SUGAR

1. Introduction

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.

Sucrose [57-50-1] (β-D-fructofuranosyl-α-D-glucopyranoside), $C_{12}H_{22}O_{11}$, formula weight 342.3, is a disaccharide composed of glucose and fructose residues joined by an α,β-glycosidic bond (Fig. 1).

The most common sugar in plants, sucrose is formed as a result of photosynthesis and occurs in abundance in sugarcane (*Saccharum officinarum*, a perennial tropical grass) and sugarbeets (*Beta vulgaris*, a hearty biennial) in amounts ranging from 12–15 and 13–20% by weight, respectively. Commercial quantities are provided only from these two sources. Other sources include sorghum (*Sorghum vulgare*), the sugar maple (*Acer saccharum*), and the date palm (*Phoenix dactylifera*) (2). Sucrose is called maple, cane, beet, and more familiarly, table sugar.

For centuries, sucrose has been valued for its pure, sweet taste. There are indications of sugar production having occurred in what is now New Guinea (the geographic origin of sugarcane) as early as 12,000 BC (3). Cane production spread to other parts of the Pacific and India by 6,000 BC, and to China by ca 800 BC. Sugarcane reached present-day Iran by 500 AD, Egypt and Spain in the eighth century, and Sicily by 950 AD (4). Knowledge of sugar spread throughout Europe during the Crusades (3). In 1493, sugarcane reached the New World with Columbus. The first sugar mill in the Western Hemisphere was built near Santo Domingo in 1508 (2).

The sweetness of sugarbeets was recorded in 1590 AD. Sugar was isolated from beets by Marggraf in 1747 and the first beet sugar factory was established in Silesia by 1802. The industry grew during the Napoleonic wars, and the year 1813 saw the presence of over 300 sugar mills in Germany, France, and Austria–Hungary. The first American beet sugar mill was built in 1838.

In the initial stages of purification, sucrose is recovered in juice form by crushing cane stalks or by extraction of sliced sugarbeets (cossettes) with hot water. The resulting solutions are clarified with lime, then evaporated to thick syrups from which sugar is recovered by crystallization. The final syrup obtained after exhaustive crystallization of sucrose is known as molasses. Enhanced recovery of sucrose from beet molasses is accomplished by ion-exclusion chromatography, a process used in some sugar mills in the United States, Japan, Finland, and Austria.

An *in vitro* enzymatic synthesis of sucrose was carried out in 1944 (5). A successful chemical synthesis was performed by Lemieux and Huber (6) in 1953 from acetylated sugar precursors. However, the economics and chemical complexities of both processes make them unlikely sources of supply.

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.

2. Physical Properties

2.1. Sucrose. Physical properties of sucrose are summarized in Table 1. Sucrose is one of the purest substances available in bulk quantities, with purities averaging ~99.96%. Water accounts for about half of the nonsugar impurities (11).

Sucrose crystals are triboluminescent and emit light when they are fractured. Aqueous sucrose solutions rotate polarized light in direct proportion to sugar concentration. This property is utilized for quantitation, purity evaluations during factory processing, and for setting the selling price of sugar. Sucrose quantitation has also been performed by colorimetric methods. However, in recent years, automated enzymatic analyzers and instrumental methods have become increasingly popular, as they provide greater sensitivity and accuracy.

The sweet taste of sucrose is its most notable and important physical property and is regarded as the standard against which other sweeteners (qv) are rated. Sweetness is influenced by temperature, pH, sugar concentration, physical properties of the food system, and other factors (12–14). The sweetening powers of sucrose and other sweeteners are compared in Table 2. The sweetness threshold for dissolved sucrose is ~0.2–0.5% and its sweetness intensity is highest at ~32–38°C (13).

Fructose is sweeter than sucrose at low temperatures (~5°C); at higher temperatures, the reverse is true. At 40°C, they have equal sweetness, the result of a temperature-induced shift in the percentages of α- and β-fructose anomers. The taste of sucrose is synergistic with high intensity sweeteners (eg, sucralose and aspartame) and can be enhanced or prolonged by substances like glycerol monostearate, lecithin, and maltol (13).

Sucrose has eight hydroxyl groups capable of hydrogen-bond formation. The glucose and fructose residues in crystalline sucrose are nearly perpendicular to each other and are held in this conformation by hydrogen bonds between the C_1–OH of fructose and the C_2–oxygen of glucose, and C_6–OH of fructose and the ring oxygen of glucose (Fig. 1**b**). In aqueous sugar solutions, the latter bond is absent; however, the overall conformation is essentially unchanged (1).

Elicitation of sweetness is explained by the AH–B–X Theory, or the Sweetness Triangle (1,17,18), wherein AH and B represent a hydrogen donor and acceptor, respectively, of sucrose. These interact with complementary regions of taste-receptor proteins. An extended hydrophobic region (X) of sucrose docks in a hydrophobic cleft of the receptor, facilitating optimal electrostatic interaction and sensory stimulation. The C_2- and C_3-hydroxyls of glucose (AH and B, respectively) and the back side of the fructose ring (X) are critical to this interaction.

The hydroxyl groups of sucrose contribute to its very high water solubility. This is enhanced by the presence of other dissolved solids and diminishes the yield of crystals produced from sugar syrups. Sucrose forms sphenoidic monoclinic crystals (Fig. 2), the shapes of which are affected by syrup impurities like raffinose and dextran, which promote growth of the B- and C-axes, respectively, resulting in formation of elongated, needle-like crystals (11,19,20). A secondary consequence is a decrease in bulk density with its accompanying packaging problems (21). Impurities included within sucrose crystals impart color, raise ash levels, and reduce sugar quality. Thus, nonsucrose impurities can seriously impact the recovery and quality of sucrose. Sucrose also has moderate solubility in pyridine, glycerol, methylpyrrolidinone, methylpiperazine, DMSO, and DMF, and is slightly soluble in methanol and ethanol (10,21). The high dielectric constant of sucrose (3.50–3.85) gives it substantial microwave-absorbing capacity and makes it a valuable ingredient in formulating microwavable foods (12).

2.2. Cane Sugar.

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 $P2_1$ (22).

The specific rotation in water is $[\alpha]_D^{20} = +66.529^\circ$ (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 (23). Bulk density, important for cane sugar as an ingredient in dry mixes, is listed in Table 3, as typical values for several types of sugars. Solubility of sucrose with other common sugars is shown in Figure 3 and in Table 4. 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 (22,24). The high osmotic pressure generated by sucrose in solution (Table 5) (22) 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 6 (23); 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 (22-27).

3. Chemical Properties

3.1. Sucrose.

The carbonyl groups of fructose and glucose partake in the glycosidic bond of sucrose, making the latter nonreducing. Therefore, sucrose has no anomeric forms, cannot undergo mutarotation or osazone formation, and is inert to alkaline copper reagents. The hydroxyl groups of sucrose are very weakly acidic (1); the C_2–OH of glucose is the most acidic. The pK_as of sucrose at 25°C are $pK_1 = 12.02$, $pK_2 = 12.56$, and $pK_3 = 12.01$ (28). The three primary hydroxyl groups of sucrose are most reactive ($6 = 6' > 1$); of the secondary hydroxyls, those on C-2 and C-3′ are more reactive (29). The hydroxyls dissociate in alkali to form alcoholates called saccharates, and can be derivatized to produce valuable sucrochemicals.

Oxidation of Sucrose. Sucrose can be oxidized by HNO_3, $KMnO_4$, and peroxide. Under selected conditions using oxygen with palladium or platinum, the 6- or 6′-hydroxyls can be oxidized to form sucronic acid derivatives (29).

Hydrolysis of Sucrose. Sucrose can be enzymatically hydrolyzed to glucose and fructose by invertase. During this reaction, the optical rotation falls to a negative value owing to the large negative specific rotation of fructose. The reversal is called inversion and the resulting glucose–fructose mixture is called invert.

Sugar is destroyed by pH extremes, and inadequate pH control can cause significant sucrose losses in sugar mills. Sucrose is one of the most acid-labile disaccharides known, and its hydrolysis to invert is readily catalyzed by heat and low pH; prolonged exposure converts the monosaccharides to hydroxymethyl furfural, which has applications for synthesis of glycols, ethers, polymers, and pharmaceuticals (10). The molecular mechanism that occurs during acid hydrolysis operates, albeit slowly, as high as pH 8.5 (12).

Alkaline Degradation. At high pH, sucrose is relatively stable; however, prolonged exposure to strong alkali and heat converts sucrose to a mixture of organic acids (mainly lactate), ketones, and cyclic condensation products. The mechanism of alkaline degradation is uncertain; however, initial formation of glucose and fructose apparently does not occur (31). In aqueous solutions, sucrose is most stable at ~pH 9.0.

Thermal Degradation. The heats of formation and combustion of sucrose are −2.26 MJ/mol (540 kcal/mol) and −5.79 MJ/mol (−1384 kcal/mol), respectively (32,33). At high temperatures (160–186°C), sucrose decomposes with charring, emitting an odor of caramel. Thermolysis of crystalline sucrose at 170°C yielded a complex mixture of products (34). The mixture contained several nonreducing trisaccharides, including 6-kestose. Acid-catalyzed thermolysis causes decomposition to glucose and fructofuranosyl cation. The latter reacts with sucrose to form a complex mixture of products, including fructoglucan and several kestoses (35). These substances are examples of fructooligosaccharides (FOS) and are known to promote the growth of beneficial intestinal microorganisms.

3.2. Cane Sugar. Among chemical properties of cane sugar that affect daily use are color, flavor, sweetness, antioxidant properties, and reactions in aqueous solution (23). 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 7 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% (see Table 2) (23). 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 4 (23). 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 (22,23,36). (*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 can cause the transformation of glucose to a mixture of mannose and fructose by this mechanism (22,23,36). (*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 (22,23). (*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 (22,23).

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.

4. Production from Sugarcane

4.1. 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.

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.

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 (26,36).

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 (23). 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 (26).

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.

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.

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.

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. The usual split of revenue from sugar is 60–70% to the grower and 30–40% of value to the factory or processor.

Processing. Sugarcane processing to raw cane sugar is outlined in Figure 5, 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, 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 (24,26,27), 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 (26,36).

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 8. 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 ton 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.

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.

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. 5), 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 (26,27). 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.

4.2. 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 6. Details of unit processes are shown in Figure 5. 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.

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 (37).

Talo 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. It has almost replaced traditional phosphatation (38).

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 (37).

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.

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 (26,27,36,38).

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 8. 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 (38).

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.

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-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.

Membrane Filtration Processes. Newest among cane sugar manufacturing systems are processes using membrane filtration to remove nonsucrose 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 in 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 (39). Ceramic membranes have been in use since 1993 in raw sugar manufacture in Hawaii (39) 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.

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.

5. Production from Sugar Beets

5.1. Cultivation. The sugar beet, *Beta vulgaris*, is a hearty biennial which produces crops of commercial impact in a wide range of climates, from the irrigated deserts of California's Imperial Valley, the high plains of Texas, the eastern slopes of the Rocky Mountains, the Great Lakes region, and Idaho's Snake River Valley, to the rich soils of the Red River Valley of North Dakota, Minnesota, and Manitoba, Canada, where a growing season as short as 100 days supports profitable crop yields. The crop is harvested at or near the time of the first hard frost (28°C) which terminates the photosynthetic production of sucrose and may threaten crop loss by freezing it in the ground. Whereas the Eastern and Idaho crops have to work around the cold winters, the nemesis of the Imperial Valley crop is the summer heat; the crops are planted in September and harvested from April through July. In northern California, the crop may be allowed to winter over for a Spring harvest, which must be completed before warm days trigger the seed production process that consumes much of the stored sucrose.

Besides traditional farmers' luck, a successful crop depends on seed quality and varietal characteristics, weed and pest control, timely irrigations or timely rains (not all beet crops are grown on irrigated land), disease control, crop rotations of at least three years, and a nitrogen management program designed to limit the amount of leaf growth to the minimum necessary to cover the rows and take full advantage of available sunlight. Most states that benefit from a healthy beet sugar growing–production system support the agricultural aspects through their University Extensions services, often in concert with USDA resources.

For a typical crop planted in the Spring and harvested in the Fall the following hold: for each hectare of land, 0.5 to 1 kg of seed (100,000 seeds/kg) are planted at 10 cm spacing in rows 55 cm apart that have been pre-fertilized. Nitrogen is by far the most important component of this fertilization treatment: too little, and the crop cannot thrive; too much, and the result is lush large crops with modest sugar content. The labor-intensive hoeing of beets has been displaced by planting to a stand of 65,000 to 85,000 plants per hectare. Mechanical thinning of beets is relatively rare.

The crop may be treated with pesticide 2 to 15 times, depending on insect and disease pressures in the area. Weed control is maintained by a combination of cultivation and pre-plant and post-emergence herbicides, and is not necessary after rows have been completely covered with a leaf canopy. All chemicals must be approved specifically for use on sugar beets by government regulatory agencies; the approved list gets shorter each year. The last irrigation usually occurs about six weeks prior to harvest, when the 1–2 kg roots are lifted with mechanical harvesters which defoliate the tops and leave them in the field.

5.2. Beet Receiving, Storage, and Handling Before Processing. Beets are loaded into side-dump or end-dump trucks in the field and taken to a receiving station, ideally located within 25 km but sometimes as remotely as several hundred km from the field. The receiving station may be the factory itself, an outside staging or piling ground which reloads the beets at a later date, or a rail car-loading facility which reloads the beets into open hopper cars for transport to the factory. At the receiving station the beets are unloaded from the truck and passed over a series of rotating grab-rolls arranged to allow trash, dirt, and small pieces of beets to fall out of the main stream. This first separation is especially important if the beets are destined for storage of more than a day or two.

Prolonged storage of sugar beets extends the factory processing campaign well past the harvest period sometimes by as much as seven months. During this storage period natural respiratory processes consume some of the sugar content of the root, reducing its commercial value. This loss of sugar can be further aggravated by yeast and mold infections beginning on bruised surfaces of beets and thriving when much dirt and trash are included in the storage piles. Because both processes are exothermic and accelerated by increased temperatures, poor storage conditions and practices can result in worthless piles of decaying material.

