# CHAPTER II
# LITERATURE REVIEW

## 1. Background of Arabica coffee

Arabica coffee (*Coffea arabica* L.) is a flowering plant, shrubs or small tree native to subtropical Africa and southern Asia and a member of ten species in *Coffea* genus in the family Rubiaceae. Coffee beans are used as a stimulating beverage known as coffee. Coffee is widely cultivated in the tropics for both local consumption and exported to temperate countries. Coffee ranks as one of the world's major commodity crops and is the major export product of some countries. In fact, coffee ranks second only to petroleum in terms of legally-traded products worldwide. There are several species of coffee that may be grown for the beans, but Arabica Coffee is considered to have the best quality. The other species (especially *Coffea canephora*: robusta) are grown on land unsuitable for *Coffea arabica*. The tree produces red or purple fruits (drupes or "coffee berries"), which contain two seeds (the "coffee beans", although not true beans). In about 5-10% of any crop of coffee cherries, the cherry will contain only a single bean, rather than the two usually found. This is called a 'peaberry' and contains a distinctly different flavor profile to the normal crop, with a higher concentration of the flavors, especially acidity, due to the smaller sized bean. As such, it is usually removed from the yield and either sold separately (such as in New Guinea peaberry), or discarded. The coffee tree will grow fruits after 3-5 years, for about 50-60 years (although up to 100 years is possible). The blossom of the coffee tree is similar to jasmine in color and smell. The fruit takes about nine months to ripen. Worldwide, estimate of 15 billion coffee trees are growing on 100,000 km$^2$ of land. Flavor quality of Arabica Coffee is related to several factors such as gene, area, topography, and the technology after harvesting. The main producing method is coffee screening, pulping, and roasting.

## 2. Coffee quality

The purpose of coffee consumption is not to gain nutrient. It is to consume pleasure and satisfaction of coffee aroma, flavor, and physical and mental desire. Thus, aroma is important to coffee quality together with acidity and bitterness (Coffee Research Institute, 2001).

### 2.1 Aroma

Coffee aroma is responsible for all coffee flavor attributes other than the mouthfeel and sweet, salt, bitter, and sour taste attributes that are perceived by the tongue. Therefore, it might be said that coffee aroma is the most important attribute to specialty coffee. Even instant coffee has the components responsible for stimulation of our taste buds. The difference, however, is that instant coffee lacks most of the aromatic volatile compounds causing a dramatic decrease in the overall coffee flavor. Coffee aroma is perceived by two different mechanisms. It can either be sensed nasally via smelling the coffee through the nose or retro-nasally. Retro nasal perception occurs when the coffee is either presents in the mouth or has been swallowed and aromatic volatile compounds drift upward into the nasal passage. The number of aromatic compounds found in coffee increases every year. Today the number is well over 800, and as our analytical methods become more precise, more will be uncovered (Angkasith and Warrit, 2002). Yet, the perception of coffee aroma is dependent upon both the concentration of the compound and its odor threshold. It is probable that a relatively small group of compounds that share both a high concentration and a low odor threshold make up the fragrance we know as coffee aroma. The aroma of coffee is for a large part determined by the roasting of the beans. The 4 main reactions during the roasting are:

1. Maillard reaction; a reaction between nitrogen containing substances (amino acids, proteins, as well as trigonelline and serotonine) and carbohydrates (sugars).
2. Degradation of individual amino acids, particularly, sulphur amino acids, hydroxy-amino acids, and proline.
3. Degradation of sugar resulting in caramel-like substances.
4. Degradation of phenolic acids, particularly the quinic acid moiety.

Coffee substances which are important to coffee aroma are described below and summarized in Table 1 and 2.

### 2.1.1 Organic Acids

Acetic acid is the only one organic acid found from distilling roasted coffee example by Purge & Trap. It occurred from decomposition of sucrose when it is heated. Acetic acid is found in significant amount (0.2% in Arabica and 0.36-0.55% in Robusta) from medium and intense roasting due to sucrose needs high temperature to disperse (Ramos et al., 2005). However, there are many acids in roasted coffee. The acids that are important to the coffee flavor are in the groups of carboxylic acid; citric, malic, oxalic, tartaric, pyruvic and lactic (Raghavan et al., 1994). The acids are not volatile and HPLC method is used to analyze the acids instead of GC-MS method.

### 2.1.2 Furans

Pyrolysis process produces furans from decomposition of elements within the beans. Furans are important to coffee flavor as they have good smell like caramel. Purge & Trap method is able to analyze all 8 furans; 2-furanmethanol; 2-furancarboxyaldehyde, 5-methyl-; 2-furanmethanol,acetate; furan, 2,2'-methylenebis-; 2-furanmethanol, propanoate; benzofuran, 2-methyl-; furan, 2-(2-furanylmethyl)-5-methyl- and furan, 2-[(methyldithio)methyl]. Seven furans were also found from HS-SPME distilling, including 2-furanmethanol; 2-furancarboxaldehyde, 5-methyl-; 2-furanmethanol, acetate; Furan, 2-(2-furanylmethyl)-5-methyl-; butanoic acid, 3-methyl-, 2-furan; furan, 2,2'-[oxybis(methylene)] and furan, 2-[(methyldithio)methyl] (Coffee Research Institute, 2001).

### 2.1.3 Phenols

2-methoxy is an important compound in coffee, and its smell is similar to that in popcorn (Jirasawat, 2003). Pyrolysis reaction of chlorogenic and caffeine causes roasted aroma and burning smell (Belitz and Grosch, 1999; Ky et al., 2001). 2-(methylthio) was found from the analysis by Purge & Trap distilling, whereas, 4-ethyl-2-methoxy- and 2-methoxy-4-vinyphenol were found by HS-SPME distilling.

**Table 1** Group of volatile compounds identified from coffee bean

| Volatile compounds | Numbers of Compounds | Volatile compounds | Numbers of Compounds |
|---|---|---|---|
| Hydrocarbons | 49 | Pyridines | 7 |
| Alcohols | 19 | Quinolines | 2 |
| Aldehydes | 24 | Pyrazines | 67 |
| Ketones | 83 | Qulnoxalines | 11 |
| Acids | 22 | Oxazoles | 25 |
| Ester | 29 | Thiazoles | 28 |
| Lactones | 7 | Thiols | 5 |
| Phenols | 21 | Sulfides | 17 |
| Amines | 4 | Thiophenes | 26 |
| Pyrroles | 25 | Miscellaneous | 54 |
| Indoles compounds | 3 | | |

Source: Jirasawat (2003)

### 2.1.4 Pyrazines

The pyrazines are the second most abundant class of aromatic compounds and contribute to the roasted, walnut, cereal, cracker, or toast-like flavors in coffee (Table 3). Along with thiazoles, the pyrazines have the lowest odor threshold and therefore significantly contribute to the coffee aroma. Next, the pyrroles are responsible for some of the sweet, caramel-like, and mushroom-like aromas in coffee. Conversely, the thiophens are known to have a meaty aroma and are thought to be produced from Maillard reactions between sulfur containing amino acids and sugars. Thiazoles have an even smaller presence in the overall aroma and are said to be formed via sugar degradation (Coffee Research Institute, 2001).

### 2.1.5 Pyrroles

Pyrroles are resulted from the reaction of amadori or furans with amino acid. The smell of pyrroles is similar to that of caramel and smoke. It also causes trigonelline disperse or combination of proline and hydroxyproline (Varnam and Sutherland, 1994).

**Table 2** Volatile compounds of coffee bean and their aroma quality

| Volatile compounds | Aroma quality |
|---|---|
| Acetic acid | Pungent |
| 4-Methoxy-benzaldehyde | Grass, hay, sweet, mint |
| 2,3-Butanedione | butter |
| β-Damascenone | fruits, flowers, honey, tea |
| 2,5-Dimethylpyrazine | roasty, nuts |
| 2,6-Dimethylpyrazine | sulfur-like, nuts |
| 2-Ethyl-5-methylpyrazine | musty, burnt |
| 2-Ethyl-3,5-dimethylpyrazine | earthy, roasty, potatoes |
| 4-Ethylguaiacol | flowers, spicy |
| 2-Ethyl-3-methylpyrazine | roasty, nuts |
| 2-Ethyl-5-methylpyrazine | caraway |
| 2-Ethyl-6-methylpyrazine | cheese, caraway |
| 2-Furfurylthiol | roasty, sulfur-like, coffee |
| Guaiacol | smoky, phenolic, spicy |
| Hexanal | grass |
| Furaneol | roasty, sweet, caramel |
| Methional | potato-like, sweet |
| 2-Methylbutanal | caramel, nuts, malt |
| 3-Methyl-2-buten-1-thiol | green, amine-like |
| 4-Vinylguaiacol | spicy |
| 2,3-Pentanedione | butter |
| 3-Hydroxy-4,5-dimethyl-2(5H)-furanone | seasoning-like |

Source: Coffee Research Institute (2001); Schenker et al. (2002)

