table 1, as typical values for several types of sugars. Solubility of sucrose with other common sugars is shown in Figure 1 and in Table 2. Colligative properties vary with concentration of sucrose in solution. The strong effect of cane sugar on freezing point depression is widely used in frozen desserts; the reduction in vapor pressure and increase in boiling point are essential for manufacture of hard candy and other confectionery (2, 4). The high osmotic pressure generated by sucrose in solution (Table 3) (2) reduces the water activity and therefore the equilibrium relative humidity, so that insufficient moisture remains to sustain microorganisms, as in jams and preserves. Most common microorganisms require at least 80% equilibrium relative humidity to grow; both crystalline sugar, and concentrated solutions such as jams and preserves, are well under 70%. Dielectric constant values for sucrose in solution are shown in Table 4 (3); the high values make sugar an important ingredient for quick heating in microwaveable foods. The viscosity of cane sugar solutions varies greatly with degree of purity of the sugar; tables for sucrose are readily available (2–7).

Table 1. Bulk Density of Sugars

Sugar type	Typical values[a] kg/m^3	lb/ft^3
confectioners AA	833–881	52–55
sanding	801–833	50–52
manufacturer's or fine granulated	785–833	49–52
bottler's or standard granulated	769–817	48–51
baker's special	785–849	49–53
powdered		
sifted	384–481	24–30
compacted	609–721	38–45
agglomerated	320–384	20–24
soft (brown) compacted	833–993	52–63

[a] Maximum value of bulk density for granulated sugar occurs at grain size 0.2 mm, and is 930 kg/m^3 (no conglomerates).

Table 2. Solubility in Pure Water Under Normal Pressure

t, °C	S,[a] wt %	L_t[b]
0	64.45	1.8127
10	65.43	1.8926
20	66.72	2.0047
30	68.29	2.1535
40	70.10	2.3450
50	72.12	2.5863
60	74.26	2.8856
70	76.48	3.2515
80	78.68	3.6899
90	80.77	4.2004
100	82.65	4.7634

[a] As calculated from the equation $S = 64.447 + 8.222\cdot10^{-2}t + 1.6169\cdot10^{-3}t^2 - 1.558\cdot10^{-6}t^3 - 4.63\cdot10^{-8}t^4$.
[b] L_t = gram sucrose per gram water.

Table 3. Osmotic Pressure of Aqueous Sucrose Solutions at 25°C[a]

Sucrose, g/100 g of water	Osmotic pressure, 10^5 Pa[b]
3	2.17
6	4.56
9	6.95
12	9.33
15	11.72
18	14.11
21	16.49
24	18.89
27	21.27
30	23.66
33	26.05
36	28.43

[a] Ref. 2.
[b] To convert Pa to psi, multiply by 1.45×10^{-4}.

Table 4. Dielectric Constant of Aqueous Sucrose Solutions

	Temperature, °C		
Sucrose wt %	20	25	30
0	80.38	78.54	70.76
10	78.04	76.19	74.43
20	75.45	73.65	71.90
30	72.64	70.86	69.13
40	69.45	67.72	66.05
50	65.88	64.20	62.57
60	61.80	60.19	58.64

Table 5. Composition of Sugars and Syrups[a]

Material	Sucrose, %	Glucose, %	Fructose, %
cane sugar, white	>99.9	<0.01	<0.01
beet sugar, white	>99.9	<0.01	<0.01
brown sugar	90–96	2.5	3–6
golden syrup	32	23–25	22–24
crystalline fructose			<99
palm (date) sugar	72–78	4–5	4–5
molasses			
treacle	32–36	18.22	16–18
fancy, hi-test	22–27	23–28	25–30
medium invert syrup	38–43	28–30	30–32
glucose syrup		20–95	
high fructose syrup (isoglucose)		55–43	42–55
maltose syrup (35% maltose)	4–5		4–5

[a] Dry basis.

Among chemical properties of cane sugar that affect daily use are color, flavor, sweetness, antioxidant properties, and reactions in aqueous solution (3). The purity of cane sugar is generally assessed by its color; lowest color sugars are highest purity sucrose with the lowest content of color and flavor molecules, and other organic and inorganic components. Table 5 shows composition of cane sugar, beet sugar (qv), and other cane sugar products. Brown sugars and golden syrup are generally made from cane sugar, for reasons of flavor.

Sucrose, traditionally cane sugar, is the standard for sweetness, and other sweeteners are ranked against sucrose as 100%, as listed in Table 6 (3). Reactions of cane sugar in aqueous solution are important both in manufacturing (process is almost entirely in solution) and in use as a food and in food processing (qv). Hydrolysis of sucrose, called inversion, forms an equimolar mixture of glucose and fructose, called invert sugar or invert, because of the change in the polarimetric measurement, or inversion from positive to negative, upon hydrolysis. Hydrolysis is the initial step for most reactions of cane sugar in food chemistry. It is depicted in Figure 2 (3). It occurs up to about pH 8; above that, nucleophilic displacement of a proton is the initial reaction in sucrose decomposition. Reactions after initial hydrolysis (inversion) include the following. (*1*) Reactions in acidic medium which lead to formation of 5-hydroxymethyl furfural (HMF). HMF rapidly decomposes into dark-colored compounds, with off-flavors (2, 3, 8). (*2*) Reactions in alkaline medium, including lactic acid formation by chemical means (rather than by fermentation), and the rearrangement of glucose to a mixture of mannose and fructose, which is often responsible for the reported presence of fructose and mannose in products that in actuality contain only glucose. An alkaline environment present during extraction or hydrolysis procedures

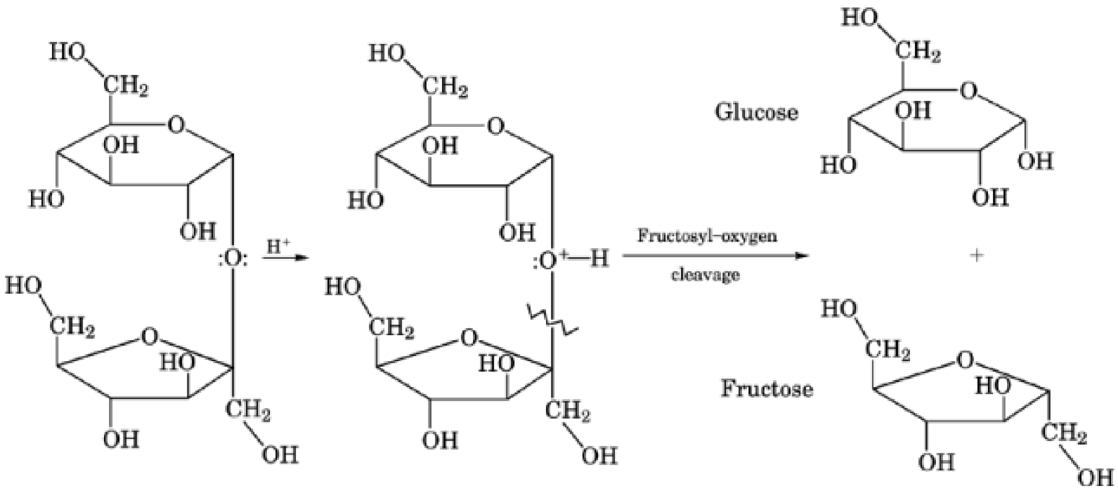

Fig. 2. Inversion of sucrose into glucose and fructose.

