TEA

1. Introduction

Tea, a "gift from God" according to the ancient Chinese, has been enjoyed for thousands of years (1). This fragrant brew is prepared from the leaves of the plant *Camellia sinensis*. At least two well-defined varieties of *Camellia sinensis* are recognized: *assamica*, a large-leaved (15–20-cm) plant, and *sinensis*, a smaller-leaved (5–12-cm) variety (2). Valued historically as the beverage of the social elite, as of the latter half of the twentieth century tea was a beverage of the masses and per capita consumption exceeded 40 liters annually (3). The processing, chemistry, and physiological functionality of tea beverages have intrigued scholars and tea drinkers over the millennia. These challenge researchers yet.

Tea is native to the East Asia region, especially the People's Republic of China, Burma, Laos, and Vietnam. Its first recorded use dates from the fourth century AD in China. A flourishing trade eventually developed, which led to the cultivation of tea. The modern tea industry has its origins in the spread of cultivated tea from China into Japan (ca 610 AD). Tea reached Europe in the sixteenth century and by the latter part of the seventeenth century had become a popular beverage, served in numerous tea houses in London. The cultivation of tea rapidly spread throughout the Indian subcontinent from 1878 to 1834. Development of tea plantations and migration of the technology of plantation operation from India to tropical areas in Africa (1850–1878), South America (ca 1900), Russia (Georgia) (1913), and Australia and the Pacific islands (1824–1909) led to a variety of localized practices and tea products (2,4–6).

Through cultivation tea has become an important agricultural product throughout the world, particularly in regions lying close to the equator. Geographical areas which receive annual rainfall of at least 19.7 cm/yr (50 in./yr) and have a mean average temperature of 30°C and slightly acidic soil are the most favorable for growth and agriculture of tea (2,6–8). Tea is generally pruned and maintained as a shrub-like bush of 1–1.5 m in height (7).

Traditionally, *Camellia sinensis* was propagated and bred through seeds; however, this practice led to genetic variability, loss of consistency of yield, and poorer beverage quality. Vegetative propagation has become a common practice. This helps to maintain genetic purity and aids in more rapid establishment of new productive stands of tea (Fig. 1). New clones of tea are generally selected based on criteria such as beverage quality, yield, ease of establishment, pest resistance, and frost resistance. Once established, new plantings of tea are economically viable for decades, barring diseases, pest infestation, or other destruction (8).

Tea estates range in size from small local holdings of 1 ha or less to large establishments of up to 800 ha. Harvesting worldwide is generally done by hand using a small knife. Shears, hand-held cutters powered by back-carried gasoline engines (9), and small self-propelled harvesters which straddle dome-contoured rows are used for harvesting in Japan. Mechanical harvesting methods have been developed and are popular only where labor is expensive and where

tea is not grown on steep mountain-slopes. Large-scale mechanical harvesting equipment is most commonly used in Georgia, Australia, and Argentina. Tea is manufactured into a consumable product in tea factories, which are usually located near large plantations. Leaf harvested from small holdings is generally combined and processed at central factories.

New growth is harvested at intervals of 6–12 d, depending on the climatic conditions. Growth is most rapid during warm weather and heavy rainfall. In some areas, such as North India (Assam), Japan, and Russia, a period of dormancy occurs during the cold season. In South India, Sri Lanka, Indonesia, and Africa, production continues year-round, permitting more efficient use of labor and manufacturing facilities. The length of the growing season, however, has little effect on annual yield.

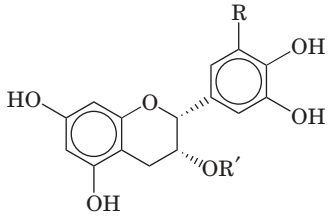
The flush of a tea shoot is defined as the apical bud and two new leaves below it (Fig. 2). This is the ideal target for harvesting fresh tea of optimum quality. Commonly, three or even four leaves are plucked in an attempt to increase crop yield.

2. Composition of Fresh Tea and Biosynthesis of Tea Polyphenols

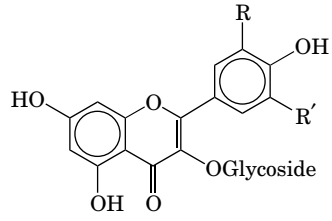
The leaves of *Camellia sinensis* are similar to most plants in general morphology and contain all the standard enzymes and structures associated with plant cell growth and photosynthesis (10–12). Unique to tea plants are large quantities of flavonoids and methylxanthines, compounds which impart the unique flavor and functional properties of tea. The general composition of fresh tea leaves is presented in Table 1.

2.1. Flavonoids. Green tea leaves contain many types of flavonoids, the most important of which are the flavanols (catechins), the flavonols, and flavanol glycosides. Tea catechins are water-soluble, colorless substances which impart the bitter and astringent taste characteristic of green teas. Localized within the cytoplasmic region of leaf cells, the flavanols (catechins) generally make up 25–40% of the water-soluble solids of tea (Table 2). Catechins are easily oxidized when catalyzed by enzymes of the general class called oxidases and autoxidize in an alkaline environment. The oxidation products of catechins are the red-brown pigments found in brewed and instant teas. They also form complexes with many other substances such as proteins and caffeine [58-08-2] (13). These polyphenolic constituents are the key reactants involved with the enzymatic fermentation of green tea to black tea. The quality of tea infusions correlates with the flavonol content of fresh green leaves (10,14). A number of flavonols including quercetin [117-39-5], kaempferol [520-18-3], myricetin [529-44-2], and their glycosides are also found in tea leaves (Table 3) (11,15,16). Flavonol glycosides generally make up 2–3% of the water-soluble solids of tea. The flavonol aglycones are not found in tea beverages owing to poor solubility in water.

2.2. Other Phenolic Compounds. There are several phenolic acids important to tea chemistry. Gallic acid (**3**) and its quinic acid ester, theogallin (**4**), have been identified in tea (17,18) and have been detected by hplc (19,20).