**Table 3** Odor description of pyrazines

| pyrazines | Thresholds in water (ppb) |
|---|---|
| pyrazine | 175,000 |
| 2,3-dimethylpyrazine | 1,800 |
| 2-methylpyrazine | 700 |
| 2-methoxy-3-methylpyrazine | 4.0 |
| 2-methoxy-3-ethylpyrazine | 0.4 |
| 2-(2-methyl-propyl )3-methylpyrazine | 0.002 |
| 2-methoxy-3-hexypyrazine | 0.001 |

Source: Jirasawat (2003)

### 2.2 Taste

It consists of acidity, bitterness and coffee body as follows:

#### 2.2.1 Acidity

The perceived acidity of coffee results from the proton donation of acids to receptors on the human tongue. Coffee acidity is typically a highly valued quality especially in Central American and some East African coffee. Sourness, however, is an extreme of acidity and can be considered as a coffee defect. Acidity has been correlated with coffees grown at very high altitudes and in mineral rich volcanic soils. The perceived acidity of washed coffees is also significantly higher than the acidity found in naturally (dry) processed coffee. This is likely due to an increase in the body of naturally processed coffees relative to wet processed coffees since body masks the acidity in coffee. The coffee acid content in a brew is also greatly dependent upon the coffee roasting degree, type of roaster, and coffee brewing method. The pH of a coffee has been found to correlate with the perceived acidity in coffee by Sivetz and Desrosier (1979); Griffin and Blauch (1999); whereas Voilley and Silmatos (1980) suggests that titratable acidity produces a better correlation to perceived coffee acidity. Moreover, chlorogenic acid found in green seeds is about 8% but it is decreased to 4.5% after roasting. Chlorogenic acid is hydrolyzed during roasting process and the process results in the increase in caffeic acid and quinic acid together with the increase in bitterness and sourness. Acids found in coffee beans are listed in Table 4.

**Table 4** Acids in coffee beans

| **Types of acids** | **Acid names** |
|---|---|
| 1.Aliphatic carboxylic | |
| - Volatile | formic, acetic, propanic, butanoic, methylpropanoic, 2- methylbutanoic, 3-methylbutanoic , hexanoic, heptanoic, octanoic and decanoic |
| -Non-volatile | lactic (2-hydroxypropanoic), pyruvic (2-oxopropanic), 3-methylbut-2-enoic, oxalic, malonic, succinic, glutaric, 2-hydroxypropane-1,2,3,-tricarboxylic |
| 2.Heterocyclic furanoid carboxylic | 2-furoic |
| 3.Chlorogenic | 3,4-and 5 – monocaffeoylquiniic acid (CQAs)<br>3,4-,3,5- and 4,5-dicaffeoylquinic acid (diCQAs)<br>3-,4-,and 5-feruloylquinic acid (FQAs)<br>3,4-3,5- and 4,5- *p*-coumaroylquinic acid (cOQAs) |
| 4.Alicyclic/phenolic | Quinic(1,3,4,5-tetrahydroxycyclohexanecarboxylic), ferulic (4-hydroxy-3-methoxy-cinnamic) and caffeic (3,4-dihydroxycinnamic) |
| 5.Inorganic acids | phosphoric |

Source: Deibler et al. (1998)

### 2.2.2 Bitterness

Coffee bitterness is sometimes a negative, but omnipresent, aspect of the beverage. At low levels, bitterness helps tame coffee acidity and adds another favorable dimension to the brew. However, at high levels, a bitter coffee compound can overpower the other components present in coffee producing an undesirable effect. Bitter coffee results from the interaction of certain compounds with the circumvallated papillae on the back of the tongue. Astringency, on the other hand is caused by compounds that can precipitate salivary proteins on the tongue. Consumers will often mistakenly attribute astringency and any other potent characteristics of the coffee to the bitterness. Compounds that give bitterness in coffee are listed in Table 5. Caffeine has a distinct bitter taste and has a test threshold of only 75-155 mg/L. However, caffeine accounts for around 10% of the perceived bitterness in coffee. The bitterness of caffeine is weakened when polyphenols are introduced (Table 6).

**Table 5** Compounds that give bitterness in coffee and their taste threshold

| **Compound** | **Taste threshold (ppm)** |
|---|---|
| Hexanol | 5 |
| Quinic | 10 |
| Tartaric acid | 20 |
| Furfuryl alcohol | 19-40 |
| Caffeic acid | 10-90 |
| Chlorogenic acid | 22-70 |
| Caffeine | 75-155 |
| Citric acid | 96-590 |
| Malic acid | 107-350 |
| Lactic acid | 144-400 |
| 5- hydroxymethylfurfural | 200 |

Source: modified from Zheng and Wang (2001)

**Table 6** Compounds that give bitterness in coffee

| Compounds | Amount in coffee (mg/l) | Test threshold (mg/ml) |
|---|---|---|
| Quinic | 3,200-8,700 | 10 |
| 5-hydroxymethylfural | 10-35 | 200 |
| 2-methyl furan | 0.05 | 0.05 |
| Furfuryl alcohol | 300 | 24 |
| trigonelline | 3,000 -10,000 | 3,000-10,000 |
| Chlorogenic acid | 20-100 | 26 |
| Caffeic acid | 10-90 | 10-90 |
| Citric acid | 1,800 - 8,700 | 96-590 |
| Malic acid | 1,900 - 3,900 | 107-305 |
| Lactic acid | 0-3,200 | 144-400 |
| Pyruvic acid | 400-1,700 | 400-1,700 |
| Acetic acid | 900-4,000 | 22-70 |
| Pyrazine | 17-40 | 1 |
| Caffeine | 10,000-20,000 | 75-155 |

Source: modified from Coffee Research Institute (2001)

### 2.2.3 Coffee Body

Body is the weight of the coffee that can best be sensed by allowing the coffee to rest on the tongue and by rubbing the tongue against the roof of the mouth. Coffee body ranges from thin, to light, to heavy and is a result of the fat content. The viscosity, however, results from proteins and fibers in the brew. Medium and dark coffee roast styles will have a heavier body than lighter roasted coffees, but conversely will have less acidity.

## 3. Relation between chemical composition of coffee beans and Arabica coffee quality

Coffee quality classified by tasting of the tester is related to caffeine content, sucrose and chlorogenic acids, which are determined by high performance liquid chromatography or HPLC. This method is able to determine the compounds in the liquid samples. The method is also able to choose the appropriate detector for the samples. HPLC is currently used for analyzing various compounds with high accuracy (Farah and Donangelo, 2006). Low quality coffee is dependent on varieties, damage during harvesting and maintaining processes before processing. These processes may affect on favorable characteristics and compound compositions in coffee beans. Each compound is unique in increasing the pleasant taste of coffee.

### 3.1 Caffeine

Caffeine is an alkaloid, which its chemical structure is in the group of methylxanthines. The important compounds in the group include caffeine, theophylline and theobromine.

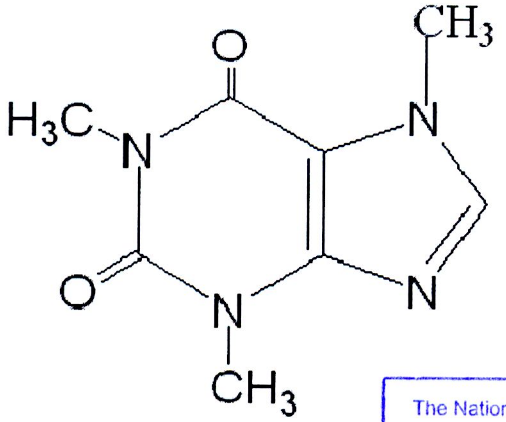


**Figure 1** Structure of caffeine
Source: Farah et al. (2006)

Caffeine is a stimulant that affects the central nervous system causing alertness. It also causes bitterness in coffee (Benjawan, 2004). Caffeine is more abundant in 'Soft' coffee than in 'Hard' coffee. Caffeine content is an important factor determining the bitter character, and the caffeine content of green beans varies according to species. Robusta coffee contains 2.2% caffeine on a dry matter basis (dm), and Arabica has 1.20% of caffeine (Varnam and Sutherland, 1994). Roasting process can reduce a trace amount of caffeine (Sivetz, 1963).

### 3.2 Sucrose

Sucrose is the principle sugar in coffee. The melting point of pure crystalline sucrose is in the 320-392 $^{0}$F with 370 $^{0}$F most commonly accepted. Degradation of dry sucrose can occur as low as 194 $^{0}$F and begins with the cleavage of the glycosidic bond followed by condensation and the formation of water. Between 338 and 392 $^{0}$F, caramelization begins. It is at this point that water and carbon dioxide fracture and out-gassing begins causing the first mechanical crack. These are the chemical reactions, occurring at approximately 356 $^{0}$F, which are exothermic. Once caramelization begins, it is very important that the coffee mass does not lose heat or the coffee will taste "baked" in the cup. A possible explanation is that exothermic of the charge mass interrupts long chain polymerization and allows cross linking to other constituents. Both the actual melting point of sucrose and the subsequent transformation, or caramelization, reaction are affected by the presence of water, ammonia, and proteinateous substances. Dark roasts represent a higher degree of sugar caramelization than light roasts. The degree of caramelization is an excellent and high resolution method for classifying roasts.

