Processing and Drying of Coffee – A Review

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Abstract— **Coffee is one of the most popular beverages in the world. One of the principle post-harvest technological processes is drying, giving rise to the formation of the characteristic colour, flavour and taste of coffee brew. Conventionally there are two types of drying techniques used in the coffee processing, (sun drying and mechanical drying). The initial moisture content of harvested coffee is about 55-60% and after drying lowers the moisture content to around 12% (wb). Drying should be uniform to obtain acceptable colour, size along with the removal of pests for a longer safe storage. Since coffee production is seasonal, traditional sun drying is quite tough. Unpredictable weather events can increase the moisture content and the time taken for drying prolongs to about 7-21 days. There are several dryers available for coffee drying including mechanical dryers as well as Combination of both solar dryer assisted with mechanical dryer. The new trend of coffee drying is the microwave drying which retains the characteristics flavor. This is a novel try to share about various drying process in different countries throughout the world.**

Keywords— ***Coffee, Processing, Drying, Sun-drying, Mechanical Drying, Mechanical dryers***

1. INTRODUCTION

This Coffee is one of the most popular beverages in the world. Nearly 25 million farmers in 50 countries around the world depend on coffee for a significant part of their livelihoods (Cague *et al*. 2009). The genus coffee belongs to the botanical family of Rubiaceae and comprises more than 90 different species (Davis, 2001). The characteristic, rich and pleasant aroma and colour of coffee brews is a result of complex processes leading from green coffee beans to the cup of coffee. One of the principal postharvest processes is drying that gives rise to the formation of the characteristic colour, flavour and taste of coffee brews. In 2010-11 according to U.S. Department of Agriculture 12 million tonnes of green coffee is produced.

Coffee plants are grown in tropical and subtropical regions of Central and South America, Africa, and South East Asia, mainly in regions with temperate and humid climates (Schenker, 2000). Coffee cherries are harvested each year when they are bright-red, glossy and firm. After removing the outer hull, the seeds inside of the cherry are commonly called "green coffee beans". The quality of the green coffee beans is dictated by a number of parameters, including bean size, colour, shape, method of drying, crop year, and presence of defects (crack, withered bean, bean in parchment, mouldy bean, etc.).

Brazil is by far the largest grower and exporter of green coffee beans in the world followed by Vietnam, Colombia, Indonesia, Ethiopia and India – producing nearly 2.5 million tonnes of green coffee beans per year (Franca and Oliveira 2009). Fig1.1 shows the main coffee producing countries as well as their share in production.

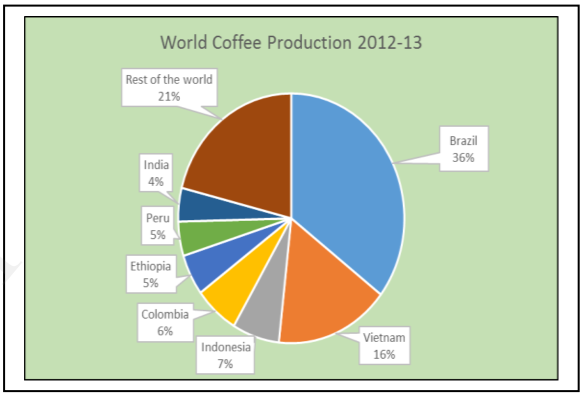


Fig 1.1 World Coffee Production [Source: Coffee Board of India; Database 2013]

2. COFFEE FRUIT AND MORPHOLOGY

Coffee belongs to the botanical family Rubiaceae, which has some 500 genera and over 6,000 species Davis (2001). Most are tropical trees and shrubs that grow in the lower storey of forests. Other members of the family include gardenias and plants that yield quinine and other useful substances, but Coffee is by far the most important member of the family economically.

Table 2.1 – Botanical Characteristics of Coffee (Clifford *et al*., 1985)

Family	Genus	Species(many including)	Varieties (examples)
Rubiaceae	Coffea	Arabica	Typica
		Canephora	Robusta
		Liberica	

According to Clifford *et al* (1985) Linnaeus first described coffee arabica in 1753. The best known varieties are 'Typica' and 'Bourbon' but from these many different strains and cultivars have been developed, such as Caturra

(Brazil, Colombia), Mundo Novo (Brazil), Tico (Central America), the dwarf San Ramon and the Jamaican Blue Mountain (Table 2.1). The average Arabica plant is a large bush with dark-green oval leaves. It is genetically different from other coffee species, having four sets of chromosomes rather than two. In case of Arabica the fruits are oval and mature in 7 to 9 months (Table 2.2); they usually contain two flat seeds (the coffee beans) - when only one bean develops it is called a peaberry. Since Arabica coffee is often susceptible to attack by pests and diseases, resistance is a major goal of plant breeding programs. Arabica coffee grown throughout Latin America, in Central and East Africa, in India and to some extent in Indonesia.

The term 'Robusta' is actually the name of a widely grown variety of this species. It is a robust shrub or small tree growing up to 10 meters in height, but with a shallow root system. The fruits are rounded and take up to 11 months to mature, the seeds are oval in shape and smaller than those of C. arabica (Table 2.2). Robusta coffee grown in West and Central Africa, throughout South-East Asia and to some extent in Brazil, where it known as Conillon.