Commercial strategies for maintaining effective storage are (*1*) careful monitoring for unremoved leaves, trash, dirt, and early signs of rot or frost damage as the crop is received; (*2*) initially piling roots with temperatures between 0 and

5°C (never $> 10°C$); (*3*) building large piles (Fig. 7) to stabilize temperatures and minimize surface area exposed to the elements (the largest piles are 70 m wide, 150 m long, and as high as 9 m; heights > 7 m risk retarding natural ventilation which dissipates the heat of respiration); (*4*) carefully monitoring the condition of the piles to detect hot spots that can be processed immediately or discarded; (*5*) protecting the piles by covering with plastic sheets or straw; (*6*) mechanical ventilation through half- or full-round culverts placed under the beets as they are piled or in large sheds (60 m wide, 150 m long, and 10 m high at the sides) with an elaborate underground ventilation air recirculation–venting system; (*7*) using mechanical ventilation to deep-freeze the beets and stop respiration altogether (freezing usually requires four or five days of uninterrupted ambient temperatures $<15°C$). Once freezing begins, rewarming or thawing leads to spoilage.

5.3. Processing of Beets to Sugar.

Whether beets are processed on the day of harvest or several months afterward, they arrive at the factory and are dropped into a cement trough of moving water which flumes them past a series of weed rakes and trash collectors. The neutral buoyancy of beets facilitates removal of stones and dirt. Spent flume water passes through a mud-removing clarifier 8–16 m in diameter and is reused, sometimes through a series of recirculating ponds. This water always contains some sugar and is unsuitable for discharge because of its high BOD levels. Such material is usually placed in holding ponds to allow the BOD levels to drop to acceptable levels, often leading to objectionable odors, particularly near residential areas. Some factories use anaerobic digesters to treat these waters and to avoid censure (Fig. 8).

Beets are either elevated or pumped to an agitated beet washer, after which they are rinsed with clean water. This rinse water is fed back to the washer from which it overflows back to the flume system, providing constant blow down. The beets are fed from bins to slicing machines configured either as a horizontal rotating disk or a rotating drum where the beets and the blades are on the inside and the slices, called cossettes, fall to the outside. For both configurations, one knife makes a serrated cut across the face of the beet, followed by a second offset knife making a second serrated cut yielding elongated pieces with a diamond-shaped cross section 3–5 mm on a side and 4–10 cm in length. The knives can be adjusted in blocks to vary the thickness and length of the cossettes (Fig. 9). Long cossettes are always desirable and thickness is kept to the minimum which still allows the beet pieces to maintain integrity in the extraction step. Under the most unfavorable conditions where the beets have been frozen or decomposed and fall apart easily, the knives may be separated so much that slabs are produced.

5.4. Continuous Countercurrent Extraction of Sucrose.

The extraction or diffusion process and the associated equipment usually define the overall beet processing capacity of a given factory. The diffuser, the centerpiece of this unit operation, may be capable of a throughput of more than 7000 t/d. The largest factories have multiple diffusers arranged to handle parallel flows of cossettes. For the many types of diffusers, the principle of operations is the same: cossettes are physically transported through the diffuser while water, which is introduced at the exit end and flows in the opposite direction as the cossettes, is constantly being mixed with the cossettes exit through screens from the end at which the cossettes are introduced. The amount of water introduced (draft) exceeds the weight of the cossettes by 5 to 20%; high draft leads to more efficient extraction of sucrose but at the costs of more energy spent on drying and evaporation and possibly higher extraction of impurities.

Extraction processes applied to sound, unfrozen beets are designed to allow the sucrose to diffuse from the beet cell wall mass and leave the intercellular material within the cells. Partial denaturing of the cell walls is accomplished by pre-scalding or heating cossettes after they leave the slicers, enough to allow free passage of the solution phase without rupturing the cell. Temperatures within the diffuser are maintained by using hot process water and indirect heating with low pressure steam. Maximum temperatures range from 50 to 70°C, depending on the integrity of the cossettes, the choice of diffuser design, and available heat-exchange capacity.

The three most common diffuser configurations are a vertical cylinder in which the semifluidized cossettes are scrolled upward (tower), a pair of upward-moving inclined twin-screw scrolls with cascading juices (slope), and a horizontal rotating drum equipped with offset compartments which allow the cossettes to fall forward as the drum turns (Raffinerie Tirlemontoise (RT) horizontal). Residence time within all of these diffusers is typically 45 to 60 minutes.

Spent cossettes (pulp) exit the diffuser with a moisture content of ca 92% and a sucrose content of ca 1%. To maximize the amount of sucrose returned to the process and minimize the amount of energy required to dry the pulp, this wet pulp is pressed in tapered twin-screw presses fitted with perforated side screens. On exiting the presses the moisture content of the pulp is ca 75% and the sucrose content ca 1%, which means that ca 2% of the sucrose that enters the factory with the cossettes leaves with the wet pulp (pulp loss). Water from the pressing step is passed through Dutch States Mines (DSM) screens and returned to the diffuser. The pressed pulp is normally mixed with molasses, dried to ca 10% moisture in rotating drum driers, stored, and sold as cattle feed, either as free shreds or pellets. Occasionally some of the pressed pulp is sold as-is to local feed operations. Processors in California use large cement strips, often disused airport runways, to solar dry wet pulp and save energy costs.

Improvements in pulp pressing technology have enabled manufacturers to reduce the moisture content of pressed pulp from 80% (moisture-to-solids ratio 4:1) to 75% (3:1 ratio), which has reduced the drying requirements by one-fourth. Beet pulp is much more difficult to press than most vegetable products, but there are indications that moisture in the mid-60% (ratios <2:1) range may be achievable with properly designed equipment.

The diffusion process has not been designed to ensure sterility, although temperatures above 65°C significantly retard microbial activity. Sulfur dioxide, thiocarbamates, glutaraldehyde, sodium bisulfite, and chlorine dioxide are all used, occasionally disregarding their redox incompatibilities, to knock down or control infections. The most common addition point is to the water from the pulp presses as it is returned to the diffuser. Surfactants are almost always used to control foaming in the diffusion process.

The raw juice exiting the diffuser is a murky dark gray solution occluded by colloidal materials from the ruptured beet tissue, small pieces of cossettes, and fine soil that escaped the fluming and washing processes. It is microbiologically and chemically unstable and unsuitable for concentration and crystallization. Common parlance assigns juice to more dilute process streams and syrup (or occasionally liquid) to steams with solids concentrations >70%.

5.5. Juice Purification.

Raw juice is heated, treated sequentially with lime (CaO) and carbon dioxide, and filtered. This accomplishes three objectives: (*1*) microbial activity is terminated; (*2*) the thin juice produced is clear and only lightly colored; and (*3*) the juice is chemically stabilized so that subsequent processing steps of evaporation and crystallization do not result in uncontrolled hydrolysis of sucrose, scaling of heating surfaces, or coprecipitation of material other than sucrose.

Active lime and CO_2 are produced as needed by calcining lime rock in kilns fired with gas or metallurgical coke. Typically the uniformly sized lime rock and coke, in a 12:1 ratio, are dumped in the top of a vertical kiln and withdrawn from the bottom. They travel through fire and cooling zones so that the rock reaches a maximum of ca 1000°C without overburning which leads to unreactive CaO. Carbon dioxide, both from the lime rock and the combustion process, is withdrawn from the top of the kiln, washed, and sent to the process, while the CaO is mixed with dilute in-process streams (sweet water of ca 4–8% solids content) to form a CaO–water slurry (milk of lime) of ca 30% solids content. This is metered to the various points in the process where needed. Overall consumption of lime rock ranges from 2 to 5% rock on beets by weight. Alternatives to the coke-fired vertical kiln are firing the kiln with oil or natural gas and the gas-fired horizontal rotary kilns used in the cement industry.

The equipment and complexity of the juice purification scheme depend on the nature and variability of the raw material and on the performance of the preceding washing, slicing, and diffusion steps. Some of the more elaborate systems have been designed to be reconfigured on the run as the nature of the beets changes during the campaign.

Unit Operations. The chemistries elaborated by all of these systems are described by seven unit operations (Fig. 10). The first six, the use of lime and carbon dioxide as clarification agents, were laid out during the first half of the twentieth century and only the application technology has changed since, mainly from small batch processes designed to handle 1000 liters in a few hours to continuous systems capable of processing up to 10,000 L/min.

Pre-liming. Lime slurry, 0.25% lime on juice (0.250 g of CaO/100 g juice), is added to bring the pH of the mixture into the alkaline range. Insoluble calcium salts are precipitated as finely dispersed colloids. Calcium carbonate in the form of recycled first carbonation sludge is added to provide colloid absorption and stabilization. Temperature may be cool (50°C) or hot (80°C) depending on the temperature of the next step, or occasionally on the type of diffusion equipment. Retention time is 15 to 30 min.

Main Liming. A further 1.50% CaO on juice is added and the juice is brought to its maximum alkalinity and pH. Conditions may be cool (50°C for ≤60 min, followed by 5–10 min at 80°C) or hot (80°C for 10–15 min). The invert sugars (glucose and fructose) are converted to organic acids, which do not form insoluble calcium salts. If this reaction does not take place in the early stages of the process, before pH stabilization, it almost always occurs later and is characterized by dropping pH and rising colors throughout the evaporation crystallization steps.

First Carbonation. The process stream *p*OH is raised to 3.0 with carbon dioxide. Juice is recycled either internally or in a separate vessel to provide seed for calcium carbonate growth. Retention time is 15–20 min at 80–85°C. *p*OH of the juice purification process streams is more descriptive than pH for two reasons: first, all of the important solution chemistry depends on reactions of the hydroxyl ion rather than of the hydrogen ion; and second, the nature of the $CO^{2-}{}_3$–H_2O–Ca^{2+} equilibria results in a *p*OH which is independent of the temperature of the solution. All of the temperature effects on the dissociation constant of water are reflected by the pH.

Clarification. Clarification is also referred to as sludge separation. First carbonation effluent is passed through a continuous clarifier where the precipitated calcium carbonate is allowed to settle while the clear juice overflows to second carbonation. Clarifiers may be rapid (10–15 min with increased flocculant, 10 ppm vs 2–3 ppm) or slow (45–60 min). The sludge that is not recycled to the pre-limer is dewatered by vacuum filtration. The sludge by-product is stored in large piles and may be sold as a soil amendment; the filtrate is returned to the process. The Spreckels factory reburns this sludge in a rotary kiln to reconvert the calcium carbonate back to lime.

Second Carbonation. Calcium is reduced to the practical minimum by the addition of carbon dioxide at a *p*OH of 4.5 at a temperature of as near to 100°C as possible. This is the maximum temperature in the purification process and the retention time is only long enough to effect the *p*OH adjustment (5 min). The sludge from this unit operation is much less in amount than for first carbonation and is easily removed by in-line filters. The filtration is made even easier by the fact that the precipitate is almost pure calcium carbonate not fouled by the colloids found in first carbonation sludge.

Sulfitation. Sulfur dioxide is added to a level of about 150 ppm on juice to discourage further color-forming Malliard reactions by tying up the small amount of invert sugars as bisulfite addition compounds.

Juice Purification Chemistry. Lime in juice purification serves as a source of calcium, a source of alkalinity, and a source of calcium carbonate which serves as the clarification–filtration medium.

As a source of calcium, lime reacts with nonsucrose components to form a precipitate. Roughly one-third of these materials, by weight, form precipitates with calcium. Examples of such reactants are proteins, citrate, sulfate, saponins, phosphate, pectins, oxalate, and sulfite. The other two-thirds of the nonsucrose components remain in solution and salt-in sucrose reducing yields during subsequent crystallization steps. Diffusion juice components which do not precipitate with calcium include sodium, ammonia, nitrite, potassium, nitrate, betaine, magnesium, chloride, lactate, acetate, raffinose, glucose, glutamine, fructose, levans, and dextrans.

The stoichiometric ratio of lime to removable nonsucrose components is nearly five or six to one. This excess calcium is removed by the addition of carbon dioxide to form calcium carbonate, which is the primary clarification agent. Suspended or colloidal materials are adsorbed onto freshly precipitated calcium carbonate. These suspended or colloidal materials include not only those in the diffusion juice but also finely suspended precipitates of calcium salts. In sucrose solutions, $CaCO_3$ precipitate has a slight positive charge which is most effective at agglomerating negatively charged juice colloids. If the beets have been grown in clay-bearing soils, and washing does not adequately remove adhering soils, some of the clay may be present in juice as positively charged colloids. Unfortunately, these positively charged clay colloids have exactly the wrong chemistry for easy agglomeration and must be removed by the bulk filtration of the calcium carbonate.

High alkalinities of limed juice serve several functions. Foremost is to retard sucrose hydrolysis, one of the oldest reactions in the literature of chemical kinetics (40). Sucrose hydrolysis proceeds much more slowly at a moderately high pH than at an even slightly acidic pH.

Sucrose hydrolysis: reaction and kinetics

$$\text{sucrose} + \text{water} \xrightarrow[\text{salts}]{[\mathrm{H}^+]\text{ or }[^-\mathrm{OH}]\text{heat}} \text{glucose} + \text{fructose}$$

$$\text{rate} = k(\text{sucrose})$$

$$k = k_{[\mathrm{H}^+]}[\mathrm{H}^+] + k_{[^-\mathrm{OH}]}[\mathrm{O}^-\mathrm{H}]^{0.3} + k_{[\text{salt}]}[\text{salt}]$$

Not only is sucrose yield directly reduced as this reaction proceeds, but more nonsucrose components are formed. If 1% of the sucrose in a juice is hydrolyzed, it turns into ~1% nonsucrose components and the resultant loss to extraction is 2.5% (1% directly + 1.5% reduced crystallization yield). Each metric ton of the newly formed nonsucrose material salts 1.5 t of sucrose into molasses. The reaction has commercial significance at levels of only a few hundred parts per million.