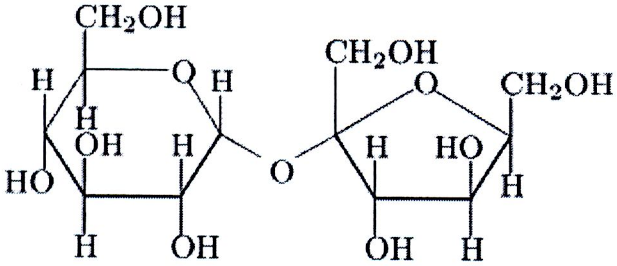


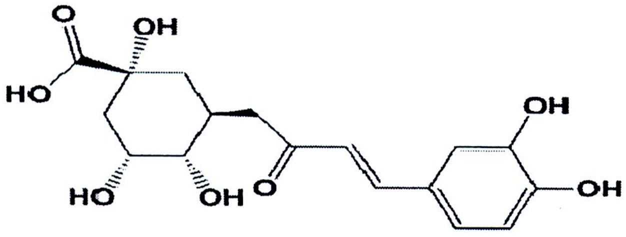
**Figure 2** Structure formula of sucrose
Source: Farah et al. (2006)

It is a sweetener and can produce color, fragrance, bitterness, and sourness after degradation. High temperature during roasting process or during making a cup of coffee results in destroying aroma and particular taste of coffee.

Sucrose can convert into glucose and fructose, and the change in sugar types can affect sweetness (Benjawan, 2004). Besides, sucrose is found at the highest level in Rioysh coffee and the lowest in Rio zona coffee. In addition, roasting considerably affects sugar content, and the longer roasting time the less sugar content occurs (Farah et al., 2006).

### 3.3 Chlorogenic acids

Chlorogenic acids constitute in a group of phenol, which is ester of quinic acid and caffeic acid or ferulic acid.



Chlorogenic Acid

**Figure 3** Structure formula of chlorogenic acids
Source: Farah et al. (2006)

Chlorogenic acids constitute 6-12% of coffee body. Chlorogenic acids are reduced by roasting. Low content of chlorogenic acids is found in good quality coffee or 'soft' coffee. High content of chlorogenic acids such as in Rio zona coffee causes poor quality of coffee because it has acerbated taste. Analysis of chlorogenic content is difficult, but it is generally recognized that Robusta coffee has a higher content than Arabica coffee. Chlorogenic acids content on dry matter basis ranged from 7.0 to 10.5% in Robusta coffee and 5 to 7.5 % in Arabica coffee. Chlorogenic acid in coffee is also dependent on agronomic practice and processing method (Varnam and Sutherland, 1994; Flament, 2002).

## 4. Sensory evaluation of coffee quality

Evaluation panel of testers is often used to evaluate sensory properties of coffee that affect drinking quality. The sensory properties include suavity, fragrance, and bitterness. These characteristics can be evaluated through organoleptic analysis of the testers. Several criteria are used for assessing food quality according to the objectives of the assessment. In general, food can be assessed by chemical compositions, physical characteristics, microbial contamination and others. In coffee, the evaluation of sensory properties is often used together with other properties.

Sensory evaluation has been defined as a scientific method used to evoke, measure, analyze and interpret those responses to products as perceived through the senses of sight, smell, touch, taste, and hearing (Stone and Sidel, 1993). This definition has been accepted and endorsed by sensory evaluation committees within various professional organizations such as the Institute of Food Technologists and the American Society for Testing and Materials.

### 4.1 Sensory evaluation

Sensory properties of food can be evaluated by sensory organs. These include appearance, taste, aroma, texture, and preference. These properties directly affect the decision making of consumers. The preference of the consumers towards these food properties changes with time, age, and culture. Five sensory organs (eyes, ears, nose, mouth, skin) are used to evaluate these properties by well-trained testers. The sensory organs work in harmony to form the sensory verdicts as shown in Table 5.

Perception of food taste is related to complex nervous systems. The smelling is perceived by direct volatile smell in the air, or perceived indirectly, while the food is being chewed and the smells enter into the nose and pharynx. Perception of food taste occurs in combination with perception of physical properties of food such as color, size, shape, delicateness and crispness. People can respond very differently to different foods, depending on their mouth feel, which is the interaction between physical and chemical properties of food.

Testing - coffee quality measure - is to evaluate the coffee affecting to drinking such as aroma and bitterness. Testing measure is performed by professional testers that can specify the difference of aroma and taste of each type of coffee. Main organs important to the testing are mouth and nose, consisting of the taste perception with senses on the tongue. In addition, smelling by nerve in the nasal cavity, the nasal cavity might be possible to identify the difference between good flavor coffee and off flavor coffee and the difference of each variety.

Coffee consists of many compounds that can be separated by the coffee odor. Most compounds are heterocyclics; furans, pyrrole, thiophene, pyrazine, and pyridine substance. The substance that is directly related to the odor of coffee is the heterocyclic compounds that consist of nitrogen. Furthermore, unroasted coffee beans are consisted of methoxypyrazines which cause foul smelling in the coffee, having the intensity volume about 10 part per million (ppm).

## 4.2 Chemical components affecting sensory properties of coffee bean

Chemical components in the coffee beans affect coffee quality in terms of taste and body of coffee. The components can be analyzed chemically to quantify the amount of chemicals and detect the changes in chemical components in coffee beans. The following chemical reactions result in the changes in chemical components in coffee beans (Varnam and Sutherland, 1994).

### **4.2.1** Nitrogen compound

Coffee beans contain 1.2 % of caffeine in the green Arabica coffee and 2.2 % in the Robusta. Trigonelline is found in smaller amount in coffee beans (1% in Arabica and 0.7% in Robusta). When trigonelline is broken down, it is transformed into substances that generate flavor and nutrients. Trigonelline degradation is proportional to roast degree. Its byproducts include pyridines, which are said to contribute a roasty aroma to the coffee. It also increases softly bitterness or about 25% of caffeine in coffee. In addition, protein and free amino acids affect coffee flavor due to combination of the compounds in the coffee beans, making the flavored substances such as Pyrazine and Pyridine. Generally, protein content is related to the species of coffee and it is found in cytoplasm or it combines with polysaccharides in the cell wall.

### **4.2.2** Carbohydrate

In raw coffee beans, carbohydrate is found in form of free sugars and polysaccharides. Sucrose is more abundant than glucose and fructose and the amount is dependent on species and age of coffee. Sugar is found about 6.0-8.3% in Arabica and 3.3-4.1% in Robusta. Other forms of reducing sugar such as arabinose, galactose, raffinose, rhamnose, ribose, fructose, and glucose are also found. Sugar is important to produce flavor and pigmentation after roasting (Varnam and Sutherland, 1994). Oosterveld et al. (2003) reported that unroasted Arabica consists of polysaccharides 48-60 %, and its main elements are arabinogalactan and galactomannans. Roasting processes result in the degradation of polysaccharides. Furthermore, de-branching of arabinogalactan and galactomannans affects the melting ability of polysaccharides. Degradation of polysaccharides from roasting processes increases oligosaccharide and monosaccharide. Redgwell et al. (2002) found that the degradation of polysaccharides in the dark roasted coffee is 40% higher than in light and medium roasted coffee.

### **4.2.3** Fat

Fat or coffee oil is found in large amount in endosperm and coffee wax is found in outer skin of coffee beans. 15% of fat on dry weight basis is found in Arabica coffee and 10% of fat is found in Robusta coffee. Triacylglycerols and other fat are also found.

### **4.2.4** Organic acids

Aliphatic, alicyclic, carboxylic, and phenolic acids are organic acids found in roasted coffee (Coffee Research Institute, 2001). In unroasted coffee, citric acid, malic acid, oxalic acid and tartaric acid (0.5 %, 0.46 %, 0.2 %, 0.4%, respectively) are found in Arabica coffee. Acidity increases during maintaining process as a result of enzymatic degradation of fatty acids (Varnam and Sutherland, 1994). In medium roasted Arabica, citric, malic, lactic, pyruvic and acetic (0.3 %, 0.22 %, 0.13 %, 0.07 % and 0.27 %, respectively) are also found, and the fatty acid content is about 1.58% in light roasted coffee. The content is reduced to 0.71% in dark roasted coffee (Clarke, 1985). Molecules of undissociate fatty acids play an important role in controlling good flavor in coffee. Types and quantity of chemicals in green beans and roasted coffee are different (Table 7 and 8).