can cause the transformation of glucose to a mixture of mannose and fructose by this mechanism (2, 3, 8). (*3*) Maillard reactions, ie, the reaction of a reducing sugar with an α-amino group to form a condensation product that can subsequently polymerize into dark-colored compounds. This is the basis of the browning reaction observed during baking and cooking processes. Several alternative pathways of color, or melanoidin, formation are possible after the initial Maillard reaction (2, 3). (*4*) Thermal degradation of sucrose and caramel formation. The thermal decomposition of solid sucrose may be the exception to the rule that the common decomposition-related reactions occur in water solution; however, moisture absorption by sucrose as it is heated can account for some thermal degradation along pathways of solution reactions. Multiple reactions, some anhydrous, some involving water, are involved in the formation of the complex mixture known as caramel (2, 3).

Color of cane sugar depends on its nonsucrose content; sucrose, glucose, and fructose are white crystalline materials. Colorant compounds are in two classes: one from the cane plant, including flavonoid and polyphenolic compounds, and one from process-developed colorant, based on sucrose degradation products. These degradation reactions occur in aqueous solution, in process, and in a relatively slow manner in the syrup layer surrounding the sugar crystal. Reactions in solution, included in those described above, that are responsible for color formation include thermal degradation of sugars, with condensation at low pH and caramel formation; alkaline degradation of fructose, with subsequent condensation; and Maillard reactions with primary amines and subsequent melanoidin formation. Many of the colorant compounds are also responsible for the caramel, butterscotch, and toasty flavors of brown cane sugar.

2.1. Structure of the Sucrose Molecule

The structure of the sucrose molecule, β-D-fructofuranosyl- α-D-glucopyranoside, in its crystalline state and in aqueous solution has been studied by many groups. The crystalline conformation can be represented as shown in Figure 3, although the inter- and intramolecular hydrogen bonding is still under debate (2). Solution conformations, as measured by nmr and optical spectroscopic methods, are known to be multiple, to interact with water structure, and to be the result of hydrogen bonding and van der Waals forces, but although several structures and theories are each supported by some physical findings, there is no single consistent explanation (2).

Table 6. Sweetness and Flavor of Selected Carbohydrates in Solution

Carbohydrate	Sweetness[a]	Flavor character
Monosaccharides		
glucose	61, 70	sweet, bitter side taste
fructose	130–180	pure sweet, fruity
Disaccharides		
sucrose	100	pure sweet
maltose (malt sugar, maltobiose)	43, 50	sweet, syrupy
lactose (milk sugar)	40, 26, 15–30	faint sweet, fruity
palatinose (isomaltulose, lylose)	50	pure sweet, masks bitter
leucrose (glucose-1,5-fructose)	50	pure sweet
Polyols (sugar alcohols, hydrogenated sugars)		
xylitol	100, 85–120	sweet, cooling
sorbitol (hydrogenated glucose) syrupy	50, 63, 70	sweet, cooling
maltitol (hydrogenated maltose)	68	sweet
mannitol	40, 65	sweet
lactitol (hydrogenated lactose)	30–40	clean, sweet
Mixtures and syrups		
lycasin 80/55 (hydrogenated glucose syrup)	75	sweet
palatinit (Isomalt; 1:1 mix of $\text{glu} - \text{sorbital} + \text{glu} - \text{mannitol}$)	45	pure sweet
high fructose corn syrup (HFCS)	100–160	sweet
invert syrup	105	sweet
maltodextrin ($\text{DE} < 20$)	0+	bland to faintly sweet
neosugar (fructo-oligosaccharides)	46–60	sweet

[a] Relative to sucrose.

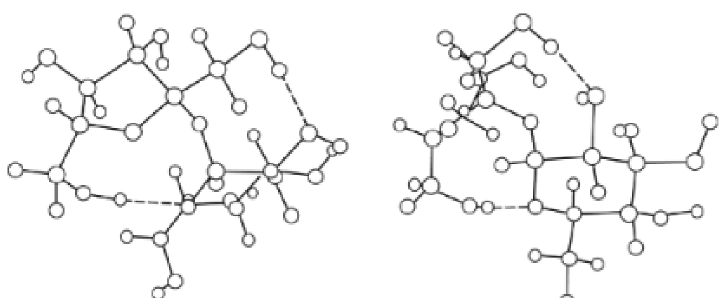

Fig. 3. Representations of sucrose in its crystalline conformation; intramolecular hydrogen bonds are shown as dashed lines.

Cane sugar is metabolized rapidly, after initial enzyme hydrolysis to glucose and fructose. As a carbohydrate, it yields 16.5 kJ/g (3.94 kcal/g).

3. Cultivation, Harvesting, and Processing of Sugarcane

Cane sugar production is accomplished in one or two stages. At sugarcane factories, located in cane-growing areas, harvested sugarcane is brought in, sugar-containing juice is extracted, and sugar crystallized from the concentrated juice. In the single-stage process, the juice is purified and bleached for the manufacture of plantation white (mill white, direct white) sugar, usually for local consumption. In the two-stage process, partially purified, unbleached juice is crystallized into yellow to brown-colored raw sugar; this is shipped in bulk to the countries of principal cane sugar consumption in North America and northern Europe, where it is refined into white and colored products for industrial and home use. Sugarcane, once cut (harvested), immediately begins to lose sucrose to deterioration by enzyme, or chemical inversion. The two-stage production system arose because sugarcane cannot be stored. Plantation white sugar, while quite suitable for use within a few weeks after manufacture, cannot be stored for long periods (ie, shipping times) because it contains more water and invert than does refined sugar, and discolors and becomes hardened and lumpy. There is a trend since the late 1970s to increased refining capacity at factories, near the cane production areas, because (*1*) energy costs are low and sugarcane residual fiber (bagasse) is burned as fuel in the factory; and (*2*) an increase in consumption is most rapid in the tropical and semitropical countries, especially in processed foods and drinks. As disposable income rises, sweet foods and carbonated beverages are among the first products to show an increase in market strength.

3.1. Cultivation

Sugarcane variety breeding programs are essential for production, from seed crossings and vegetative reproduction, of healthy new varieties with appropriate disease resistance, weather tolerance, and high sugar content, along with agronomic characteristics for each area. The great variation in geography and weather among areas has led to many different varieties and programs. The short growing season in Louisiana has led to development of cold-tolerant varieties, whereas plans for cogeneration of electricity from incineration of bagasse in Florida have placed emphasis on development of high fiber varieties.

Sugarcane requires at least 60 cm moisture each year, whether from rainfall or irrigation. It is propagated vegetatively, from cuttings; each cutting of seed cane must contain at least one bud. Pollinated sugarcane does not breed true because of somaclonal variation (cane is a polyploid hybrid). Most of the world's cane is planted by hand, and some 60% is still harvested by hand in the tropics where labor is low cost and high agricultural employment levels are government policy.