Coffee cherries are harvested when they become bright-red, glossy, and firm, either by selective hand-picking or non-selective stripping of whole branches or mechanical harvesting. The hand-picking method is very time-consuming, but it gives a superior product quality. Ripe cherries will be available 9-11 months after flowering.

The coffee fruit (also called berry or cherry) consists of a smooth, tough outer skin or pericarp, usually green in unripe fruits, which turns to red-violet or deep red when ripe (Fig 2.1). The pericarp covers the soft yellowish, fibrous and sweet pulp or known as outer mesocarp. When the fruit is ripe a thin hydrated slimy layer will be formed know as mucilage (also called pectin layer). Then there will be a thin endocarp, yellowish in color known as parchment. Underneath the parchment, the beans are covered in another thinner membrane, the silver skin (the seed coat). The silver skin covers the coffee seed or bean (Fig 2.2). Each cherry generally contains two coffee beans. If there is only one it assumes a rounder shape and it is known as pea-berry. (Belitz *et al*., 2009; Queiroz *et al*., 1998; Purseglove, 1974).

Table 2.2 - Basic differences between Arabica and Robusta are (Wrigley, 1988)

	Arabica	**Robusta**
Date species described	1753	1895
Time from flower to ripe cherry	9 months	10-11 months
Ripe cherries	Fall	Stay
Yield (kg beans/ha)	1500-2000	2300-4000
Optimum temperature (yearly average)	15-24^{0}C	24-30^{0}C
Optimal rainfall	1500-2000mm	2000-3000mm
Optimum altitude	1000-2000m	0-700m
Caffeine content of beans	0.8-1.4%	1.7-4%
Shape of bean	Flat	Oval

According to Avallone (1999) from a morphological perspective, the coffee cherry is an ellipsoidal fruit (about 1x2 cm) with two curved sides on one side and flat by the other having an elliptical or egg geometry, flat-convex, with a division on the flat surface (Dedecca, 1957). Measures carried out on several seeds show that the grain has an average length of 10 to 18 mm and 6.5 to 9.5 mm of wide (Dedecca, 1957). Some species have smaller grains and *C. ramenosa* (5-7 mm long and 3 to 3.5 mm wide), while others have larger grains and *C. liberica*. The proliferation of cells during fruit growth is limited because the thickness of the mesocarp never exceeds 2 mm. The pericarp corresponds to the fleshy part in drupes and its thickness varies from 1 to 1.7 mm depending on the species of coffee. (Avallone, 1999). The endocarp, also called "parchment" is a hard, protective and woody tissue with lignified secondary walls of about 110-150 µm of thickness (Avallone, 1999). Its functions are varied: it was proposed that protects the coffee bean against certain enzymes (Avallone, 1999), and that it acts as a physical barrier that limits the diffusion of certain biochemical compounds from the pericarp (exocarp, mesocarp) and other tissues (Geromel *et al.*, 2006; Avallone, 1999).

Fig.2.1 Ripped and un-ripped Cherry

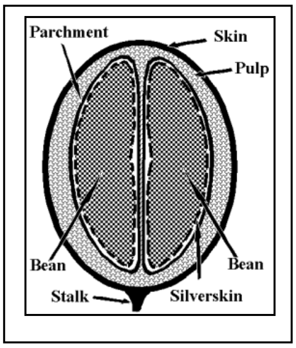


Fig.2.2 (a) Inner view of the Cherry

Fig.2.2 (b) Cherry with beans inside

2.1 Coffee Production

Coffee consumption takes place all the year around. However the production of coffee is seasonal. So long term storage is necessary to maintain the better quality. About 60 tropical and subtropical countries produce coffee extensively, being for some of them the main agricultural export product (Lashermes *et al*., 2008; Vieira, 2008). Most coffee beverage consumed around the world is produced by the species *Coffea arabica* (Arabica) and *Coffea canephora* (Robusta). Arabica is considered as the superior one due to its sensory properties and therefore it has a higher price in the international market (Gielissen *et al*., 2009). The top ten countries producing coffee is shown in Table 2.3.

India is the seventh largest producer of coffee in the world. It produces both variety of coffee i.e. Arabica and Robusta. The bulk production taking place in the southern states and most noted is Monsooned Malabar variety. Indian coffee has created a niche for itself in the international market, particularly Indian Robusta which is highly preferred for its good blending quality. Arabica coffee from India is also well received in the international market.