High alkalinity not only protects sucrose from acid hydrolysis, but also helps produce a stable thin juice by acting on specific nonsucroses. The invert sugars glucose and fructose are oxidized to organic anions; lactate is the most common. If this reaction does not occur early in the sugar production process, glucose and fructose participate in Malliard reactions with free amino groups on other nonsucrose components, followed by Amadori rearrangements (41), and eventually produce medium to high molecular weight colorants. Excessive amounts of these colorants in crystallizing syrups frustrate the production of white sugar and lead to rework.

Glutamine, the most abundant amino acid in sugar beets and raw juice, is converted to 2-pyrollidinone-5-carboxylic acid and ammonia. The reaction is promoted by heat and the ammonia is driven off by the high pH of the process streams. The odor of ammonia is often easily detectable in beet sugar factories. Healthy, mature beets generally contain manageable amounts of glutamine, for which all purification systems have been designed. Immature beets contain appreciably higher levels of glutamine which leave residual amounts in thin juice. During evaporation ammonia is driven off and pH drops, sometimes leading to slightly acidic syrups. The most common way to counter this pH drop is by the addition of soda ash to second carbonation. Unfortunately, this addition increases the nonsucrose level of the juice.

Nonsucrose Components from Storage or Damage of Beets. Some nonsucrose components are associated with the conditions under which the beets have been stored prior to processing, as respiration products or products of microbial attack. In either case they directly and indirectly reduce sucrose yield and may cause other processing problems. Glucose and fructose have already been discussed and can derive from either source.

Raffinose, a nonreducing galactose–glucose–fructose trisaccharide, is observed when the whole beet is subjected to long periods of cool weather, either in the ground or in storage. Betaine, zwitterionic trimethyl glycine that the sugar beet uses to regulate osmotic pressure within its cells, seems to increase just prior to freezing. Levans and dextrans, the slimy products of microbial attack, are removed in carbonation with great difficulty. Dextrans have been shown to ruin the chemistry calcium carbonate precipitation in carbonation, retarding coagulation with colloids (42). Usually, the amount of calcium carbonate (and hence the amount of lime) must be greatly increased to provide enough surface area to deal with these nonsucroses. Their presence is usually associated with degraded beets; although they can be a sign of factory process infections.

Nitrite is usually one indicator of the infection level in the diffuser. Exposure of nitrite to sulfur dioxide, either as a diffusion additive or later to thin juice, results in the production of potassium imidodisulfonate which precipitates when sugar is later crystallized, a cause of turbid or cloudy sugar.

Removal of Calcium Prior to Evaporation and Crystallization. The second carbonation step is designed to minimize the amount of calcium in thin juice by removing it as $CaCO_3$, the solubility of which is minimized by high temperature, high carbonate concentrations, and low nonsucrose concentrations. Counterbalancing these factors is the high solubility of calcium bicarbonate, which predominates as the pH drops below 8.4. The addition of CO_2 provides carbonate ion, but also lowers the pH. Upstream infection problems produce acids leading to lower juice pH. After prolonged heating the bicarbonate eventually expels CO_2 and produces carbonate, leading to $CaCO_3$ scaling on evaporation and heating surfaces, a common consequence and a significant cost increase in processing degraded beets. The minimum calcium content may vary from 20 ppm to more than 350 ppm depending on the raw material. Juice softening with resins, commonplace in European factories, has been installed in about one-third of U.S. factories, justified not only by process advantages but also by the need for molasses having low calcium/magnesium levels for molasses desugarization operations.

5.6. Crystallization and Recovery of Sucrose.

The three-boiling scheme, typical of U.S. beet sugar production, is shown in Figure 11. Incoming thick juice is combined with recycled lower grade sugars, filtered, and crystallized under vacuum to yield about half the sucrose separated from the mother liquor and washed in batch centrifugals. The process is repeated two more times using continuous centrifugals for the separation of syrups and crystals; only the first crop of crystals is used for finished product. The third crop is washed with a slightly higher purity syrup (affined) to reduce the load of nonsugars and color. Both the second and third crops are returned to the first stage. After the liquor has been concentrated to about 10% past supersaturation, crystal growth is initiated by fully seeding each pan with enough crystals, 1–5 μm in diameter, to account for the finished pan.

All of these processes are carried out under kinetically controlled conditions and vacuum pan operations may be followed by a crystallizer in which the massecuite (crystals/mother liquor) is allowed more time for crystal growth, sometimes for as long as 48 hours for the third stage. Crystal growth is enhanced by higher purities, lower viscosities, higher concentrations, agitation of the crystallizing mass, higher temperatures, and time. The first boiling typically takes 1½ to 2 hours; the second, 4 hours; and the final boiling, 8 hours or longer plus at least 12 hours of crystallizer time. Surfactants designed to reduce viscosities are commonly added to each stage. The batches are referred to as strikes, a holdover from the practice of initiating crystallization by hitting the pan with a large hammer or iron bar. Some older equipment may show signs of this abuse.

Crystallization batches range from 30,000 to 60,000 liters for each pan. Continuous centrifugals are typically used for second, third, and affination steps; continuous vacuum pans are less common but are used in the U.S. for intermediate strikes. Most horizontal batch crystallizers have been replaced by continuous units, and all are designed for controlled cooling of the massecuite to maintain supersaturation.

Balancing these crystallization steps to maximize the yield and maintain high product quality is a significant operational challenge, especially when confronted with changing thick juice quality, ie, color, purity, and pH stability (Table 9). These values reveal the critical dependence of performance on the quality of the thick juice and, by inference, on the nature of the beets. Calculations have assumed the same yield for each of the boilings. The higher nonsucrose loading has reduced the final yield by 5% for the low purity thick juice. For the same 100 kg of sugar entering crystallization, each stage of the low purity scenario has to handle 40–50% more material because of increased concentrations of returned sugar from the second and third stages. Because the process is controlled by kinetics, either pan yields must be sacrificed or overall throughput must be reduced; either choice has costly results. Low purity juices tend to be less stable with respect to color, pH, and calcium precipitation, and the choice is always between bad and worse.

5.7. Conditioning and Storage of Sucrose. Washed, wet sugar contains about 1% moisture which must be reduced to about 0.03% without glazing over the crystals. This is accomplished in a rotating drum granulator–cooler in which warm air is passed over the crystals as they roll down the length of the drum. This is followed by cooler air to stabilize the crystals at <35°C before conditioning. Best practices allow sugar to cure for 24 hours before long-term storage or shipping as bulk sugar in rail cars or trucks. The most common customer complaint for every beet sugar producer is hard and lumpy sugar caused chiefly by failure of these processes.

Because beets are processed for only a portion of the year, a factory may store as much as half of the production sugar in order to provide continuous distribution to customers. This is accomplished either in sets of tall, vertical cement silos, each capable of holding 6800 t, or single large-diameter Weibul-type curing silos of 23,000 t capacity. The cement silos are theoretically first-in first-out configuration in which the sugar is dropped in the top and withdrawn from the bottom; in practice, sugar tends to funnel through the center of the silo, resulting in a last-in first-out scheme. A Weibul silo has a central distribution column with a rotating arm which scatters the sugar allowing it to fall through dehumidified air in even layers about the bin. Withdrawing sugar is accomplished by using the same arm to rake sugar from the top toward the center where it falls to the bottom into an annular opening around the central column. This last-in first-out system provides the best conditioning for the product which must be stored the longest.

5.8. Molasses Desugarization.

Chromatographic separation of diluted molasses streams into a high purity fraction suitable for concentration and crystallization and a second low purity by-product, which can be concentrated and sold as an animal feed product, has been employed in Finland since the 1970s and in the United States since the mid-1980s.

Strong cationic sulfonic acid resin beads of very uniform size (325 μm) are used as a stationary phase. Their active sites exist in a mixed sodium–potassium form depending on the makeup of the molasses being separated. Sugar has a slight affinity for these resins, betaine an even higher affinity, and most ions have little or no affinity, hence the term ion exclusion for this process. This places two fairly strict requirements on the feed molasses: the molasses must have low concentrations of calcium and magnesium (<500 ppm), which not only compete for the active sites but may precipitate within the resin bed, and the molasses constituents should be as uniform as possible so the nature of the resin is not constantly changing.

The separation uses either of two modes of operation: (*1*) a pulse method in which batches of feed are sequentially placed on the column and eluted with water, taking product and by-product fractions as desired, and (*2*) a simulated moving bed (SMB) configuration in which the feed is continually placed on the column at the point where its purity matches the separation. The pulse method provides more flexibility, less dilution, and better separations but suffers from a waiting time for the previous pulse to clear. The steady-state method has higher capacity and is easier to manage, but requires more valves on a series of sections in order to move the point of addition. The SMB separation is most effective when only two components are involved, ie, sucrose and salt or sucrose and betaine. Under normal operating conditions, 15 m of column length is required to economically separate molasses components on this 325-μm resin.

The product has purities typically in the 90–92% range and can be combined with thin juice, concentrated and crystallized, or concentrated and stored for later use. Crystallizing the desugarization thick juice apart from the normal beet campaign may be desired because the secondary molasses produced after the separation contains the nonsucrose components, which are the most difficult to separate from sucrose and perhaps should be set aside and sold instead of resubmitted to the columns.

The desugarization by-product is normally sold as a low value molasses. Pulse method systems also produce a relatively high value betaine-rich (at least 50% on solids) fraction. The concentrated betaine-rich by-product is used as a custom animal feed, whose European markets are well established and may provide a future opportunity in the U.S. feed industry. Beet sugar molasses contains from 3 to 6% betaine, by weight, about three-quarters of which may be recoverable as a potential by-product (∼40–50% purity).

6. Economic Aspects

The United States Department of Agriculture projects for fiscal year 2006 national sugar beet production at 4.375×10^6 short tons, raw value (STRV), 248,000 STRV lower than fiscal 2005. Sugar cane production is expected at 3.589×10^6 STRV, which is 262,000 STRV higher than fiscal 2005. The projected sugar production quantity is 7.964×10^6 STRV (which is the same as 2005) (43).

In August-September of 2005 the USDA announced a number of actions concerning the sugar allotment program plus the sugar tariff rate quota (TRQ) for FY 2006 because of an expectation of a sugar shortage in the U.S. market and the closure of two sugar refineries in Louisiana due to Hurricane Katrina.

Table 10 gives data on the sugar refining capacity of U. S. states.

Table 11 shows the estimates of domestic sugar deliveries for food and beverage use sugar in imported products, sugar in exported products, sugar in USDA's Sugar-Containing Products Re-export Program, and domestic deliveries of sugar for food and beverages adjusted for trade. Estimated FY2005, deliveries for food and beverage should sum to 9.875×10^6 STRV, an increase of 3.0% relative to the same period in FY2004.

Sugar in imported products has continued to growth, but the rate has slowed.

The Economic Research Service makes calendar year estimates of total sweeteners deliveries that are available for food and beverage consumption by U.S. consumers. The sweeteners include refined sugar, corn sweeteners (high fructose corn syrup), glucose syrup, and dextrose, honey and other edible syrups including maple syrup and maple sugar. They have developed a simulation model that projects deliveries by end-user, sugar availability, and import of sugar-containing products by tariff chapter. Table 12 shows some of the modeling details.

Table 13 shows U.S. sugar supply and use.

6.1. Trade. In each country of the modern world, sugar production and trade play major social, political, and economical roles. In order to regulate and protect export, import, stocks, subsidies, tariffs, etc, an enormous number of laws have been enacted and agreements concluded on sugar, both domestically and internationally. Also, insofar as sugar is a basic staple for a large population, each country keeps a watchful eye on sugar production, consumption, and price, which vary widely from country to country.

TRQ sugar projected for entry in FY 2006 is 1.412 million STRV. The implementation of the Central American Free Trade Agreement, including the Dominican Republic (CAFTA-DR), is expected on January 1, 2006. To date, four of the six countries have signed (Nicaragua and Costa Rica have not signed yet). The sugar expected to enter from the already-signed countries totals 70,000 STRV.

FY 2006 refined sugar TRQ entries are specialty sugars, 31,587 STRV; and the Canadian, Mexican, and global allocations that are set at the same levels as in FY 2005 less amounts estimated to have entered the United States prior to the start of the new fiscal year (22,425 STRV, less 13,000). All of the additional refined sugar TRQ announced in 2005, 75,000 STRV is estimated to arrive before FY 2006. Total refined sugar TRQ entries in FY 2006 are therefore projected at

41,012 STRV. Adding this amount to projected raw sugar TRQ entries yields the 1.412 million STRV amount.

The USDA estimates high-tier imports for FY 2005 at 107,000 STRV. This total is comprised of 80,000 STRV bulk raw sugar and 27,000 STRV refined sugar. Imports for FY 2006 are projected at 50,000 STRV.

6.2. Mexico. Mexican sugar production continued through July and reached a record 5.796 million metric tons, tel quel, or 6.148 million metric tons, raw value. Sugarcane production is estimated at a record 50.893 million metric tons. The sugar recovery rate is calculated at 11.39 percent, which is slightly higher than the previous record of 11.36 percent set in the 2001/02 harvest. Sugar production increased in all producing regions except the high-cost Northwest (Sinaloa). Refined sugar production is estimated at 1.943 million tons or over 33 percent of total production, with most of the remainder constituted by estandar (3.852 million tons).

6.3. European Union. On June 22, 2005, the European Commission presented new proposals for the reform of the European Union (EU) sugar regime. The proposals called for a 39 percent price cut, as well as offering a quota buyback scheme and some new quota that the more efficient sugar processors can effectively purchase through the Commission. This quota sale, along with a temporary restructuring charge on remaining quota holders, will finance the buyout. Sugarbeet growers will be compensated with direct income payments equal to around 60 percent of the value of the price cut they face.