3.2. Diseases and Pests

Sugarcane is subject to a number of bacterial, fungal, and viral diseases, in part because sucrose is such a desirable substrate. At any one time in any given location, there are usually three or four prevalent diseases of concern. The severity of infestations increases and decreases in various parts of the world depending on the varieties grown and control measures. The most recent diseases to appear in the Western Hemisphere are smut, caused by the fungus *Ustilago scitaminea* Sydow, which arrived in the United States (Florida) in 1978, and rust, caused by the fungus *Puccinia melanocephala* H. & P. Sydow, which arrived in 1979. Other important diseases include sugarcane mosaic, a viral disease which caused severe losses throughout the world in the earlier part of the century, and ratoon stunting disease, caused by the bacterium *Clavibacterium xyli*.

Pests include rats, a severe problem in some areas, wild animals, nematodes, and a number of insects. The most severe insect pests are the various types of borers, ie, the sugarcane borer, *Diatrea saccharalis* (F.) and the eldana borer, *Eldana saccharina*, which cause damage first by boring into the cane stalk, then by providing entry points for other diseases, and finally by reducing cane and juice quality.

Weeds cause problems in sugarcane culture by competing for nutrients and crowding or overgrowing the young plants. Perennial grasses are the most serious weeds, harboring insects and diseases. Preemergent herbicides are commonly used for control.

Chemical treatment of diseases is not common, because of legislative controls and costs caused by the difficulty of application through the leaf canopy. Breeding of resistant varieties is the main weapon for disease control. Some diseases, chiefly ratoon stunting disease, are controlled by hot water treatment of cane (6, 8).

Sugarcane is the most efficient collector of solar energy in the plant kingdom, converting 2% of available solar energy into chemical bonds of stored compounds, chief among them sucrose (3). Yield in metric tons of cane per hectare varies from 55–60 t in poor growing areas to more than 200 t for cane grown for 18–24 months in optimum areas, eg, Hawaii. The quantity of sugar produced per hectare varies from ca 5.0 (Ethiopia) to ca 26.0 (Campos, Brazil). Sugar recovery averages 10–12% on cane (6).

Harvest season is generally during the cooler, drier part of the year, varying from three months (October–December) in Louisiana, to the first half of the year in most Northern Hemisphere tropics and the second half in most Southern Hemisphere tropics, to year-round in Hawaii, Colombia, and Peru. Generally, replanting is not necessary after each harvest; buds on the plant base and roots remaining sprout again to produce another crop, called ratoon or stubble; this ratooning is repeated until the yearly decline in yield (successive ratoons yield lower cane tonnage) is no longer economical. Ratoon crops vary from none in Hawaii, where pushrake harvesters can harvest roots with the stalks, to eight to ten in optimum regions; two to six ratoon crops are customary. The use of chemical ripeners, or senescence enhancers, to speed up maturation and increase sugar content of cane, is becoming widespread, but requires careful time control.

3.3. Harvesting

In hand cutting practice, cane knives range from long machetes to shorter-handled Australian and Brazilian knives with hand guards. Cane leaves and tops (known as trash), which contain little sugar, add weight to transport, hinder cane cutters, and wear down mill rolls, are removed first by burning the cane field and then by hand or mechanical harvesters. Cane stalks are sufficiently high in moisture so that controlled and rapid burns (fire in a 50-ha field is complete in 3 min) incinerate only the leaves, tops, and trash. In Australia, Hawaii, and the Dominican Republic, cane is harvested without burning, to provide more fiber as fuel (for electricity cogeneration at the factory) and for environmental protection. A trash blanket is left on the field to encourage regrowth and discourage disease and pests. The harvesting of green cane is becoming more widespread, for environmental reasons, and as mechanical harvesting progresses. Important factors in cutting are to produce clean, undamaged cane, free of trash, and to leave viable root stock in the field. Mechanical harvesting is found in Australia, the United States, some Caribbean and Latin America countries, and new developing cane areas in Southeast Asia, and is gradually being introduced almost everywhere. Most common are combine harvesters, or chopper harvesters, developed in Australia, which cut cane stalks at the base, cut the stalk into billets, 28–38 cm long, blow excess leaves and trash off the billets, and drop the billets into a cane cart pulled alongside the combine harvester. In Louisiana, or where tonnage is light, soldier harvesters cut and top erect cane, leaving rows of whole stalks in the field, which are burned after harvest because the canopy is too light to support a burn on standing cane. Other whole-stalk harvesters in Hawaii, where cane tonnage is heaviest, are the V-cutter, which cuts cane at base but not at top, and the push-rake, used on hilly areas, which pushes cane, including the roots, out of the ground, necessitating replanting. Under good conditions, 0.5 t of cane per hour can be cut by hand and 30 t/h of cane by a combine harvester, with other mechanical systems between 15 and 30 t/h. Mechanical cutting is generally more expensive than hand cutting and yields lower quality, more damaged cane, but is increasing for sociological reasons.

3.4. Transportation

Cane loading in the field is accomplished by hand, grab loaders, or continuous belt loaders, into small bins or wagons, which collect at transloader stations for transfer to larger transport containers. In some areas, eg, India, Pakistan, Southeast Asia, and Africa, cane is still transported in small bullock carts. Transport by rail, the cheapest method, continues to be used in Australia and the Philippines; by water, in China, Southeast Asia, and Guyana; and by road, elsewhere. Chopper-harvested cane must be shipped directly to the mill and be processed on arrival, not stored in the millyard, to prevent serious deterioration and loss of sugar; delivery time of less than 24 h is recommended. Harvesting and shipping schedules are decided between grower and processor to ensure a constant supply of cane for the mill, and a fair distribution of maturity and quality.