Coffee is one of the important plantation crops of India cultivated in 4,15,341 hectares mainly in the southern states of Karnataka (55.5%), Kerala (20.6%), Tamilnadu (7.6%) and to a small extent in other non-traditional and non-conventional areas such as Coastal tribal Andhra Pradesh and Orissa and North Eastern Region (14.9%). The production in 2012-13 is estimated to be 3, 18,200 metric tonnes. Coffee in India is cultivated by a large number of small holders (holding less than 10 acres), numbering 2,89,743 accounting for 70 % of area under coffee and the rest cultivated in 3,88,195 large holdings. Most of the coffee produced in India is exported and India has a share of 4.53% in the world market. During 2012-13, world coffee production was 14, 46, 11,000 bags (each bag contains 60 kg) and India's production was 53, 03,000 bags where as India exported 2, 98,063 tonnes of coffee. Indian coffee is exported to over 40 countries but the top six markets are Russian federation, EU countries like Italy, Germany, Belgium, Spain, Finland, Greece and USA accounting for 70% of Indian coffee exports. The specialty coffee exports from India are comprised of Malabar Monsoon Coffee, Mysore Nuggets extra bold, Robusta Kapi Royale. Major ports of export are Cochin, Chennai and Tuticorin. During recent years small quantity of coffee from Indonesia and Vietnam are imported to India. Domestic consumption is mostly in the states of Tamilnadu and Karnataka.

Table 2.3 - Top 10 countries in coffee production FAO (2012) report

S. No	Name of the country	Tonnes
1	Brazil	2,609,060
2	Vietnam	1,200,000
3	Indonesia	495,000
4	Colombia	468,000
5	Ethiopia	390,000
6	Peru	326,580
7	India	319,980
8	Honduras	270,000
9	Mexico	258,000
10	Guatemala	225,000

2.2 Chemical Composition and Nutritional value of Coffee

Green coffee beans are mainly composed, like most plant tissues, by insoluble polysaccharides like cellulose and hemicellulose (50% w/w). They contain also soluble carbohydrates, such as the monosaccharaides fructose, glucose, galactose and arabinose, the oligosaccharides sucrose, raffinose and stachyose, and polymers of galactose, mannose, arabinose and glucose. Soluble carbohydrates act binding aroma, stabilizing foam, sedimenting and increasing viscosity of the extract. In addition, non-volatile aliphatic acids (citric, malic and quinic acids) and volatile acids are also present (such as acetic, propanoic, butanoic, isovaleric, hexanoic acids). Oils and waxes are also important constituents, accounting for 8 to 18% of the dry mass, together with proteins and free amino acids (9-12% w/w) and minerals (3-5% w/w). (Arya & Rao, 2007; Belitz *et al*., 2009; Clifford, 1985a; Gonzalez-Rios *et al*., 2007). Table 2.4 shows the chemical composition of green Arabica and Robusta beans.

There are many compounds in coffee that are often thought to have implications upon human health. These include caffeine, micronutrients and chlorogenic acid. The coffee beverage is rich in biologically active substances such as nicotinic acid, trigonelline, quinolinic acid, tanninc acid, pyrogolic acid and caffeine (Minamisawa *et al.*, 2004).

Sometimes coffee quality became low due to the hydrolysis of triacylglycerols (the major constituent of coffee lipid) releasing free fatty acids which are oxidized at the time of storage. Multon *et al* (1973) reported that free amino acids and sugars are degraded while lipids are oxidized and produce off flavour at the end of the storage after drying.

Table 2.4 - Chemical composition of green Arabica and Robusta coffee beans (g/100g)

Component	Arabica coffee	Robusta coffee
Polysaccharides	49.8	54.4
Sucrose	8.0	4.0
Reducing sugars	0.1	0.4
other sugars	1.0	2.0
Lipids	16.2	10.0
Proteins	9.8	9.5
Amino acids	0.5	0.8
Aliphatic acids	1.1	1.2
Quinic acids	0.4	0.4
Chlorgenic acids	6.5	10.0
Caffeine	1.2	2.2
Trigonelline	1.0	0.7
Minerals (as oxide ash)	4.2	4.4
Volatile aroma	traces	traces
Water	8 to 12	8 to 12

2.3 Green Coffee Processing

Green coffee is produced either by dry processing or by wet processing. After harvesting, the coffee fruits are separated from the pulp, which is carried out by dry or wet processing (Clarke & Macrae 1987; Illy & Viani 1995). The dry process is simple and inexpensive. The whole cherries are dried under the sun in open air, followed by the separation of the hull (dried pulp and parchment) for getting the green beans. On the contrary, the wet process requires more care and investment, but results in a superior coffee quality. In the wet process, the pulp of the coffee cherries, which is made up of exocarp and mesocarp, is removed mechanically, but the parchment remains attached to the beans. After drying either under the sun or in a dryer, the parchment is removed to produce the green coffee beans. Flow diagram for green coffee processing is given in Fig 2.3.

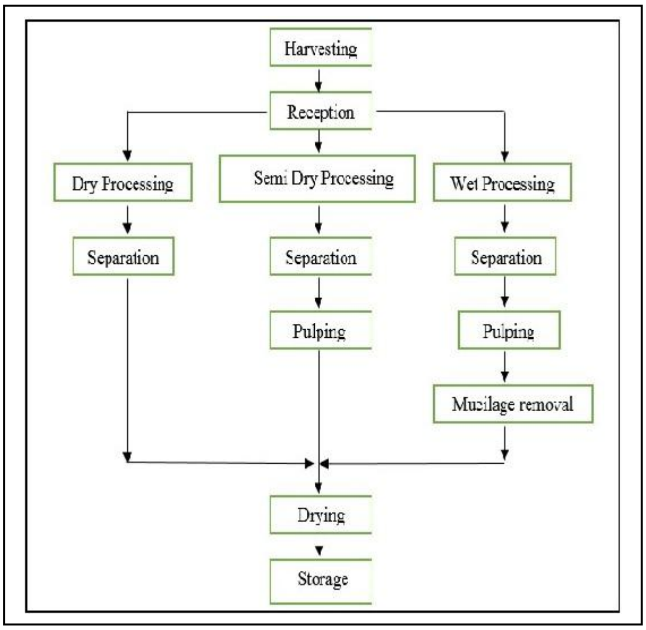


Fig 2.3. General scheme of coffee processing and preparation of green coffee beans