7. Specifications and Standards

The trend toward international standardization and harmonization of methods used in trading has had a significant impact on the methods used for sugar analysis. The Codex Alimentarius Commission was established in 1962 by FAO/WHO of the United Nations to develop an international compilation of food and commodity standards, which includes those pertaining to sugar and many sugar-containing products. In Europe, the European Union (EU) is carrying out a similar function for its member nations. The Nutrition and Labeling Act (NLEA) passed by the U.S. Congress in 1990 has provided some impetus toward developing more accurate analytical methods for sugars.

The International Commission for Uniform Methods of Sugar Analysis (ICUMSA) promulgates official methods of sugar analysis for the cane and beet sugar industry by the standardization and validation of methods through collaborative testing (44). The Corn Refiners Association (CRA) establishes methods used in the corn sugar industry (45). The Association of Official Analytical Chemists (AOAC) reviews methods of sugar analysis along with a vast array of other methods, many of which are required by the U.S. Food and Drug Administration (FDA) for setting standards of identity for foodstuffs and for labeling purposes (46).

At least six specifications of standards for granulated sugar quality are applicable in the United States. These include *Codex Alimentarius*, *Food Chemicals Codex* (FCC) (47), *U.S. Pharmacopeia* (USP) and *National Formulary* (NF) (48), National Soft Drink Association (49), National Canners Association, and

Military Standard-900 for white sugar. These standards are intended to set limits on various components, including, but not necessarily limited to, polarization, invert or reducing sugar, ash, moisture, color, sulfur dioxide, arsenic, lead, and copper.

Sugar trading is controlled by contractual agreements between buyers and sellers. The contracts set specifications and limits and detail the required tests that must be conducted. In the United States, three parties participate in the analyses of raw sugar: the buyer, the seller, and the New York Sugar Trade Laboratory (NYSTL). The settlement value for polarization is determined as the average of the two closest results; if all three results are equidistant, all three results are averaged.

7.1. Product Quality and Requirements. The most common parameters used to measure product quality are moisture, color, granulation, sediment, and ash.

Moisture. Moisture is usually determined by a vacuum oven-dry method at 80°C. Moisture levels of more than 0.05% are likely to lead to caking or lumping problems which can make storage and transfer of bulk sugar difficult. The usual standard is 0.03%, which manufacturers can easily meet. Care must be taken to avoid temperature differentials in storage which cause moisture to migrate and establish pockets of unacceptably high moisture levels.

Color. Color is usually specified as white and measured as a solution color using the specific absorbance at 420 nm. If the measurement is made on a filtered (0.45 μ) solution, it is reported as International Commission for Uniform Methods of Sugar Analysis (ICUMSA) units. More commonly, a second transmittance reading is taken at 720 nm, a turbidity correction made, and the result reported in Reference Basis Units (RBUs). Turbidity can also be used as a quality parameter. Using either scale, sugar begins to be noticeably off-white at about 50 units. The upper limit is usually 35 units, which corresponds to a straw-colored solution at 50% solids. High color in sugar is a harbinger of other problems such as foaming, off-odors, cloudiness or floc, or generally poor performance in production which is why many customers who use sugar in highly colored or opaque products insist on low color sugar.

Granulation. Granulation is important to customers who do not want too much dust (fines), lumps, or grittiness, and/or who have a very specific need to mix the sugar with other dry ingredients or to turn it into a fondant. Customers in the latter categories are willing to pay a premium for specially screened sugar. Beet sugar is commonly produced with crystal sizes in the 0.400 mm range with a coefficient of variation of 25–30%. The size distribution is determined on a stack of three to eight sieves of decreasing sizes using U.S. Sieve values for reference.

Sediment. Sediment is most commonly used as an operational check of filter efficiency and leakage, although some customers, especially those who intend to melt the sugar into clear solutions, write sediment restrictions. The measurement is normally done by passing the 50% solution used for the color determination through a half black–half white filter pad and visually counting the white and black specks.

Ash. This can be determined by a gravimetric method using sulfuric acid to digest the sugar followed by burning in a muffle oven at 650°C. Measuring conductivity on the 50% solution and then referencing this value to the sulfated ash method is much more common. Typical values are 0.003–0.008%, with the upper limit on specifications usually written at 0.015%. Ash is a good indication of the general level of impurities in beet sugar and unacceptably high ash levels usually are accompanied by other problems. This is not an important parameter for cane sugar which can be quite acceptable with ash levels of more than 0.035%.

8. Analytical Methods

8.1. Physical Methods of Sugar Analysis. The concentration of a pure sugar solution is determined by measurements of polarization (optical rotation), refractive index, and density.

Polarimetry. Polarimetry, or polarization, is defined as the measure of the optical rotation of the plane of polarized light as it passes through a solution. Specific rotation $[\alpha]$ is expressed as $[\alpha] = \alpha/lc$, where α is the direct or observed rotation, l is the length in dm of the tube containing the solution, and c is the concentration in g/mL. Specific rotation depends on temperature and wavelength of measurement, and is a characteristic of each sugar; it may be used for identification (50).

Polarization is the most common method for the determination of sugar in sugar-containing commodities as well as many foodstuffs. Polarimetry is applied in sugar analysis based on the fact that the optical rotation of pure sucrose solutions is a linear function of the sucrose concentration of the solution. Saccharimeters are polarimeters in which the scales have been modified to read directly in percent sucrose based on the normal sugar solution reading 100%.

The normal sugar solution corresponds to 26.000 g of pure sugar dissolved in water at 20.000°C to a final volume of 100.000 mL. The International Sugar Scale is calibrated in °*Z*. The 100°*Z* point is the optical rotation of the normal solution of pure sucrose at the wavelength of the green line of the mercury isotope 198 Hg (546.2271 nm *in vacuo*) at 20.00°C in a 200.000-mm tube and is established as 40.777 angular degrees (on the old °*S* scale, this value was 40.765). For other wavelengths, the Bünnagel formula for the rotatory dispersion of sucrose solutions is used. For quartz wedge instruments, the effective wavelength has been fixed at 587.0000 nm, and the 100°*Z* point is established as 34.934 (on the old °*S* scale, this value was 34.924). For the double line of yellow sodium light, the mean effective wavelength has been fixed at 589.4400 nm, and the 100°*Z* point is established as 34.626 (on the old °*S* scale, this value was 34.616) (44). Because of the changeover of the sugar scale from °*S* to °*Z* in 1988, some saccharimeters are calibrated in both scales, as some contracts continue to call for the older scale.

For turbid or colored sugar solutions, such as raw sugar, clarification of the solution is required. Lead acetate solution was used, but with the growing prominence of health and environmental concerns, lead was phased out, and use of other clarification agents, usually based on aluminum salts, was implemented. An alternative to clarification has been to extend the wavelength of determination into a higher wavelength region, namely 880 nm, where a simple filtration to obtain an optically clear solution suffices to obtain a polarimetric reading. Values obtained using different methods of clarification and different wavelengths are not always the same, and issues of equivalence are still being determined.

Polarimetric determination of the sucrose concentration of a solution is valid when sucrose is the only optically active constituent of the sample. In practice, sugar solutions are almost never pure, but contain other optically active substances, most notably the products of sucrose inversion, fructose and glucose, and sometimes also the microbial polysaccharide dextran, which is dextrorotatory. Corrections can be made for the presence of impurities, such as invert, moisture, and ash. The advantage of polarization is that it is rapid, easy, and very reproducible, having a precision of ±0.001°.

The value obtained as a result of a polarization measurement for sucrose is expressed as "pol" or "polarization" or "degrees pol" and not as percentage of sugar, but it is considered to closely approximate the sugar content.

Double Polarization. The Clerget double polarization method is a procedure that attempts to account for the presence of interfering optically active compounds. Two polarizations are obtained: a direct polarization, followed by acid hydrolysis and a second polarization. The rotation of substances other than sucrose remains constant, and the change in polarization is the result of inversion (hydrolysis) of the sucrose.

Refractive Index. The refractometric value of sugar solutions is used as a rapid method for the approximate determination of the solids content (also known as dry substance), because it is assumed that the nonsugars present have a similar influence on the refractive index as sucrose. Measurement is usually carried out on a Brix refractometer, which is graduated in percentage of sucrose on a wt/wt basis (g sucrose/100 g solution) according to ICUMSA tables of refractive index at 20.0°C and 589 nm. Tables are available that give mass fraction corrections to refractometric values at temperatures different from 20°C.

ICUMSA (44) has adopted tables showing the relationship between the concentration of aqueous solutions of pure sucrose, glucose, fructose, and invert sugar and refractive index at 20.0°C and 589 nm.

Equations have been developed that determine the relationship of the refractive index of sucrose solutions between 0–85% concentration, 18–40°C, and 546–589 nm.

Density. Measurement of density is widely used in the sugar industry to determine the sugar concentration of syrups, liquors, juices, and molasses. The instrument used is called a hydrometer or a spindle. When it is graduated in sucrose concentration (percent sucrose by weight), it is called a Brix hydrometer or a Brix spindle. Brix is defined as the percent of dry substance by hydrometry, using an instrument or table calibrated in terms of percent sucrose by weight in water solution. Hydrometers are also graduated in °Baumé, still in use in some industries. The relationship between °Baumé and density, d, in g/cm^3, is °Baumé $= 145(1-1/d)$.

Although spindles are calibrated for pure sucrose, other components are normally present in sugar that contribute to the density, such as ash and invert. Because the densities of these components are not much different from that of sucrose, the spindle value is considered a measure of total dissolved substances.

Purity. This is a widely used expression in the industry and represents, as a percentage, the proportion between polarization (considered a measure of sucrose) and dry solids (usually obtained by refractometry).

$$\text{purity} = 100 \times \text{sucrose}/\text{dry substance}$$

8.2. The Determination of Reducing Sugars.

Many methods exist that utilize the reduction of copper or other compounds by aldose and ketose sugars, the most important being glucose and fructose. In relatively pure samples, it is assumed that the reducing sugars are present in essentially equal quantities of glucose and fructose, which may not be the case. In less pure samples, such as molasses, it is understood that other reducing substances are present, so the test is a general test for reducing substances.

The most common methods for determining reducing sugars are based on the reduction of the copper(II) complex with tartaric acid in alkaline solutions. The differences among them lie mostly in the composition of the alkaline solution. The choice of the method for reducing sugars depends on the concentration of the reducing sugars as well as the product matrix. Because the reaction is not quite stoichiometric, the reagents and procedures for all copper reduction methods are strictly standardized, and large errors result if deviations from the method occur. The methods for reducing sugars are listed as follows.

Lane and Eynon Constant Volume Procedure. Probably the most common test for reducing sugars, this method is based on the reduction of Fehling's solution, Soxhlet's modification. The constant volume modification, a more recent change to the method, has allowed for greater standardization, increased sensitivity, and the use of a simple formula instead of tables to determine the amount of invert. The method determines reducing sugars in the presence of sucrose, and is used for raw cane sugar, cane processing products, and specialty sugars having low levels of invert. This test forms the basis for some molasses purchasing contracts and is required in several standards, including the *National Formulary* and *Food Chemicals Codex*.

Berlin Institute Method. This method is for determination of invert sugar in products containing not more than 10% invert in the presence of sucrose. It is a copper reduction method that utilizes Müller's solution, which contains sodium carbonate.

Emmerich Method. This method is for determination of trace amounts of reducing sugars in pure sucrose and white and refined sugars with reducing sugar content up to 0.15%. The test is carried out in a nitrogen atmosphere and is based on the reduction of 3,6-dinitrophthalic acid.

Knight and Allen. This is a copper reduction method for reducing sugars in white sugar up to 0.02%. It utilizes EDTA to determine excess unreacted copper. Tests undertaken in 1994 to extend the range of this method were unsuccessful. In spite of poor performance in ring tests, it remains an official ICUMSA method.

Luff Schoorl. This method is for the determination of total reducing sugars in molasses and refined syrups after hydrolysis. It is a copper-reducing method that forms the basis of some molasses purchasing contracts.

Ofner Method. This method is for the determination of invert sugar in products with up to 10% invert in the presence of sucrose and is a copper-reduction method that uses Ofner's solution instead of Fehling's. The reduced cuprous oxide is treated with excess standardized iodine, which is black-titrated with thiosulfate using starch indicator.

8.3. Other Methods. *Colorimetric Methods.* Numerous colorimetric methods exist for the quantitative determination of carbohydrates as a group (51). Among the most popular of these is the phenol–sulfuric acid method of Dubois (52), which relies on the color formed when a carbohydrate reacts with phenol in the presence of hot sulfuric acid. The test is sensitive for virtually all classes of carbohydrates. Colorimetric methods are usually employed when a very small concentration of carbohydrate is present, and are often used in clinical situations. The Somogyi method, of which there are many variations, relies on the reduction of cupric sulfate to cuprous oxide and is applicable to reducing sugars.

Enzymatic Methods. Since their earliest use to determine blood glucose, applications of enzyme methods have expanded to include sugar analysis in foodstuffs, beverages, and sugar processing (53). Commercial enzyme analyzers are based on immobilized enzymes embedded in membranes. When the membrane or biosensor contacts a solution of the material to be analyzed, glucose is oxidized by glucose oxidase, releasing hydrogen peroxide, which is then measured electronically, giving an estimation of the amount of glucose present:

$$\beta-\textsc{d}-\text{glucose}+\text{O}_2 \xrightarrow{\text{Glc O}} \text{glucono}-\delta-\text{lactone}+\text{H}_2\text{O}_2$$

Three enzymes are required to determine sucrose: invertase to hydrolyze sucrose and produce α-glucose, mutarotase to produce β-glucose, and glucose oxidase for the standard reaction. Enzyme methods have the advantage of being rapid and simple, requiring little sample pretreatment except for solubilization and dilution. The methods require frequent calibration. Enzyme membranes have variable lifetimes and may need to be replaced frequently. Enzyme analyzers are used for quality control in sugar processing, for monitoring wastewater, and in determining sugar in animal feed.

Chromatographic Methods. These methods are ideally suited for the identification and measurement of individual sugars in many matrices. Chromatographic methods have their widest application in research and in commercial laboratories dealing with food analysis, where both gas liquid chromatography (glc) and high performance liquid chromatography (hplc) are in use. Among the older techniques, paper chromatography is obsolete. Thin-layer chromatography is mostly used for qualitative identification, as quantitation of spots by densitometry has not been widely applied.