(**1**)



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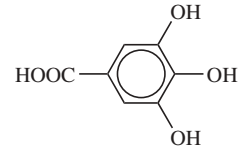

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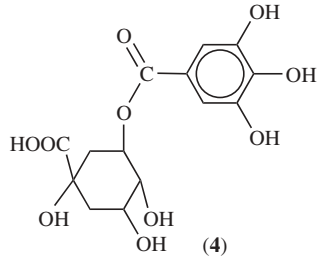
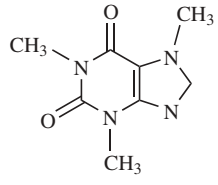


(**4**)

2.3. Caffeine and Other Xanthines. Tea flush contains 2.5–4.0% caffeine (**5**) on a dry weight basis and much smaller quantities of the related methylxanthine theobromine [83-67-0] (**6**). Whereas theophylline [58-55-9] has been reported to be a constituent of tea (21), there are no recent reports that theophylline can be found in tea and it is not possible to detect theophylline in tea beverages using modern analytical techniques (22). On average, a 6-ounce (180-cm^3) cup of tea contains 20–70 mg of caffeine, compared to 40–155 mg of caffeine in a 6-ounce (180-cm^3) cup of freshly brewed coffee (qv). Infusions of black, green, and oolong teas all contain about the same amounts of caffeine when prepared using similar amounts of leaves. The amount of caffeine in a tea beverage is largely determined by brewing conditions (time, temperature, leaf size, and amount of tea). Caffeine forms complexes with the polyphenolic constituents in tea and these complexes have poor solubility and often precipitate under cold storage. This precipitate is called cream because of its milky appearance. This physical and chemical property of tea affects the behavior of iced tea beverages as well as the technology of instant-tea manufacture.



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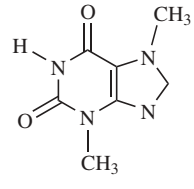
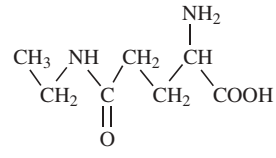


(**6**)

2.4. Theanine and Other Amino Acids. Amino acids (qv) make up 4–8% of the soluble solids found in brewed tea. There is an amino acid unique to tea, γ-*N*-ethyl glutamine, called theanine [3081-61-6] (**7**) (23).



(**7**)

2.5. Minerals and Ash. The water-soluble extract solids which infuse from tea leaves contain 10–15% ash. The tea plant has been found to be rich in potassium (24) and contains significant quantities of calcium, magnesium (25), and aluminum (26). Tea beverages are also a significant source of fluoride (27), owing in part to the uptake of aluminum fluoride from soils (28,29).

2.6. Volatiles or Aroma. The essential oil, or aroma, of tea provides much of the pleasing flavor and scent of green and black tea beverages. Despite this, volatile components comprise only ∼1% of the total mass of the tea leaves and tea infusions. Black tea aroma contains over 300 characterizing compounds, the most important of which are terpenes, terpene alcohols, lactones, ketones, esters, and spiro compounds (30). The mechanisms for the formation of these important tea compounds are not fully understood. The respective chemistries of the aroma constituents of tea have been reviewed (31).

2.7. Enzymes. The enzymes most important to the chemistry and manufacturing of tea are those responsible for the biosynthesis of tea flavonoids (Table 4) and those involved in the conversion of fresh leaf into manufactured commercial teas.

Alcohol dehydrogenase (5) and leucine α-ketoglutarate transaminase (33,34) contribute to the development of aroma during black tea manufacturing. Polyphenol oxidase and peroxidase are essential to the formation of polyphenols unique to fermented teas.

Polyphenol oxidase (PPO) (EC 1.14.18.1; monophenol monooxygenase [tyrosinase] or EC 1.10.3.2; *o*-diphenol: O_2-oxidoreductase) is one of the more important enzymes involved in the formation of black tea polyphenols. The enzyme is a metallo-protein thought to contain a binuclear copper active site. The substance PPO is an oligomeric particulate protein thought to be bound to the plant membranes. The bound form of the enzyme is latent and activation is likely to be dependent upon solubilization of the protein (35). PPO is distributed throughout the plant (35) and is localized within in the mitochondria (36), the cholorplasts (37), and the peroxisomes (38). Using antibody techniques, polyphenol oxidase activity has also been localized in the epidermis palisade cells (39). Reviews on the subject of PPO are available (40–42).

PPO from tea reacts effectively with both 3′-4′ and 3′-4′-5-hydroxylated catechins, with specificity for the *o*-diphenol (43,44). Studies defining the kinetics of PPO from tea in relation to substrate type are lacking. Tea PPO has good functionality in the pH range 4.6–5.6 (43,45–48).

Peroxidase (POD) (EC 1.11.1.7) is thought to play in integral role in the fermentation process and is found in fresh green leaf (43,49,50). It is a heme-based enzyme which catalyzes the reductive decomposition of hydrogen peroxide to water, and organic peroxide species to the corresponding alcohol. PPO is thought to produce peroxide, which activates the POD system (50). However, catalase is quite active in tea and rapidly removes peroxides as they form. Along with PPO, POD plays a role in the oxidation processes involved with the formation of the black tea components.

2.8. Biosynthesis of Tea Flavonoids. The pathways for the *de novo* biosynthesis of flavonoids in both soft and woody plants (Figs. 3 and 4) have been generally elucidated and reviewed in detail (32,51). The regulation and control of these pathways in tea and the nature of the enzymes involved in synthesis in tea have not been studied exhaustively. The key enzymes thought to be involved in the biosynthesis of tea flavonoids are 5-dehydroshikimate reductase (52), phenylalanine ammonia lyase (53), and those associated with the shikimate/arogenate pathway (52). At least 13 enzymes catalyze the formation of plant flavonoids (Table 4).

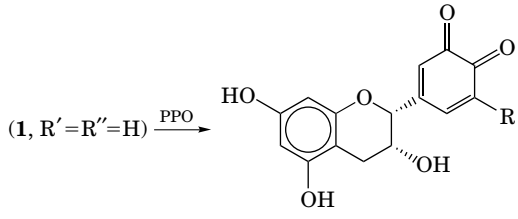
3. Manufacturing

Freshly harvested tea leaves require manufacturing to be converted into green, white, oolong, and black teas (Fig. 5). Black tea, the dominantly manufactured tea product worldwide, is made through a polyphenol oxidase-catalyzed oxidation of fresh leaf catechins. Green tea is processed in a manner designed to prevent the enzymatic oxidation of catechins before drying. Green tea consumption is growing worldwide, but Japan, the People's Republic of China, North Africa, and the Middle East are traditionally the sites of greatest consumption. Oolong tea, a partially oxidized tea, is manufactured primarily in the People's Republic of China and Taiwan. Instant tea, usually a powder, is generally prepared by the aqueous extraction of tea leaves, followed by concentration and drying. In some cases, instant teas are prepared by removal of cold water-insoluble constituents via filtration (qv) or centrifugation (see CENTRIFUGAL SEPARATION). Technology, ie, tannase (galloyl esterase) treatment, exists to solubilize the usually cold-insoluble constituents of black tea. It is also possible to make instant tea from green tea or from oxidized leaf before the drying step of the process. Tea concentrates, often dried by spray drying, can also be dried by freeze drying or vacuum drying technologies.