2.4.1 Dry processing

This is the simpler of the two methods and is popular in Brazil to process Robusta coffee and in Sri Lanka to process Arabica coffee. In case of dry processing coffee cherries are dried as such in the open yard until the moisture content reduce up-to 12% (wb). In this case one of the most important processing is racking. The more number of racking gives a uniform and better quality product

Drying

The coffee cherries are dried immediately after harvest. This is usually sun drying on a clean dry floor or on mats. The bed depth should be less than 40mm and the cherries should be raked frequently to prevent fermentation or discoloration. However, there are problems associated with this method. The most serious problem is dust and dirt blown onto the produce. Another problem is rainstorms often appear (even in the dry season) with very little warning, this can soak the produce very quickly. Finally, labour has to be employed to prevent damage or theft. Sun drying is therefore not recommended.

Hulling

The dried cherry is then hulled to remove the pericarp. This can be done by hand using a pestle and mortar or in a mechanical huller. The mechanical hullers usually consist of a steel screw, the pitch of which increases as it approaches the outlet so removing the pericarp.

Cleaning

The hulled coffee is cleaned by winnowing. Defective beans are also removed. Sorting takes place both in the producing and manufacturing countries to achieve high quality coffee beans, and is carried out by either mechanical or optical means. In the mechanical method, defective beans are hand-picked and fed into air classifiers (catadors) where they enter an adjustable rising current of air.

2.4.2 Wet processing

In this method the cherry is squeezed in a pulping machine or pestle and mortar which removes the outer fleshy material (mesocarp and exocarp) leaving bean covered in mucilage. This mucilage is fermented and dispersed. The bean is washed and dried.

Pulping

Pulping involves the removal of the outer red skin (exocarp) and the white fleshy pulp (mesocarp) and the separation of the pulp and beans. Immature cherries are hard and green and very difficult to pulp. If the coffee is to be wet processed, correct harvesting is essential. For small-scale units, the cherries can be pulped in a pestle and mortar, this is very labour intensive. The two most common pulpers and most suitable for small-scale units are the drum and the disc pulpers.

Drum pulpers

This involves a rotating drum with a punched sheet surface and adjustable breast plate between which the coffee cherries are pulped, the pulp and the beans separated. The distance between the drum and the breast plate has to be adjusted so that the pulp is removed without the beans being damaged. These can be manually operated or attached to a treadle or bicycle. For larger scale units, motorised drum pulpers are available.

Disc pulpers

The same concept is involved with the disc pulper. The only difference is that rather than the cherries being squeezed between a breast plate and a drum, a disc with a roughened surface is used.

Mucilage removal

Fermentation of the mucilage takes place in large tanks over 24 to 40 hours. However, the fermentation procedure which results in the best quality, as well as allowing a reasonably convenient and rapid factory routine is the two-stage 'dry' fermentation process (Wootton 1971). During the first stage the mucilage is degraded and during the second stage it is soaked in water for 24 to 48 hours.

The amorphous gel of mucilage around the bean consists of hemicelluloses, pectic substances and sugars and is insoluble in water. This can be removed by chemical methods, warm water or by an 'aqua pulper'. However, for small-scale units the only feasible method is fermentation. Fermentation involves the beans being placed in plastic buckets or tanks and left until the mucilage has been broken down. Natural enzymes in the mucilage and feasts; bacteria in the environment work together to break down the mucilage. The coffee should be stirred occasionally and a handful of beans should be tested by washing them in water. If the mucilage can be washed off and the beans feel gritty rather than slippery, the beans are ready. The beans should then be washed immediately as 'off' flavours develop quickly.

After fermentation, the coffee is known as 'parchment coffee', since the seed retains its endocarp layer. It must be dried to about 10-12% (wb) moisture content to ensure stability.

Drying

To prevent cracking the coffee beans should be dried slowly to 10% moisture content (wet basis). Drying should take place immediately after to prevent 'off' flavours developing. The same drying methods can be used for this as for the dry processed coffee.

Hulling

After drying the coffee should be rested for 8 hours in a well-ventilated place. The thin parchment around the coffee is removed either by hand, in a pestle and mortar or in a small huller.

Cleaning

The hulled coffee is cleaned by winnowing.