Although chromatography offers a more accurate measurement of individual sugars in a sample, it has not supplanted polarization as the method of commerce in the sugar industry. Chromatography lacks the precision of polarimetry, being in the range of 0.5–1.0% for sucrose, about a magnitude higher than polarimetry, and it has longer analysis times. As recently as the early 1980s, the precision of chromatography was in the range of 3–5%. The large improvement in precision is the result of incremental advancements in column technology, flow control, and detection systems. Chromatographic methods have been used to show sources of interference that contribute to inaccuracies in polarimetric measurements (54).

The glc analysis of sugars requires chemical derivatization to produce a volatile molecule. Many derivatization methods for sugars exist, but the simplest and most rapid for routine analysis is silylation to produce trimethylsilyl derivatives. Excess water in the sample interferes and must be carefully controlled. Direct silylation produces single peaks for enantiomerically pure nonreducing sugar, such as sucrose, and multiple peaks for reducing sugars, representing the equilibrium of conformations and anomeric configurations. Reactions are available that produce single peaks, but their use adds to the complexity and time of the analysis. Separation is generally done on methyl silicone or phenyl–methyl silicone phases with detection by flame ionization. Glc analysis is limited to lower molecular weight carbohydrates, and does not usually exceed the level of tri- or tetrasaccharides.

Sugar analysis by hplc has advanced greatly as a result of the development of columns specifically designed for carbohydrate separation. These columns fall into several categories. (*1*) Aminopropyl-bonded silica used in reverse-phase mode with acetonitrile–water as the eluent. (*2*) Ion-moderated cation-exchange resins using water as the eluent. Efficiency of these columns is enhanced at elevated temperature, ca 80–90°C. Calcium is the usual counterion for carbohydrate analysis, but lead, silver, hydrogen, sodium, and potassium are used to confer specific selectivities for mono-, di-, and oligosaccharides. (*3*) Size exclusion columns packed with sulfonated polystyrene–divinylbenzene copolymer using water alone as eluent. These columns are designed primarily for analysis of corn syrups containing oligomeric materials. Larger molecules elute before smaller ones. (*4*) Pellicular anion-exchange columns using dilute sodium hydroxide eluent having pulsed amperometric detection. This latter technique is known variously as high performance anion-exchange chromatography, ion chromatography, hpaec, hpic, or ic.

Near-Infrared Spectroscopy. Near-infrared spectroscopy (nir) is increasingly applied in the sugar industry for several types of analyses (55). Current feasible applications include sucrose, pol, Brix, and purity. The technique has the advantage of requiring little or no sample preparation, having a great saving in time resulting from multiple determinations being done simultaneously, and the elimination of chemical usage. It is a secondary technique, depending on results from the primary techniques for calibration, hence it can only be as precise and accurate as the primary method used for calibration. It is expected to eventually have wide usage in process control (qv) and has already been accepted as a commercial method for payment purposes in at least one country.

8.4. Determination of Other Components. In the sugar industry, where the goal is to determine the exact amount of sucrose present, the analysis of other components is essential to determine purity. The most important of these, besides reducing sugars discussed, are moisture, ash, and color. Also relevant are methods used to determine particle-size distribution and insoluble matter.

Moisture. In relatively pure sugar solutions, moisture is determined as the difference between 100 and Brix. In crystalline products, it is usually determined by loss-on-drying under specified conditions in an oven or by commercial moisture analyzers that have built-in balances. Moisture in molasses and heavy syrups is determined by a special loss-on-drying technique, which involves coating the sample onto sand to provide a greater surface area for oven drying. The result of this test is usually considered dry substance rather than moisture.

Small amounts of moisture (up to about 0.5%) in crystalline sugars can be determined chemically by titration with Karl Fisher reagent. A volumetric Karl Fisher titration procedure for moisture in molasses is accepted by AOAC. Automatic Karl Fisher titrators are available, and as acceptance of pyridine-free reagents increases, their use may increase.

Ash and Inorganic Constituents. Ash may be measured gravimetrically by incineration in the presence of sulfuric acid or, more conveniently, by conductivity measurement. The gravimetric result is called the sulfated ash. The older carbonate ash method is no longer in use. Ash content of sugar and sugar products is approximated by solution conductivity measurements using standardized procedures and conversion factors.

Tests for elements such as arsenic, lead, and copper are specified in the relevant standards. The methods specified are usually of the colorimetric or atomic absorption types.

Color. The visual color, from white to dark brown, of sugar and sugar products is used as a general indication of quality and degree of refinement. Standard methods are described for the spectrophotometric determination of sugar color that specify solution concentration, pH, filtration procedure, and wavelength of determination. Color or visual appearance may also be assessed by reflectance measurements.

Particle-Size Distribution. Particle-size specifications for sugar are not usually a part of the legislated standards, but they are of concern to commercial users and suppliers and are often specified in contracts. Grain-size distribution is determined by using a series of sieves, either hand-sieved or machine-sieved (56).

Insoluble Matter. Insoluble matter in sugar is determined as the dry weight of material left on a filter or membrane after passage of a sugar solution. This may include bits of sand, filtration medium, plant material, and polymeric material.

9. 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 (57).

For many years, there has been concern by medical professionals and nutritionists over the effects of dietary sugar on human health. Sucrose has been implicated as a cause of juvenile hyperactivity, tooth decay, diabetes mellitus, obesity, atherosclerosis, hypoglycemia, and nutrient deficiencies.

In 1986, the FDA's Sugars Task Force assessed the impact of sugar consumption on human health and nutrition and concluded that sucrose is not an independent risk factor for heart disease, nor does it cause or contribute to the development of diabetes (58). Although diet is important after the onset of diabetes, sucrose can be well tolerated by insulin-dependent diabetics (59-61).

Other studies indicate that sucrose does not cause hyperactivity. Carbohydrate ingestion increases levels of serotonin (5-hydroxytryptamine), a brain neurotransmitter that promotes relaxation and sleep. Dietary sucrose should theoretically have a calming effect and reduce activity, manifestations which have been observed in case studies (59). To date, clinical investigations have failed to show a significant connection between sucrose consumption and aggressive or disruptive behavior (62).

The rising incidence of obesity has not paralleled sucrose consumption. The FDA Task Force concluded that sugars have no unique role in obesity and that dietary fat rather than carbohydrate is a significant contributor to this condition (58,63,64). However, sugar can promote weight gain in individuals with lifestyles marked by excess caloric intake and insufficient exercise.

The notion that complex carbohydrates elicit a gradual, steady secretion of insulin while sugars cause a sudden release of this hormone accompanied by a rapid drop in blood glucose has fostered the belief that hypoglycemia is affected by sucrose ingestion. However, research does not support this conclusion (59).

The Sugars Task Force's Select Committee on Nutrition and Human Needs recommended a daily consumption of sugars at 10% of total calories, which approximates current (11%) daily intake levels in the United States. At this level, sucrose does contribute to the development of dental caries; however, no firm evidence exists that it causes dietary imbalances or deficiencies of vitamins (qv), minerals, or trace nutrients (58).

10. Uses

10.1. Sucrose.

Food Applications. On the basis of intake, sucrose is the leading food additive (2). Its principal contribution to food is sweetness. However, it provides many other functionalities, eg, body, mouthfeel, texture, and moisture retention. Cereals and baked goods are the leading consumers of sucrose, followed closely by confectionery products (65).

Sucrose helps minimize earthy tastes of vegetables, while enhancing inherent flavors and aromas, and preserving color and texture (66). Addition of sucrose inhibits enzymatic browning of canned and frozen fruits, and prevents loss of color, flavor, and aroma from fruit during processing (67).

In baking, chemicals produced from sucrose by yeast contribute to bread flavor and sponginess of the dough (68); during cooking, reducing sugars formed by sucrose inversion combine with amino acids to form Maillard reaction products called melanoidins that impart brown color to breads, cakes, cookies, and cereals (12,13). Sugar raises the gelatinization temperature of starch, so cakes and breads rise more during baking and become softer and lighter (67). Sucrose also improves moisture retention by baked goods so they remain fresh for longer periods.

Subthreshold levels of sucrose enhance meat flavor (13); in cured meats, sucrose is a preservative and improves flavor by reducing the salty taste (67). Similarly, the acidity of condiments is softened by sugar. Sucrose stabilizes protein foams in meringues, and imparts body and smoothness to sauces and puddings. In candy mixes, sucrose raises the cooking temperature and minimizes formation of small sugar crystals during cooling. The reaction of milk proteins with sugars produces the caramel flavor in some candies (12).

Sucrose is often used as a decorative agent to impart a pleasing appearance to baked goods and confections (65). In jams and jellies, sugar raises osmotic pressure and lowers water activity to prevent spoilage (12). Sucrose is a fermentation substrate for lactic acid in cultured buttermilk (69) and lowers the freezing point of ice cream and other frozen desserts to improve product mouthfeel and texture.

Feedstock for Chemical Synthesis. It is estimated that $<0.5\%$ of the sucrose produced each year is used for nonfood purposes (70). An alternative application, namely the production of chemicals, is an attractive option as the feedstock is plentiful, renewable, and of consistently high purity. Moreover, the biodegradability of many sucrochemicals makes them environmentally friendly.

Sucrose reacts with fatty acids to produce esters with degrees of esterification (DE) from 1 to 8 and hydrophilic/lipophilic balances that provide them with numerous applications. Sucrose esters are nontoxic and biodegradable, and are approved for use in the EC, Japan, and the United States.

Sucrose monoesters (SMEs) are used as nonionic surfactants, in detergents and as emulsifiers in foods. Some SMEs have bacteriostatic activity and are used to prevent spoilage in beverages. Semperfresh, an SME produced in the U.K., is used as a coating to extend the shelf life of fruits and vegetables (15,29).

Sucrose esters of mixed degree of esterification improve flour and starch quality, prevent amylose crystallization in baked goods and help maintain crispiness in cereals and other starch-based snacks. They also prevent sugar crystallization in jams, jellies, and ice cream, and ice crystal growth in frozen desserts. In sugar manufacture, sucrose esters improve sucrose recovery from low grade massecuites. Other sucrose esters are used as alcohol denaturants, plasticizers, lubricants, bleach boosters, and in lacquer, ink, and cosmetic formulations (10,15,29,70).

Sucrose acrylate derivatives can be converted into polymers and hydrogels that can be used as flocculants, water adsorbents, bioimplantables, and drug delivery devices (71). Sucrose ethers have applications as surfactants and surface coatings, and as feedstocks for synthesis of polyurethane foams and plastics used for insulation, packaging materials, and wood replacements in furniture (15,70,72). Controlled oxidation of sucrose produces carboxylic acid derivatives used as cross-linking agents and detergent additives.

A chlorination process (14,15,73–75) converts sucrose into sucralose [56038-13-2] (4,1′,6′-trichloro-4,1′,6′-trideoxy-galactosucrose), a heat-stable, noncariogenic, noncaloric, high intensity sweetener. Sucralose is approved for food use in Canada, Australia, Russia, and the United States. McNeil Specialities markets sucralose as Splenda.

Several interesting and useful sucrose derivatives are enzymatically synthesized. One of these, called coupling sugar, is a mixture of glucosyl- and maltooligosyl-sucroses formed from starch hydrolysates and sucrose by cyclodextrin-transferase and is used as a noncariogenic sweetener in Japan (76). Similarly, fructosyloligosaccharides (FOS) are mixtures of fructosyl sucroses made from sucrose by fungal invertases (15,76–78) and are used in foods in Japan and Europe. Although less sweet than sucrose, FOSs are noncariogenic and noncaloric, and they promote the growth of beneficial intestinal flora (Bifidobacteria).

Actilight, eg, a mixture of D-glucose, sucrose, and fructooligosaccharides with one to three fructofuranosyl residues linked by way of β-(1→2) bonds to the fructosyl moiety of sucrose, is commercially produced by microbial fermentation of sucrose using fructosyl transferase enzyme from *Aspergillus niger*. It is marketed by Bighen Meiji. Actilight has obtained GRAS (Generally Regarded as Safe) status in the U.S. It is a recognized food ingredient in Europe (79).

Fermentation Feedstock. Sucrose, in the form of beet or cane molasses, is a fermentation feedstock for production of a variety of organic compounds, including lactic, glutamic, and citric acids, glycerol, and some antibiotics. Lesser amounts of itaconic, aconitic, and kojic acids, as well as acetone and butanol, are also produced (70,80–82). Rum is made by fermentation of cane molasses. Beet and cane molasses are used for production of baker's and brewer's yeast (qv).

A more abundantly produced substance is ethanol for use in alcoholic beverages, and as a fuel, solvent, and feedstock for organic syntheses. Ethanol (qv) production from sucrose is carried out in Europe (eg, France and the Netherlands), India, Pakistan, China, and on a very large scale in Brazil, where it is used as a motor fuel. A valuable by-product of ethanol fermentation is industrial CO_2 (see Carbon dioxide).

The above chemicals can be obtained by fermentation (qv) of other sugars. However, some compounds require sucrose as a unique feedstock. Examples are the polysaccharides dextran, alternan, and levan, which are produced by specific strains of bacteria (77,83–85). Dextrans are used to make chromatographic separation media, and sulfated dextran derivatives are used as plasma extenders (70). Levans show promise as sweetness potentiators and, along with alternan, have potential as food thickeners and bulking agents in reduced-caloric foods (84,85) (see Carbohydrates).

Sucrose is also a fermentation feedstock for production of palatinose [13718-94-0] (6-*O*- α-D-glucopyranosylfructose, or isomaltulose) and leucrose [7158-70-5] (5-*O*- α-D-glucopyranosylfructose). Palatinose is produced by fermentation using *Protaminobacter rubrum*, or enzymatically using α-glucosyltransferase; leucrose is produced by *Leuconostoc mesenteroides*. Both sugars are used as noncariogenic sweeteners in Japan and Europe (76,77,86).