**Table 7** Chemical components of green beans (dry weight basis)

| **Classes and Components** | **percentages** | |
|---|---|---|
| | **Soluble** | **Insoluble** |
| 1. Carbohydrates (60%) | | |
| reducing sugars | 1.0 | - |
| sucrose | 7.0 | - |
| starch | - | 10.0 |
| pentasans | - | 5.0 |
| hemi-celluloses | - | 15.0 |
| holo-cellulose | - | 18.0 |
| lignin | - | 2.0 |
| 2. Oil | - | 15.0 |
| 3. Proteins (N x 6.25) | 9.0 | 4.0 |
| 4. Ash (oxide) | 2.0 | 2.0 |
| 5. Non-volatile | | |
| chlorogenic | 6.8 | - |
| oxalic | 0.2 | - |
| malic | 0.3 | - |
| citric | 0.3 | - |
| tartaric | 0.4 | - |
| 6. Trigonelline | - | 1.0 |
| 7. Caffeine (Arabica 1.0%, Robusta 2.0%) | - | 1.0 |
| Total | 29.0 | 71.0 |

Source: Sivetz (1963)

**Table 8** Chemical components of roasted coffee beans (dry weight basis)

| **Classes and Components** | **percentages** | |
|---|---|---|
| | **Soluble** | **Insoluble** |
| 1. Carbohydrates (53%) | | |
| reducing sugars | 1.0-2.0 | - |
| caramelized sugars | 10.0-17.0 | 7.0-10.0 |
| hemi-celluloses (hydrolysable) | 1.0 | 14.0 |
| fiber (not hydrolysable) | - | 22.0 |
| 2. Oil | - | 15.0 |
| 3. Proteins (N x 6.25) ; amino acids are soluble | 1.0-2.0 | 11.0 |
| 4. Ash (oxide) | 3.0 | 1.0 |
| 5. Acids, non-volatile | | |
| chlorogenic | 4.5 | - |
| Caffeic | 0.5 | - |
| quinic | 0.5 | - |
| oxalic, malic ,citric, tartaric | 1.0 | - |
| volatile acids | 0.35 | - |
| 7. Caffeine (Arabica 1.0%, Robusta 2.0%) | 1.2 | - |
| 8. Phenolics (estimate) | 2.0 | - |
| 9. Volatiles | | |
| carbon dioxide | trace | 2.0 |
| essence of aroma and flavor | 0.04 | - |
| Total | 27.0-35.0 | 65.0-73.0 |

Source: Sivetz (1963)

## 5. Environmental effects on coffee quality

Arabica coffee is native to Ethiopian tropical forests at altitudes of 1,600-2,800 m. In this region, air temperature shows little seasonal fluctuations, averaging annually at about 20 °C. Rainfall is well distributed, varying from 1,600 to more than 2,000 mm, with a dry season lasting 3-4 months coinciding with the coolest months. In this environment, Arabica coffee became established as an under storey shrub (Sylvain, 1952). The optimal mean annual temperature range for Arabica coffee is 18-21 °C (Ale`gre, 1959). Above 23 °C, development and ripening of fruits are accelerated, often leading to loss of quality (Camargo et al., 2006). Continuous exposure to temperatures as high as 30 °C results not only in depressed growth but also in abnormalities such as yellowing of leaves and growth of tumors at the base of the stem (Franco, 1985). Relatively high temperature during blossoming, especially when the coffee crop is subjected to a prolonged dry season, may cause abortion of flowers (Camargo, 2008). In regions with mean annual temperature below 18 °C, growth is largely depressed. Occurrence of frosts, even if sporadic, may limit strongly the success of the crop. In addition, slow development of fruits results in late ripening which, in several cases, may overlap or even surpass the next blossoming (Camargo et al., 2006). Both leaves and fruits neither withstand temperatures below 5-6 °C nor long periods at 15 °C (Wintgens, 2004). The optimal annual rainfall range is 1200-1800 mm for Arabica coffee (Ale`gre, 1959). In Arabica, a short dry spell, lasting 2-4 months, corresponding to the quiescent growth phase, is an important factor to stimulate flowering (Castro and Marraccini, 2006). Abundant rainfall throughout the year is often responsible for scattered harvest and low yields. Lack of a dry period can also limit coffee cultivation in lowland tropical regions (Huang and Kuo, 1996). Air humidity has a significant impact on the vegetation of coffee trees. Arabica coffee requires a less humid atmosphere, comparable to that of the Ethiopian highlands (Berry et al., 2006). Wind can also have profound effects on coffee. Hot winds increase evapotranspiration and therefore rainfall (or irrigation) requirements to the trees increase. Strong winds may severely damage leaves and buds in addition to exacerbating shedding of developing flowers and fruits (Camargo, 2008). Where strong wind is frequent, wind-breaks need to be provided.

### 5.1 Temperature

Suitable temperature for coffee growth is 15-25 °C. However, the temperature of plantation is subjected to some factors; day time light, humidity, area height, density of coffee tree, and growing direction. The suitable temperature in day time that is good for the growth of Arabica coffee is about 25 °C. It should be about

15 °C at night. The photosynthesis range of the coffee leaves is reduced at higher 30 °C. The leaves turn to yellow and then fall (Velino et al., 2005).

Temperature is related to light energy effecting to photosynthesis in plants. Coste (1992) found that suitable temperature for photosynthesis in Arabica coffee leaves is 20-25 °C. Also, suitable light energy is about 600 $\mu Em^{-2}s^{-1}$. If there is higher light energy, leaf temperature is increased but the photosynthesis is reduced. However, if leaf temperature is suitable, increase in light intensity does not reduce photosynthesis. The photosynthesis is about 4 $mgCO_2dm^{-2}h^{-1}$ under light energy of 300 $\mu Em^{-2}s^{-1}$ and temperature of 10 °C. This photosynthetic range increases with temperature until the temperature is 20 °C. Then, the increase in photosynthetic range is slow and the photosynthesis is the highest at 25 °C. The photosynthesis reduces with the temperature higher than 25 °C and stops at the 45 °C (Cannell, 1985; Barradas and Fanjul, 1986).

Coffee grown under full sun light has temperature 10-15 °C higher than that grown under shade (Cannell, 1976). Strong light intensity causes yellowing leaves as a result of chlorophyll damage. As a consequence, the photosynthesis is as low as 7 $\mu$ mole $CO_2m^{-2}s^{-1}$ at 20 °C. Net photosynthesis in shaded leaves is two times higher than that in full sun leaves at canopy temperature of 25 °C (Cannell, 1985). Therefore, high alleviation is more suitable for growing coffee than low alleviation because of lower temperature. Besides, coffee that is affected by cold night temperature and high day temperature shows yellowing leaves at the leaf margin and slow growth.

Low temperatures adversely affect coffee photosynthesis and yield through both stomatal and non stomatal factors (Da Matta and Ramalho, 2006). In regions with relatively high mean annual temperatures, Arabica coffee is often raised under shade, as occurs in Central America (Beer et al., 1998). This has been traditionally explained because at temperatures above 24 °C, the net photosynthesis would decrease markedly, approaching 0 at 34 °C (Coste, 1992). This statement, although misleading, was to some extent supported by other work. Barradas and Fanjul (1986) found that the internal $CO_2$ concentration of coffee leaves increased logarithmically up to 30 °C and then more rapidly to 35 °C (higher temperatures were not evaluated), indicating a thermal limitation on photosynthesis. Similar results were noted by Berry et al. (2006).

### 5.2 Light

Light is a sole energy source for photosynthesis. Light has direct effect on plant growth. Besides, the shape and the inner activity of leaves on the outside of canopy receiving full sun light are different from the inside bush leaves (Magalhaes and Angelocci, 1976). Significant reduction in photosynthetic rate can radically affect plant functions such as floral initiation and root and shoot growth. This can be followed by death of branches, or even of the whole plant (Rosenzweig et al., 2004). Thus yield loss is usually indirectly related to the severity of the disease. Kumar and Tieszen (1980) found that photosynthesis of coffee started at light intensity of 18 $\mu Em^{-2}s^{-1}$, and photosynthetic rate increased linearly when light intensities were between 27 $\mu Em^{-2}s^{-1}$ and 300 $\mu Em^{-2}s^{-1}$. Non-linear increase in photosynthesis was observed from 300 $\mu Em^{-2}s^{-1}$ to 600 $\mu Em^{-2}s^{-1}$, when the photosynthesis reached plateau. The photosynthesis was at the plateau until 1,200 $\mu Em^{-2}s^{-1}$ and then decreased. The fourth and third pairs of coffee leaves had the highest photosynthesis, whereas the photosynthesis was reduced in the sixth pair (Velino et al., 2005). Photosynthesis is directly related to chlorophyll content and the density of stomata, but it was inversely related to leaf respiration and leaf temperature.

As a shade plant, Arabica coffee is rather susceptible to full sun light. Light intensities suitable for the production of Arabica coffee are 600 $\mu Em^{-2}s^{-1}$ for full sunlight and 300 $\mu Em^{-2}s^{-1}$ under shade. Light intensity of 2,500 $\mu Em^{-2}s^{-1}$ in the tropics is too high for the Arabica coffee and the high light intensity is associated with high temperature. The suitable temperature for photosynthesis is 20-25 °C but the temperature in tropics is about 35-40 °C, causing the reduction in photosynthesis. The temperature higher than 45 °C would permanently stop the photosynthesis (Da Matta and Ramalho, 2006). Kodama (2005) found that at altitude of 1,250 m.a.s.l. in the Northern Thailand, light intensities were 1,700 $\mu Em^{-2}s^{-1}$ in the rainy season, 1,400 $\mu Em^{-2}s^{-1}$ in the winter, and 2,000 $\mu Em^{-2}s^{-1}$ in summer.