3. DRYING OF COFFEE

Drying is one of the most important steps in the coffee processing. The use of natural sun drying process of coffee in terraces is still very common among the coffee producers however it requires high labour, it is a time requiring operation and on dependency on the climatic conditions. As the coffee production increases the sun drying operation in terraces happen to be problematic in terms of coffee production operation and the mechanical drying becomes a need due to the possibility of advancing the harvesting operation, allowing to harvest better coffee in terms of quality and quantity and make possible to destine usable areas for other activities.

Drying is mainly concern for the degradation of the moisture content up to a certain limit12% (w.b). Drying diminishes the respiration rate of the product and increases the storage time with the minimum possible loss. If the beans are over dried it will be brittle in nature and if moisture content is more than safe storage moisture then there is a probability of mould growth in the beans for further processing. Technical data of the post-harvest processing of coffee in both dry process and wet process is given in Table 3.1.

Conventionally there are 2 types of drying techniques used in the coffee processing that is sun drying and mechanical drying. The initial moisture content of the coffee is about 55-60% and after drying the final moisture content should be around 12% (wb) and the drying should be even and homogenised to obtain the proper colour, size and to get rid of pests for the longer storage time. Generally coffee beans can be stored almost for 8 months but the pest problem and increase in moisture content during storage period are the problem.

Table: 3.1 Technical data of post-harvest processing (CIRAD CP)

DRY PROCESSING						WET PROCESSING			
PRODUCTS		ARABICA		ROBUSTA		PRODUCTS		ARABICA	
(at each stage of processing)	Moisture content (% wb)	Weight (in kg)	Bulk density (kg/m^2)	Weight (in kg)	Bulk density (kg/m^2)	(in each stage of processing)	Moisture content (% wb)	Weight (in kg)	Bulk density (kg/m^2)
Fresh cherry	65	100.00	616	100.00	645	Fresh cherry	65	100.00	616
						Pulped cherry	Nd	54.00	846
						Wet parchment coffee	55	45.00	665
Dry coffee cherry	12	37.20	422	42.20	440	Dry parchment coffee	12	23.00	352
Green Coffee	12	19	650	22.00	750	Green Coffee	12	19.00	250

The study of the drying system, its design, optimization, its feasibility for an application for commercial use could be obtained through the mathematical simulations. For simulation, which is based on principle of successive thin layer drying, it is used a mathematical model that represents satisfactory the water loss during the drying process (Berbert *et al*., 1995); although the coffee thin layer drying curves vary with the species, variety, environmental conditions and post-harvest processing methods among others.

It has been pointed out that beverages from coffee drying processed by different methods have significant difference (Selmar *et al*., 2006; Leloup *et al*., 2008). Coffee produced by the wet method has less body and higher acidity; it is also more aromatic than coffee produced by the dry method, resulting in a higher acceptance by consumers. It is currently accepted that the metabolic reactions in the coffee fruits that occur during different types of processing can affect the chemical composition of beans and thereby affect beverage quality (Bytofet *et al*., 2005, 2007).

Studies focusing on the coffee behaviour during the drying process have been reported by several researchers. Corrêa *et al.* (2006) studied the drying characteristics and kinetics of coffee berry under the drying temperatures of 40°, 50° and 60°C. Corrêa *et al.* (2010) also observed the moisture sorption isotherms and isosteric heat of sorption of coffee in different processing levels. Coradi *et al.* (2007) tried to determine the effect of drying and storage conditions on the quality of natural and washed coffee. This research emphasized the importance of the adequate storage besides the correct drying process to preserve coffee's qualities. Ciro-Velásquez *et al*. (2010) conducted a numerical simulation of thin-layer coffee drying by control volumes. Similar to Corrêa *et al.* (2006), this simulation also used drying air temperatures of 40°, 50° and 60°C.

According to Muhidong *et al.* (2013) drying of coffee bean was performed under different air velocity (0.5, 1.2, and 1.8 m/s) with a temperature of 47^0C. Among the various thin layer drying models Hii *et al.* model (2008) gave the best fit with a R^2 up to 0.99. It was also observed that increasing air velocity from 0.5 m/s to 1.8 m/s failed to improve the drying rate considerably.

In a study assessing intermittent drying of parchment coffee, Martin *et al.* (2009) combined 12 hours of drying with 50º C heated air and 12 hours of rest and observed a 24.56% reduction in effective drying time relative to continuous drying.

While drying of parchment coffee, Isquierdo *et al.* (2011), observed that interrupting the drying process when the moisture content was 24% (wet basis, w.b) with a rest period of 2 to 12 days and later drying to 11% (w.b) resulted in lower values of potassium leaching and electrical conductivity and, consequently, greater integrity of the cellular membrane system of the beans compared to coffee subjected to continuous drying to 11% (w.b).

Afonso *et al*. (2003) studied the shrinkage evaluation of different coffee berries during the time of drying process. They concluded that moisture content in the coffee berries affects its physical properties causing significant decrease in the superficial area, volume and diameter during the drying process. Different variety of coffee has different shrinkage behaviour. The shrinkage behaviour during the drying process was well explained by a polynomial model with a coefficient of determination greater than 90%.

