COFFEE

1. Introduction

Coffee was originally consumed as a food in ancient Abyssinia and was presumably first cultivated by the Arabians in ~575 AD (1). By the sixteenth century it had become a popular drink in Egypt, Syria, and Turkey. The name coffee is derived from the Turkish pronunciation, kahveh, of the Arabian word *gahweh*, signifying an infusion of the bean. Coffee was introduced as a beverage in Europe early in the seventeenth century and its use spread quickly. In 1725, the first coffee plant in the Western hemisphere was planted on Martinique, West Indies. Its cultivation expanded rapidly and its consumption soon gained wide acceptance.

Commercial coffees are grown in tropical and subtropical climates at altitudes up to ~1800 m; the best grades are grown at high elevations. Most individual coffees from different producing areas possess characteristic flavors. Commercial roasters obtain preferred flavors by blending or mixing the varieties before or after roasting. Colombian, and washed Central American or East African coffees are generally characterized as mild, winey-acid, and aromatic; Brazilian coffees as heavy body, moderately acid, and aromatic; and African and Asian robusta coffees as heavy body, neutral to slightly earthy, slightly acid, and slightly aromatic. Premium coffee blends contain higher percentages of Colombian, East African, and Central American coffees.

2. Green Coffee Processing

The coffee plant is a relatively small tree or shrub belonging to the family Rubiaceae. It is often controlled to heights between 3 and 5 m. Two main species are in cultivation and of importance worldwide; *Coffea arabica* (also referred to as milds, which accounts for 70–80% of world production) and *Coffea Canephora* (also referred to as robustas and accounting for most of the remaining word's production) are the main varieties. *Coffea liberica* and >20 others comprise the remaining species. Each of the commercial species include several varieties.

Following spring rains, the plant produces white flowers. After fertilization, the flower drops and is followed by a "coffee button", which matures into a fruit approximately the size of a small cherry. The coffee bean is the endosperm part of the seed. Due to the nature of climate and species, subsequent rains may produce additional flowering and subsequent fruit set. Because of this, the fruit on the tree may include under ripe, ripe (red, yellow, and purple color) and over ripe cherries. Coffee may be selectively picked (ripe only), or strip picked (predominately ripe plus some underripe and overripe). Selective picking during harvest to maximize the yield of the more desirable ripe fruit is considered optimum.

Green coffee processing is effected by one of three methods: the wet method (washed or semiwashed, which appears to be growing in popularity) and the natural or dry process method.

In the wet (fully washed) method (practiced in Colombia and many Central American origins), the harvested ripe coffee cherry is passed through a tank for washing that removes stones and other foreign matter. The coffee is then passed through a depulper, removing the outer covering or skin and most of the pulp. Some pulp mucilage remains on the parchment layer covering the bean. This remaining pulp is removed by utilizing a fermentation process. Depending on the amount of mucilage remaining on the bean, fermentation may last from 12 h to several days. Because excessive fermentation may cause development of undesirable characters in the flavor and odor of the beans, enzymes may be added to speed the process. The fermentation breaks down the remaining pulp so it can then be easily washed away.

The wet (semiwashed) method is similar. Here, a partial or reduced fermentation after hulling may be used. The coffee is then washed to remove the remaining pulp (other variations include aggressively mechanically washing the beans to remove the pulp without fermentation).

From both wet methods, the resultant beans (covered with parchment) will be dried to uniform moisture using natural or mechanical methods before going through the milling process. The mechanical methods have gained in popularity despite higher costs. They are faster and not dependent on weather conditions. A potential negative of this method is the use of wood fuel for the dryers that may impart smoke/ash flavors to the coffee.

After drying, the coffee is further mechanically processed to remove the parchment and silverskin before grading. The wet process generally produces coffee of more uniform quality and flavor.

The dry method is favored by Brazil and other countries where available water is limited and a relatively uniform flowering allows strip picking with a predominance of ripe coffee. This method involves setting the harvested coffee cherries on a patio to dry naturally (mechanical methods can be used but are much more costly). The coffee is periodically turned to ensure uniform drying and to help prevent the occurrence of mold. Once proper drying has occurred (7–21 days based upon conditions) the resultant coffee may then be stored or hulled to remove the husk, parchment, and silverskin.

After being processed by any of the above methods, the coffee may need to be further dried to bring it to the desired 11–13% moisture range.

Coffee prepared by either method is then machine graded using oscillating screens, density separating tables, and airveyors to separate the coffee into varying sizes. The beans are then further processed to remove foreign matter, and any undesirable and damaged beans. This is accomplished by hand picking, machine separating, or color sorting (Sortex or Deltron electronic color sorters may sometimes be used) or any combination of the aforementioned to achieve the desired result.

Unroasted green coffee, once processed and properly stored, can be expected to maintain its quality for 6–12 months.

Coffee is valued and offered for sale based on its grade as determined by the number of imperfections contained in a 300-g sample (imperfections are considered to be beans that are black, broken, insect damaged or otherwise unsound, and foreign material). Coffee processors and roasters will also grade the coffee based on final moisture and bean color as well as the cup quality of the prepared beverage.

Consumers more conscious of health and also those interested in conservation have driven niche markets for coffee that has been organically grown, farms that are sustainable, and fair traded coffee.

Organic coffee is coffee that has been certified by an acceptable agency as being grown under conditions considered to be organic in nature and have not used synthetic fertilizers and pesticides.

Sustainable coffee farms employ techniques beneficial to the environment. Effective land management, the use of fertilizers and pesticides that are safe for animal and bird populations, and following clean water practices ensures farms remain sustainable for future generations.

Fair traded coffee is coffee that has a guaranteed minimum price, provides credit to producers, and establishes long-term relationships directly with cooperatives. Fair traded coffee encourages organic and sustainable farming by providing financial incentives to the farmers and growers through the elimination of the intermediaries (middlemen).

3. Coffee Chemistry

3.1. Chemical Composition of Green Coffee. The composition of the green coffee bean is complex; carbohydrate polymers and protein make up ~60% of the bean, the rest consists of low molecular weight compounds of various types, including lipids, acids and sugars. The composition can vary according to species, variety, growing environment, postharvest handling (including wet and dry processing), and storage time, temperature, and humidity. Table 1 summarizes the analyses of robusta and arabica green beans [data from various sources including (1,2)].

3.2. Chemistry of Coffee Constituents. *Chlorogenic acids.* The chlorogenic acids result from the esterification of the hydroxyl groups at the 3, 4, and 5 positions of quinic acid with various phenolic acids, the principal two of which are caffeic and ferulic acid. In green coffee, the 3 [327-97-9], 4 [905-99-7], and 5-caffeoylquinic acid [906-33-2] (CQA) isomers are present; the 5-isomer has the highest content. Also present are 3 [1899-29-2], 4, and 5-feruloylquinic acid [40242-06-6] (FQA), the latter dominates. Iso-chlorogenic acids, which are diesters, ie, 3,4 [14534-61-3]; 3,5 [2450-53-5], or 4,5 [57378-72-0] linked phenolic acids, occur at lower levels. Other phenolic acids, eg, *p*-coumaric acid [501-98-4], have also been found as quinic acid esters in coffee beans. Robusta and arabica beans differ in their chlorogenic acid content and composition; the former contains somewhat more, mainly due to higher levels of FQA and iso-CQAs (3). FQA is particularly important with respect to bean roasting behavior as it leads to higher yields of guaiacol derivatives, which contribute to the spicy, medicinal, phenolic flavor characteristic of robustas.