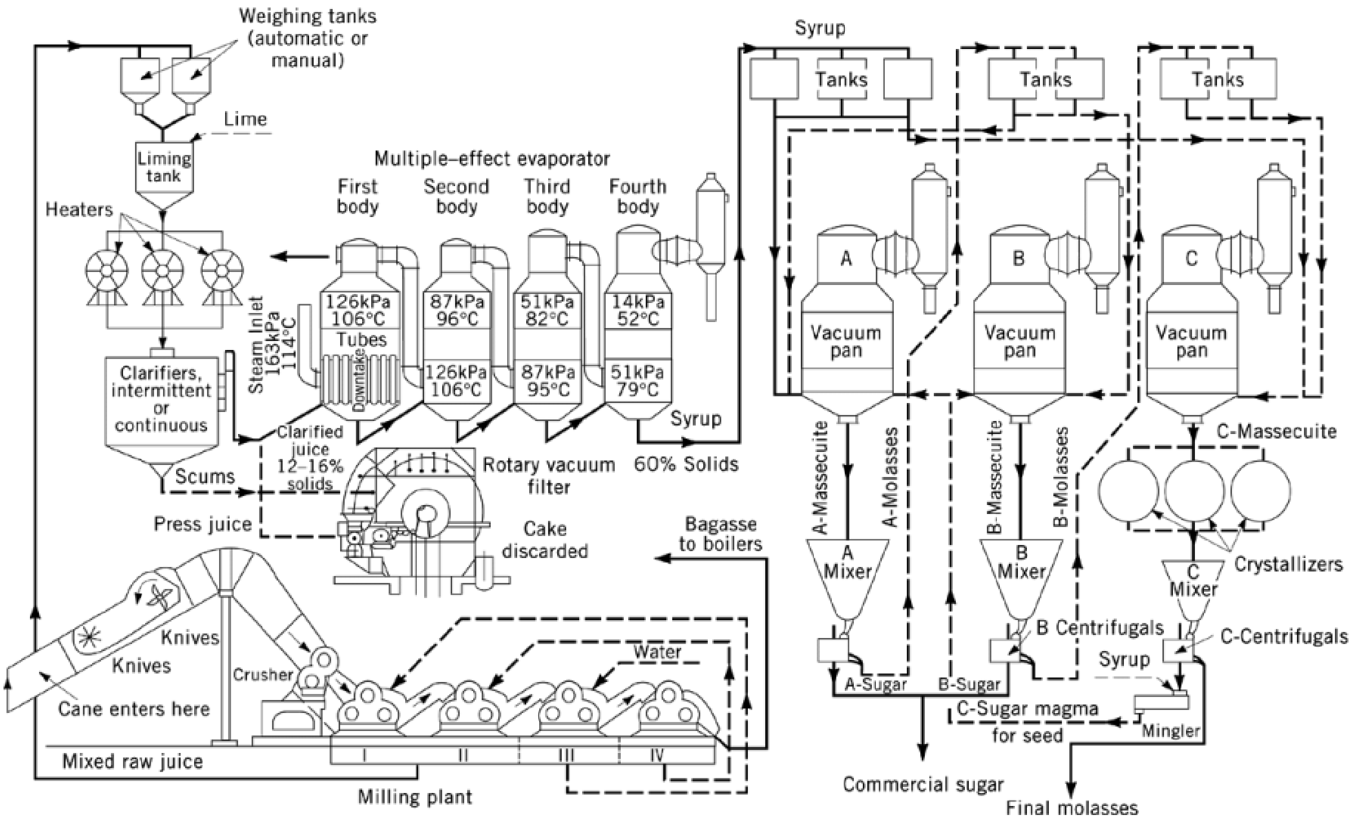

Fig. 4. Flow diagram of a raw sugar factory. To convert kPa to psia, multiply by 0.145.

Cane is usually sampled at the factory gate for payment. Cane payment is generally based on weight, with a deduction for trash, and on sugar content, measured by polarimetric measurement of juice. Where payment for cane quality, ie, weight, sucrose content, fiber, or sugar yield, has been introduced, eg, in the United States, South Africa, Australia, Brazil, Colombia, and the Philippines, the quality and efficiency of the industry have greatly improved (9). The usual split of revenue from sugar is 60–70% to the grower and 30–40% of value to the factory or processor.

3.5. Processing

Sugarcane processing to raw cane sugar is outlined in Figure 4, with equipment and concentrations labeled. Because cane deterioration is a direct function of time delay between harvest and milling, cane is stored in as small amounts and as short a time as possible in the mill yard. Factories run around the clock in most countries, closing for weekends in areas with long seasons or strong labor unions, but cane delivery is usually limited to daylight hours. All factories stop for cleaning of evaporators (unless a spare set is available) and other equipment, every 8–20 days.

After weighing, in very muddy areas sugarcane is washed on the cane table before entering the mill, eg, in Hawaii, Louisiana, and some Central American countries. Cane is then cut into chips by one or two sets of revolving knives, and nowadays often further broken up by a shredder. Shredded cane then moves through a series of mills, usually four to seven mills with four rolls each. Mills were originally three rolls, but a fourth,

Table 7. Composition of Sugars

Component	Raw cane sugar	White refined cane sugar	Mill white	Blanco Directo	Brown cane sugars
sucrose, %	96–99	99.3	99.6	99.9	92.96
glucose, %	0.2–0.3	0.007	0.07	0.02	1–2
fructose, %	0.2–0.3	0.006	0.06	0.03	2–3
color, ICU	900–8,000	35	100–200	40–80	2000–9000
ash, %	0.3–0.6	0.012	0.15	0.05	1–2
moisture, %	0.3–0.7	0.015	0.15	0.03	1–2
organic non-sugars, %	0.3–0.8	0.014	0.40	0.03	1–2
SO_2, mg/kg			20–50	1–5	

pressure-feed roll is now usual. Imbibition water, or water of maceration, is run countercurrent to the cane, from the last mills back, to increase extraction of sugar from fiber. Juices from the first mill, ie, the crusher, and other mills are combined, and the mixed juice is pumped to the heaters and to the clarification station. Bagasse comes off the mills at about 50% moisture and goes directly to factory boilers as fuel. To heated (98–105°C) juice is added lime (milk of lime, usually in sugar solution) to pH 7, and flocculation aids, usually polyacrylamides. Cold liming is also employed. Solids are allowed to settle out of juice in juice clarifiers, large settling tanks, with various arrangements of baffles. Heat and lime stop enzyme action in juice and raise pH to minimize inversion. Control of pH is important throughout sugar manufacture because sucrose inverts, or hydrolyzes, to its components, glucose and fructose, at acid pH <7, and all three sugars decompose quickly at high pH (>11.5). Clear juice flows off the upper part of the clarifier; muds are withdrawn below. The settling separation is known as defecation. Muds are pumped to rotary vacuum filters, and residual sucrose is washed out with water spray on the rotating filter. Clear (clarified) juice is pumped to a series of multiple-effect evaporators (4, 6, 7), where steam from one effect heats the next effect. Nonsugars deposit on the walls and tubes of the evaporator, creating scale and reducing heat transfer; it is removal (boiling out) of this scale that most often causes a routine shutdown of factory operation. Mixed juice (11–16% sucrose) yields clarified juice of 10–15% sucrose, which is concentrated to evaporator syrup of 55–59% sucrose and 60–65 Brix (wt % total solids). Evaporator syrup is sent to vacuum pans, where syrup is heated, under vacuum, to supersaturation: fine seed crystals are added, and the sugar mother liquor yields about 50% by weight crystalline sugar. This is a serial process. The first crystallization of A-sugar or A-strike yields a residual mother liquor (A-molasses) that is concentrated to yield a B-strike. Many schemes of blending and cutting various streams have been developed, leading to open crystallizers stirring lowest grade massecuite (a mixture of crystals and mother liquor) to yield C-sugar and final molasses (blackstrap) from which no more sugar can economically be removed (6, 8).

Continuous vacuum pans have been successfully developed for raw sugar crystallization, and are widely applied in South Africa, Australia, South America, and the United States. Continuous crystallizers, developed for beet sugar manufacture, are being adapted for use in cane sugar factories.

After crystallization, crystals and mother liquor are separated in basket-type centrifuges; continuous machines are used for C- and sometimes B-sugars, but batch machines are still best for A-sugars because of crystal breakage in continuous machines. Mother liquor is spun off the crystals, and a fine jet of water is sprayed on the wall of sugar against the centrifugal basket to reduce the syrup coating on each crystal. Raw sugar is dumped onto moving belts, on which it dries as it is moved to storage. In modern factories, washing is increasingly extensive to produce high pol raws, a development of the 1970s that changed the raw sugar market by tailoring a raw material for refineries. Composition of raw cane sugar is shown in Table 7. This is the raw sugar traded on the futures market.