3.1 Sun drying or Natural Drying

Fresh coffee cherry assuming with a 4 to 6 cm layer ($25\text{-}30 kg/m^2$) in the sun requires energy up-to the extent of about 17000 kJ/kg according to FAO research. Removal of fruit tissues in the pulping step of wet-processing reduces this energy requirement by mechanically removing water and by removing tissues that inhibit water loss. However, the decision as to which processing system to apply is much more complex than mere consideration of drying efficiency. It depends from place to place. Previously it was considered that sun dried green coffee are the best in quality but now a days increase in the production and as a seasonal crop it is very difficult to go for only sun drying method. Researches also proved that mechanically dried and the sun dried coffee both gives to some extent same quality. There are different types of sun drying method (Fig 3.1).

Drying ground is another mode of natural drying. Here the yard is usually made of concrete, tiles or asphalt with a small slope (0.5-1%) to drain water. Depending on climatic conditions, sun drying of coffee in patios takes from 7 to15 days for parchment and from 12 to 21 days for cherries. Parchment requires more careful handling than cherry to avoid cracking and physical damage to the beans. Raking must be gentler. In tropical areas parchment is often covered during the hottest hours of the day to avoid cracking caused by overheating.

Drying racks are used which makes the coffee clear and avoid contamination from the ground. Racks are also more exposed to wind; this helps remove saturated air which helps to shorten the drying time. Plastic sheds are light wooden or metallic structures with a plastic roof and walls. The flat floor is made of concrete or tiles like a patio. Transparent or translucid plastic creates a greenhouse effect that may raise the temperature 10-15°C. Fans may be used to help remove the saturated air. Drying procedures are similar to those in a patio except that coffee is permanently sheltered from dew and rain.

3.2 Mechanical Driers

In mechanical drying the beans are heated by the passage of hot air which also carries the moisture away. Temperatures must be monitored during natural and artificial drying. Coffee temperature should not exceed 40°C for parchment and 45°C for cherries. It is often thought that overheating can only occur in mechanical dryers. There are mainly 2 types of dryers, static and revolving. In revolving dryers, there are tray dryers with stirrer, vertical dryers and rotary dryers, cascade driers, column driers, and flex driers. In all the cases woods, coffee husk, other solid fuel, fuel oils, diesel, gases are used as the main fuel or energy sources. In case of mechanical dryers drying time varies from 20-60 hours according to the type of driers used. Different type of mechanical dryers are represent in Fig 3.2.

According to Cordeiro (1982) it can be concluded that drying air temperature of 50°C and 12 h of tempering is the best dryeration treatment for natural coffee. It results in a final moisture difference of 1.7 percentage points; almost 50% less than the difference obtained with the conventional drying method. Now a day's solar assisted dryer is also available. The combination of two driers or pre-treated sun dried sample is used for the final drying in mechanical dryers. The main disadvantage of the mechanical dryers are that the drying is not uniform.

Rolz *et al.* (1969) reported on the use of fluidized beds in the drying of coffee cherries. They found that the best quality coffee was obtained when drying was done in two stages, an initial period at a low temperature (20°C) followed by a longer one at a higher temperature (60°C).

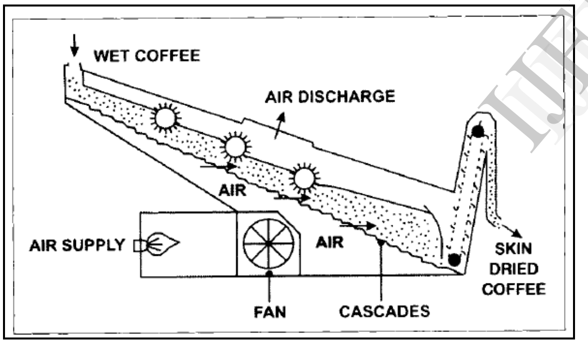
Some new technologies and dryers were invented for the better quality and uniform drying. S.S.S Coordinadora de Cafeticultores Yaxalwitz is an indigeneous corporative society of small coffee growers. They developed a solar coffee dryer with low cost and easy to handle dryer in the northern rainforest region of Mexico. It is very useful for the rainforest communities where money and material are hard to obtain.

Finzer *et al* (2001) conducted a study in Brazil with coffee berries. They developed a vibratory bed dryer for the drying of the berries and calculated the dispersion coefficient ranged from 2.32×10^{-4} to 76.81×10^{-4} m^2/s. The average Peelet number was equal to 6.5.

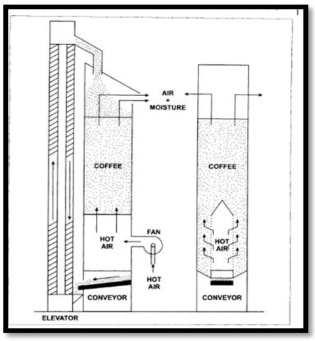
Reinato *et al* (2011) reported that quality of coffee, physico-chemical properties depends on the different types of grounds (earth, concrete and asphalt by products) used and the thickness of layers. Washed parchment coffee dried in thin layer on concrete and asphalt surfaces gave the best beverage quality.