High light intensity provides high light energy to the crop and increases temperature of canopy and crop transpiration. Guard cells lose turgor and stomata are closed due to water loss. Stomata start opening at light intensity of 300 $\mu Em^{-2}s^{-1}$, and the opening of stomata is highest at light intensity of 600 $\mu Em^{-2}s^{-1}$. Stomatal aperture is low at high light intensity under natural conditions. Under high light intensity conditions, canopy temperature is generally 10% higher than ambient temperature. Furthermore, chlorophyll density in shaded plants is higher than that in sun plants (Cannell, 1985). The highest photosynthesis is found in the fourth and fifth leaf pairs from the top and carbon dioxide accumulation rate is 9.5 mg $CO_2$ $dm^{-2}$ $hr^{-1}$ (Kumar and Tiezen, 1980).

Plants adapt to shade conditions in several ways to optimize photosynthesis. Plants under shade conditions produce more leaf area than that of plants under full sun light because assimilates are partitioned to leaves rather than other non-photosynthesis organs. The leaves are also thinner in order to increase more leaf area for photosynthesis. The physiology of the leaf may also change in response to shading. Long-term physiological changes have been termed adaptation and include an increased quantum efficiency in leaves grown in shade, measured as a higher value of a, the initial slope of the curve relating photosynthesis to PAR level. Another typical shade adaptation is a low light compensation point. Shade plants may also have leaves capable of using irradiation at levels considerably higher than those under which they were grown in full sunlight. Such ability has been termed "adjustment" by Prioul & Bourdu, and has the ecological advantage of utilizing in photosynthesis the short periods of high irradiation encountered in sun flecks under canopies of natural vegetation. Coffee is a crop that can survive and produce economic yields under the shade of nurse trees. The use of shade trees is not necessary in some areas as long as the trees are adequately fertilized, and may even reduce yields. Previous work has determined that the rate of photosynthesis per unit leaf area in coffee increased after leaf emergence and reached a maximum about 90 days later, before declining. Plants grown at an irradiance of 25% daylight had optimal rates of photosynthesis lower than that of plants grown in full daylight. This contrasts with the result of Kumar and Tiesen (1980), who reported that plants grown under shade in a greenhouse had a higher rate of photosynthesis at light saturation than that of plants grown in the field in full sun, although the saturating irradiation was 600 μmol $m^{-2}s^{-1}$ for sun-grown plants, compared with 300 μmol $m^{-2}s^{-1}$ for shade-grown plants.

Consequently, there may be some benefits of shade culture for coffee growers in these areas, while the sufficient fertilization and ameliorative irrigation in harsh climatic conditions, shading can be a cost-effective cultural practice to address field and microclimate inadequacies (Beer et al., 1998). In addition, consumers and farmers often associate shade-grown coffee with environmental benefits and increase sustainability, and it is the basis for some sustainable certification schemes (Perfecto et al., 2004). Furthermore, some evidences demonstrate that shade has an influence on coffee's organoleptic properties (Bosselmann et al., 2009). As organoleptic quality is vital to a consumer's decision to purchase coffee (Siles et al., 2010). Coffee yields may decrease with increasing shading because of (i) lower whole-tree carbon assimilation under excessive shading, (ii) greater stimulus to vegetative rather than flower buds (Cannell, 1985), and (iii) fewer nodes formed per branch and flower buds at existing nodes (Soto-Pinto et al., 2000). If the number of nodes is the key component of coffee production (Cannell, 1985), yields should then decrease with increased shading. Shaded coffee tends to flower and produce a good crop each year, whereas under unshaded plantation conditions, the crop tends to alternate between years with heavy flowering and light flowering leading to a biennial production trend. As a teleological discussion by Cannell (1976), coffee produces very few flowers in its shaded native habitat, and thus fails to evolve satisfactory mechanisms, common in many fruit trees, to maintain its fruiting burden in balance with carbohydrate and mineral resources when it grows under full exposure. Hence, the coffee tree becomes committing to fill all the beans that are formed after the fruit expansion stage. According to this point of view, the causes of overbearing are associated with profuse flower initiation without shading and very sparse compensatory fruit shedding, resulting in a large sink capacity in the seed endosperms (Cannell, 1985). Overbearing exhausts the tree's reserves and limits both the production and retention of leaves, leading to poor crop in the next year. This allows an excessive foliage to form which, in turn, permits a profuse flowering and hence a heavy crop. As a consequence, unshaded coffee plantations produce irregularly even under good cropping conditions, production is often irregular and follows a biennial pattern. The use of shelter trees reduces overbearing and buffers biennial fluctuations of crop yields. This should reduce exhaustion of the coffee tree, and allow it to satisfactorily produce for longer. On economic grounds, higher yields per harvest in unshaded plantations might be compensated for, within given limits, by the larger number of more regular crop harvests in shaded plantations.

Shade trees, particularly those with deep rooting, seem not to adversely affect the water balance of the coffee crop. In Mexico, Steiman (2008) estimated the annual evapotranspiration of an open plantation of Arabica coffee to be 1,327 mm, compared with 703 mm for the crop shaded by *Inga leptoloba* and 1,052 mm for a system with a mixture of shade trees. As compared with unshaded schemes, adequate shade management may even improve the water status of the soil after prolonged droughts, as found in India by Nobel (1976) or the water status of the crop, as found in northeastern Brazil by Muschler (2001). Therefore, comparisons amongst different experiments dealing with effects of shading on coffee production are difficult since, most investigators, always have omitted important data such as intensity and quality of irradiance at the crop level, daily and seasonal fluctuations of temperature and RH, nutrition, crown architecture, proper shade management and design, from among other conditions. Furthermore, it should be emphasized that in many comparative studies in which production of shaded plantations exceeds that of open ones, such a higher yield refers to the first harvests; in the longer term, this may not be true due to severe competition between the coffee plant and the shelter tree (Vaast et al., 2006)

## 6. Environmental effects on growth and physiology of coffee plants

### 6.1 Plant height

Shading generally increase the height of plants (Aminuddin, 1986; Begonia et al., 1988; de Castro et al., 1962; Guiscafre and Gomez, 1942; Huxley, 1967; Kohyama and Hotta, 1990; Kjelgren, 1994; Lakshmamma and Rao, 1996; McClelland, 1934; Orlando, 1963; Vaast et al., 2006). In shade tolerant species shading increases growth in height for future exploitation of better lit conditions at higher levels in the canopy. Sturdy (1935) observed an increase in internodal length under shade in coffee.

### 6.2 Stem diameter

Shading increased stem diameter growth (Guiscafre and Gomez, 1942; Aminuddin, 1986). In coffee, stem diameters increase in intermediate shades and were significantly higher than heaviest shades and open grown plants (de Castro et al., 1962). However, Aminuddin (1986), Kjelgren (1994), Orlando (1963); Sylvain (1952) observed an inverse relation of stem diameter to the degree of shade.

### 6.3 Branches

Shaded plants have a more horizontal branch orientation. Plants grown in 100% sunlight had a more vertical branch orientation (Marler et al., 1994). The most conspicuous developmental response to low Red: Far Red is a concomitant reduction in branching. Regnier and Harrison (1993) found a decrease in branch length under shade.

Axillary bud growth (branching) decreased considerably with increasing amounts of shade (Begonia et al., 1988; Sylvain, 1952) and utilization of assimilate in shade to increase stem extension led to a marked reduction in development of axillary buds into branches. However, in coffee, number of pairs of primary branches increases under shade. There was a highly significant difference in number of pairs of lateral branches between the trees in full sunlight on one hand and the trees in shade on the other (de Castro et al., 1962; Huxley, 1967; Vaast et al., 2006). Lower axillary buds were not inhibited under shade (Muschler, 2001). However Ducrey (1992) found that occurrence of branching depended more on species type than on light conditions.

### 6.4 Number of leaves

Regnier and Harrissons (1993), Sturdy (1935) and Sylvain (1952) found that plants had fewer leaves under shade. But increase in the number of leaves under shade is also reported by many others (Alvin, 1960; Castillo, 1961; Huerta, 1954; Huxley, 1967; Vaast et al., 2006). Ducrey (1992) also found that for all species the maximum number of leaves was obtained in partial shade.

### 6.5 Leaf thickness

Leaf thickness decreases under shade (Marler et al., 1994; Messier et al., 1989; Regnier et al., 1988; Shiraishi et al., 1996; Utsunomiya and Higuchi, 1996). Thicker leaves in plants grown in full sunlight have been attributed primarily to increases in the thickness of the palisade mesophyll layer (Chabot et al., 1979; Fails et al., 1982; Nobel, 1976; Patterson et al., 1977). Photosynthetic tissue per unit leaf area is therefore increased. Patterson et al., (1978) suggested that the greater mesophyll thickness in high irradiance grown plants may lead to chloroplast shading one another within the leaf, causing photosynthetic to become saturated at higher light intensities than in plants grown under shade.