Pharmaceutical Applications. Sucrose has a long history in the manufacture of pharmaceuticals. It imparts body to syrups and medicinal liquids and masks unpleasant tastes. Sucrose also functions as a diluent to control drug concentrations in medicines, as an ingredient binder for tablets, and to impart chewiness to the latter. Sustained-release medications and protective tablet glazes are prepared using sucrose (70). Sucrose-based sugar pastes are used to promote wound healing (87).

Sucralfate [54182-58-0], an aluminum salt of sucrose octasulfate, is used as an antacid and antiulcer medication (88). Bis- and tris-platinum complexes of sucrose show promise as antitumor agents (89). Sucrose monoesters are used in some pharmaceutical preparations (15). A sucrose polyester is under evaluation as a contrast agent for magnetic resonance imaging (mri) (90). Oral administration of this substance opacifies the gastrointestinal tract and eliminates the need for purging prior to mri.

10.2. 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.

10.3. Specialty Sugars. Specialty sugars do not seem to be tightly defined either in the United States or Europe. Descriptions that follow are from various sources. Since there are no official definitions, the products can be whatever the manufacturer wants them to be as long as they have the generally expected appearance. They do, however, are considered by health food devotees as more natural than refined sugar and considered to have a higher iron and nutrient content (91).

Demerara Sugar. This sugar is named from the Demerara area of Guyana, South America, from which it originally came. It is often described as a natural, unrefined cane sugar. It is a light brown sugar with large, lightly sticky crystals. Maruitius is the major supplier. It is very popular for tea and coffee in England, Australia, and Canada. It is not well known in the U.S.

Muscovado Sugar. This sugar is very dark brown with a strong molasses flavor. The crystals are larger than brown sugar, but not as large as turbinado or demerara sugar. The flavor is said to be strong, deep, dark, etc. Muscovado is an old term that was synonymous with raw sugar. Barbados sugar is a term often used as a synonym for muscovado sugar.

Turbinado Sugar. This sugar is partially refined raw sugar from which some of the molasses film has been removed. Its color ranges from golden to brown with large crystals and a mild, cane flavor.

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.

10.4. 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.

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 (36,92,93), 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 (92,93). 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 (93).

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.

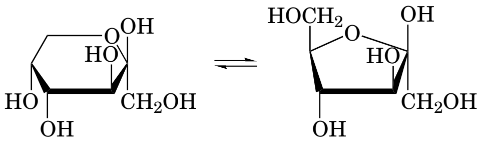
11. Special Sugars

Although sucrose is commercially the most important sugar, there are also special sugars with special applications, among which fructose is the most important.

11.1. Fructose. D-Fructose [57-48-7] (levulose, fruit sugar) is a monosaccharide constituting one-half of the sucrose molecule. It was first isolated from hydrolyzed cane sugar (invert sugar) in the late nineteenth century (94,95). Fructose constitutes 4–8 wt % (dry sugar basis (dsb)) of many fruits, where it primarily occurs with glucose (dextrose) and sucrose (see Carbohydrates; Sweeteners). It also makes up 50 wt % (dsb) of honey (96,97).

Despite this ubiquity, fructose remained a noncommercial product until the 1980s because of the expense involved in its isolation and the care required for its handling. The development of technologies for preparing fructose from glucose in the isomerized mixture led to a greater availability of pure, crystalline fructose in the 1970s (98–100). However, the price for pure fructose was high enough in 1981 that the product was not competitive with sucrose and corn syrups as a commercial sweetener (see Syrups). With the entry of corn wet-milling companies into the crystalline fructose market in the late 1980s, raw material economies and enlarged manufacturing scale led to a nearly 10-fold production increase within a five-year period, making fructose prices competitive with other sweeteners for specific applications.

Pure D-fructose is a white, hygroscopic, crystalline substance and should not be confused with the high fructose corn syrups (HFCS) which may contain 42–90 wt % fructose and 23–29% water (101,102). The nonfructose part of these syrups is glucose (dextrose) plus small amounts of glucose oligomers and polymers. Fructose is highly soluble in water; at 20°C it is 79% soluble, compared with only 47% for glucose and 67% for sucrose.



(1) **(2)**

The sweetness of fructose is 1.3–1.8 times that of sucrose (103). This property makes fructose attractive as an alternative for sucrose and other commercially available sweeteners. Fructose is probably sweetest in comparison with sucrose when cold and freshly made up in low concentrations at a slightly acidic pH (5). This relative sweetness difference is commonly attributed to changes in fructose structure when cold (β-D-fructopyranose (**1**), sweet) as compared to the structure when the sweetener is warm (β-D-fructofuranose (**2**), less sweet). Based on nmr spectroscopy and sensory panel evaluation of sweetness, however, it has been observed that the absolute sweetness of fructose is the same at 5°C as at 50°C, and is not dependent on anomeric distribution (104). Rather, it may be the sweetness of sucrose, which changes with temperature, that gives fructose sweetness the appearance of becoming sweeter at low temperatures.

Also notable is the unique sweetness response profile of fructose compared to other sweeteners (96,97). In comparison with dextrose and sucrose, the sweetness of fructose is more quickly perceived on the tongue, reaches its intensity peak earlier, and dissipates more rapidly. Thus, the sweetness of fructose enhances many food flavor systems, eg, fruits, chocolate, and spices such as cinnamon, cloves, and salt. By virtue of its early perception and rapid diminution, fructose does not have the flavor-masking property of other common sugars.

The sweetness of fructose is enhanced by synergistic combinations with sucrose (105) and high intensity sweeteners (106), eg, aspartame, saccharin, acesulfame K, and sucralose. Information on food application is available (107,108). Fructose also reduces the starch gelatinization temperature relative to sucrose in baking applications (109–111).

Fructose possesses colligative properties that distinguish it from sucrose, glucose, and other nutritive sweeteners. It is one of the more effective monosaccharide humectants, binding moisture and lowering water activity, A_w, in food applications, thereby rendering the food products less susceptible to microbial growth and more stable to moisture loss (96,97). Ratios of fructose and higher molecular weight saccharides, oligosaccharides, and polysaccharides can be balanced to give increased control over freezing temperatures and storage stability in frozen products.

Fructose is a highly reactive molecule. When stored in solution at high temperatures, fructose not only browns rapidly but also polymerizes to dianhydrides [38837-99-9], [50692-21-2], [50692-22-3], [50692-23-4], [50692-24-5]. Fructose also reacts rapidly with amines and proteins in the nonenzymatic or Maillard browning reaction (98). This is a valued attribute in baked food products where crust color is important. An appreciation of these properties allows the judicious choice of conditions under which fructose can be used successfully in food applications.

Because of its relatively high degree of sweetness, fructose has been the object of commercial production for decades. Early attempts to isolate fructose from either hydrolyzed sucrose or hydrolyzed fructose polymers, eg, inulin (Jerusalem artichoke), did not prove economically competitive against the very low cost for sucrose processed from sugarcane or sugar beets.

Commercial quantities of crystalline fructose initially became available when the Finnish Sugar Company developed ion-exchange methods first for hydrolyzing sucrose and then for separating the hydrolysate into the constituents, ie, glucose and fructose. The latter step involves the calcium form of a sulfonated-polystyrene ion-exchange resin. Further economies in production were realized when the same company developed a method for crystallizing fructose from an aqueous rather than a water–alcohol solution (98).

Other technologies also involve ion-exchange separation of fructose from glucose in a mixture obtained through the isomerization of glucose by means of immobilized glucose isomerase or microbial cells containing the enzyme (100), a technique pioneered by Hoffmann-La Roche. Another procedure for making crystalline fructose has been detailed (112), in which glucose (dextrose) is oxidized by glucose-2-oxidase to glucosone, which is then selectively hydrogenated to fructose. This procedure has the advantage of not requiring isomer separation in order to isolate the crystalline product.

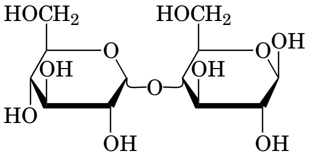
Early applications of crystalline fructose focused on foods for special dietary applications, primarily calorie reduction and diabetes control. The latter application sought to capitalize on a significantly lower serum glucose level and insulin response in subjects with noninsulin-dependent diabetes mellitus (113,114) and insulin-dependent diabetes (115). However, because fructose is a nutritive sweetener and because dietary fructose conversion to glucose in the liver requires insulin in the same way as dietary glucose or sucrose, recommendations for its use are the same as for other nutritive sugars (116). Review of the health effects of dietary fructose is available (117).

Fructose has been successfully incorporated into formulas for the preparation of light and reduced calorie beverages and sports beverages; table syrup and table top sweeteners; baked goods; dairy products, including yogurt and chocolate milk; jams, jellies, and preserves; dry mix beverages, puddings, gelatins, and cake mixes; confectionery caramel fillings and starch-based jelly candies; and frozen dairy products and novelties (see Food processing).

Because of its hygroscopicity, fructose must be properly dried, packaged, and stored to prevent lumping and preserve free-flowing handling. Recommended storage and bulk handling conditions call for conditioned air at a relative humidity of less than 50% and a maximum temperature of 24°C (102).

11.2. Maltose.

Maltose [69-79-4] (malt sugar) is a disaccharide, 4-*O*-α-D-glucopyranosyl-D-glucose (**3**), comprising two molecules of glucose (dextrose). Although occurring in some plants and fruits (118,119), it is more frequently recognized as a structural component of starch. Pure maltose is isolated with difficulty from a directed starch hydrolysate, ie, high maltose corn syrup, by precipitation with ethanol. Purification can be achieved by way of the β-maltose octaacetate. Removal of the acetate groups allows crystallization of the monohydrate of β-maltose. Commercial maltose typically contains 5–6 wt % of the trisaccharide maltotriose with traces of glucose (120). High maltose syrups from starch typically contain ca 8–9 wt % glucose, 40–80 wt % maltose, with higher saccharides as the remainder (121,122).

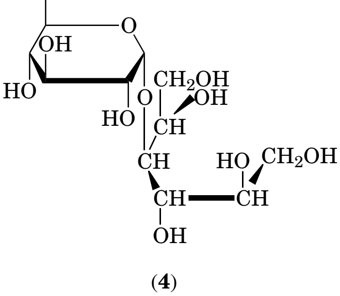


(**3**)

Such syrups are used in the preparation of confections, preserves, and other foodstuffs. The maltose in malt syrups is important in brewing (see Beer). Intravenous feeding (primarily in Europe and Japan) and sports beverage formulations take advantage of the fact that energy release from maltose becomes accessible to the body at a slower rate than energy supplied by monosaccharides (123).

Important physical and functional properties of maltose and maltose syrups include sweetness, viscosity, color stability, humectancy, freezing point depression, and promotion of beneficial human intestinal microflora growth. Maltose possesses ca 30–40% of the sweetness of sucrose in the pure state (124).

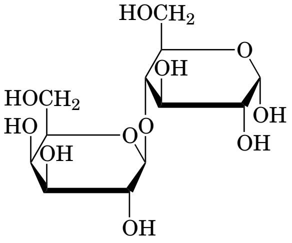
Hydrogenation of high maltose syrups gives a mixture of sugar alcohols, from which maltitol [585-88-6] (**4**) can be isolated in crystalline form. Maltitol is almost as sweet as sucrose (0.9 times) and has been promoted as a sweetener in various food applications (125).



(**4**)

11.3. Lactose.

Lactose [63-42-3] (milk sugar) is the only commercially available sugar that is derived from animal rather than plant sources. It is a disaccharide consisting of one galactose and one glucose moiety, 4-*O*-β-D-galactopyranosyl-D-glucose (**5**). The concentration of lactose in milk products ranges from 4.8 wt% in whole milk to 73.5 wt% in sweet dried whey (126). There have been reports of the presence of lactose in plant materials, eg, sapote and acacia, but this has not been confirmed (127,128).



(**5**)

Lactose is isolated commercially as the crystalline α-monohydrate from the whey by-products of cheese or caseinate production. It is available in varying degrees of purity. Fermentation grade is 98 wt% pure, whereas USP lactose is refined to 99.8 wt% purity (129). Although the α-monohydrate is the commercially available form of lactose, the sugar can be crystallized at high temperature to give the β-anhydride [56907-28-9]. The sugar is not very soluble in water (ca 22 g/100 g water at 25°C), nor is it very sweet (ca one-fifth the sweetening power of sucrose) (130). Lactose is a reducing sugar that reacts with amines and amino compounds with resultant browning.

Uses of lactose production by application include baby and infant formulations, human food, pharmaceuticals, and fermentation and animal feed. It is used as a diluent in tablets and capsules to correct the balance between carbohydrate and proteins in cow-milk-based breast milk replacers, and to increase osmotic property or viscosity without adding excessive sweetness. It has also been used as a carrier for flavorings, volatile aromas, and synthetic sweeteners. Physiologically, lactose promotes the absorption of calcium, phosphorus, and essential trace minerals; has low cariogenicity; and is more slowly and gradually absorbed than sucrose, therefore of potential benefit to diabetes mellitus patients (130).

Lactose, and the lactose in substances such as milk and whey, has been hydrolyzed commercially by enzymes to yield products that can be tolerated physiologically much more easily by people who have a lactose intolerance (131–133).

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Table 1. **Physical Properties of Sucrose**[a]

Property	Value
density, d_4^{15}, kg/m^3	1587.9
melting point, °C	160–186 dec
specific rotation, degrees	+66.53
solubility in water at 20°C, g/g	2.00
apparent molar volume at 20°C, cm^3/mol	209.5
specific heat, J/mol[b]	
crystalline, at 20°C	415.8
amorphous, at 22°C	90.2
heat of solution, kJ/mol[b]	4.75 ± 0.26
dipole moment, C·m[c]	3.1×10^{-18}
enthalpy of crystallization at 30°C, kJ/mol[b]	10.5
bulk density, kg/m^3	
crystalline	930
powdered	600
normal entropy, J/(mol·K)[b]	360.5
angle of repose, degree	34

[a] Refs. 7–10.

[b] To convert J to cal, divide by 4.184.