Cunha M *et al* (2003) summarized that when compared to conventional drying processes the development process of microwaves to pulped coffee cherries production, to reduce the drying time and to increase the industrial yield and product quality was better. Two drying cycles were tested a) hot air drying conventional batch process using a rotary dryer from 45-50 to 11-13% (wb) moisture product b) a two stage process, whereby the product was pre dried with hot air from 45-50 to 30% (wb), followed by the final microwave and hot air drying stage, to reduce product moisture from 30 to 11-13% (wb). The overall drying time was reduced from 15 to 37.5 hours to about 10 hours, respectively. The sensory quality of the product was evaluated by the "cup test", complemented by scanning electronic microscope analyses (EMS) and showed satisfactory results. A preliminary study of the economic aspects involved in up-grading an industrial scale coffee processing line.

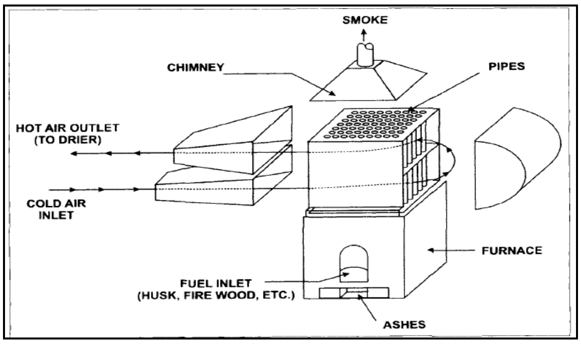
Fig.3.1 Different Types of sun drying method



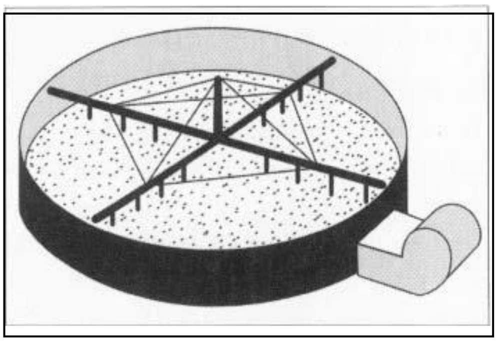
Cascade skin Dryer



Column Dryer



Combination of dryer (heat exchanger)



Rotary Dryer with Stirrer

Fig.3.2 Different Types of mechanical dryers

In a study assessing intermittent drying of parchment coffee, Martin S. (2009) combined 12 hours of drying with 50º C heated air and 12 hours of rest and observed a 24.56% reduction in effective drying time relative to continuous drying. Generally mechanical dryers are used in the coffee industry in the second stage of drying. According to ICO in case of mechanical dryers for 1kg of sample vertical and horizontal dryers were taking 21.5 h to 10.2 h to reduce the moisture content from 30% (w.b) to 12% (w.b). Concurrent flow dryers were taking 7-5h to reduce the moisture content from 25% (w.b) to 12% (w.b) and combination of concurrent and counter current dryer took 22.5 h to 12.5 h to reduce the moisture content from 35% (w.b) to 12% (w.b).

Isquierdo et al. (2011), also studying the drying of parchment coffee, observed that interrupting the drying process when the moisture content is 24% (wet basis, wb) with a rest period of 2 to 12 days and later drying to 11% (wb) results in lower values of potassium leaching and electrical conductivity and, consequently, greater integrity of the cellular membrane system of the beans compared to coffee subjected to continuous drying to 11% (wb).

Very few reports for drying of green coffee beans were found. Heat and mass transfer during drying of green coffee (Nilnont *et al*., 2012; Burmester and Eggers, 2010; Hernandez-Diaz *et al*., 2008; Perez-Alegria and Ciro-Velasquez., 2001) and coffee cherries (Sfredo *et al*., 2005; Varadharaju *et al*., 2001) have been reported by few researchers.

According to Correa *et al* (2006) different temperature variation affected the drying kinetics of coffee berry. Coffee berries were dried at 40°, 50° and 60°C. It was concluded that the Verna and Page model represented the best coffee fruit drying phenomenon. The effective diffusivity was calculated according to Fick's second law and the diffusivity coefficient for coffee fruit were found as 2.91 x 10^{-10} , 3.57 x 10^{-10} and 4.96 x 10^{-10} m^2/s for the drying air temperatures of 40°, 50° and 60°C respectively.

Correa *et al* (2010) summarized the change in physical properties with and without parchment in coffee beans. For drying of coffee four different temperature levels (20, 35, 45 and 55^{0}C) and five different relative humidity levels (30, 40, 50, 60 and 80%) was selected. There was no change in the desorption isotherms. True density was higher for the parchment coffee but when the moisture content increased it was similar for both of the sample. In case of bulk density and porosity, it was higher in parchment coffee than without parchment.

Limited studies have been reported on moisture diffusivity of coffee bean (Varadharaju et al., 2001; Hernandez-Diaz et al., 2008). Varadharaju et al. (2001) reported that moisture diffusivity of coffee cherry can be expressed by an Arrhenius type function of temperature. Hernandez-Diaz et al. (2008) reported average effective moisture diffusivity as a function of moisture content and temperature. Varadharaju et al. (2001) reported moisture diffusivity of coffee cherry to be within the range of 8.78–10.00 × 10^{-10} m^2/s for drying of 40^{0}C, 50^{0}C and 60^{0}C which is within the range of 4.63–10.75 × 10^{-10} m^2/s found in the study reported by Hernandez-Diaz et al. (2008). The average value of the study was 7.17 ×10^{-10} m^2/s according to Hernandez-Diaz et al. (2008).