3.1. Chemistry of Tea Fermentation Oxidation. The chemical changes which take place during the manufacture of green, white, oolong, and black teas are responsible for the unique color and flavors characteristic of each tea type. The most significant and well-understood of these reactions occurs during the manufacture of black tea. During the process called tea fermentation the colorless catechins (**1**) found in green tea (see Table 2) (54,55) proceed through a series of oxidative condensation reactions leading to the formation of a range of products of orange-yellow to red-brown color, plus the development of a large number of unique volatile constituents. These changes are reflected in the

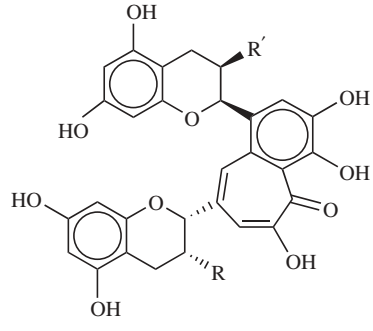
red amber color, reduced astringency, and more complex flavor found in black tea beverages.

Flavonol Oxidation. The fermentation process is initiated by the oxidation of catechins (**1**) to reactive catechin quinones (**13**), a process catalyzed by the enzyme polyphenol oxidase (PPO) (56). Whereas the gallocatechins, epigallocatechin, and epigallocatechin gallate, are preferred, polyphenol oxidase can use any catechin (Table 2) as a substrate. This reaction is energy-dependent and is the basis of the series of reactions between flavanoids that form the complex polyphenolic constituents found in black and oolong teas.



(**13**)

Theaflavins. One of the more well-defined groups of flavonoid polymers that forms during black tea manufacturing is that of the theaflavins (**14**). Exhibiting a bright orange-red color in solution, these are important contributors of brightness, a desirable visual attribute used by professional tasters to describe the appearance of tea infusions.

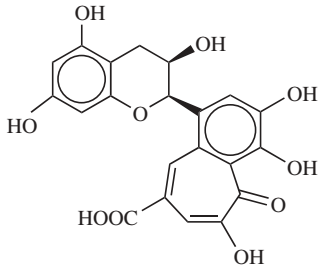


(**14**)

There are four main theaflavins common to black teas, and a second group of minor theaflavins, including the isotheaflavins (55) and neotheaflavins (57) (Table 5). The total theaflavin concentration in black tea leaves does not usually exceed 2% and can be as low as 0.3%. At most, only 10% of the catechins in tea flush can be accounted for as theaflavins in black tea and the fate of the remaining catechins is less clear. Theaflavins can be readily determined by direct hplc analysis of tea beverages (48,58,59).

Theaflavic Acids and Theaflagallins. Although gallic acid (**3**) is not directly oxidized by polyphenoloxidase, it can be converted to gallic acid quinone

through other oxidation processes occurring during black tea fermentation (55,60). Gallic acid reacts with catechin quinones (**13**) to form a group of compounds called theaflavic acids, eg, epitheaflavic acid (**15**), or a gallocatechin quinone to form theaflagallins such as epitheaflagallin (**16**) (61). The theaflavic acids are bright red, acidic substances present only in small quantities in black tea (11).



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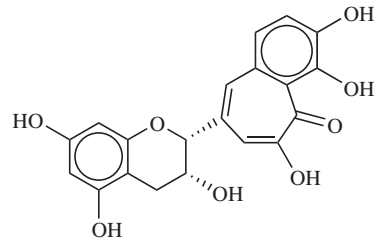
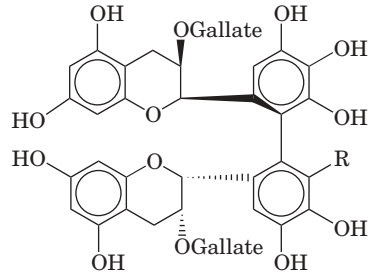


(**16**)

Bisflavanols (Theasinensins). The paired condensation of two gallocatechins forms a group of colorless substances called bisflavanols (62,63). The bisflavanols have been isolated and reclassified under the name of theasinensins (64) and have been found in both green and oolong teas (65). Bisflavanols such as theasinensin A (**17**, R=OH) and theasinensin F (**17**, R=H) are reactive compounds and can in part rearrange to form other black tea flavonoid compounds.



(**17**)

Complex Tea Polyphenols. The catechins (**1**) are reduced by ~85% during black tea manufacturing, yet only ~10% can be accounted for in the form of theaflavins (**14**) and theaflavic acids. The remaining ~75% of the catechins form undefined, water-soluble polyphenolic substances thought to be the pigments which provide tea its brown-to-black color. These compounds have historically been termed thearubigens (66,67). One subgroup of this complex mixture of materials has been classified as proanthocyandin polymers (68). These form cyanidin [528-58-5] (53) and delphinidin [528-53-0] (56) upon acid hydrolysis. Attempts to separate and purify the thearubigens of black tea via chromatography (qv) and reverse-phase hplc have not met with much success (59,69). Purification of a black tea fraction termed theafulvin (70) and oolongtheanin (71) has been accomplished. This class of polyphenolic compounds might make up a portion of the group of polyphenols of the general class historically termed thearubigens.

3.2. Black Tea. The black tea manufacturing process has evolved over hundreds of years, until the early part of the twentieth century, little was known about the chemical changes. The process consists of the unit operations of withering, rolling, fermentation, firing, and sorting (4).

Withering. Immediately after harvesting, tea leaves are brought to factories situated close to the tea gardens for manufacturing. Leaves are handled carefully to prevent bruising and to dissipate the heat generated by biochemical reactions associated with continued respiration. The leaves are distributed in thin layers on open-meshed fabric netting or, more efficiently, in troughs designed for effective air flow through deep (up to 30-cm) beds of leaf. This procedure allows more rapid loss of water without the heat buildup which is detrimental to quality.