The quality, intensity and duration of radiation that impinges on plants have profound effects on many physiological processes. Light is amongst the most important requirements for plant life at every stage, being the driving force of the fundamental assimilatory process photosynthesis and the chief source of biochemical energy. It is also important in many ways in growth and development as an overall determinant of the plant habitat (Noggle and Fritz, 1977). Light influences the plant growth mainly through photosynthesis and light induced growth processes. Seasonal, diurnal and spatial (such as within a canopy of a given plant stand) variations both in light intensity and spectral composition are known (Bjorkman, 1981). Shade plants have been found to thrive well under low light habitants; for instance, under the canopy of a given plant stand or in the lower strata of multistoried plant communities. The shade plants are mostly of the obligate type whose leaves suffer damage and the growth gets drastically affected upon exposure to high light regimes (Hariri and Prioul, 1978). Even within the same species, sun and shade ecotypes are common (Bjorkman and Holmgren, 1963). Facultative responses are more common in the sun plants. Whether of obligate or facultative nature, the growth of sun plants in shade results in photosynthetic light dependence characteristics tending towards those of obligate shade plants (Bjorkman et al., 1972). Thus a classification of plants into sun and shade species cannot be made on the basis of light saturation curves or light compensation points alone. Plants are classified into sun or shade plants depending on their adaptability to a selected light intensity (Bjorkman, 1968). This adaptability is inherited and it is determined by the genotype and results from genetic adaptation to the light environment prevailing in the native habitat (Boardman, 1977). Extreme shade species can survive at much lower light intensities than sun species.

### 6.6 Ratio of photosynthetic tissue to support tissue

In order to utilize available photosynthetic photon flux density (PPFD) efficiently, shade adaptable plants also maximize the photosynthetically active tissue of the total plant biomass by redistributing dry matter. This redistribution maximizes efficiency of light interception by increasing the proportion of total dry matter in leaf tissue (Regnier et al., 1988). Stoller and Myers (1989) computed the ratio of support tissue to leaf as a refinement of the leaf area index because the additional support type tissue, stems and petioles also require maintenance energy while contributing very little photosynthate to help to maintain a positive carbon balance, especially when grown in shaded environment. A decrease in the ratio of support tissue to leaves reflect greater portioning of plant biomass in to leaf tissues that harvest the available PPFD, with less biomass diverted to tissues that deplete photosynthate. Certain weeds which survive under soybean canopy (which permits only less than 5% of the total sunlight) are found to utilize a sizable amount of its biomass in order to harvest the available light.

### 6.7 Total leaf area per plant

The response of the leaf area under shade is primary observed to be related to the foliar anatomy of the species concerned. For instance, the extend to the leaf expansion observed in the case of coffee with thick evergreen type leafs was lesser in comparison to cotton plants with thinner leafs, when subjected to similar growth conditions (Huxley, 1967). Thicker leaf shows lesser capability to alter the total surface area or specific leaf area. However an increase in leaf area under shade has invariably been reported by several others (Alvim, 1960; Castillo, 1961; Ducrey, 1992; Hampson et al., 1996; Huang and Kuo, 1996; Huerta, 1954; Marler et al., 1994) Sturdy (1935) found that in coffee, shade plants had fewer leaves but more total leaf area than in full sun. On the contrary in white pine, a species classified as intermediate in shade tolerance, total leaf area was greater in open grown saplings than in understory saplings (O'Connell and Kelty, 1994).

## 7. Effect of postharvest processing on coffee quality

Main processing is selecting of coffee, pulping, and roasting that affects to coffee flavor. In addition, roasting is also important for making different flavors.

### 7.1 Coffee processing

The factors affecting on the coffee quality include coffee maturity and dry processing. Processing of coffee is the method converting the raw fruit of the coffee plant into the coffee. The cherry has the fruit or pulp removed leaving the seed or bean which is then dried. While all green coffee is processed, the method that is used varies and can have a significant effect on the flavor of roasted and brewed coffee.

### 7.2 Roasting process

Roasting coffee transforms the chemical and physical properties of green coffee beans into roasted coffee products. The roasting process is what produces the characteristic flavor of coffee by causing the green coffee beans to expand and to change in color, taste, smell, and density. Unroasted beans contain similar acids, protein, and caffeine as those that have been roasted, but lack of the taste. It takes heat to speed up the Maillard reaction and other chemical reactions that develop and enhance the flavor. As green coffee is more stable than roasted, the roasting process tends to take place close to where it will be consumed. This reduces the time that roasted coffee spends in distribution, helping to maximize its shelf life. The vast majority of coffee is roasted commercially on a large scale, but some coffee drinkers roast coffee themselves in order to have more control over the freshness and flavor profile of the beans. Roasting is a time-temperature dependent process, whereby chemical changes are included in the green beans, with a loss of dry mass primarily as gaseous carbon dioxide and other volatile products of the pyrolysis (Clarke, 1985). The Maillard reaction, Strecker degradation and other chemical reactions generate most of different volatile compounds. So far more than 800 different volatile compounds have been identified in roasted coffee (Flament, 2002; Schenker et al., 2002). Roasting process is the taking of green coffee to heat or steam pipe in the roasting tank. It takes around 120-300 °C. There are 3 ways of roasting process (Coffee research Institute, 2001). Roasting coffee process changes its chemical compounds, making the concordant aroma and flavor. First step is to absorb heat and coffee turn to be yellow and then popcorn smell occurs. As temperature increased up to 205 °C, coffee beans is double inflating and turning to be light brown. This makes coffee lost its 5% weight and it has agtron number about 90-95. When the temperature increased up to 220 °C, the coffee beans turn to be brown and have lower agtron number at 60-65. This makes the coffee lost 13% weight. The change of chemical compounds during this processing called ‘Pyrolysis’. This process is a cause of carbohydrate compound dispersing and carbon dioxide releasing. When the roasting process is finished, the coffee will be cool down (Coffee Research Institute, 2001). Roasting duration is different because it is subjected to the type of roasting process.

There are generally three types of roasting process (Table 9). Different roasting levels resulted in different aroma and flavor (Table 10). Mostly, it is considered on the roasting level from agtron number after roasting process by using Agtron Roast Analyzer (Coffee Research Institute, 2001). Domination of roasting state affects on the physical and chemical properties of the coffee. Thus, there is measuring and controlling variables, for example, heat transfer, water lacking, roasting temperature, and coffee temperature. This helps to control the chemical reactions affecting on protein, fat and acids volumes, and caffeine as well as aroma of coffee (Schenker et al., 2002).

**Table 9** Effects of roasting levels on smell of coffee

| | Roast level | Notes | Surface | Flavor |
|---|---|---|---|---|
| Light | Cinnamon roast, half city, New England | After about seven minutes the beans "pop" and double in size, and light roasting is achieved. American mass-market roasters typically stop here. | Dry | Light-bodied and somewhat sour, grassy, and snappy |
| Medium | Full city, American, regular, breakfast, brown | At nine to eleven minutes the beans reach this roast, which U.S. specialty sellers tend to prefer. | Dry | A bit sweeter than light roast; full body balanced by acid snap, aroma, and complexity |
| Dark | High, Viennese, Italian Espresso, Continental | After 12 to 13 minutes the beans begin hissing and popping again, and oils rise to the surface. Roasters from the U.S. Northwest generally remove the beans at this point. | Slightly shiny | Somewhat spicy; complexity is traded for rich chocolaty body, aroma is exchanged for sweetness |
| Darkest | French | After 14 minutes or so the beans grow quiet and begin to smoke. Having carmelized, the bean sugars begin to carbonize. | Very oily | Smokey; tastes primarily of roasting, not of the inherent flavor of the bean |

Source: Oosterveld et al. (2003)

### 7.3 Change of coffee bean during roasting

Roasting is aroma and flavor coffee adjustment; heating to clear the humidity out. It affects on the changes of chemical and physical properties. Roasting is an essential step in coffee production for generating aroma, flavor and color of the coffee beans. The mode of heat transfer and the applied temperature profile is the most critical process parameters that have the major impact on the physical and chemical properties of roasted coffee beans (Schenker et al., 2002; Oosterveld et al., 2003). The physical changes in the coffee beans during roasting are also technically important, leading to considerably decreased density and expansion of the beans (Clarke, 1985). The chemical reaction changes include Maillard or nonenzymatic browning reaction, Strecker degradation and degradation of proteins, sugar, polysaccharides and other components. Degree of roasting is controlled by roasting time and temperature such that they are sufficient for the required chemical reactions to occur, without burning the beans and compromising the flavor of the beverage (Mendes, 2001). The degree of roasting is qualitatively assessed from color, for example, simple categorization as a light, medium or dark roast (Clarke, 1985).