Acids. Apart from the chlorogenic acids, the principal acids in coffee beans are, in order of decreasing content: citric, malic, quinic, phytic, and phosphoric (4). As the pH of green coffee aqueous solutions is in the region of 6, the

Table 1. **Typical Analyses of Green Coffee (% Dry Weight Basis)**

	Type[a]	
Constituent	Robusta	Arabica
lipids	11.5 (9–13)	16 (15–18)
ash	5.0 (4.5–5.3)	4.7 (4.2–5.2)
caffeine	2.3 (1.8–2.8)	1.3 (1.2–1.5)
chlorogenic acids	10.5 (9–11)	9 (8–10)
other acids	3.0 (2.7–3.3)	3.5 (3.2–3.8)
trigonelline	1.0 (0.7–1.2)	1.3 (1.1–1.5)
protein	12 (11–14)	11 (10–13)
free amino acids	0.2	0.2
sucrose	4 (2–5)	7 (5–8.5)
other sugars	0.5 (0.2–1.0)	0.5 (0.1–0.8)
polymeric carbohydrate		
mannan	22	22
arabinogalactan	17	14
cellulose	8	8
others		
other compounds	2.0	2.0

[a] Robustas generally have lower levels of lipid, trigonelline [535-83-1], sucrose [57-50-1], and phytic acid [83-86-3] but higher levels of caffeine [58-08-2], chlorogenic acids (mainly 5-caffeoylquinic acid [906-33-2]) and arabinogalactan [9036-66-2] than arabicas.

acids occur almost completely in the salt form with potassium as the dominant cation.

Alkaloids. Caffeine, due to its physiological properties, is the best known component of the coffee bean. In the pure form it has a bitter taste, but it is not considered to be the main source of the bitterness perceived in coffee beverages. It forms complexes with chlorogenic acids. Robusta caffeine levels, at ~2%, are about twice as high as those in arabica beans. Trigonelline tends to be present at a higher level in arabica beans.

Lipids. The coffee oil fraction consists of ~75% triglycerides, 20% free and esterified diterpene alcohols, 5% free and esterified sterols, and a small quantity of other lipid types. The principal bound fatty acids are palmitic (C16, 35–41%), linoleic (C18:2, 37–46%), oleic (C18:1, 8–12%) and stearic (C18, 7–11%) [57-11-4]. The diterpene alcohols are principally cafestol [469-83-0] and kahweol [6894-43-5], the only structural difference is an unsaturated instead of a saturated C–C linkage in the latter. Arabica and robustas show differences in their lipid profiles: The arabicas have higher total lipid contents (~15 vs 10% in robusta), and contain more kahweol, which is present in only low levels in robusta beans (5). Only robustas contain the diterpene, 16-*O*-methylcafesteol [108214-28-4], which because of its stability to the roasting process has been proposed as a means of detecting robusta beans in arabica blends.

The surface of green coffee beans contains a cuticular wax layer (0.2–0.3% wt. basis). The wax contains insoluble hydroxytryptamides derived from 5-hydroxytryptamine [61-47-2] and saturated C18, C20, and C22 fatty acids.

Carbohydrates. Sucrose [57-50-1] is the principal low molecular weight carbohydrate with the content in arabica beans about twice that of robustas. Glucose [50-99-1] and fructose [57-48-7] are the main sugars in the immature seeds but levels decrease during maturation and are very low in the mature beans (6). Other sugars are present at only minimal levels.

The polysaccharides constitute the major fraction in the coffee bean and together with protein they form the basis of the cell wall material in the bean. The major polysaccharides are arabinogalactan [9036-66-2], mannan [9052-06-6], and cellulose [9004-34-6] (7). The arabinogalactan is a high molecular weight polymer with a β(1–3)-linked galactan backbone with frequent side chains containing arabinose [147-81-9], galactose [59-23-4], and glucuronic acid [6556-12-3] units (8). The mannan is a linear, lower molecular weight polymer. Its linear structure allows it to form hydrogen-bonded tight structures, which are responsible for the hardness of the beans. Due to the one unit galactose side chains substituted at ~5–10% of the main chain mannose units, this polymer is sometimes termed "galactomannan" in coffee. Cellulose is found in most plant material. There is evidence of small quantities of other polymers, including one of a pectin-type (8). Polysaccharide contents of green beans are similar. Robustas tend to have 2–3% more arabinogalactan than arabicas and this is mainly responsible for their slightly higher total polysaccharide content.

Proteins. Protein content of robustas tends to be slightly higher than that of arabicas. The total amino acid composition, ie, that released by acid hydrolysis, is similar for both types. Free amino acid levels in green beans are of the order of 0.2% and vary significantly according to samples (9). This is to be expected due to the significant protease enzyme activity in green coffee.

3.3. Roast Coffee Composition. The pleasant taste and aroma characteristics as well as the brown color of roast coffee are developed during the roasting process. The chemical and physical changes associated with this process are very complex. In the first stage of roasting, loss of free water (~12% in the green bean) occurs. In the second stage, chemical dehydration, fragmentation, recombination, and depolymerization reactions occur. Many of these reactions are of the Maillard type and lead to the formation of lower molecular weight compounds such as carbon dioxide, free water, and those associated with flavor and aroma as well as higher molecular weight compounds termed melanoidins that are responsible for the brown color. The chemical reactions of roasting are exothermic and cause a rapid rise in temperature, usually accompanied by a sudden expansion or puffing of the beans with a volume increase of 50–100% depending on variety and roasting conditions. The loss of carbon dioxide and other volatile substances, as well as the water loss produced by chemical dehydration during the second stage, accounts for most of the 2–6% dry weight roasting loss. Most of the lipid, caffeine, inorganic salts, and polymeric carbohydrate survive the roasting process.

Table 2 indicates some of the chemical changes that occur in arabican green coffee as a result of processing. Data are presented as a range and typical values (when appropriate) compiled from the literature and other sources and reflect the fact that the chemistry is highly dependent on degree of roast and starting material. The principal water-soluble constituents, ~25% of the green coffee, are involved. These include some of the protein, the free amino acids, organic acids,

Table 2. **Approximate Analyses of Roasted, Brewed, and Instant Coffee, % Dry Wt. Basis**

Constituent	Roasted	Brewed	Instant
lipids	17 (16–20)	0.2[a]	0.1
ash	4.5 (4–5)	15	8
caffeine	1.2 (1.0–1.6)	5	2.5 (2–3)
chlorogenic acids	3.5 (1.5–5)	15	5 (3–9)
other acids	3 (2.5–3.5)	10	5.5 (4–8)
trigonelline	0.8 (0.5–1.0)	2 (1–2.5)	1.5 (1–2)
protein	8–10	5	3 (2–5)
sucrose	0.1 (0–0.3)	0.2 (0–0.5)	0.1 (0–0.3)
reducing sugars	0.1 (0–0.3)	0.2 (0–0.5)	2 (1–5)
polymeric carbohydrate[b]			
mannan	22	1	15 (10–18)
arabinogalactan	13	2	17 (15–20)
cellulose	8	0	0
other compounds[c]	18	45	40

[a] Maximum level in brew (filtered), espresso levels higher, even higher levels in "Scandanavian" brews.
[b] Much of polymer is converted in Instant Coffee processing to lower molecular weight (oligosaccharides) material.
[c] Most of "other" material is in the form of "browning products', such as the melanoidins.

and inorganic salts. Most sucrose disappears early in the roast. Its decomposition products include low molecular weight acids, oxygen-containing heterocylic compounds such as 5-hydroxymethylfurfural [67-47-0] and the volatile and non-volatile flavor contributing compounds, which are formed as a result of Maillard reactions with free and bound amino acids.