Reduction of the leaf moisture converts the turgid leaf to a flaccid material which is easily handled without excessive fracture. The withering process takes a period of 6–18 h, depending on the weather conditions and the type of equipment employed. Biochemical changes to the tea leaves occur during withering. For example, cell membrane permeability is increased, allowing for easier disruption of the cell contents during the succeeding stage of the process; the concentration of amino acids, caffeine, organic acids, and polyphenols increases; and polyphenol oxidase is transformed from its latent to active form (72). These biochemical changes occur as a function of leaf senescence rather than owing to water loss and thus has been termed chemical withering (73).

Rolling. The next step is the initiation of the enzymic oxidation of the flavanols by molecular oxygen. This is accomplished by disruption of the cell structure to effect enzyme–substrate contact. The primary unit operation of this process, called rolling, is primarily a cutting and squeezing process but includes a twisting action to enhance leaf appearance. The traditional roller consists of a circular table, 1–1.3-m in diameter, equipped with battens. Above this, a smaller circular sleeve moves eccentrically over the surface of the table. Withered leaf is charged into the sleeve and a pressure cap is lowered into the sleeve. The result depends on the pressure and the rate of movement. Intermittently, leaf sufficiently rolled and reduced in size is separated by sieving and the remainder is rerolled. At the end of the rolling process, leaf juices are well-distributed on the surface of the cut, twisted leaf.

More modern equipment has come into use in most of the tea-growing areas. The McTear Rotorvane consists of a cylinder (20 or 37.5 cm dia) lined with vanes, through which a vaned rotorshaft propels withered leaf, thereby enhancing maceration. Rotating cutter blades are sometimes added to the shaft. Following Rotorvane treatment, leaves are frequently passed through a crush, tear, curl (CTC) machine, which consists of a pair of ridged cylindrical rollers revolving at different speeds and having a narrow clearance between rolls.

The Rotovane–CTC combination provides efficient and uniform maceration and is well suited to the establishment of a continuous manufacturing process. Macerated leaf is fluffed up by passage through a high speed Rotorvane without back pressure to eliminate matting and facilitate air diffusion. Leaf temperature should be kept below 35°C during maceration to prevent flavor deterioration. The

Legg cutter, originally designed for cutting tobacco, is widely used in North India for macerating unwithered leaf and is called an LTP process in the trade.

Fermentation. The term fermentation arose from the misconception that black tea production is a microbial process (73). The conversion of green leaf to black tea was recognized as an oxidative process initiated by tea–enzyme catalysis circa 1901 (74). The process, which starts at the onset of maceration, is allowed to continue under ambient conditions. Leaf temperature is maintained at less than 25–30°C as lower (15–25°C) temperatures improve flavor (75). Temperature control and air diffusion are facilitated by distributing macerated leaf in layers 5–8 cm deep on the factory floor, but more often on racked trays in a fermentation room maintained at a high rh and at the lowest feasible temperature. Depending on the nature of the leaf, the maceration techniques, the ambient temperature, and the style of tea desired, the fermentation time can vary from 45 min to 3 h. More highly controlled systems depend on the timed conveyance of macerated leaf on mesh belts for forced-air circulation. If the system is enclosed, humidity and temperature control are improved (76).

During the oxidation process, leaf color changes from green to copper and a pleasant characteristic aroma develops. In most instances, the proper termination point is determined by the skill of the process supervisor (tea maker) on whose judgment the value of the final product is highly dependent. However, some attempts to control a suitable end point by instrumental techniques have been made. The fermentation step is terminated by firing (drying).

Firing. A hot-air oven having forced circulation in a countercurrent mode is used to dry the fermented tea leaves and inactivates the key enzymes required for fermentation. The firing process generally occurs over an 18–20-min period, which is optimum for normal process efficiencies.

The firing process reduces the moisture of the fermented leaf mass from ~60–70% to 2.5–3.0%. The chemical and enzymatic reactions which occur during firing lead to important changes in leaf color owing to chlorophyll degradation (77) as well as development of many volatile constituents which characterize green, oolong, and black teas. Lower boiling aroma components are volatilized and alcohols and carbonyl compounds are oxidized during firing. Cyclic nitrogen compounds, such as pyrazines, pyridines, and quinolines, form owing to degradation of amino acids and proteins.

Grading. Fired tea is fractionated into characterizing grades using a series of oscillating screens. The most common grades of tea in descending particle size are: orange pekoe (OP), pekoe fannings (PF), broken orange pekoe (BOP), broken orange pekoe fannings (BOPF), fannings, and dust. Dust, debris, and some fiber are removed by winnowing. Stalky materials are generally more moist than the fired leaf and may be removed using an electrostatic sorter although tea has been traditionally packed in foil-lined, plywood chests measuring $40 \times 50 \times 60$ cm^3 and holding ~60 kg, paper sacks have become very common. The use of chests is being phased out.

Process Variations. The conventional techniques for tea manufacture have been replaced in part by newer processing methods adopted for a greater degree of automation and control. These newer methods include withering modification (78), different types of maceration equipment (79), closed systems for fermentation (80), and fluid-bed dryers (81). A thermal process has been

described which utilizes decreased time periods for enzymatic reactions but depends on heat treatment at 50–65°C to develop black tea character (82). It is claimed that tannin–protein complex formation is decreased and, therefore, greater tannin extractability is achieved. Tea value is believed to be increased through use of this process.

3.3. Green Tea. Green tea is made by rolling and firing without enzymic oxidation. Fresh leaf is subjected to a rapid steaming process in a rotating cylindrical drum for ~20 s. Steamed leaf is cooled and rolled lightly in a hot-air environment. Partially dried leaf is then rolled more vigorously, dried further, and the process repeated until moisture is reduced to 3%. Drying temperatures are lower than for black tea, yielding further differences in both the volatile and nonvolatile fractions. The aroma components of green tea have been extensively studied and compared with those of fresh leaf and black tea (83). A high proportion of catechins (**1**) are retained in green tea, and the amino acid content is much higher. In the People's Republic of China, dry heat is commonly used to inactivate enzymes and can impart a smokey flavor to the tea.