### 7.3.1 Physical change

Roasted coffee changed in shape, size, and other physical properties as follow:

#### 7.3.1.1 Total weight loss

Moisture content of green beans (15-18%) is generally reduced to 10-12% as a result of dehydration during roasting. Extended period of roasting leads to Pylolysis which result in a further weight loss down to 4-6% moisture content (Ky et al., 2001). While the moisture contents of coffee bean were reducing from 7% to 4%, phenolic compounds, mainly chlorogenic acid, were dispersing out (Ky et al., 2001). The loss of chlorogenic acid during roasting negatively affected the coffee flavor. Furthermore, carbon dioxide was also lost as a result of pyrolysis. However, very small amount of caffein was lost during roasting.

#### 7.3.1.2 Change of pH

The pH of coffee changed because pyrolysis caused carbohydrate to be broken down to carboxylic acid. It causes the reducing of pH of coffee from 5.5 to 4.9 that is subjected to roasting level.

#### 7.3.1.3 Change of color and flavor

The color changed after roasting because of carbon pyrolysis and protein breakdown. Flavor changed because protein and fatty acid are hydroyed (Sivetz, 1963).

### 7.3.2 Change of chemical properties

Roasting process affecting on the important reactions, for example, Millard reactions, Caramel reactions, Strecker degradation and Pyrolysis reactions, cause the chemical changes including the appearance of new compounds. Chemical compounds changing are as follows (Table 10):

#### 7.3.2.1 Sucrose

Sucrose ($C_6H_{12}O_6$) is the most important disaccharides in coffee. Disaccharides contain two monosaccharides joined together by a glycosidic linkage. Sucrose is commonly known as table sugar, is found in the free state throughout the plant kingdom. It consists of one glucose unit and one fructose unit. Disaccharides are not used directly in the body but are first hydrolyzed to monosaccharides. It yields two monosaccharide molecules when hydrolyzed in the experiment elevated temperatures in the presence of hydrogen ions (acids) as catalyst. In biological systems, enzymes (biochemical catalyst) carry out the reaction. For each different hydrolysis of disaccharide, different enzyme is required. For sucrose, sucrase is needed. The structure of disaccharide is derived from two monosaccharide molecules by elimination of a water molecule between them. (Manach et al., 2004)

#### 7.3.2.2Non volatile acids

Carboxylic acid is a non volatile acid, caused by carbohydrate dispersion when it is heated. It affects on pH of coffee. However, the low phenolic acid does not affect the alkalinity but it affects the aroma, making hard smell. The acidity of medium roasted coffee is much more than the acidity of dark roasted coffee. According to the research, organic acids important to coffee are chlorogenic acid, acetic acid and citric acid. The chlorogenic acid is found in green coffee at 7% but it is damaged during the roasting (Sivetz and Foote, 1963).

#### 7.3.2.3 Volatile compounds

Volatile compounds are flavoring the coffee and they come from some organic compounds dispersing by heat. They are kept in the cell of seeds. Although the volatile compounds are present at very low amount at 0.04% of roasted coffee weight but they have considerable effect on the coffee flavor. These volatile compounds are in the group of Aldehyde and Ketone, caused by heat dispersing of protein and carbohydrate (Sivetz and Foote, 1963).

#### 7.3.2.4 Protein

Protein is present at 13% of coffee dry weight. Proteins are hydrolyed to peptide, amino acid, amine and disulfide which are kept in the coffee bean and dissolved when it is distilled. Hydrolysing of protein resulted in flavors and substances interacted with other molecules, causing changes in aroma and flavor (Sivetz and Foote, 1963).

#### 7.3.2.5 Carbon dioxide

Actually, there is no carbon dioxide in the coffee seeds but it appears during roasting. It comes from the dispersing of carboxylic acid in pyrolysis process, leading to the production of the carbon dioxide at 1-2%. Uncrushed roast coffee has more carbon dioxide than that of the crushed one. Carbon dioxide in the seeds protects the spreading of water and humidity, protecting the occurrence of rancid smell. So, it could be stored for longer time (Sivetz and Foote, 1963).

#### 7.3.2.6 Oil

Coffee beans contain about 12% oil. 95% of oils does not change during the roasting. The oil is hydrolyzed to release free fatty acids and glycerine causing some changes in the coffee flavor. Some oils are floating on the surface of coffee beans while brewing. In addition, coffee surface is softened during roasting, releasing the oil. Coffee seed surface is covered with oil. Strecker degradation is the reaction between dicarbonyll and amino acid that is 1-deoxyosone and 3-deoxyosone, affecting retroaldolization. Dicarbonyll - an intermediate substance -is aldehyde and α-amino ketone that may combine to each other forming flavoring substance such as pyridine, pyrazine, and imidazole (Figure 4) (Sivetz and Foote, 1963).

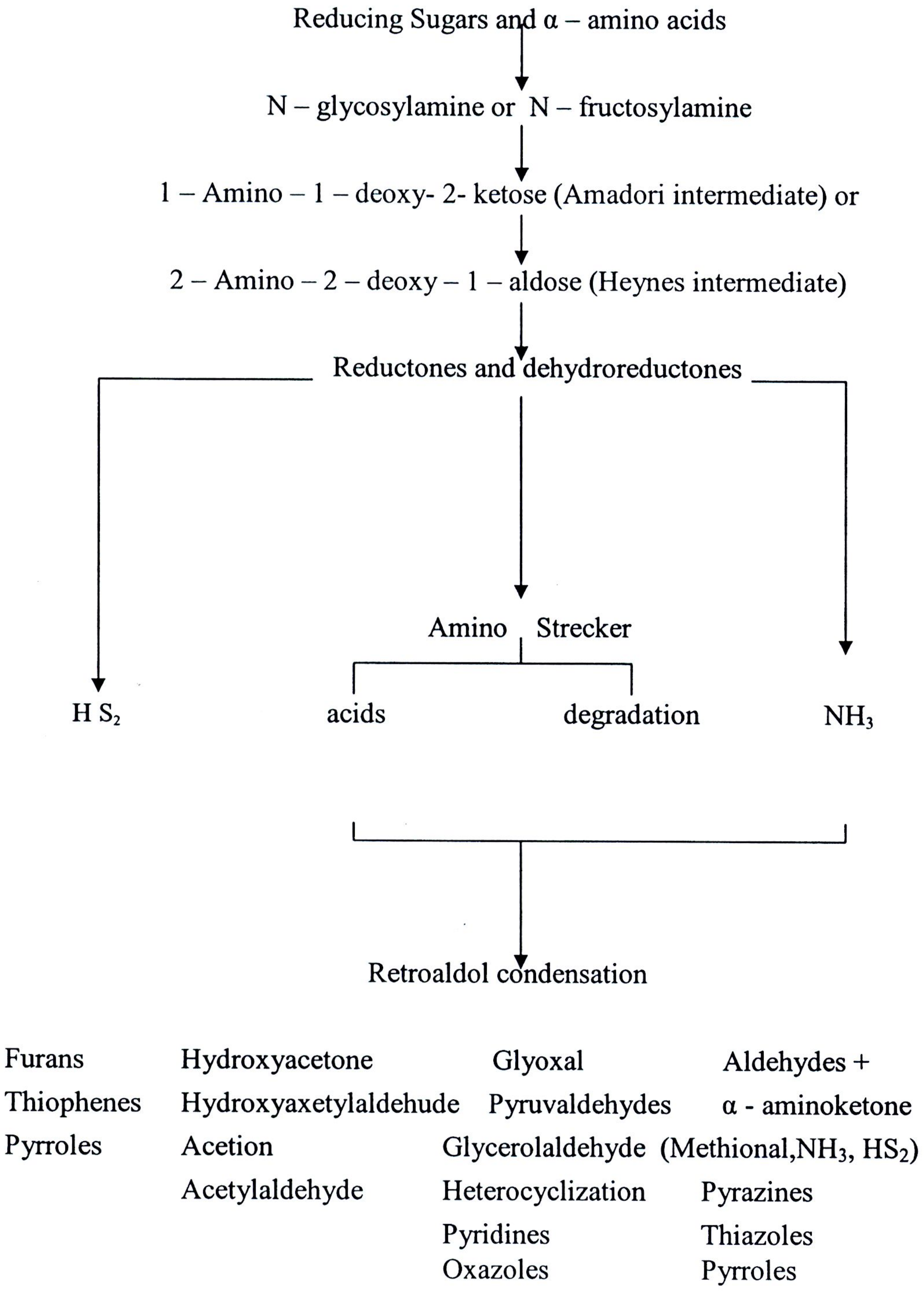


**Figure 4** Chemical changes in coffee resulted from roasting

Source: Jirasawat (2003)

**Table 10** Physical and chemical properties of Arabica and Robusta coffee after roasting

| Properties | Green bean | | Roasted bean | |
|---|---|---|---|---|
| | Arabica | Robusta | Arabica | Robusta |
| Moisture | 5-13 | 5-13 | 1-3 | 1-3 |
| Alkaloids | | | | |
| Caffeine | 0.8-1.4 | 1.7-4.0 | 1.0-1.6 | 1.2-2.6 |
| Trigonellin | 0.6-1.2 | 0.3-0.9 | 0.1-1.2 | 0.1-1.2 |
| Carbohydrate | | | | |
| Soluble | 55.0-65.5 | 40.0-55.5 | 16.2-37.5 | 16.2-37.5 |
| Insoluble | 6.0-12.5 | 6.0-12.5 | 6.2-16.5 | 6.2-16.5 |
| Acids | | | | |
| Chlorogenic | 7.0-9.0 | 7.0-12 | 0.2-3.5 | 0.2-3.5 |
| Aliphatic | 1.0-3.0 | 1.0-2.0 | 1.8-4.6 | 1.8-4.6 |
| Protein and amino acid | 9.0-13.0 | 9.0-13.0 | 13.0-15.0 | 13.0-15.0 |
| Lipid | 15.0-18.0 | 8.0-12.0 | 15.5-20.0 | 8.5-13.5 |
| Ash | 3.0-5.4 | 3.0-5.4 | 3.5-6.0 | 3.5-6.0 |

Source: Viani and Rinantonio (1985) cited by Jirasawat (2003)

### 7.4 Effect of degree of roasting

Duration of roasting effects coffee color including physical and chemical property. Moreover, roasting level effect other properties as follow:

7.4.1 Acidity

Acidity of coffee is affected by roasting level; the pH is high with light roasting and low with dark roasting.