[c] To convert C·m to debye, multiply by 3×10^{29}.

Table 2. **Relative Sweetness of Sucrose and Other Sweet Substances**[a]

Sweetener	Relative sweetness	Sweetener	Relative sweetness
fructose	1.2–1.8	saccharin	250–550
sucrose	1.00	aspartame	120–200
glucose	0.60	sucralose	550–750
maltose	~0.5	cyclamate	30–50
lactose	0.15–0.30	acesulfame K	~200
galactose	0.32	alitame	2000

[a] Refs. 12, 14–16.

Table 3. **Bulk Density of Sugars**

Sugar type	Typical values[a] kg/m^3	Typical values[a] 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 4. **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 $S = 64.447 + 8.222 \cdot 10^{-2}t + 1.6169 \cdot 10^{-3}t^2 - 1.558 \cdot 10^{-5}t^3 - 4.63 \cdot 10^{-8}t^4$.

[b] L_t = gram sucrose per gram water.

Table 5. **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. 22.

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

Table 6. **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 7. **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.

Table 8. **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	

Table 9. **Material Balance and Purity Effects of Thick Juice Purity**[a]

	Low purity juice		High purity juice	
Material	Sugar, kg	Purity, %	Sugar, kg	Purity, %
thick juice	100.0	88.0	100.0	92.0
white pan	208.2	93.5	143.8	93.9
intermediate pan	72.8	83.4	50.3	84.5
low pan	32.8	69.1	22.6	70.8
molasses	16.2	54.3	11.2	56.3
product	83.8		88.8	

[a] Purity = sugar content as percent of total dissolved solids content.

Table 10. **U. S. Sugar Refining Capacity in 2005**[a]

Location	Daily capacity[b]	Monthly capacity	Yearly capacity[c]
Baltimore, Md.	3,000	85,000	1,020,000
Chalmette, La.	3,100	87,833	1,054,000
Clewiston, Fla.	2,400	68,000	816,000
Crockett, Calif.	3,400	96,333	1,156,000
Gramercy, La.	2,200	62,333	748,000
Port Wentworth, Ga.	3,150	89,250	1,071,000
South Bay, Fla.	1,100	31,167	374,000
Yonkers, N.Y.	2,000	56,667	680,000
Total	*20,350*	*576,583*	*6,919,000*

[a] Source: U.S. Cane Sugar Refiners Assoc. and Ref. 43.

[b] 24 hour melting capacity.

[c] 340 days.

Table 11. **Estimated U. S. Sugar Deliveries and Sugar in Traded Sugar-containing Products, 1000 STRV**[a,b]

Fiscal year	Population	Oct.-Dec.	Jan.-Mar.	Apr.-June	July-Sept.	FY total	Per capita[c]
Domestic sugar deliveries for food and beverage use							
1993	260.3	2,280	2,046	2,172	2,432	8,930	64.1
1994	263.4	2,277	2,121	2,265	2,533	9,196	65.2
1995	266.6	2,260	2,105	2,311	2,542	9,218	64.6
1996	269.7	2,379	2,191	2,355	2,519	9,445	65.5
1997	272.9	2,430	2,143	2,401	2,591	9,565	65.5
1998	276.1	2,443	2,233	2,428	2,568	9,672	65.5
1999	279.3	2,458	2,208	2,553	2,655	9,873	66.1
2000	282.3	2,580	2,318	2,484	2,611	9,993	66.2
2001	285.0	2,564	2,370	2,486	2,680	10,000	65.6
2002	287.7	2,474	2,227	2,439	2,645	9,785	63.6
2003	290.3	2,497	2,183	2,360	2,464	9,504	61.2
2004	293.0	2,504	2,286	2,368	2,520	9,678	61.7
2005	NA[d]	2,563	2,325	2,483			
Estimated sugar in imported sugar-containing products							
1993		73	79	76	70	298	
1994		73	59	64	78	274	
1995		75	79	86	95	335	
1996		95	80	89	104	368	
1997		107	95	112	122	437	
1998		121	110	132	144	507	
1999		136	133	152	168	589	
2000		167	153	167	181	668	
2001		179	166	184	207	736	
2002		208	184	210	238	841	
2003		228	217	243	273	961	
2004		258	241	273	299	1,072	
2005		279	261	275			
Est. sugar in exported sugar-containing products							
1993		59	56	52	62	229	
1994		74	63	63	68	267	
1995		68	74	78	91	311	
1996		97	85	90	103	376	
1997		103	98	102	108	411	
1998		109	91	98	103	401	
1999		106	96	99	109	409	
2000		116	104	107	128	456	
2001		134	115	129	130	508	
2002		130	112	118	125	485	
2003		138	123	130	140	531	
2004		150	137	140	148	575	
2005		152	139	153			
Est. sugar in USDA sugar-containing product re-export program							
1993		26	23	26	57	132	
1994		24	20	39	43	126	
1995		28	18	18	39	103	
1996		21	20	30	32	104	
1997		22	68	22	45	157	
1998		21	24	32	46	123	
1999		44	58	35	32	169	
2000		21	21	22	22	86	

2001	18	21	29	30	98	
2002	40	39	35	42	156	
2003	43	44	49	47	183	
2004	35	28	40	39	142	
2005	28	24	37			
Est. sugar deliveries for domestic consumption (adj. for trade in sugar-containing products)						
1993	2,320	2,092	2,222	2,497	9,131	65.6
1994	2,300	2,137	2,304	2,588	9,329	66.2
1995	2,295	2,128	2,337	2,584	9,345	65.5
1996	2,398	2,206	2,384	2,552	9,540	66.1
1997	2,457	2,209	2,432	2,650	9,747	66.8
1998	2,476	2,276	2,494	2,655	9,901	67.0
1999	2,532	2,303	2,641	2,746	10,222	68.4
2000	2,652	2,387	2,566	2,686	10,292	68.1
2001	2,626	2,442	2,569	2,888	10,326	67.7
2002	2,592	2,338	2,567	2,800	10,297	66.9
2003	2,630	2,321	2,521	2,645	10,116	65.1
2004	2,647	2,419	2,540	2,711	10,317	65.8
2005	2,718	2,470	2,642			

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[a] Source: USDA (deliveries data), ERS (sugar in traded products) and Ref. 43.

[b] includes Puerto Rico.

[c] Pounds (refined value).

[d] NA = not available.

Table 12. **Sector Composition of ERS Stochastic Sugar Delivery Projections Model**[a]

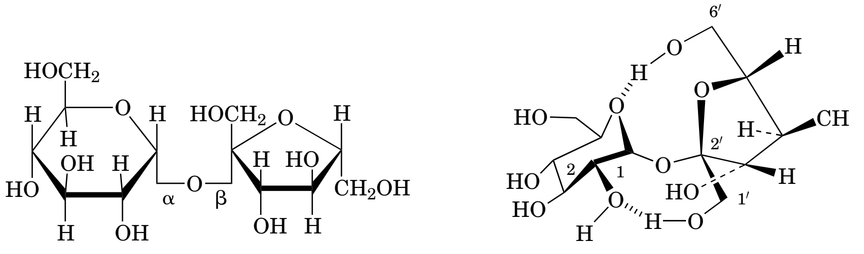
Eqn. No.	End user sector description	Eqn. No.	Combines data from *Sweetener Market Data*:	Eqn. No.	With data from sugar est. in sugar-containing products from following HTS chapters[a]
1	bakery/cereal	9	bakery, cereal, and related products	17	HTS chapter 19 - Preparations of cereals, flour, starch or milk; bakers' wares
2	confectionery	10	confectionery and related products	18	HTS chapter 1704 - Sugar confectionery, not cont. cocoa
				19	HTS chapter 1806 - Chocolate and other food prep. cont. cocoa
3	beverages	11	beverages	20	HTS Chapter 2202 - Carbonated soft drinks
4	processed foods	12	canned, bottled, and frozen foods	21	HTS Chapter 21 - Misc. edible preparations
5	multiple uses	13	multiple and all other food uses		
6	dairy	14	ice cream and dairy products		
7	nonfood	15	nonfood uses		
8	nonindustrial	16	hotels, restaurants, and institutions wholesale grocers, jobbers, dealers retail grocers, chain stores Government agencies all other deliveries		

[a] Ref. 43.

Table 13. **U. S. Sugar Supply and Use**[a]

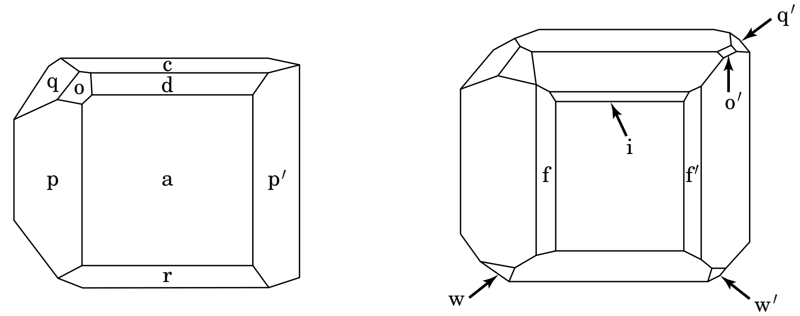
Item	2003/04	2004/05	2005/06 Projections	
			June	July
	1,000 short tons, raw value			
beginning stocks	1,670	1,897	1,343	1,476
production	8,649	8,110	8,140	8,152
beet sugar	4,692	4,721	4,370	4,443
cane sugar	3,957	3,389	3,770	3,709
Florida	2,154	1,690	1,950	1,899
Hawaii	251	268	250	254
Louisiana	1,377	1,271	1,400	1,376
Texas	175	160	170	180
imports	1,754	1,729	1,591	1,591
TRQ	1,230	1,209	1,206	1,206
other program	464	400	325	325
other	60	120	60	60
Supply, total	*12,073*	*11,736*	*11,074*	*11,219*
exports	288	240	200	200
deliveries	9,862	10,020	10,115	10,115
food	9,678	9,875	9,950	9,950
other	184	145	165	165
miscellaneous	26	0	0	0
Use, total	10,176	10,260	10,315	10,315
ending stocks	1,897	1,476	759	904
stocks to use ratio	18.6	14.4	7.4	8.8

[a] Ref. 43, FY begins Oct. 1 and includes Puerto Rico.



(a) (b)

Fig. 1. Structural representations of sucrose: (**a**) Haworth perspective formula, and (**b**) conformational structure of sucrose in solid crystals. Adapted from Ref. 1.



(a) (b)

Fig. 2. Normal sucrose crystal showing: (**a**) a combination of the eight most important and frequent forms (aopp′drqo), and (**b**) the 15 simple forms determined with certainty for sugar crystals (acpp′droo′qq′ww′ff′i) (19).

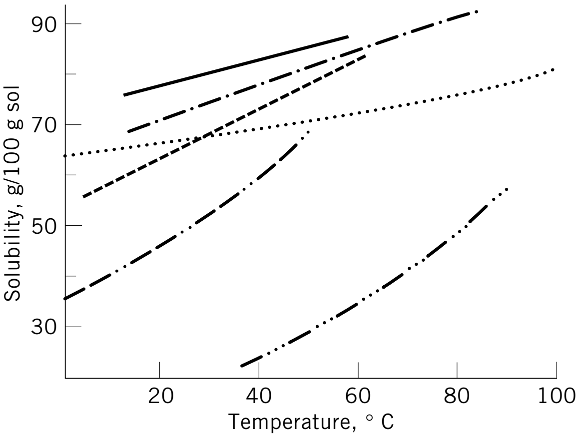


Fig. 3. Solubility of some sugars, where (——) represents fructose; (– · –), sorbitol; (–), xylitol; (····), sucrose; (–··–), glucose; (–···–), lactose.

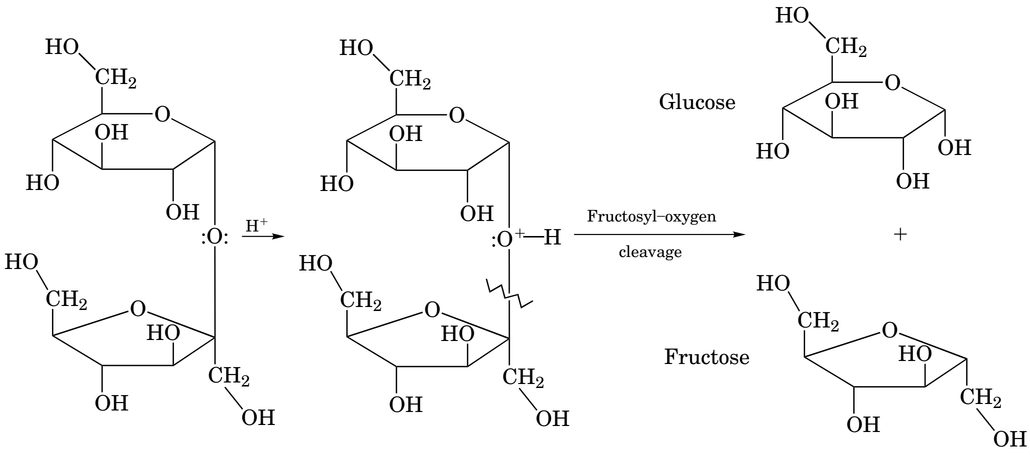


Fig. 4. Inversion of sucrose into glucose and fructose.