Green or black tea can be prepared from any fresh leaf. In practice, however, different tea varieties and horticultural techniques are used, depending on the product desired. Plants grown for green tea production usually have smaller leaves, fewer catechins, and more amino acids (10). The green tea beverage is pale yellow to green, slightly more astringent than black tea, and has a brothy characteristic imparted by theanine and other amino acids.

3.4. Other Types. *Oolong Tea.* Oolong tea is produced in the People's Republic of China and on Taiwan. Withered leaf is lightly rolled and only partially fermented. Enzymatic action is terminated by a heating process. Vigorous rolling to achieve the desired appearance, additional heat treatment, and firing complete the process. In some respects, the beverage characteristics are between those of green tea and black tea, but oolong contains a unique array of volatile and polyphenolic compounds not found in either green or black tea.

Minor Varieties. Brick teas are prepared in the former Soviet Union and in parts of the People's Republic of China (82). These products are often cooked as a soup with butter or other fats. Flavorants such as jasmine flowers may be added during processing. Oil of bergamot is used to prepare Earl Grey tea.

3.5. Instant Teas. Instant tea is manufactured in the United States, Japan, Kenya, Chile, Sri Lanka, India, and China. Production and consumption in the United States is greater than in the rest of the world. The basic process for manufacture of instant tea as a soluble powder from dry tea leaf includes extraction, concentration, and drying. In practice, the process is considerably more complicated because of the need to preserve the volatile aroma fraction, and produce a product which provides color yet is soluble in cold water, all of which are attributes important to iced tea products (84).

Extraction. Traditionally tea leaf is extracted with hot water either in columns or kettles (84,85), although continuous liquid solid-type extractors have also been employed. To maintain a relatively low water-to-leaf ratio and achieve full extraction (35–45%), a countercurrent system is commonly used. The volatile aroma components are vacuum-stripped from the extract (86) or steam-distilled from the leaf before extraction (87). The diluted aroma (volatile constituents) is typically concentrated by distillation and retained for flavoring

products. Technology has been developed to employ enzymatic treatments prior to extraction to increase the yield of solids (88) and induce cold water solubility (89,90).

Decreaming. Extract is separated from leaf by centrifugation or filtration. The resulting extract is cooled and a milky precipitate, or cream, forms. Tea cream is a coacervate formed of a complex between caffeine, catechins, and the oxidized catechins of black tea. The conditions under which cream forms determine the chemical composition of the complex and its physical properties. This material is typically removed in order to obtain a product that is soluble in cold water. Several techniques have been described for the solubilization of this fraction to permit the reincorporation of the desirable substances into the product (84,91). The most common of these techniques is an air–oxygen-induced oxidation reaction, induced under alkaline conditions (92). Enzymatic treatment of tea cream using an enzyme called tannase has also been used to render cream cold water soluble (89). The addition of green teas or green tea polyphenols to black teas has been reported to block or reduce formation of cold water insoluble complexes in black tea (93). In practice, a significant portion of the cream solids are entrapped water-soluble tea constituents. Recovery of these solids through extraction using spent tea has been reported (94).

Concentration. Tea extracts are generally concentrated under vacuum to the solids content desired for drying. Freeze concentration has been described (95), as has reverse osmosis (qv) (96). Preserved aroma and the solubilized cream fraction may be added before drying.

Drying. Spray drying is the method most typically used for producing powdered teas. Freeze drying and vacuum tray drying have also been used. Low (0.1 g/cm^3) density products are generally prepared to assure solubility and to provide for delivery of the proper weight (700 mg) of tea solids for a cup of beverage in a teaspoon (700 mg/200 mL). However, high density products are also prepared when the materials are to be reconstituted for preparation of ready-to-drink beverages, tea concentrates, or powdered drink mixes.

Other Methods. Instant tea may also be prepared by directly extracting fermented leaf before the firing stage. These processes, only suited for practice in the tea-growing countries, have been carried out on a small scale in Sri Lanka, India, and Kenya (97).

Instant Tea-Based Products. Powdered soft drinks and ready-to-drink teas are produced by formulating instant teas with acids, flavors, sugars, or noncaloric sweeteners. Lemon is by far the predominant flavor used but tropical, citrus, and berry flavors are also quite common.

4. Decaffeination

Decaffeinated teas are now commonly available, as caffeine can be removed from tea leaves or instant tea by a variety of processes. Solvent extraction of caffeine from tea leaf has been described in several patents (98). The typical solvents are ethyl acetate and methylene chloride. Ethyl acetate is an approved solvent in the United States; methylene chloride is approved for use in Canada and Europe.

Supercritical carbon dioxide is also used to decaffeinate teas (see SUPERCRITICAL FLUIDS). The most recent decaffeination technologies have explored decaffeination of fresh green tea using either supercritical carbon dioxide (99) or methylene chloride, followed by fermentation of the fresh green tea to a final black tea product. This process leads to products of superior flavor because most of the characteristic flavors of black tea develop during fermentation and firing. One drawback of this approach is that it requires a source of fresh tea leaves and therefore is easily accomplished only in the growing regions. Instant teas can be decaffeinated by solvent (ethyl acetate or methylene chloride) extraction and solid-phase adsorption (qv) processes.

Decaffeination processing is not regulated by the U.S. Food and Drug Administration and adhering to industry standards is completely voluntary (100). The FDA does not have its own guidelines, but depends on the expertise of the Tea Association Technical Committee for its best practices. If a group does not meet the standards, the Tea Association would first try to settle the problem. If they were not successful, the FDA would be notified and follow up on the problem.

The guidelines include the following: Teas labeled "decaffeinated" will contain no more than 0.4% caffeine on a dry weight basis; Caffeine-free tea is an inappropriate labeling term; only two methods are approved for decaffeinating tea leaves, solvent extraction using ethyl acetate the use of carbon dioxide in the supercritical state. Both are selective for extraction and create no toxicity hazard. Carbon dioxide is considered the better of the two since it keeps more of the benefits and flavor in tact.

5. Blending and Packaging

5.1. Blending. The tea taster plays an important role in purchasing and blending tea. The goal is usually the establishment and maintenance of a chosen standard of tea under constantly changing conditions. It is necessary to include teas from many countries and many gardens within a country in a blend to ensure constancy in flavor, color, and price over a long period of time. The tea taster's jargon includes terms such as bold, tippy, brisk, bright, dull, pungent, flavory, all of which need careful definition for use (101).