A cane factory generates its own requirements for energy, from burning bagasse to produce electricity; one tonne of mill run bagasse (50% moisture) is equivalent in fuel value, at 3,700 kJ/kg (884 kcal/kg), to one barrel (159 L) of fuel oil. An efficient raw sugar or plantation white factory will use 70–80% of the bagasse available from its cane, and the remainder can be used for cogeneration of electricity for sale to the local grid, as in Hawaii, Mauritius, and elsewhere. The excess power can be used to run a distillery or to run a year-round refinery to refine raw sugar products from a group of raw sugar factories. This is an increasingly frequent occurrence in Australia, the Far East, and Central and South America, and is developing in Florida.

3.6. Diffusion

The alternative to extraction by milling is extraction by diffusion. The sugarcane diffusion process has been developed from sugarbeet diffusion. Here, cane from the shredder must be prepared further in a fiberizer, or extended shredder, for best extraction. Because of this finer preparation, diffusion gives a higher degree of extraction (93–98%) than milling (85–95%); therefore, further cane preparation is increasingly used in mill trains also. Finely prepared cane enters a multicell, countercurrent diffuser of linear, diagonal, or circular design. In the diffusers, shredded cane moves countercurrent to hot water (75°C). This system is for cane diffusion. There are various combinations of sets of mills with a diffuser, for diffusion of partially milled cane; these systems are called bagasse diffusers. Bagasse emerging from the diffuser must be dewatered to reach the approximately 50% moisture of mill-run bagasse; at this moisture bagasse can be fed as fuel to factory boilers. Diffusers tend to be cheaper than mills with a lower energy requirement, but do not handle poor cane and high trash and mud well and are subject to infection.

3.7. Direct Consumption Sugar

This sugar (plantation white, mill white, crystal, superior) is the regular table and industrial product in most cane-growing countries outside the United States. This white but not sparkling white crystalline cane sugar product is produced from sugarcane juice by the raw sugar production process (see Fig. 4), with the addition of sulfur dioxide gas, SO_2, generally produced by burning sulfur in air. The SO_2 is injected into juice where it bleaches colorant (by reduction process, or formation of sulfite addition compounds) and is itself oxidized to sulfate. Sulfate reacts with dissolved lime to form calcium sulfate, which precipitates as scale in evaporators and pans. Sulfitation factories operate at rather lower pH than raw cane-sugar factories, and so suffer higher losses. Sulfate is a major anion in sulfitation sugars, often equaling or exceeding chloride in content. Nonsugar components are not removed in process; they are at the same levels as in raw sugar, but the color is bleached.

Sulfitation sugar, the most common type of white sugar in the world, is therefore not suitable for industrial use or food and beverage manufacturers because it contains high ash, turbidity, and reducing sugars, and generally has a high sediment content. Higher grades of plantation white are made through addition of a carbonatation plant, where lime and CO_2 gas are reacted in the juice to form calcium carbonate, entrapping many nonsugar molecules during formation of the chalk crystals. Calcium carbonate is filtered off, entrapping more nonsugars, especially color, in the filter bed. By removing nonsugars from the stream and not recycling them, the carbonatation process improves the quality of the sugar. This process, with many variations, is common in India, Pakistan, China and Southeast Asia, and is discussed thoroughly in older literature (6, 7). Powdered carbon treatment, before press filtration, is another additional process to improve quality and lower color. As demand for higher quality (refined quality) sugars increases in the cane-growing countries, there is increasing production of "improved" plantation white sugar. The best direct production sugars are made by the Blanco Directo process, where color precipitating reagents are used, again to remove nonsugars rather than bleach them. Blanco Directo entails syrup clarification and clarification of muds filtrate by phosphatation processes similar to those described.

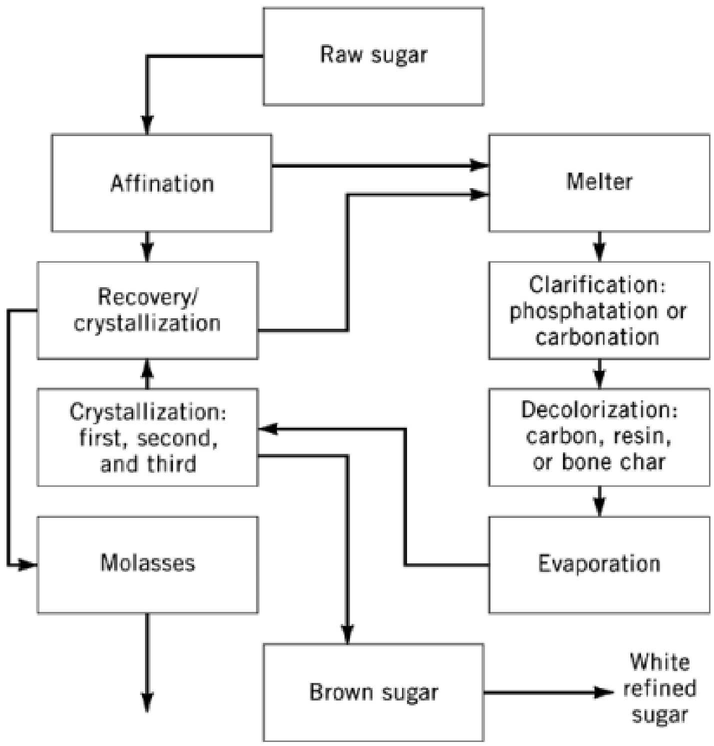

Fig. 5. Outline of a cane sugar refinery process.

4. Cane Sugar Refining

Refining cane sugar processes raw cane sugar into very high purity white and brown sugars and liquid products, including edible molasses. Content of water, ash, and reducing sugars is controlled. Products are of consistent quality and safe for home consumption and for the food and beverage industry. Refined products can be stored well for long periods; white refined sugars stored at ambient conditions for over 60 years show a slight increase in color as the only change. Traditionally, refineries have large packaging departments for their full range of products. The new white-end refineries, or a raw sugar factory or group of factories, tend to produce bulk white sugar only. These refineries have the cost benefit of returning their low grade material to a factory, rather than having to process it.

Refinery input (melt) is raw cane sugar at 96° to 98°Z polarization (% sucrose read by rotation of polarized light). The brown products have characteristic palatable cane and cane molasses flavors, not available from sugarbeet. A generalized refining scheme is shown in Figure 5. Details of unit processes are shown in Figure 4. Refineries are large processing plants operating around the clock typically for five (weekend shutdown) or 10 days (four-day shutdown). Fuel for freestanding refineries is fuel oil, natural gas, or coal, according to local availability; a few refineries have extended their power plants to generate extra electricity for the local grid; refineries attached to raw sugar factories use the factory's excess bagasse fuel.