Roasting denatures and insolubilizes much of the protein. Some of the constituent amino acids in the protein are destroyed during the latter stages of roasting and thus contribute to aroma and flavor development. Analysis of the protein amino acids in green and corresponding roasted coffee show marked decreases in arginine, cysteine, lysine, serine, and threonine in both Arabica and Robusta types after roasting. Alanine, glycine, leucine, glutamic acid, and phenylalanine are relatively stable to roasting (10). Cysteine [52-90-4] and methionine [63-68-3] are the probable sources of the many potent sulfur compounds found in coffee aroma, eg, mercaptans, organic sulfides, and thiazoles. Other amino acids are capable of generating aromatic compounds such as pyrazines, pyrroles, etc.

About 50–80% of the trigonelline is decomposed during roasting. Trigonelline is a probable source for niacin [59-67-6] but also a source of some of the aromatic nitrogen compounds such as pyridines, pyrroles, and bicyclic compounds found in coffee aroma (11). Certain acids, such as acetic, formic, propionic, quinic, and glycolic, are formed or increase upon roasting, while other acids present initially in the green coffee, such as the chlorogenic acids, citric, and malic, decrease in level with increasing degree of roast (12). The composite of acids in brew of a lightly roasted coffee contribute to the taste quality termed "fine acidity". Brews of darkly roasted coffees are less acidic. Slight cleavage of the triglycerides and the diterpene and sterol esters occurs during roasting. It is likely that some oxidation of lipid components is initiated during the roasting stage.

However, some of the Maillard products generated upon roasting may act as antioxidants, slowing down the deterioration of the lipids upon storage. The aromatic, oil-soluble aroma compounds slowly partition into the oil phase after the roasted bean is allowed to cool and equilibrate.

Aroma. The chemistry of aroma compound formation is complex. In the early and middle stages of roasting, a significant portion of these compounds is derived from carbohydrates (mainly sucrose and arabinose from arabinogalactan), proteinaceous material (including amino acids and peptides), and other bean components (chlorogenic acids, trigonelline, organic acids, lipids, etc). Reactions involve degradation to form reactive products, which include saturated and unsaturated aldehydes, ketones, dicarbonyls, amines, and hydrogen sulfide, or interactions via nonenzymatic browning reactions. As roasting progresses, the precursor profile changes (less reactive small molecules) and structurally more complicated sulfur-, oxygen-, and nitrogen-containing heterocyclic compounds are formed with the brown colored polymeric melanoidins dominating. Table 3 lists the number of aroma compounds found in coffee (presently ~850) according to substance class. The identification of so many compounds can be attributed to major advances in instrumental analysis, in particular, high-resolution gas chromatography (HRGC) and mass spectrometry (MS).

In order to identify which of this large number of compounds are the major contributors to the coffee aroma (the "potent odorants"), a number of specialized analytical approaches have been utilized (13). Coffee aroma is extracted and separated by HRGC; aroma potency is then determined by means of aroma extraction dilution analysis (ADEA) or combined hedonic and response measurements (CHARM). Highly volatile aroma compounds are detected by gas chromatography–olfactometry of headspace samples (GCOH). Following enrichment and identification, aroma activity values of the aroma compounds (OAVs) are determined. Finally, the relative importance of the aroma compounds is

Table 3. **Aroma Compounds of Roasted Coffee**[a]

Class of Compound	Number
hydrocarbons	80
alcohols	24
aldehydes	37
ketones	85
carboxylic acids	28
esters	33
pyrazines	86
pyrroles	66
pyridines	20
other bases (eg, indoles)	32
sulfur compounds	100
furans	126
phenols	49
oxazoles	35
others	20
total	*841*

[a] See Ref. 13.

determined by sensory evaluation of the impact of compound omission from a synthetic blend of all the compounds. As a result of such studies, only 20–30 compounds are deemed important and it has even been suggested that only ∼15 compounds have major impact on the final aroma (13). These compounds include four alkyl pyrazines, four furanones, 2-furfurylthiol, 4-vinylguaiacol, acetaldehyde, propanol, methylpropanol, and 2- and 3-methylbutanol.

3.4. Chemistry of Brewed Coffee. The chemistry of brewed coffee is dependent on the extraction of water-soluble and hydrophobic aromatic components from the coffee cells and lipid phase, respectively. Factors that affect extraction and flavor quality of brewed coffee are degree of roast; blend composition; grinding technique; particle size and density; water quality; water to coffee ratio; and brewing technique or device, such as drip filter, percolator, or espresso, which defines the water temperature, steam pressure, brewing time, water recycle, etc. Extraction yields of home brewing range from ∼9 to 28% and typically ∼23% dry basis roasted and ground (R&G) (14). The trend in the United States, with some notable exceptions, has been toward weaker brew strengths, with typical recipes of ∼5 g of R&G coffee per 6 oz cup (brew solids concentration ∼0.7%), compared to ∼10 g a generation ago (brew solids ∼1.2%). In comparison, espresso typically uses ∼8–12 g of coffee per 2 oz of beverage (brew solids ranging from ∼3 to 5%). As espresso is brewed rapidly under steam pressure (brew time ranging from ∼15 to 35 s), it contains a relatively large amount of oil droplets (∼0.1–0.2% basis brew) and suspended colloidal solids (∼0.3% basis brew) that contribute to the greater turbidity and mouthfeel of this beverage compared to filter brewed coffee (15).

3.5. Instant Coffee. The chemistry of instant or soluble coffee is dependent on the R&G blend and processing conditions. This is indicated in Table 2 by the wide range of constituents. In addition to the atmospherically extractable solids found in brewed coffee, commercial percolation generates water-soluble carbohydrate by hydrolysis that contributes to the yield. This additional carbohydrate includes the sugars, arabinose, mannose, and galactose; oligosaccharides derived from mannan and arabinogalactan; and the partially hydrolyzed polysaccharides, mannan, and arabinogalactan. It improves the drying properties and retention of volatiles by the extract, and reduces hygroscopicity. These water-soluble carbohydrates formed the basis for the first 100% pure instant coffee developed by General Foods Corp. in the late 1940s.

4. Roasted and Ground Coffee Processing and Packaging

The main processing steps in the manufacture of roast and ground coffee products are blending, roasting, grinding, and packaging. Green coffee is shipped in burlap bags (60–70 kg) or in bulk containers (16,500–18,000 kg). Prior to processing, the green coffee is mechanically cleaned to remove string, lint, dust, husk, and other foreign matter. Coffee of different varieties or from different sources may be blended before or after roasting at the option of the manufacturer.

4.1. Roasting Technology. Commercial roasting is generally by hot combustion gases in either rotating cylinders or fluidized-bed systems. Though steam pressure, infrared (ir) and microwave roasting systems are found in the patent literature none are believed to be used to a significant extent. Roasting times in batch cylinders were traditionally 8–15 min, whereas much of the coffee produced today is roasted in batch or continuous fluidized beds in only 0.5–4 min (16–18). In either case, the initial step of roasting is a moisture elimination and uniform heating step. The onset of roasting reactions has been reported to be as low as 151°C and when the bean temperature exceeds ~165°C, the reactions have switched from endothermic to exothermic and the roast has begun to fully develop. This stage is generally accompanied by a noticeable crackling sound like that of corn popping and the beans swell to as much as twice their unroasted volume. The final bean temperature of 185–250°C is determined by the flavor development desired for the finished goods, whether a blend or individual varieties are roasted. A water or air quench terminates the roasting reaction. Most, but not all, of any water added is evaporated from the heat of the beans. Theoretically, ~700 kJ is needed to roast 1 kg of coffee beans. A roaster efficiency of 75% or more (933 kJ/kg) is possible with recirculation of the roaster gas, whereas older, nonrecirculating units operate with an efficiency as low as 25% (2800 kJ/kg). Though cupping for flavor is the ultimate test, the acceptability of the roast is often judged off-line by a photometric reflectance measurement on a ground sample of the bean, and adjustments of the temperature controls that initiate the quenching end point. Typically, the bean temperature measurement is used as the process control parameter, but at least one fluid bed unit is controlled via roasting gas exhaust temperature. Attempts to utilize *in situ* photometric reflectance measurements for process control have met with limited success due to the varying nature of the agricultural commodity and the fact that these systems quickly get coated with an oily brown residue. State-of-the art roaster controls can also be set to provide a specific heat input profile or to store and replicate an historical pattern. The desired patterns are chosen to deliver cup quality and strength for a given consumer recipe. The faster fluidized-bed roasting processes (batch or continuous) are the basis of high yield coffee products. These units are generally operated at lower air temperature, ie, 185–400°C vs 425–490°C, resulting in a more uniform roast throughout the bean, an increase in extractable soluble solids of 20% or more, and higher aroma retention. The higher circulation rate of roaster gas required for fluidization increases heat transfer to allow a faster roast at lower temperature. Exhausted roaster gas often must be incinerated in an afterburner for environmental pollution purposes. The use of IR heat (gas-fired ceramics) or microwave energy to speed up the roasting process while providing a more even roast has also been patented (19,20).