5.2. Packaging. In most countries, tea is sold in packets. In the United States, more than 90% of leaf tea is sold in tea bags, frequently packaged at 200 bags/lb (454 g). Larger, family-sized bags containing about 7 g are now very common and bags of up to 28 g are also used, especially in food service operations. An important consideration is tea bag paper quality which must be selected so as to avoid flavor contamination, allow efficient infusion, and retain tea fines. Papers must also have sufficient wet strength so as not to break open when gas is released as hot water is poured onto the bags.

Innovative developments have occurred in the form and functionality of tea bags or infusion packages. Round tea bags have been introduced into the consumer markets in both Europe and the United States (102). Pyramid or tetrahedral bags have also been developed and sold commercially in the United Kingdom, Japan, and the United States (103). Functional tea bags are also being

developed. Some of these bags have strings which when pulled, squeeze the bags to remove the retained liquid (70,104).

The outer packaging must protect the tea from light and moisture absorption. Polypropylene or coated cellophane outer wraps for paperboard tea packages provide a barrier to loss of tea aroma and retard permeation of oxygen and foreign flavors. Low temperature improves storage stability. Properly packaged and stored teas retain acceptable flavor for about a year.

6. Economic Aspects

6.1. Consumption. Hot black tea is the most common form of tea consumed worldwide. Tea in general is prepared from tea bags infused in hot water at a water-to-tea ratio of ~100:1. The beverage achieves a solids concentration of ~0.35% in ~3 min. The composition of typical green and black tea beverages as a percentage of extract solids is given in Table 6. A typical tea beverage contains 2500–3500 ppm solids. Hot black tea is generally consumed with milk and sugar in the United Kingdom and India, and neat in Europe, Asia, and the United States. Iced tea is becoming more common, especially in the form of ready-to-drink canned and bottled teas. Flavoring agents such as lemon, herbs, spices, and fruit flavors are commonly added to hot or cold tea beverages.

Green tea, consumed hot or cold, is most common in Japan and China and is growing rapidly in the United States owing to the numerous reports of health benefits. In 2005, Americans consumed well over 50×10^9 servings of tea or over 2.25×10^9 gallons. About 87% of all tea consumed was black tea, 12.5% was green tea, and a small remaining amount was oolong tea. Approximately 85% of tea consumed in the U.S. is iced. Over the last ten years, ready-to-drink (RTD) tea has grown 10-fold. In 2005, over 65% of the tea brewed in the United States was prepared using tea bags. Ready-to-drink and iced tea mixes comprise about one forth of all tea prepared. Instant and loose teas account for the balance. Instant tea is declining and loose tea is gaining popularity, especially in specialty tea and coffee outlets.

6.2. Sales. 2005 was the 14th consecutive year that consumer purchases of tea increased.

Comparisons of sales in the U.S. for 1990 and 2005 are listed in Table 7 (105). Growth is expected to rise 10–12% for RTD, 3–5% for foodservice, 6–10% for specialty tea, and 2–5% for traditional tea.

7. Physiological and Health Effects of Tea

There are numerous synthetic and natural compounds called antioxidants which regulate or block oxidative reactions by quenching free radicals or by preventing free-radical formation. Vitamins A, C, and E and the mineral selenium are common antioxidants occurring naturally in foods (106,107). A broad range of flavonoid or phenolic compounds have been found to be functional antioxidants in numerous test systems (108–110). The antioxidant properties of tea flavonoids

have been characterized using models of chemical and biological oxidation reactions.

New findings have been documented that lend credibility to tea's health properties. For the most part, studies of green and black tea have yielded similar results. Herbal teas do not come from *Camelia sinesis*, but are an infusion of leaves, roots, bark, seeds or flowers of other plants. They are not linked with the research on the potential health benefits of the traditional tea listed below.

7.1. Chemical Antioxidant Systems. The antioxidant activity of tea extracts and tea polyphenols have been determined using *in vitro* model systems which are based on hydroxyl-, peroxyl-, superoxide-, hydrogen peroxide-, and oxygen-induced oxidation reactions (111–115). The effectiveness of purified tea polyphenols and crude tea extracts as antioxidants against the autoxidation of fats has been studied using the standard Rancimat system, an assay based on air oxidation of fats or oils. A direct correlation between the antioxidant index of a tea extract and the concentration of epigallocatechin gallate in the extract was found (109).

A model system which determines the oxygen radical absorbance capacity (ORAC) was used to evaluate the antioxidant potency of extracts of teas or vegetables in reactions against hydroxyl or peroxyl radicals (111). Green and black tea extracts were found to be eight times more active in blocking peroxyl radical-induced oxidation reactions than any vegetable extract tested. Teas were also effective in blocking hydroxyl-induced oxidation reactions.

The total antioxidant activity of teas and tea polyphenols in aqueous phase oxidation reactions has been determined using an assay based on oxidation of 2,2′-azinobis-(3-ethyl benzothiazoline-sulfonate) (ABTS) by peroxyl radicals (116–119). Black and green tea extracts (2500 ppm) were found to be 8–12 times more effective antioxidants than a 1-m*M* solution of the water-soluble form of vitamin E, Trolox. The most potent antioxidants of the tea flavonoids were found to be epicatechin gallate and epigallocatechin gallate. A 1-m*M* solution of these flavanols were found respectively to be 4.9 and 4.8 times more potent than a 1-m*M* solution of Trolox in scavenging an $ABTS^{+}$ radical cation.

7.2. Biological Antioxidant Models. Tea extracts, tea polyphenol fractions, and purified catechins have all been shown to be effective antioxidants in biologically based model systems. A balance between oxidants and antioxidants is critical for maintenance of homeostasis. Imbalances between free radicals and antioxidants may be caused by an increased production of free radicals or decreased effectiveness of the antioxidants within the reaction system. These imbalances can be caused by the radicals overwhelming the antioxidants within the system, or by an excess of antioxidants leading to a prooxidant functionality (107–120). When antioxidant defense systems are consistently overwhelmed by oxidative reactions, significant damage can occur, leading to the development of chronic diseases such as cancer and coronary heart disease (107,121–123).

Coronary Heart Disease. A theory for atherogenesis (122) has been developed whereby oxidation of low density lipoprotein (LDL) within the arterial wall is the critical first step. It has been hypothesized that sufficient intake of antioxidants would prevent oxidation of LDL and reduce development of coronary heart disease (124). Interest in determining the role of antioxidants in blocking LDL oxidation has led to the development of *in vitro* test systems.