7.4.2 Water soluble

Roasting level affects on the quantity of soluble part. It is distilled at 100 °C. Medium roasting is distilled by water more than dark roasting. Because a lot of oil is released in dark roasting, this affects distilled soluble substance (Sivetz, 1963).

According to the analysis of Arabica coffee using High Resolution Gas Chromatography-Mass Spectrometry (HRGC-MS), roasting caused the degradation of trigonelline, sucrose, amino acid, and arabinogalactan. Roasting cause the appearance of compounds such as furans, pyrazine, pyridine, and pyrole. The change in physical feature during roasting makes popping to the coffee seed due to change of its microstructure. That causes the increasing of the coffee bean capacity, decreasing density, and increasing the large micropore in the cell wall. It also causes the higher extractability (Clarke, 1985; Redgwell et al., 2002).

7.4.3 Roasting process

Roasting is the step related to coffee aroma and flavor development in the processing of green coffee beans. Although the green coffee beans vary in chemical and physical properties, the chemical and physical changes they undergo during roasting are similar even though they vary in degree (Sivetz, 1963). The degree of roasting is qualitatively assessed from color, for simple categorization as a light, medium or dark roast. Roast color will also be broadly correlated with percentage loss of coffee matter, expressed on a dry weight basis. So that a light roast will show about 3-5%, medium 5-8%, dark 8-14% loss of moisture content that the green beans will have contained (Clarke, 1985). Coffee Research Institute (2001) reported that the volatile compositions were developed from roasting process, which affected many chemical reactions.

7.4.3.1 Maillard or non-enzymatic browning reaction between nitrogen containing substances, amino acids, proteins, as well as trigonelline, serotonine, and carbohydrates, hydroxy-acids and phenols on the other.

7.4.3.2 Strecker degradation

7.4.3.3 Degradation of individual amino acids, particularly, sulfur amino acids, hydroxyl amino acids, and proline.

7.4.3.4 Degradation of trigonelline.

7.4.3.5 Degradation of sugar.

7.4.3.6 Degradation of phenolic acids, particularly the quinic acid moiety.

7.4.3.7 Minor lipid degradation

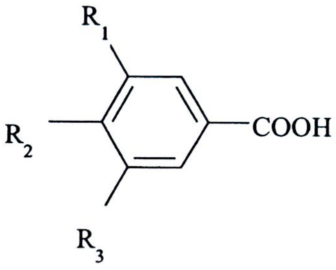
#### 7.4.3.8 Interaction between intermediate decomposition products.

Moreira et al. (2005) determined roasted Arabica coffee by High Resolution Gas Chromatography/Mass Spectrometry (HRGC/MS). It was found that the roasting process was impact on the degradation of trigonelline, sucrose, amino acid and arabinogalactan to develop furans, pyrazines and pyridines. Scalbert and Williamson (2000) investigated the effect of reaction conditions on pyrolysis of chlorogenic acid. The highest weight loss in the tubular reactor for chlorogenic acid (80%) was observed at 450 °C and above. Although a bulk of pyrolysis of chlorogenic acid was complete below 400 °C, small but significant decomposition was observed at higher temperature. The physical changes in the coffee beans during roasting are also technically important. The expansion of the beans including a popping phase, leading to considerably decreased density and increased large micropore in cell wall, which increased extractability in production process of instant coffee (Clarke, 1985; Redgwell et al., 2002).

## 8. Phenolic compounds

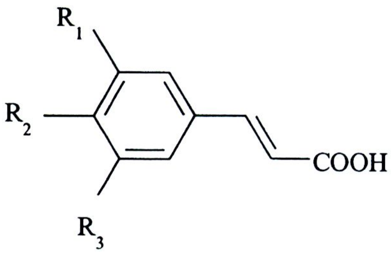
Phenolic compounds are defined as substances possessing a benzene ring bearing one or more hydroxyl substituent(s), including their functional derivatives. Phenols have many favorable effects on human health. They reduce the risk of heart diseases by inhibiting the oxidation of low-density lipoprotein (LDL) (Bonilla et al., 1999). A large range of low and high molecular weight phenols exhibiting antioxidant properties have been studied and proposed to be used as antioxidants against lipid oxidation. This is particularly true for those phenolics with multiple hydroxyl groups that are generally the most efficient for preventing lipid oxidation. Phenolic compounds are also known to possess antibacterial, antiviral, antimutagenic and anticarcinogenic properties (Moure, 2001). Phenolic compounds, ubiquitous in plants are an essential part of the human diet, and are of considerable interest due to their antioxidant properties. These compounds possess an aromatic ring bearing one or more hydroxyl groups and their structures may range from that of a simple phenolic molecule to that of a complex high-molecular weight polymer. Phenolic acids are derivatives of benzoic acid and cinnamic acid with hydroxyl groups and methoxy groups substituted at various points on the aromatic ring (Marinova and Yanishlieva, 2003). Ferulic acid, *p*-coumaric acid, caffeic acid, vanillic acid and syringic acid are all examples of phenolic acids (Pratt and Hudson, 1990). Structures of some phenolic acids are shown in Figure 5. It is widely accepted that phenolic compounds significantly contribute to the overall antioxidant properties of grain. Phenolic acids have been strong inhibitors of carcinogenesis at the initiation and promotion stages induced by different compounds (Kaul and Khanduja, 1998).

**Benzoic acid derivatives**



| Name of acid | Position of the functional groups | | |
|---|---|---|---|
| | $R_1$ | $R_2$ | $R_3$ |
| Gallic | OH | OH | OH |
| p- Hydroxybenzoic | H | OH | H |
| Protocatechuic | OH | OH | H |
| Vanillic | $OCH_3$ | OH | H |
| Syringic | $OCH_3$ | OH | $OCH_3$ |

**Cinnamic acid derivatives**



| Name of acid | Position of the functional groups | | |
|---|---|---|---|
| | $R_1$ | $R_2$ | $R_3$ |
| p-Coumaric | H | OH | H |
| Caffeic | OH | OH | H |
| Ferulic | $OCH_3$ | OH | H |
| Sinapic | $OCH_3$ | OH | $OCH_3$ |

**Figure 5** Phenolic compounds as antioxidants

Phenolic compounds are ubiquitous constituents of higher plants found in a wide range of commonly consumed plant foods such as fruits, vegetables, cereals and legumes, and in beverages of plant origin, such as wine, tea and coffee. These compounds are secondary metabolites of plants generally involved in defense against ultraviolet radiation or aggression by pathogens. Several thousands of phenolic compounds have been described in plant foods and can be grouped into different classes according to their basic chemical structure (such as type and number of phenol rings), and into different subclasses, according to specific substitutions in the basic structure, association with carbohydrates and polymerized forms (Iqbal et al., 2005). Most of these compounds have received considerable attention as potentially protective factors against human chronic degenerative diseases (cataracts, macular degeneration, neurodegenerative diseases, and diabetes mellitus), cancer and cardiovascular disease (Scalbert et al., 2005). While condensed tannins are the main phenolic compounds in coffee pulp, in the seed, phenolic compounds are present predominantly as a family of esters formed between certain hydroxycinnamic acids and quinic acid, collectively known as chlorogenic acids (CGA) (Clifford, 1985). Other phenolic compounds, such as tannins, lignans and anthocyanins are also present in coffee seeds although in minor amounts. CGA, which are present in high concentrations in green coffee seeds (up to 14 %), have a marked influence in determining coffee quality and play an important role in the formation of coffee flavor (Farah et al., 2005). Moreover, these compounds have several beneficial health properties largely explained by their potent antioxidant activity. In addition, they have exhibited hypoglycemic, antiviral, hepatoprotective and antispasmodic activities (Cuvelier et al., 1992; Adom and Liu, 2002). Their 1, 5-γ-quinolactones have also been studied not only for their potential hypoglycemic effects but for their action in the brain function, more specifically, at the adenosine receptors (Farah, 2005).