The roasted and quenched beans are air cooled and conveyed to storage bins for moisture and temperature equilibration before grinding, this storage step, called curing, also allows the carbohydrate matrix to harden properly before grinding. Residual foreign matter (mostly stones), which may have passed through the initial green cleaning step, is removed in transit to the storage bins by means of a high velocity air lift that leaves the heavier debris behind. The roasted beans may flow by gravity or be airveyed to the grinders.

4.2. Grinding. Grinding of the roasted coffee beans is tailored to the intended method of beverage preparation. Average particle size distributions range from very fine (500 μm or less) to very coarse (1100 μm). The classic way to measure and control particle size distribution has been via use of stacked standard sieves. Many commercial roasters now use laser light scattering devices to provide a quick and reproducible measure of this critical parameter. A finer grind will allow greater solids extraction, but may slow the brewing process because of increased flow resistance and reduced wettability. Most coffee is ground in multistep steel roll mills in order to produce the most desirable particle size distribution. After passing through cracking rolls, the broken beans are fed between two more rolls, one of which is cut or scored longitudinally; the other, circumferentially. The paired rolls operate at speeds designed to cut rather than crush the cracked particles. For finer grinds, a second pair of more finely scored rolls running at higher speed is positioned below the first set. Some coffee is flaked, to increase extractability without slowing the brewing speed, by passing it through closely spaced smooth rolls after grinding (21). Unlike grinding, flaking is a crushing step that disrupts the cellular structure to reduce the diffusion path for extraction. Flaking can increase extraction yield by as much as 15% regardless of the roasting profile. A normalizer/homogenizer mixing section, generally an integral part of the grinder, assures a uniform particle distribution and may be used to increase density before packaging. Like flaking, attempts to stretch the bean even further by more severe crushing have met with limited consumer acceptance due to the need for a consumer behavior change with the denser ground product.

4.3. Packaging. Most roasted and ground coffee sold directly to consumers in the United States is vacuum-packed with 0.33–0.37 kg in 10.3-cm (4 1/16 in.) diameter metal cans or with three times as much in 15.7-cm (6 3/16 in.) diameter metal cans. Whether packing 0.33 or 0.37 kg of coffee, the 10.3-cm diameter cans generally have a fill volume of $\sim$1000 cm^3. Ground coffee pack density is managed via modern roasting and grinding technology to deliver a full can with the desired flavor profile. After roasting and grinding, the coffee is conveyed, usually by gravity, to weighing-and-filling machines that achieve the proper fill by tapping or vibrating. A loosely set cover is partially crimped. The can then passes into the vacuum chamber maintained at 3.3 kPa (25 mm Hg) absolute pressure or less. The cover is clinched to the can cylinder wall and the can moves through an exit valve or chamber. This process removes 95% or more of the oxygen from the can. Polyethylene snap caps for reclosure are placed on the cans before they are stacked in cardboard cartons for shipping. A case or tray usually contains 12 of the smaller diameter cans or 6 of the larger diameter, and a production packing line usually operates at a rate of 250–350 smaller cans per minute or $\sim$100–150 larger cans per minute. Though other can sizes are present in the marketplace the growth of grocery club stores and supercenters has helped to drive the bulk of the volume to the larger packs both in the United States and in Canada.

Vacuum-packed coffee retains a high-quality rating for at least 1 year. The slight loss in fresh roasted character that occurs is because of chemical reactions with the residual oxygen in the can and previous exposure to oxygen prior to packing (22).

Coffee vacuum-packed in flexible, bag-in-box packages has gained wide acceptance in Europe and is the prevalent format for prepackaged ground coffee. The inner liner, usually a plastic-laminated aluminum foil, is formed into a hard brick shape during the vacuum process (23). In the United States, a similar printed multilaminated flexible structure is used to form the brick pack that is sold as is at retail. The aluminum foil layer of these types of packages provides a barrier to moisture and oxygen similar to that of a metal can.

Inert gas flush packing in plastic-laminated or metalized nylon pouches, although less effective than vacuum packing, can remove or displace 80–90% of the oxygen in the package. These packages offer satisfactory shelf-life and are sold primarily to food service operators (restaurants, office coffee service, caterers, and institutions).

An appreciable amount in Europe and more often than before coffee in the United States, is distributed as whole beans, which are ground in stores or by consumers in their homes. Whole-bean roasted coffee remains fresh longer than ground coffee. The specialty gourmet shop trade based on this system has continued to grow significantly in the United States since the early 1980s. Nearly 20% of the coffee now consumed in the United States is now classified as premium whole bean or ground gourmet coffee, whereas 10 years ago this category was not considered a significant factor in the market and was not tracked separately (24). Fifty eight percent of gourmet coffee consumption is away from home in specialty gourmet coffee shops, at work, while traveling, and in other foodservice outlets. Unprotected whole bean coffee, in bins or bags, can be considered as little different from fresh if it is used within 10–12 days and significant flavor differences can take as long as 40 days to be noticeable (25).

Packaging of roasted whole beans in foil laminate barrier bags generally is carried out with the use of a one-way valve that allows carbon dioxide gas released from the beans to escape and prevent air and moisture from entering the package. This permits packing the coffee soon after roasting and a nitrogen purge or vacuum evacuation of the pack before sealing assures that long-term oxygen exposure is minimized. Whole bean coffee packed in this manner would be expected to be of excellent quality at least for the 1 year claimed for roast and ground coffee.

The one-way valve is now often used with ground coffee in flexible foil laminate pouches. A common packing scheme calls for filling the pouch, evacuating the pack to minimize retained oxygen, and then backflushing with nitrogen or another inert gas before sealing. The ground coffee continues to respire significant amounts of carbon dioxide and carbon monoxide over the first weeks after packing such that these pouches are soft rather than rigid like the brick pack described above. This system allows one to pack the coffee sooner after grinding, with the potential to retain more of the desirable coffee aromatics.

5. Instant Coffee Processing and Packaging

Instant coffee is the dried water-extract of ground, roasted coffee. Although used in Army rations as early as the U.S. Civil War, the popularity of instant coffee as a grocery product grew only after World War II, coincident with improvements in manufacturing methods and consumer trends toward convenience. Extensive patent literature dates back to 1865. Instant coffee products represented only

7% of the coffee consumed in the United States in 2001, less than one-half that consumed in 1991 in both absolute and percentage terms (24).