Tea extracts and tea polyphenols inhibit copper- and peroxide-induced oxidation of LDL *in vitro* (118,125,126). The inhibitory concentration for 50% reduction (IC_{50}) values for inhibition of copper-induced oxidation of LDL by some phenolic antioxidants are listed in Table 8. The IC_{50} for epigallocatechin gallate was found to be 0.075 μmM, which was the most potent of all the phenolic antioxidants tested (125,126). Similar results have been reported elsewhere (117,118,127,128).

Recent studies have indicated that tea drinkers reduced their risk of heart attack by tea's ability to lower their LDL levels (129–131).

Cancer. Carcinogenesis may be inhibited or even prevented by numerous factors, including diet, cessation of smoking, or the use of blocking or suppressive agents (132–134). Mutation of protooncogenes and tumor suppressor genes are important steps in the development of cancer (135). Oxidative reactions are a possible cause of these mutational events. The role of dietary constituents (132–134) and tea (136) in prevention of cancers has been the subject of numerous scientific papers. The role of tea and phenolic antioxidants in control of carcinogenesis has been reviewed in detail (123,136–138).

Animal studies have shown that teas are effective in blocking or slowing carcinogenesis (123,136–138). Administration of teas or tea polyphenols to mice or rats have also been shown to decrease oxidative biomarkers, suggesting that tea polyphenols act as antioxidants (127,139).

Studies to determine the physiological effects of tea consumption associated with antioxidant activity and other relevant biomarkers of cancer risk have been conducted with human volunteers. Glucuronide and sulfate conjugates of tea catechins can be measured in human blood plasma at levels of up to 200 ng/mL after consumption of 1–2 cups of green tea (140), demonstrating that tea polyphenols are absorbed. Consumption of black and green teas (300 mL) resulted in an increase in the antioxidant status of blood plasma (141). Two human trials have found that tea drinking prevented oxidative damage to genetic material of blood cells, ie, white blood cell micronuclei formation (142) and sister chromatid exchange frequency (143) induced by tobacco smoking. Tea drinking was also found to block nitrosation reactions in human subjects (144). These studies demonstrate that tea polyphenols are absorbed into the body and appear to have physiological effects that are consistent with antioxidant activity.

Green tea has been studied as a cancer preventative in Japan. Work involving epigallocatechin gallate (the main constituent of green tea) revealed a wide range of target organs for cancer prevention (145). Tea drinking has resulted in the reduction of cancer risk for other forms of cancer such as colon cancer (146,147) and skin cancer (148,149).

Antiobesity and Diabetes. Green tea, green tea catechins, and epigallocatechin gallate have been demonstrated in cell culture and animal models of obesity to reduce adipocyte differentiation, lipogenesis, fat mass, body weight, fat absorption, plasma levels of triglycerides, free fatty acids, cholesterol, glucose, insulin, and leptin, as well as to increase beta oxidation and thermogenesis (150). Tea catechins appear to have antiobesity and antidiabetes effects (151).

Bone Density. Two recent studies found that tea-drinking women had higher bone mineral density than nondrinkers, especially in habitual tea drinkers of six or more years (152,153).

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Table 1. **General Composition of Fresh Tea Leaves**[a]

Components	Quantity, wt%[b]
flavanols	25.0
flavonols and flavonol glycosides	3.0
polyphenolic acids and depsides	5.0
other polyphenols	3.0
caffeine	3.0
theobromine	0.2
amino acids	4.0
organic acids	0.5
monosaccharides	4.0
polysaccharides	13.0
cellulose	7.0
protein	15.0
lignin	6.0
lipids	3.0
chlorophyll and other pigments	0.5
ash	5.0
volatiles	0.1

[a]Ref. 11.
[b]On a dry weight basis.

Table 2. **The Principal Tea Flavanols (Catechins)**

Name	Abbreviation	R	R′
epicatechin	EC	OH	H
epicatechin gallate	ECG	OH	gallate
epigallocatechin	EGC	OH	H
epigallocatechin gallate	EGCG	OH	gallate

Table 3. **The Flavonol Glycosides**

Name	Abbreviation	R	R′
kaempherol glycoside	KaG	H	H
quercetin glycoside	QuG	OH	H
myricetin glycoside	MyG	OH	OH

Table 4. **Enzymes Involved with Biosynthesis of Tea Polyphenols**[a]

Enzymes	EC number
acetyl-CoA carboxylase	6.4.1.2
phenylalanine ammonia-lyase	4.3.1.5
cinnamate 4-hydroxylase	1.12.12.11
4-coumarate-CoA ligase	6.2.112
chalcone synthase	2.3.1.74
chalcone isomerase	5.5.1.6
2-hydroxyisoflavanone synthase	
flavone synthase	
(2*S*)-flavanone 3-hydroxylase	1.14.11.9
flavonol synthase	
dihydroflavonol 4-reductase	
flavan-3,4-*cis*-diol 4-reductase	

[a] Ref. 32.

Table 5. **The Theaflavins** (**14**)

Name	Abbreviation	R	R′
theaflavin	TF	H	H
theaflavin 3-gallate	TF3G	gallate	H
theaflavin 3′-gallate	TF3′G	H	gallate
theaflavin 3,3′-digallate	TFDG	gallate	gallate

Table 6. **The Composition of Typical Green and Black Tea Beverages, % wt/wt solids**

Substance(s)	Green tea	Black tea
catechins	30	9
theaflavins		4
simple polyphenols	2	3
flavonols	2	1
other polyphenols	6	23
theanine	3	3
amino acids	3	3
peptides/protein	6	6
organic acids	2	2
sugars	7	7
other carbohydrates	4	4
lipids	3	3
caffeine	3	3
other methylxanthines	<1	<1
potassium	5	5
other minerals/ash	5	5
aroma	trace	trace

Table 7. **Comparison of Estimated Wholesale Value of the Tea Industry, $ $\times$ 10^9**

Market	1990	2005
traditional	0.87	1.90
RTD	0.2	2.41
food service	0.5	1.0
specialty	0.27	0.85
Total Sales	*1.84*	*6.16*

Table 8. **Antioxidant Potency of Vitamins and Phenolics based on LDL Oxidation *in Vitro*[a]**

Compound	IC_{50}, μM
trolox	1.26
vitamin E	1.45
beta-carotene	4.30
EGCG	0.075
EGC	0.097
ECG	0.142
catechin	0.187
genistein	14.3
naringenin	>16.0
quercetin	0.224
rutin	0.512
gallic acid	1.25

[a]Adapted from Ref. 125.