According to Correa et al., (2006) activation energy for coffee fruit drying is 22.61kJ for temperature range 40^0-60^{0}C. Oliveira et al.,(2011) reported that activation energy required for coffee berry drying is in the range of 36.22-39.31 kJ/mol for relative humidity of (55-25)%.

Application of a solar tunnel dryer for coffee drying was reported by Amir et al.(1991) that consist of a centrifugal blower, solar air heater and a tunnel drying chamber. The tunnel (width 2 m) and solar collector (width 1 m) were attached side by side and measured 20 m in length. The air was initially heated in the collector and the flow was channeled back into the tunnel through a U-shaped duct at the end of the drying unit. Drying temperatures of 40 – 60°C can be achieved by adjusting the air flowrate from 400 – 900 m3/hr. Fermented coffee beans of 500 – 600 kg were loaded into the dryer and it took 50 hours to reach the final moisture content below 125 while sun drying required 75 hours. Consumption of electrical energy was 41.7 Wh/kg dry material or 5.0 kWh/drying batch.

Abdullah et al. (2001) develop prototype of a greenhouse effect (GHE) solar dryer and tested it performances for various crops including coffee .The GHE unit consisted of several important components such as the radiation absorber, heat exchanger (two units with 100 W blower attached), the auxiliary heating using hot water, air blowers (0.5 HP) and chimneys. To enhance thermal performance, a blackened steel plate was installed inside the structure either on the upper section or at both sides of the wall. Studies on coffee drying were carried out using UV stabilized plastic sheet (1.5 mm thick, 70% transmissivity) to form the GHE enclosure. The floor size was 6 m x 2.2 m with height 2.8 m. A wooden bin (3 m x 2 m x 1 m) was placed at the middle of the drying floor and loaded with 1.1 ton of wet coffee berries at 0.3 m depth. Results were obtained for the drying of Robusta coffee in this dryer. Drying efficiency was recorded at 57.4% as compared to conventional drying at 21.1% while specific energy was recorded at 5.5 and 11.6 MJ/kg water, respectively, in each method. Dying time was recorded at 58 hours in the GHE unit as compared to 70 hours in conventional drying.

4. PHYSICOCHEMICAL CHANGES DURING DRYING

Drying is important to decrease the moisture content from (45-50) % (w.b) to (10-12) % (w.b) and for the safe storage of the coffee beans for a long period of time. Researches have reported that the size and the dimension changes as a function of moisture content as size expansion is probably due to moisture absorption.

Amin *et al* (2004) stated that the thickness of lentil seeds increased linearly with increase in moisture content. A similar trend was also reported for the thickness and surface area of pistachio nut (Razavi *et al*, 2007a) and caper seeds (Dursum & Dursum, 2005).

Chandrasekar and Viswanathan (1999) reported coffee parchment size does not increase with an increase in moisture content even though the mass increased. The hard nature of coffee parchment contribute to its size being independent of moisture absorption.

In another study (Tharappan & Ahmad, 2006) concluded that coffee beans undergoing a monsooning process in India could increase 1.5 times of their original size due to moisture absorption. Ismail *et al* (2012) showed that in case of Liberica beans moisture content decreased but the size of the bean increases at the time of storage period of 8 months. The beans expansion is not because of moisture content but for some unknown factors.

Nelson (2005) from Research Department Coffee Industry Board Kingston, Jamaica reported in the study of using colorimeter as analytical technique for quality assessment of green coffee beans that colorimeter can easily detect the difference between green bean, greenish bean and whitish and pale beans. The L, a* and b* value obtained for the pure green bean is 51.29, 1.3, 5.19 respectively.

Ismail *et al* (2012) reported that the moisture content has a significant effect on the brightness of the beans. Brightness increases with the increase in moisture content and vice versa.

Sharma and Prasad (2001) concluded that retention of volatile components responsible for flavour was more in hot air microwave drying compared to conventional hot air drying alone. Nilnont et al., (2012) conducted a study of coffee drying at different temperature range (40^0,50^0,60^0C) and the overall acceptance is better for the coffee bean dried at 50^0 and 60^0C. Chuna Ml et al., (2003) studied final drying of coffee in microwave and reported that the cup testing result was good with mild flavour and slight astringency. Isquierdo et al., (2012) reported in case of sensory analysis moisture content of the bean at the interruption of drying did not have a significant effect on coffee quality. Beverage quality progressively improved with the increase in rest period.

5. CONCLUSION

The drying step in coffee processing is of critical importance for preserving the intrinsic quality characteristics of the coffee and for ensuring that food safety problems do not develop. In light of this, research institutions in coffee producing countries have spent time in the development of dryers that better suit the needs of the local industry. One institution that is heavily involved in such work is the Federal University of Viçosa (UFV) in Brazil. Few other institution throughout the whole world are doing research on the coffee drying process to obtain the safe storage moisture content with a good product quality.

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