Green beans for instant coffee are blended, roasted, and ground similarly to those for roasted and ground products. A concentrated coffee extract is normally produced by pumping hot water through the coffee in a series of cylindrical percolator columns. The extracts are further concentrated prior to a spray- or freeze-drying step, and the final powder is packaged in glass or other suitable material. Some soluble coffees, both spray- and freeze-dried, are manufactured in producing countries for export.

5.1. Blend/Roast/Grind. Blends of Brazilian, Central American, and Colombian milds as well as African, Asian, and Brazilian robustas are prepared to achieve desired flavor characteristics. The batch- or continuous-type roasters used for roasted and ground coffee also are used for instant coffee. Grinding of roasted beans for an instant coffee process is adjusted to suit the type of commercial percolation system to be used. The average particle size is generally larger than that used for domestic brewing to avoid excessive pressure drops across the percolator columns. Similarly, very fine particles are avoided.

5.2. Extraction. Commercial extraction equipment and conditions have been designed to obtain the maximum yield of soluble solids with the desired flavor character. Conceptually, most commercial systems can be represented by a series of countercurrent batch extractors. The freshwater feed, at pressures well above 1 atm and temperatures high enough to hydrolyze the coffees' polysaccharides to oligosaccharides, contacts the most spent coffee grounds. During the final extraction stage, fresh ground coffee is contacted with an extract of these oligosaccharides at temperatures near the atmospheric boiling point.

Significant factors influencing extraction efficiency and product quality are grind size, feed water temperature and temperature profile through the system, percolation time, coffee/water ratio, premoistening or wetting of the ground coffee, design of extraction equipment, and flow rate of extract through the percolation columns.

Percolation trains consisting of 5–10 columns are the norm. Height/diameter ratios usually range from 4:1 to 7:1. To improve extraction, the ground coffee may be steamed or wetted. Feed water temperatures ranging from 154 to 182°C are common and the final extract exits at 60–82°C. To minimize flavor and aroma loss prior to drying, the effluent extract may be cooled in a plate heat exchanger. The yield, a function of the properties of the particular blend and roast, the operating temperatures, and the percolation time, is generally controlled through adjustment of the soluble solids drawn off from the final stage. Extraction yield is calculated from both the weight of extract collected and the soluble solids concentration as measured by specific gravity or refractive index. Soluble yields of 24–48% or higher on a roasted coffee basis are possible. Robusta coffees give yields ~10% higher than arabica because of a higher level of available polysaccharides and caffeine. The latest technology in thermal extraction of spent grounds provides roasted yields in excess of 60% (26).

Extract is stored in insulated tanks prior to drying. Because high soluble solids concentration is desirable to reduce aroma loss and evaporative load in the driers, most processors concentrate the 15–30% extract to 35–55% prior to drying (27). This may be accomplished by vacuum evaporation or freeze concentration. Clarification of the extract, normally by centrifugation, may be used to assure the absence of insoluble fine particles.

The flavor of instant coffee can be enhanced by recovering and returning to the extract or finished dry product some of the natural aroma lost in processing. The aroma constituents from the grinders, percolation vents, and evaporators may be added directly or in concentrated or fractionated form to achieve the desirable product attributes.

5.3. Drying. The criteria for good instant coffee drying processes include minimization of loss or degradation of flavor and aroma, uniformity of size and shape in a free-flowing form, acceptability of the bulk density for packaging, product color acceptability, and moisture content below the level required to maintain shelf-stability (<5%). Operating costs, product losses, and capital investment are also considerations in the selection of a drying process.

Spray Drying and Agglomeration. Most instant coffee products are spray-dried. Stainless steel towers with a concurrent flow of hot air and atomized extract droplets are utilized for this purpose. Atomization, through pressure nozzles, is controlled based on selection of the nozzles, properties of the extract, pressures used, bulk density, and capacity requirements. Low inlet air temperatures (200–280°C) are preferred for best flavor quality. The spray towers must be provided with adequate dust collection systems such as cyclones or bag filters. The dried particles are collected from the conical bottom of the spray drier through a rotary valve and conveyed to bulk storage bins or packaging lines. Processors may screen the dry product to assure a uniform particle size distribution.

Most spray-dried instant coffees have been marketed in a granular form, rather than the small spherical spray-dried form, since the mid-1960s. The granular appearance is achieved by steam fusing the spray-dried material in towers similar to the spray drier. Belt agglomerators are also common.

Freeze Drying. Commercial freeze drying of instant coffee has been a common practice in the United States since the mid-1960s. The freeze-drying process provides the opportunity to minimize flavor degradation due to heat (28).

Sublimation of ice crystals to water vapor under a very high vacuum, ~67 Pa (0.5 mm Hg) or lower, removes the majority of the moisture from the granulated frozen extract particles. Heat input is controlled to assure a maximum product end point temperature below 49°C. Freeze drying takes significantly longer than spray drying and requires a greater capital investment.

5.4. Packaging. In the United States, instant coffee for the consumer market is usually packaged in glass jars containing from 56 to 340 g of coffee. Larger units for institutional, hotel, restaurant, and vending machine use are packaged in bags and pouches of plastic or laminated foil. In Europe, instant coffee is packaged in glass jars or foil-laminated packages.

Protective packaging is primarily required to prevent moisture pickup. The flavor quality of regular instant coffee changes very little during storage. However, the powder is hygroscopic and moisture pickup can cause caking and flavor impairment. Moisture content should be kept <5%.

Many instant coffee producers in the United States incorporate natural coffee aroma in coffee oil into the powder. These highly volatile and chemically unstable flavor components necessitate inert-gas packing to prevent aroma deterioration and staling from exposure to oxygen.

6. Decaffeinated Coffee Processing

Decaffeinated coffee products represented 9% of the coffee consumed in 2001 in the United States; less than one-half that consumed in 1991 (24). Decaffeinated coffee was first developed commercially in Europe ~1900. The process as described in a 1908 patent (29) consists of first, moisturizing green coffee to at least 20% to facilitate transport of caffeine through the cell wall, and then contacting the moistened beans with solvents.

Until the 1980s, synthetic organic solvents commonly were used in the United States to extract the caffeine, either by direct contact as above or by an indirect secondary water-based system (30). In each case, steaming or stripping was used to remove residual solvent from the beans and the beans were dried to their original moisture content (10–12%) prior to roasting.

In the 1980s, manufacturers' commercialized processes that utilized either naturally occurring solvents or solvents derived from natural substances to position their products as naturally decaffeinated. The three most common systems use carbon dioxide under supercritical conditions (31), oil extracted from roasted coffee (32), or ethyl acetate, an edible ester naturally present in coffee (33). Specificity for caffeine and caffeine solubility is key to selection and system design. Because caffeine can be selectively removed from water extracts of green beans by activated charcoal, several processes that utilize water or recycled green coffee extract have been described and are also considered natural decaffeination. If water is used, the green coffee extract produced is externally decaffeinated and the noncaffeine solids containing important flavor precursors are reabsorbed before drying and roasting. In what is commonly advertised as the "Swiss Water Process", the use of recycled green extract obviates the need for a separate reabsorption step as the caffeine deficient green extract selectively leaches caffeine. Preabsorbing sugar on activated charcoal to improve its specificity also has been commercialized (34). The degree of decaffeination, based on comparison to the starting material, is controlled using known time–temperature relationships for the particular process for each bean type.

In all the above mentioned processes of coffee decaffeination, changes occur that affect the roast flavor development. These changes are caused by the prewetting step, the effects of extended (4 h plus) exposure at elevated temperature as required to economically extract the caffeine from whole green beans, and the postdecaffeination drying step.

To make an instant decaffeinated coffee product, the decaffeinated roast and ground coffee is extracted in a manner similar to nondecaffeinated coffee. Alternatively, the caffeine from the extract of untreated roasted coffee is removed by using the solvents described previously.