The quality of incoming raw sugar is paramount for efficient operation. Polarization is a universal quality criterion. Color, ash (inorganic), invert sugar, moisture, dextran content, and grain size are other criteria that may be included in raw sugar purchase contracts.

Raw sugar is weighed into the refinery from rail car, ship, or raw sugar warehouse, and conveyed to the affination station, where it is mingled with a heavy syrup (80% solids content, or 80° Bx where Bx = Brix, wt %), then spun in basket centrifugals and washed with a spray of water to remove the added and the integral syrup coatings. The washed raw sugar is dissolved (melted) to give a washed sugar liquor of ca 70% solids content, which is pumped to clarification. Three types of clarification are in use.

4.1. Phosphatation

Phosphoric acid to give a concentration up to 400 mg/kg as P_2O_5 and calcium hydroxide as milk of lime or sugar solution of lime, up to pH 7.5–8.3, are combined with the sugar liquor in an aerated flotation clarifier. Calcium phosphate forms, occluding suspended solids and inorganics in its mass, and floats to the surface where it is scraped off by rotating blades. Clarified liquor (syrups are called liquors in refineries) is pumped out from the bottom of the clarifier. The process removes 25–40% color, ash, and turbidity from the sugar liquor (10).

4.1.1. Talo Phosphatation

Phosphatation is performed as described above with the addition of color-precipitating chemicals and a series of mud-desweetening steps, which remove a greater amount of color (30–50%), ash, and turbidity. Talo (a trademark of Tate & Lyle, plc, U.K.) phosphatation is the process mentioned above that is widely used in white end refineries. It has almost replaced traditional phosphatation (11).

4.2. Carbonatation

In this process, called carbonation in Europe, lime and carbon dioxide are mixed in liquor in a two-stage process similar to that for beet sugar processing but carried out on liquor of 65–70% solids (10).

4.3. Filtration

Any type of clarification is followed by filtration through leaf-type vertical or horizontal pressure filters. Carbonatated liquors, containing calcium carbonate, may require addition of diatomaceous earth as a filter precoat. Phosphatated liquors are generally filtered with the addition of diatomaceous earth as precoat and body feed.

4.4. Decolorization

Filtration, often a refinery bottleneck, especially with poor-quality raw sugar, is followed by decolorization with bone char (traditional), granular activated carbon (now most common), ion-exchange resins, or any combination of these. Comparative merits and regeneration of these decolorizing systems are a frequent topic in the literature (r6–r8,r11).

4.5. Crystallization

Decolorized liquor, or fine liquor of very pale yellow color, is evaporated further to 72–74% solids and sent to crystallization in a series of vacuum pans, as with raw cane sugar. Refinery strikes are designated 1, 2, 3, etc. Four to six white sugar strikes are common. The lowest grade runoff syrups are sent to a second series of pans and crystallized to improve sugar recovery in a process called remelt in the United States or recovery in the U.K. Brown low grade runoff syrups and refiners' final molasses are sold for food processing, brewing, and blending to make cane syrups and edible molasses.

Refined brown sugars, called soft sugars in the trade, are made by crystallizing sugar from a mixture of third and fourth runoff syrups and affination syrup (boiled brown sugars), or by coating white sugar crystals with a brown sugar liquor–caramel syrup (painted or coated brown sugar). Compositions of raw cane sugar, refined granulated, direct mill white, and Blanco Directo sugar are shown in Table 7. The white sugar from the centrifuges is dried in a rotary dryer using hot air. This dryer is universally misnamed the granulator because by drying in motion, it keeps the sugar crystals from sticking together, or keeps them granular. The hot sugar from the granulator is cooled in a similar rotary drum using cold air. Newest driers and coolers employ a fluidized-bed system (11).

4.6. Conditioning

After storage, sugar can become moist from water that has been trapped under the outside syrup coating of the crystal by the very high rate of crystallization and drying. After a few days, this moisture migrates outside the crystal and the sugar is wet again. This water can dissolve sugar in neighboring crystals and set up a hard cake of sugar. The moisture is removed by a process known as conditioning, in which the sugar is stored for about four days with a current of air passing through it to carry away the moisture. In one of many variants, a single silo is used with sugar being continuously added to the top and removed from the bottom, and a current of dry air blowing upward. In another system, the sugar is stored in a number of small bins. It is continuously transferred from bin to bin with dry air blowing around the conveyors that move the sugar.

4.7. Packing, Storing, and Shipping

Some refineries store bulk sugar and then package as needed, but more package the sugar and then warehouse the packages. The present trend is away from consumer-sized ($<50-\mathrm{kg}$) packages and toward bulk shipments. There are various resale companies that buy bulk sugar and package it in small packages, or individual servings, for consumer distribution. Some refineries use their extensive packaging facilities to package other food products that require the same equipment.

4.8. Membrane Filtration Processes

Newest among cane sugar manufacturing systems are processes using membrane filtration to remove non-sucrose solids from juices and syrups. The low energy requirements, reduced effluent, and flexibility of throughput from these processes are the factors providing the impetus expected to result in viable membrane filtration factories by around the year 2005. There are two basic classes of membrane: plastic types with metal ions in the matrix, and ceramic types with a porous layer (stainless steel is a variation on ceramic), all with controlled porosity. The use of the plastic membranes, in combination with carbon-type adsorbent, to make white sugar directly from cane juice, without any sulfitation or other bleaching, has been reported (12). Ceramic membranes have been in use since 1993 in raw sugar manufacture in Hawaii (13) to make a very high quality raw sugar and a molasses that can be treated with ion-exclusion desugarization, described herein. Trials on all processes are being run throughout the sugarcane world.

4.9. Molasses Desugarization

The process of separating sucrose from final molasses by ion exclusion is common in beet sugar manufacture. Sugarbeet molasses contain about 50% sucrose on solids and only 1–2% invert; whereas sugarcane molasses contains 20–30% sucrose on solids and 15–25% invert. Separation of invert from the sucrose product fraction is expensive. It appears uneconomical to use this system to separate sucrose from cane molasses unless an invert syrup product fraction is also produced. This may be a salable product in cane-producing countries; it is not in the United States, where cheaper corn syrups have replaced liquid cane sugar and beet sugar products.

Table 8. Cane Sugar[a] Production, World and Selected Countries[b], 10^3 t

	Years	
Area	1994–1995[c]	1992–1993[c]
world	80,614 (69.4)	70,445 (61.5)
United States	4,130	3,980
Central America and Caribbean	11,491	12,072
South America	18,002	15,067
Australia	5,215	4,365
South Africa	1,780	1,600
People's Republic of China	4,710	6,827
India	15,850	11,525
the Philippines	1,650	2,130
Thailand	5,510	3,790

[a] Centrifugal raw value (96 pol).
[b] Ref. 14.
[c] Figures in parentheses represent percent of total cane and beet sugar production.