Fig. 1. Clonal tea propagation: cuttings and seedlings.

Fig. 2. The flush: two leaves and a bud.

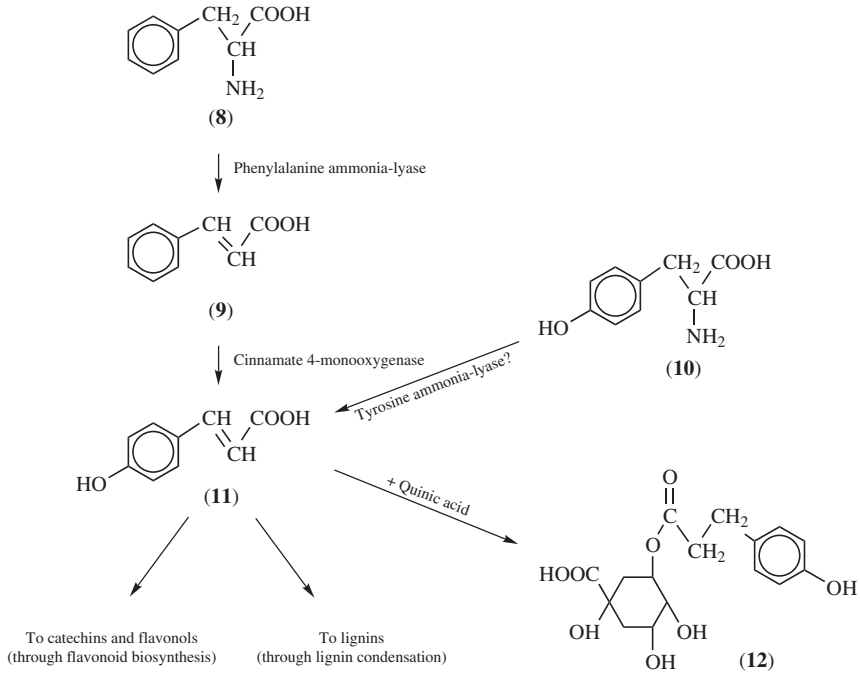

Fig. 3. Cinnamate biosynthesis from phenylalanine (**8**) to cinnamic acid (**9**) or from tyrosine (**10**) to coumaric acid (**11**). Coumarylquinic acid (**12**) is also formed.

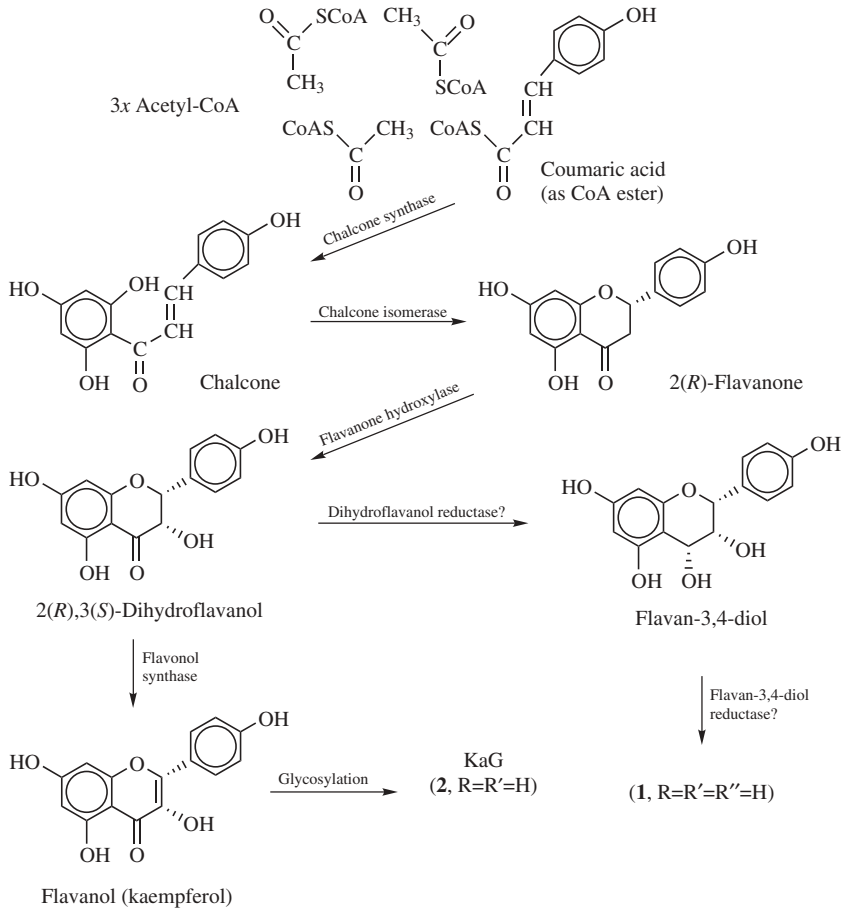

Fig. 4. Biosynthesis of flavonoids where CoA = coenzyme A.

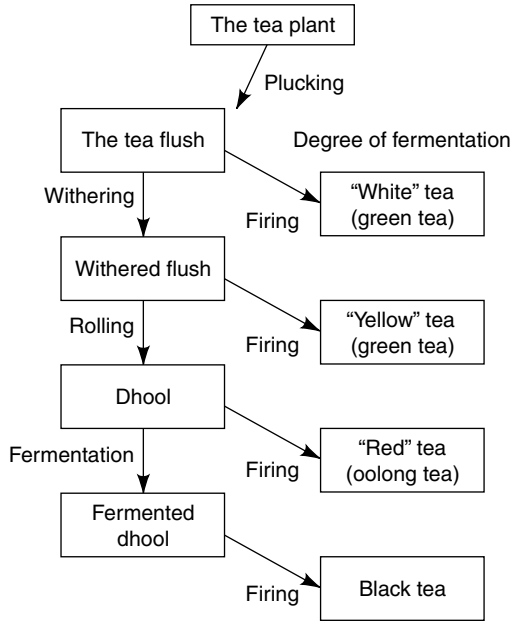

Fig. 5. Tea manufacturing processes.