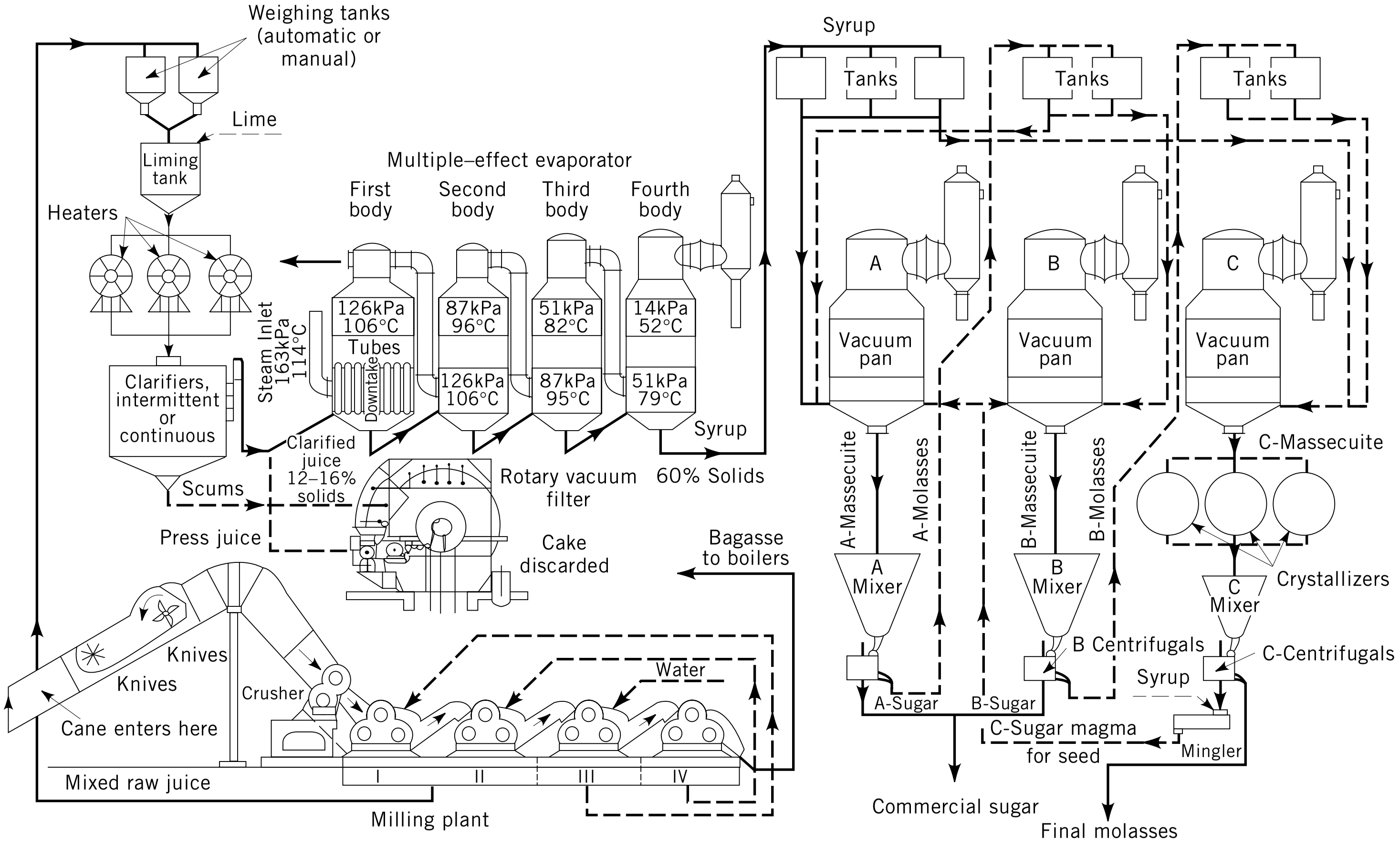


Fig. 5. Flow diagram of a raw sugar factory. To convert kPa to psia, multiply by 0.145.

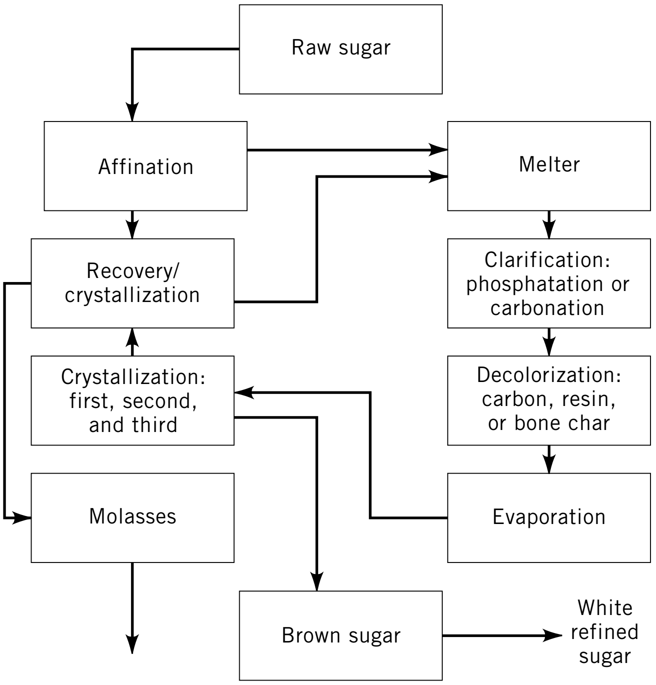


Fig. 6. Outline of a cane sugar refinery process.

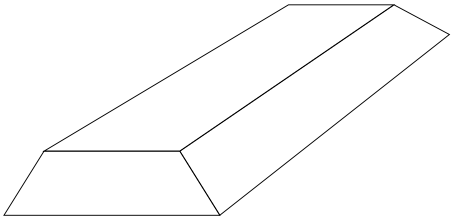


Fig. 7. Typical shape of a pile of stored sugar beets.

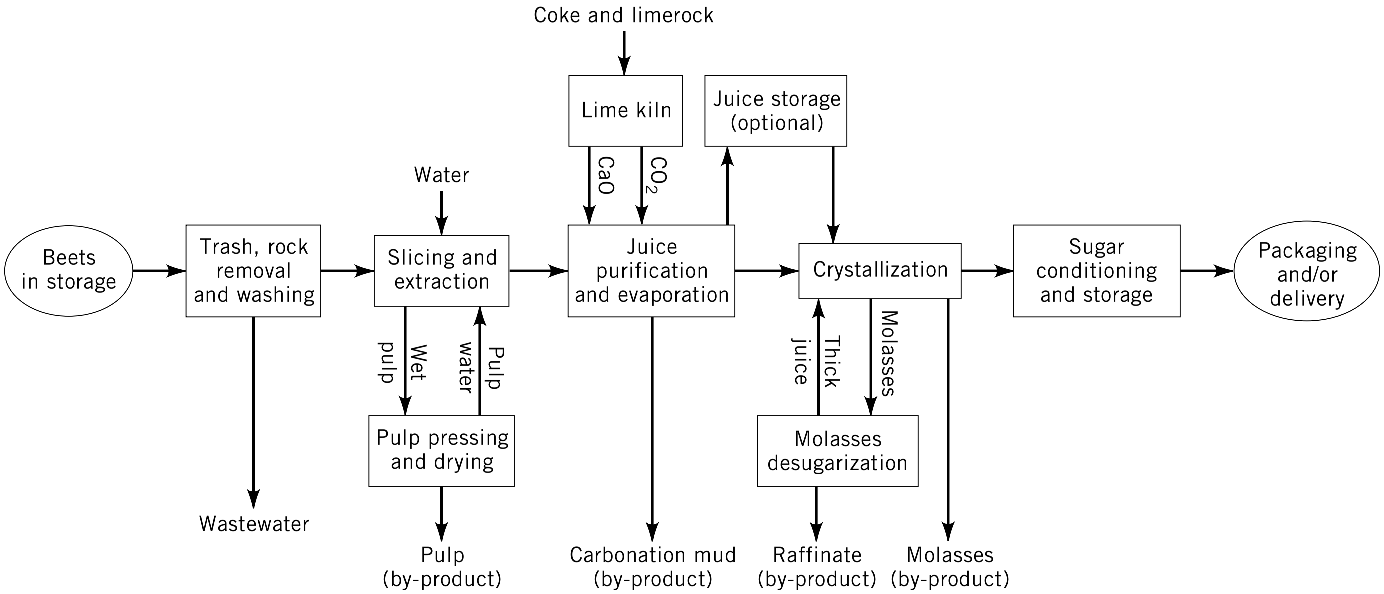


Fig. 8. Basic schematic of a beet sugar factory.

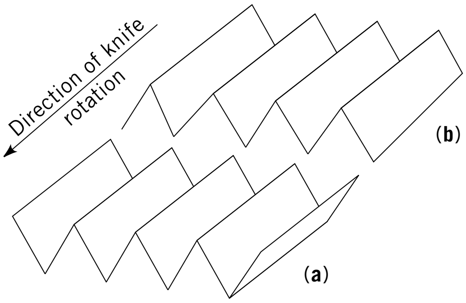


Fig. 9. Offset arrangement of slicer knives where (**a**) shows the first cutting edge, and (**b**), the second.

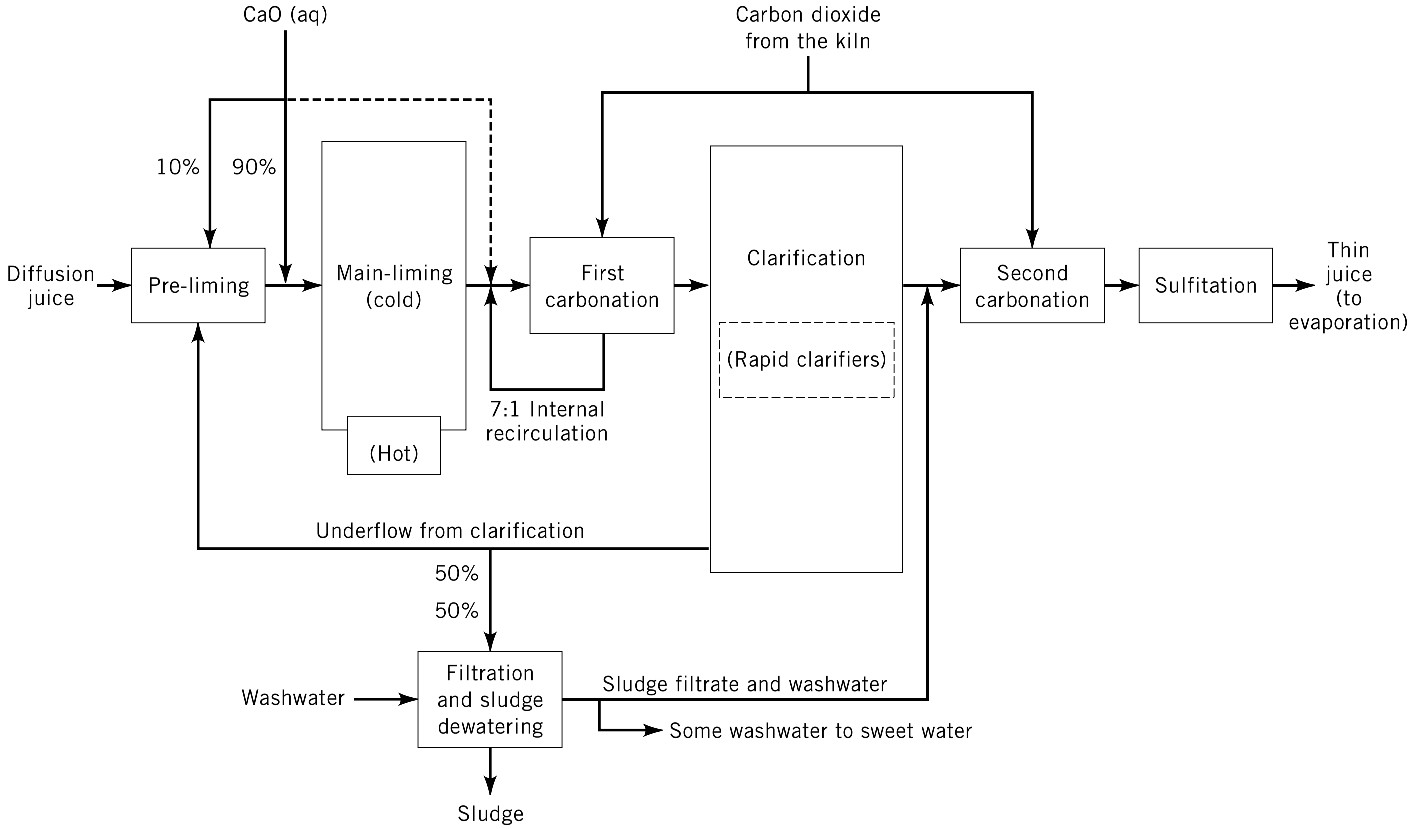


Fig. 10. Juice purification unit operation schematic where retention times are proportional to the size of the boxes and (–) are common optional processes.

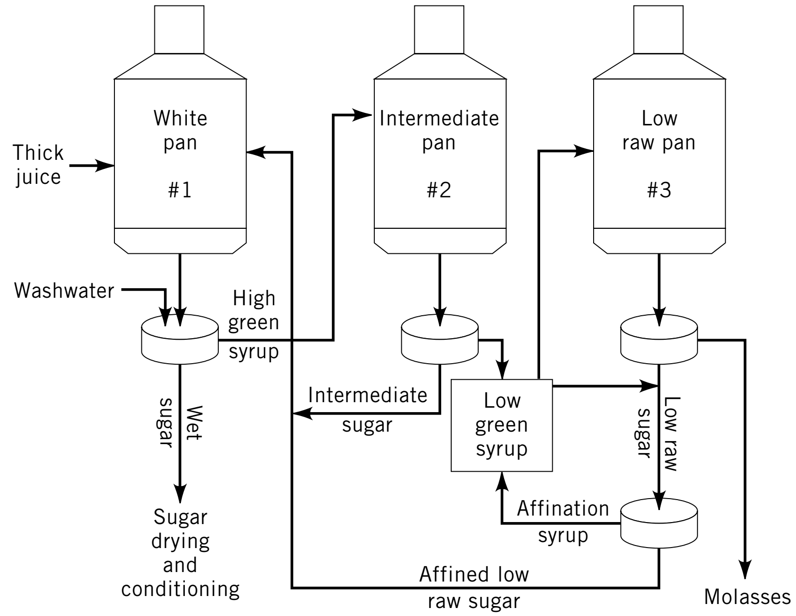


Fig. 11. The three-boiling beet sugar crystallization scheme.