5. Economic Aspects

In sugarcane-growing countries, including the United States, a price or range is set by the government on raw sugar, and often also on cane and white sugar, to ensure a sufficient degree of domestic production. In many tropical countries, sugarcane cultivation and cane sugar production are principal sources of employment. Sugar produced for export is generally sold on long-term contracts, as with those for raw sugar to the United States. Sugar produced over domestic and contractual requirements is sold on the world market. Futures prices are listed on the U.S. and European futures exchanges for raw and white sugars classified by the various contractual specifications. Somewhat less than 10% of world production of cane and beet sugars ever reaches the world market; world market price is not relevant for national costs which are based on production. Production costs for cane sugar and beet sugar in the United States are published annually (1). Other producer countries' cost figures are not so readily available.

Increase in production of high quality white sugar in the tropics (white end refineries) has decreased the export of refined white sugars from Europe and sometimes from the United States. Total world production, and production in the United States and several other principal producer countries are given in Table 8. Consumption figures are listed in Table 9. All figures are given, as is traditional, in equivalent of 96 pol raw sugar value, where pol represents "polarization" or "degrees pol," a measure for sucrose (ie, 96% sucrose, or 96 g sucrose per 100 g product).

5.1. Noncentrifugal Sugar

In South and Central America, and in Asia, particularly India and Pakistan, there is considerable production of noncentrifugal cane sugar. Cane juice is simply boiled down in open vessels at atmospheric pressure until it begins to crystallize, and then scooped into molds, usually wooden, where it hardens into cakes, cones, or whatever shape of mold has been chosen. This product is dark brown and contains all plant parts, soils, microorganisms, and solids that were in the cane juice. The product is a standard component of the daily diet for the low income populations where it is produced. The hard light to dark brown cakes are known as panela in South America, piloncillo in Mexico, panocha or pile in other Latin countries, gur or jaggery in the Indian subcontinent, and pingbian tong in China. Some $12 - 13 \times 10^6$ t of noncentrifugal sugar are produced each year, with India, at about 9×10^6 t, the primary producer. Colombia produces almost 10^6 t and Pakistan about 0.5×10^6 t. Because this sugar is produced from cane that could be sent to regular factories, there is some

Table 9. Consumption of Sugar in Selected Countries[a,b]

Area	Total, 10^3 t	Per capita, kg
Europe (>90% beet)	31, 500	36.6
Great Britain (50% cane)	2, 510	43.0
North America	9, 680	33.4
Canada (90% cane)	1, 230	42.2
United States (55% cane)	8, 450	32.4
Central America	7, 496	47.1
Cuba	850	77.6
Haiti	85	12.1
South America (95% cane)	13, 217	42.1
Brazil	7, 750	48.7
Bolivia	186	25.7
Asia	40, 741	12.5
China (85% cane)	8, 516	7.0
India	13, 300	14.5
Singapore	152	53.9
Africa	9, 616	13.5
Egypt	1, 710	27.7
Ghana	92	5.4
South Africa	1, 430	35.3
Australia	900	50.4
world (65% cane)	113, 500	20.1

[a] Ref. 14.
[b] Data are for 1994. All figures are on a 96 pol basis. Unless otherwise noted, sugar is assumed to be cane in origin, although imported beet may be included in Africa and Asia.

variability in production depending on the relative prices paid for cane by centrifugal and noncentrifugal sugar manufacturers.

5.2. Impact of HFCS

The U.S. sugar market changed dramatically in the late 1970s and early 1980s, with the introduction of high fructose corn syrup (HFCS). This liquid product is made from enzymatic hydrolysis of corn starch and processed, with chemical and enzymatic processes, to a range of low color liquid mixtures of fructose and glucose with sweetness equivalent to, or greater than, sucrose (see Sugar, properties of sucrose). Because of other products from corn (by-product credits for major products of corn oil, gluten feed, and gluten meal), corn sweetener can be produced at a very cheap price (15). In the United States, some 3.5×10^6 t/yr of cane (and some beet) sugar were replaced by corn syrups; replacement was in beverages, canned goods, and other food products that could use a liquid sweetener. Almost all carbonated soft drinks in the United States have been made with corn syrups, not sugar, since the early 1980s. Because of this substitution, effects on sweetener markets by nonnutritive sweeteners have had little effect on the sugar market in the United States. However, nonnutritive sweeteners have seriously affected the sugar market in Europe.

6. Specifications and Standards

Specifications for raw cane sugar are set by purchase contracts. There are no international specifications, although the *Codex Alimentarius* is composing a draft specification. Because raw sugar is not sold as a food

Table 10. Quality Criteria for White Sugar, According to EC Sugar Market Regulations[a]

	Grade[b]		
Quality criterion[c]	1	2	3
sucrose content (polarization), °Z		99.7	99.7
moisture content, %	0.06	0.06	0.06
invert sugar content, %	0.04	0.04	0.04
color type, Brunswick unit points[d]	2	4.5	6
	4	9	12
ash content as conductivity, $ points[e]	0.0108	0.0270	
	6	15	
color of solution, ICU points[f]	22.5	45	
	3	6	
points according to EC point system	8	22	

[a] Ref. 16.
[b] Grade 2 is white sugar of standard quality.
[c] Quality criteria for all grades: sound, fair and marketable quality, dry, inhomogeneous granulated crystals, or free-flowing. All values are maximum except for sucrose content, which are minimum.
[d] Where 0.5 unit = 1 point.
[e] Where 0.0018% = 1 point.
[f] Where 7.5 units = 1 point.

product in the United States (it is transported in bulk, like grain or coal), it is not subject to food regulations. Purchase contracts outside the United States are generally based only on pol; U.S. contracts are discussed in the literature (6).

For white sugars, there are no U.S. specifications or standards; specifications are decided among buyers and sellers. There are bottler's specifications for white sugars (generally outside the United States, because little sugar is used within the country by bottlers). Most white sugar buyer specifications emphasize color and turbidity or sediment. There are also limits on reducing sugars, ash, and moisture (r2–r6,r8).

The European Union (EU) has a systematic classification of white sugars, shown in Table 10. *Codex Alimentarius* also has issued specifications for white sugars (17). The EU standards are widely used throughout Eastern Europe and Asia. Other countries, eg, Brazil and the People's Republic of China, have their own domestic specifications, which are also applied to imports.

7. Health and Safety Factors

Sugar is one of the purest foods made, from natural sources, and has never been known to contain any toxic or harmful components. Intensive investigations by the U.S. Food and Drug Administration resulted in a book in 1986 on the health and safety factors of sugar (cane and beet) in the diet (18). The conclusion was that sugar has no deleterious effect on health in regard to heart disease, diabetes, or other metabolic disorder.

Sugar can, the report concluded, be a cause of dental cavities; rinsing the mouth with water after consuming a sugar product reduces this risk considerably. Dental cavities appear to be the only disease for which sucrose could be a cause.

Microbiological standards for sugars are as follows: (*1*) Canners' standards: for flat sour spores, an average of not more than 50 spores/10 g, with a maximum of 75 spores/10 g; for thermophilic anaerobic spores, present in not more than 60% in five samples; and for sulfate spoilage bacteria, present in not more than 40% in five samples and in any one sample to the extent of not more than 5 spores/10 g. (*2*) Carbonated beverage standards:

not more than 200 mesophilic bacteria per 10 g, 10 yeast per 10 g, and 10 molds per 10 g. (*3*) “Bottler’s” liquid sugar standards: not more than 100 mesophilic bacteria per 10 g (dry sugar), 10 yeast per 10 g (dry sugar), and 10 molds per 10 g (dry sugar). The reduction of water activity in highly concentrated sugar solutions retards microbiological growth on such products as jams, preserves, and canned fruit.