7. Economic Importance

Coffee ranks second only to petroleum as the worlds largest traded commodity. The total world production of green coffee in the 1999–2000 growing season was 113.5 million bags a (35); exportable production was 88.2 million bags (Table 4) with an export value of $7.5 billion (36). Of particular interest is the rapid climb

Table 4. **World Production of Green Coffee, 1999–2000**[a]

Country	Exportable production[b]	%
Brazil	18,000	20.4
Vietnam	10,660	12.1
Colombia	7,982	9.0
Ivory Coast	5,640	6.4
Indonesia	5,225	5.9
Mexico	5,138	5.8
India	4,070	4.6
Guatemala	3,964	4.5
Uganda	3,017	3.4
Honduras	2,803	3.2
El Salvador	2,445	2.8
Costa Rica	2,347	2.7
Peru	2,341	2.7
Ethiopia	2,200	2.5
Kenya	1,662	1.9
Papua New Guinea	1,385	1.6
Cameroon	1,270	1.4
Ecuador	985	1.1
Tanzania	823	0.9
Zaire	550	0.6
Madagascar	371	0.4
others	5,377	6.1
Totals	*88,255*	*100.0*

[a] Ref. 37.
[b] Thousands of 60-kg bags.

of Vietnam to become the no. 2 producer of coffee surpassing all producers except Brazil.

From 1999–2000, the United States import from producing countries totaled 21.1 million bags of green coffee equivalent. This includes 19.1 million bags of green coffee, 0.7 million bags of roasted coffee, and 1.3 million bags of soluble coffee with a total value of ~$1.8 billion (38) (Table 5).

Table 5. **World Imports of Green Coffee (Selected Countries), 2000**

Country	Imports[a]	%
United States[b]	21,095	23.9
Germany[c]	14,442	16.4
France[c]	6,506	7.4
Japan[c]	7,360	8.3
Italy[c]	6,335	7.2
Spain[c]	3,819	4.3
United Kingdom[c]	3,000	3.4
Canada[c]	3,140	3.6
Belgium/Luxembourg[c]	3,273	3.7
All Others[c]	19,285	21.8
Totals	*88,255*	*100.0*

[a] Thousands of 60-kg bags.
[b] Ref. 39.
[c] Ref. 40.

8. Coffee Biotechnology

Biotechnology has made rapid progress in recent years. There has been considerable interest in applying biotechnology to coffee through both conventional breeding using tissue culture techniques and molecular markers, and through the application of genetic modification (GM) technology.

8.1. Advances in Coffee Breeding and Culture Methods. Application of modern plant breeding methods to coffee improvement, including production of F_1 hybrids, has led to improvements in crop performance (41). Breeding targets remain a combination of agronomic factors such as disease resistance and yield, and quality, eg, cup-quality and caffeine content. Disease resistance targets include coffee leaf rust, coffee berry disease, and nematodes. Clonal propagation methods have been used to improve multiplication efficiency of robusta coffee with the added advantage of maintaining uniformity. Somoclonal variation, a natural phenomenon that occurs during the tissue culture technique somatic embryogenesis, has been used to generate new sources of genetic variation in coffee. For example, the arabica variety Bourbon LC was developed through somoclonal variation of the parent *Laurina* line, a natural mutation with a caffeine content 50% lower than typical arabica varieties (42). The result is a new variety with superior agronomic performance than the parent line but retaining the reduced caffeine content. The variety has now been well characterised at both the agronomic and molecular level. The variety is genetically distinct from its parent as well as other common arabica varieties (43).

8.2. Application of Molecular Markers to Coffee Breeding. Like other tree-based crops, coffee's long generation time make it a good candidate for application of marker-assisted selection in breeding. Programs seeking to identify genes controlling traits such as host resistances to diseases and pests, caffeine content and cup quality, and to develop molecular markers for these traits are underway. Mapping populations based on interspecific crosses [eg, *C. liberica* X *C. pseudozanhuebariae*, (44)] have helped identify a number of genes controlling caffeine content. A similar approach is being used to identify candidate genes controlling biochemical pathways that make a major contribution to cup quality such as chlorogenic acid accumulation (45).

8.3. Advances and Applications of Coffee Molecular Biology. *Coffee Transformation and Genetic Modification.* Coffee transformation using Agrobacterium sp. vectors has been reviewed recently (46). Arabica coffee has proved to be more amenable to transformation than robusta coffee. There are also strong variety effects on transformation and regeneration efficiency (47). However, this has not prevented the development of the genetically modified coffees described in the following section.

Isolation of Genes from Coffee. Rapid progress has been made in isolating and identifying genes from coffee. The NCBI gene databank (GenBank; www.ncbi.nlm.nih.gov) currently holds ~200 isolated sequences from coffee. These can be grouped as coding genes (eg, enzymes) and genetic markers [eg., internally transcribed spacers (ITS) and microsatellite sequences]. In addition, at least two groups have prepared expressed sequence tag (EST) libraries from coffee tissue at different stages of development (48,49). These libraries are a valuable resource for understanding the link between biology and quality.

Table 6. **Summary of Major Functional Genes Cloned from Coffee**

Gene	Application	Reference
xanthosine-N^7- methyltransferase	caffeine-free coffee	53
ACC synthase and ACC oxidase	controlled-ripening coffee	54
11S storage protein	manipulation of bean biochemistry	57
seed-specific promoters	manipulation of bean biochemistry	57
coffee mannanase	soluble coffee processing, manipulation of bean biochemistry	58

Genetic marker sequences can be used to develop markers for breeding purposes or for use in studying the genetic diversity of coffee species (50). However, it is the application of coding genes that is of immediate interest for improving coffee agronomy and quality. Table 6 summarizes the main developments in this area. Of particular interest is the application of GM technology to produce caffeine-free coffee and controlled-ripening coffee (51,52). Genes coding for xanthosine-N^7-methyltransferase, ACC synthase, and ACC oxidase, respectively, were isolated and used to transform arabica coffee to block synthesis of these key enzymes of caffeine and ethylene biosynthesis. This is claimed to block caffeine accumulation (53) and fruit ripening (54). The latter is of interest as it allows mechanical harvesting of uniformly developed fruit followed by synchronous ripening of the coffee berries by application of exogenous ethylene. This has already been applied to other climacteric fruits such as tomatoes (55). A third application has been introduction of the *Cry1Ac* gene for *Bacillus thuringiensis toxin* (Bt) into robusta coffee to confer resistance to coffee berry borer (56). Trees are now in field trials in French Guyana. Looking to the future, seed-specific promoters (the molecular 'switches' that turn genes 'on'), seed storage proteins and germination-specific mannanases have now been isolated from coffee (57,58). These hold potential to manipulate coffee bean biochemistry and quality by genetic transformation.

Despite the technical progress that has been made, there are currently no GM coffee varieties in the marketplace. There has been much adverse publicity surrounding GM foods generally, and GM coffee in particular (59). Until there are clear consumer benefits, this is unlikely to change.

Process Biotechnology. Biotechnology has been applied to roast and ground and soluble coffee processing. The flavor profile of roast and ground coffee has been manipulated by treating green or partially roasted coffee with a cocktail of hydrolytic enzymes (60). The process is claimed to generate a novel and pleasant flavor profile. Fermentation of a green coffee extract has been used to produce flavour compounds, principally diacetyl [431-03-08, 21]. Treating steam-expanded coffee with a mixture of hydrolytic enzymes is claimed to increase yield in soluble coffee processing (61). Since last reviewed, enzymes technology has been applied to improving the solubility of polysaccharides extracted during soluble coffee processing. By using fungal mannanase [from *Aspergillus* sp, (62)] or a coffee mannanase sourced from either coffee beans or produced using a recombinant bacterium (58), the claimed benefit is reduced sedimentation during high-temperature extraction/cooling cycles. It is likely that there will be increased activity in this area as a wider range of coffee and food-grade enzymes become available.

9. Coffee Regulations and Standards

Soluble and roast and ground coffee is covered by a range of international and national legislation (eg, EEC, United States, Germany) and voluntary Codes of Practice (eg, National Coffee Association). The standards and regulations provide definitions for green and processed coffee and potential health risks (eg, ochratoxin in coffee, decaffeination of coffee). Additionally, the International Standards Organization (ISO) maintains standards for coffee and coffee-based products (63). The following list of regulations is by no means meant to be complete, but it covers the major points of general interest.

9.1. Roast and Ground Coffee. Roast and ground coffee in regulated at the national level, which leads to a range of regulations from very strict definition of roast coffee (eg, Austria, Germany) to an absence of regulation (eg, United Kingdom). The exception to this is regulation governing decaffeinated coffee that states maximum caffeine content of 0.1% db and states maximum limits for solvent residues. (In the United States, decaffeinated signifies 97% caffeine removal.)

Soluble Coffee. Soluble coffee is regulated within the EU (64). The regulations cover extraction solvent (water only) and hydrolysis methods (the use of acids and bases is forbidden). Composition is also regulated. For example, soluble coffee powder must contain not less than 95% coffee-based matter and may not contain >12% edible sugars. In addition, decaffeinated soluble coffee must not contain >0.3% caffeine.

Coffee Consumption and Health. Coffee contains between 1.2 and 3.4% db caffeine, a pharmacologically active alkaloid. The stimulant and diuretic effects of caffeine are well documented. A small number of people are sensitive to caffeine so that consumption in these individuals can cause anxiety, restlessness, sleeping difficulties, headache, and palpitations of the heart. This findings has lead to many studies over the years seeking to determine a link between coffee consumption and physiological conditions. However, extensive reviews of the available literature show no negative effects from moderate coffee consumption of between 3 and 5 cups a day (65).

Ochratoxin in Coffee. Ochratoxin A (OTA) is a by-product of mould growth on a range of foodstuffs including cereals, fruits, and coffee. OTA has been shown to be a kidney toxin in several species. In rats and mice it has been shown to be a carcinogen and teratogen. Europe is the main region where OTA occurs in food, with cereals contributing 60% of dietary intake. Of the remainder, wines contribute 25% of intake and coffee and grape juice contributes 5–7% each. Thus, coffee is not the major contributor of dietary OTA. Despite this, there is legislation in force within Europe (eg, Italy, Romania) at the national level that restricts OTA in green coffee and/or finished products. There are moves to introduce EU-wide legislation. As a point of reference, the Joint/World Health Organization (FAO/WHO) Expert Committee on Food

Additives (JEFCA) set a tolerable weekly intake for OTA of 100 g/kg body weight per week in 1995 (66).

10. Coffee Substitutes

Coffee substitutes, which include roasted chicory, chick peas, cereal, fruit, and vegetable products, have been used in all coffee consuming countries. Although consumers in some locations prefer the noncoffee beverages, they are generally used as lower cost beverage sources. Additionally, it is not unusual for consumers in some of the coffee producing countries to blend coffee with noncoffee materials.

Chicory is harvested as fleshy roots that are dried, cut to uniform size, and roasted. Chicory contains no caffeine, and on roasting develops an aroma compatible with that of coffee. It gives a high yield, ~70%, of water-soluble solids with boiling water and can also be extracted and dried in an instant form. Chicory extract has a darker color than does normal coffee brew (67).

BIBLIOGRAPHY

"Coffee" in *ECT* 1st ed., Vol. 4, pp. 215–223, by L. W. Elder, General Foods Corp.; "Coffee, Instant" in *ECT* 1st ed., Suppl. 2, pp. 230–234, by H. S. Levenson, Maxwell House Division of General Foods Corp.; "Coffee" in *ECT* 2nd ed., Vol. 5, pp. 748–763, by R. G. Moores and A. Stefanucci, General Foods Corp.; in *ECT* 3rd ed., Vol. 6, pp. 511–522, by A. Stefanucci, W. P. Clinton, and M. Hamell, General Foods Corp.; in *ECT* 4th ed., Vol. 6, pp. 793–811 by G. Wasserman, H. D. Stahl, W. Rehman, P. W. Heilmann, Kraft General Foods Corporation; "Coffee" in *ECT* (online), posting date: December 4, 2000, by Gerald Wasserman, Howard D. Stahl, Warren Rahman, Peter Whitman, Kraft General Foods Corporation.

CITED PUBLICATIONS

1. R. J. Clarke and O. G. Vitzthum, eds., *Coffee, Recent Developments*, Blackwell Science, London, U.K., 2001, Chapt. 2–4.
2. R. J. Clarke and R. Macrae, eds., *Coffee*, Vol. 1, Chemistry, Elsevier Applied Science Publishers, Ltd., Barking, U.K., 1985, Chapt. X.
3. M. N. Clifford in Ref. 2, pp. 153–202.
4. A. Scholze and H. G. Maier, *Z. Lebensmittel. Unters. Forsch.* **178**, 5 (1984).
5. K. Speer and I. Kolling-Speer, in Ref. 1, pp. 33–49.
6. J. R. Rogers, S. Michaux, M. Bastin, and P. Buchell, *Plant Science* **149**, 115 (1999).
7. A. G. W. Bradbury, in Ref. 1, pp. 1–17.
8. R. J. Redgwell, D. Curti, M. Fischer, P. Nicolas, and L. B. Fay, *Carbohydrate Res.* **337**, 239 (2001).
9. U. Arnold, E. Ludwig, R. Kuhn, and U. Moeschwitzer, *Z. Lebensmittel. Unters. Forsch.* **199**, 22 (1994).
10. R. MacRae, in Ref. 2. pp. 141–142.
11. R. MacRae, in Ref. 2. pp. 125–135.
12. H. H. Balzer, in Ref. 1, pp. 18–30.