8. Cane Sugar Products

There are many variations on crystalline cane sugar from refineries, in addition to the direct production and noncentrifugal sugars described above.

Refined granulated sugar is the principal output of a cane sugar refinery. The particle size of the refined granulated sugar for table use varies from region to region. Different particle sizes have different names and are not standardized. Particle size is specified by the buyer, usually at a price premium. North American fine granulated averages 0.2–0.3-mm grain size, whereas standard European fine granulated averages 0.5–0.6 mm. Sugar of standard U.S. crystal size is known as caster sugar in the United Kingdom. Sugar crystals are separated into four to eight size groups by a series of vibrating screens, after the driers in the refinery.

Large-grain specialty sugars are used for candy and cookies. White large-grain sugar can be made only from the very purest of liquors; therefore, customers interested in the best sugar specify coarse grain. The highest quality best sugar is made by redissolving large-grain sugar and recrystallizing.

Fine-grain sugar, or fruit sugar, used because it is quick-dissolving, consists of small crystals obtained by screening.

Powdered sugar is made by grinding granulated sugar and adding 3% corn starch (in the United States) to help prevent caking. The fineness is designated by labels such as 4X, 6X, 10X. However, the label is misleading; 12X is not twice as fine as 6X. In other countries, calcium phosphate, or maltodextrins are used as hygroscopic additives.

Cubes are made by mixing a syrup with granulated sugar to the right consistency to form cubes. These are then dried. The process is expensive and the price of cubes is high relative to ordinary granulated sugar. Production of the cube is much greater in Europe and the Middle East than in North America. Many variations on the cubing process exist, from cutting up slabs of solidified sugar (the hardest cubes) to pressing and drying in various types of cube molds. Infrared drying is an effective modern addition.

Liquid sucrose and liquid invert, generally made by redissolving white sugar and inverting with invertase enzyme, are refinery products in Europe and outside the United States. In the United States they have been almost completely replaced by cheaper corn syrups made by enzymatic hydrolysis of starch and isomerization of glucose.

Brown sugar, including light and dark brown and occasional intermediate grades, comprises only a small part of the output of most refiners, ranging from only 3% in warm climates to perhaps 10% in cold regions. The area of highest brown sugar consumption in the world is British Columbia, Canada, where brown sugar accounts for 20% of total use. In this region, a favorite is a distinctly yellow sugar. Brown sugar is not raw sugar, but rather, as its manufacture is described herein (crystallization), it is refined. The difference between raw sugar and brown sugar is not so much the sucrose content, the color, or taste, but rather the absence of field soil, cane fiber, bacteria, yeasts, molds, and insect parts which may be present in raw sugars. Composition is outlined in Table 7.

8.1. Other Products

Other products from sugarcane, in addition to cane sugar, are cane fiber (known as bagasse) and molasses, the final thick syrup from which no more sugar may be economically removed by crystallization. In some cane-growing countries, cane tops and leaves, separated during harvest, are used for cattle feed.

8.1.1. Bagasse

Cane fiber comes from a standard mill or diffuser at 50–55% moisture, and in most countries is used as fuel for the factory. In the People's Republic of China and some parts of India, sugarcane factories burn low grade coal, because wood is in short supply and bagasse fiber is used for paper or board manufacture. Excess bagasse is burned for cogeneration (8, 19, 20), or to run a refinery or distillery. Bagasse is also used in paper manufacture, for all grades from coarse brown to newspaper to fine papers, depending on other fibers and processing used. Some 7×10^6 t are used annually for pulp production for papers, particle boards, and fiber boards of various grades and durabilities. Bagasse has been used as a cellulose source for single cell protein production, and as animal feed. Feed quality is improved by steam hydrolysis/sodium hydroxide treatment of bagasse fiber (19, 20). In the Dominican Republic, the United States, South Africa, and several countries in South America and Asia, bagasse, which contains 85–95% xylose, is treated by steam hydrolysis and subsequent dehydration to produce furfural; an estimated 90,000 t furfural is produced annually in this manner. Diacetyl (artificial butter flavor) is a by-product of this process in South Africa (20).

8.1.2. Molasses

The final molasses product from sugarcane factories is blackstrap molasses, containing 25–35% sucrose and 8–15% each glucose and fructose. Because of the high mineral (primarily KCl) and browning polymer content, blackstrap is too bitter for human consumption; most is used for animal feed, alone or as an ingredient, and it is traded in international commerce for this purpose. Refinery molasses, and blends of both factory and refinery with various lighter syrups, are the sources of a wide range of food-grade molasses, known as treacle in Europe. Molasses is fermented to ethanol at sugarcane factories in almost all cane-growing areas outside the United States, for industrial alcohol. Molasses is the basis for almost all rum production (some rum is produced directly from sugarcane juice in the French-speaking Caribbean), and for other beverage alcohol, in Asian countries. Molasses has been used as a carbon source in a multitude of chemical and microbial reactions; it is usually the sugars in molasses that serve as the carbon source; hence, these products are included herein. Chemical and fermentation reactions can cause problems in storage, if molasses is put into storage too hot: it should always be at a temperature under 45°C.

High test molasses is not a residual material, but cane juice, sometimes partly clarified, concentrated by evaporation, with at least half its sucrose hydrolyzed to invert (glucose and fructose) by heating at the low juice pH (5.5).

Condensed molasses solubles (CMS) is a product made by drying molasses (spray or drum drying) on a neutral carrier; CMS is a more portable and storable form of molasses for animal feed.

8.2. Sucrochemistry

A wide range of fermentation and chemical products can be made from sucrose either per se or in juice or molasses. Products and substrates depend on the economics of each area. There is an extensive literature on the subject (19, 20). Among the classes of products chemically derived from sucrose are the following. (*1*) Ethers (alkyl, benzyl, silyl, allyl, alkyl, and the internal ethers or anhydro derivatives, which last have generated a new sweetener. (*2*) Esters of fatty acids, including surfactants, emulsifiers, coatings, and a new fat substitute. (*3*) Other esters, eg, sulfuric acid esters that polymerize well; sulfate esters, including an antiulcerative; and other mixed esters. (*4*) Acetals, thioacetals, and ketals that act as intermediates and may have biocide activity. (*5*) Oxidation products, most of which are products of the hydrolyzed monosaccharide products and reduction products, including mannitol and sorbitol, and reductive aminolysis products, including methyl piperazine. (*6*) Halogen and sulfur derivatives and metal complexes, some with applications in water-soluble agricultural chemicals. (*7*) Polymers and resins: polycarbonates, phenolic resins, carbonate–, urea–, and melamine–formaldehyde resins, acrylics, and polyurethanes. Some of the many classes of compounds and products to be made from the sugarcane plant have been outlined (19); most of these are made from cane sugar.

Because sugarcane is the most efficient plant at converting photosynthesis into chemical bonds, it can be the basis of a renewable resource economy.

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