13. W. Grosch, in Ref. 1, pp. 68–89.
14. G. Pictet, in Ref. 2, Vol. 2. *Technology*, 1987, pp. 221–225.
15. M. Petracco, in Ref. 1, pp. 140–164.
16. U.S. Pat. 4,322,447 (Mar. 20, 1982), M. Hubbard (to Hills Bros. Coffee Co.).
17. U.S. Pat. 4,737,376 (Apr. 12, 1988), L. Brandlein and co-workers (to General Foods Corp.).
18. U.S. Pat. 4,988,590 (Jan. 29, 1990), S. E. Price and co-workers (to Procter & Gamble Co.).
19. U.S. Pat. 4,860,461 (Aug. 29, 1989), Y. Tamakiand co-workers (to Pokka Corp. and NGK Insulators Ltd.).
20. U.S. Pat. 4,780,586 (Oct. 25, 1988), T. Le Viet and T. Bernard (to Nestec S.A.).
21. U.S. Pat. 3,615,667 (Oct. 26, 1971), F. M. Joffe (to Procter & Gamble Co.).
22. W. Clinton, *"Evaluation of Stored Coffee Products,"* Proceedings of the 9th Colloquium of ASIC, London, 1980, p. 273.
23. A. L. Brody, *Food and Flavor Section*, Arthur D. Little, Inc., Cambridge, Mass.; *Flexible Packaging of Foods*, CRC Press, Division of the Chemical Rubber Co., Cleveland, Ohio, 1970, pp. 41–42.
24. *National Coffee Drinking Trends*, National Coffee Association, New York, 2001.
25. R. Clarke in Ref. 2. p. 206.
26. Eur. Pat. Appl. 0363529A3 (June 10, 1988), H. D. Stahl and co-workers (to General Foods Corp.).
27. U.S. Pat. 4,107,339 (Aug. 15, 1978), B. Shrimpton (to General Foods Corp.).
28. U.S. Pat. 3,438,784 (Apr. 15, 1969), W. P. Clinton and co-workers (to General Foods Corp.).
29. U.S. Pat. 897,763 (Sept. 1, 1908), J. F. Meyer (to Kaffee-Hag).
30. U.S. Pat. 2,309,092 (Jan. 26, 1943), N. E. Berry and R. H. Walters (to General Foods Corp.).
31. U.S. Pat. 4,820,537 (Apr. 8, 1989), S. Katz (to General Foods Corp.).
32. U.S. Pat. 4,465,699 (Aug. 14, 1964), F. A. Pagliaro and co-workers (to Nestlé SA).
33. U.S. Pat. 4,409,25 (Oct. 11, 1983), L. R. Morrison, Jr. (to Procter & Gamble Co.).
34. W. Heilmann, in *Proceedings of the 14th Colloquium of ASIC*, San Francisco, Calif., 1991, pp. 349–356.
35. Green Coffee: Total Production in Selected Countries Horticultural and Tropical Products Division, FAS/USDA, December 2001.
36. Coffee: ICO Monthly and Composite Indicator Prices on the New York Market Horticultural and Tropical Products Division, FAS/USDA December 2001.
37. Green Coffee: Exportable Production in Specified Countries: Horticultural and Tropical Products Division, FAS/USDA December 2001.
38. Coffee: ICO Monthly and Composite Indicator Prices on the New York Market Horticultural and Tropical Products Division, FAS/USDA, December 2001.
39. U.S. *Coffee Imports by Type and Origin Source*: U.S. Department of Commerce Horticultural and Tropical Products Division, FDA/USDA, December 2001.
40. Coffee: *Specified Country Imports Source*: U.S. Department of Commerce Horticultural and Tropical Products Division, FDA/USDA, December 2001.
41. H. A. M. Van der Vossen in Ref. 1, pp. 184–201.
42. M. R. Sondahl "Coffee breeding assisted by somoclonal variation: case of 'Bourbon LC' variety", *Proceedings of the 19th Colloquium of ASIC*, Trieste, Italy, 2001.
43. S. Zezlina, M. Soranzio, P. Rovelli, M. A. Kriger, M. R. Sondahl, and G. Graziosi, "Molecular characterisation of the cultivar Bourbon LC", *Proceedings of the 18th Colloquium of ASIC*, Helsinki, Finland, 1999, pp. 314–321.
44. P. Barre, S. Akaffou, J. Charrier, A. Hamon, and M. Noirot, *Theor. and Appl. Gen.* **96**(2), 306 (1998).

45. C. Campa, H. Chrestin, A. de Kockko, C. Bertrand, T. Leroy, and M. Noirot, "Towards Identification and Characterisation of Candidate Genes Involved in Coffee Cup Quality", *Proceedings of the 19th Colloquium of ASIC*, Trieste, Italy, 2001.
46. J. Spiral, T. Leroy, M. Paillard, and V. Petiard, *Biotechnol. Agr. Forestry* **44**, 55, (1999).
47. J. I. Stiles Ref. 1, pp. 224–234.
48. A. Pallavicini, L. Del Terra, B. De Nardi, P. Rovelli, and G. Graziosi, "A catalogue of genes expressed in *Coffea arabica* L.", in Ref. 5 *Proceedings of the 19th Colloquium of ASIC*, Trieste, Italy, 2001.
49. P. Marraccini, C. Allard, M. L. André, C. Courjault, C. Garborit, N. Nicolas, A. Meunier, S. Michaux, V. Petit, P. Priyond, J. W. Rogers, and A. Deshayes, "Update on Coffee Biochemical Compounds, Proteins and Gene Expression during Bean Maturation and in Other Tissues.", *Proceedings of the 19th Colloquium of ASIC*, Trieste, Italy, 2001.
50. F. Anthony, B. Bertrand, O. Quiros, A. Wilches, J. Berthaund, and A. Charrier, *Euphytica* **118**, 53, (2001).
51. S. Moisyadi, K. R. Neupane, and J. I. Stiles, *Acta Horticult* **461**, 367, (1997).
52. K. R. Neupane S. Moisyadi, and J. I. Stiles, "Cloning and Characterisation of Fruit-Expressed ACC Synthase and ACC Oxidase from Coffee", in Ref. 42, pp. 322–326.
53. International Pat. WO 98/42848 (Oct. 1, 1998), J. I. Stiles and co-workers (to University of Hawaii).
54. International Pat. WO 98/06852 (Feb. 19, 1998), J. I. Stiles and co-workers (to University of Hawaii).
55. M. Nagata, H. Mori, Y. Tabei, T. Sato, M. Hirai, and H. Imaseki, *Acta Horticult.* **394**, 213, (1995).
56. B. Perthuis, R. Philippe, J. L. Pradon, M. Dufour, and T. Leroy, "Premiéres observations sur la résistance au champ de plants de *Coffea canephora* génétiquement modifiées contre la mineuse des feuilles *Perileucoptra coffeella* Guérin-Méneville", *Proceedings of the 19th Colloquium of ASIC*, Trieste, Italy, 2001.
57. International Pat. No. WO 99/02688 (to Societe de Produits Nestle SA).
58. International Pat. WO 99/02688 (Jan. 21, 1999), P. Marraccini and co-workers (to Societe de Produits Nestle SA).
59. 'Robbing coffee's cradle', ActionAid briefing, 2001 (www.actionaid.org).
60. U.S. Pat. 4904484 (Feb. 27, 1990), L. E. Smith and T. N. Asquith (to Proctor & Gamble Co.).
61. U.S. Pat. 4867992 (Sept. 19, 1989), B. Boniello and co-workers (to General Foods Corp.).
62. U.S. Pat. 4983408 (Jan. 8, 1991), R. Colton.
63. U.S. Pat. 5714183 (Feb. 3, 1998), P. Nicols and co-workers (to Nestec SA).
64. R. J. Clarke in Ref. 1, pp. 235–237.
65. Directive 1999/4/EC of the European Parliament, 1999.
66. B. Schilter, 'Health Benefits of Coffee', *Proceedings of the 19th Colloquium of ASIC*, Trieste, Italy, 2001.
67. J. I. Pitt 'The Importance of Ochratoxin A in Foods: Report of the 56th Meeting of JEFCA', *Proceedings of the 19th Colloquium of ASIC*, Trieste, Italy, 2001.
68. Ref. 2, Vol 5, *Related Beverages*.

GENERAL REFERENCES

R. J. Clarke and O. G. Vitzthum, eds., *Coffee, Recent Developments*, Blackwell Science, London, U.K., 2001.

R. J. Clarke and R. Macrae, eds., *Coffee*, Vol. 1, *Chemistry*, 1985; Vol. 2, *Technology*, 1987; Vol. 3, *Physiology*, 1988; Vol. 4, *Agronomy*, 1988; Vol. 5, *Related Beverages*, 1987; Vol. 6, *Commercial and Technico-Legal Aspects*, 1988; Elsevier Applied Science Publishers, Ltd., Barking, U. K. An excellent reference series.

M. Sivetz and N. Desrosier, *Coffee Technology*, AVI Publishing Co., Inc., Westport, Conn., 1979. Somewhat dated but good reference for the basic coffee processing technology.

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THEODORE CRUZ
SIMON PENSON
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