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PORTO

PHYSICAL PROPERTIES OF COFFEE RELATED TO THE ROASTING PROCESS

by
Francesco Diaferia

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Thesis presented to *Escola Superior de Biotecnologia* of the *Universidade Católica Portuguesa* to fulfill the requirements of Master of Science in Food Engineering

by
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ABSTRACT

Roasting is one of the most important processes regarding the final quality and physical properties of coffee. This work was done with the aim of analyzing the change in the physical properties of coffee during the roasting process. More specifically, the variations of the orthogonal axes, the circularity, the sphericity, the mass loss and the surface and volumetric expansions of the coffee beans subjected to the roasting process were analyzed. The *Arabica* coffee variety was classified in shape and size using a sieve. The samples were then stored in polyethylene bags in refrigeration chambers at 18 °C to maintain the initial characteristics before roasting. After that, roasting was carried out at the temperatures of either 220, 240, 260, 280 or 300 °C over a period of 600 seconds. Specifically, the rotary cylinder direct gas firing roaster, used at 45 rpm, was held for 10 min at one of the respective roasting temperatures (220, 240, 260, 280, 300 ºC) in each case. The air temperature was measured by a type k thermocouple positioned inside the cylinder and controlled manually with a gas step valve. Five air temperatures were set inside the cylinder. The surface temperature was measured by an infrared thermometer (Testo 830-T1). The experiment was performed with 3 repetitions for each temperature and each sample. Every 20 seconds, 10 grams of coffee beans were taken from the roaster and measurements were taken using a caliper rule, in order to obtain the dimensions of the beans.

In general, the physical parameters analyzed were evidently affected by temperature, the impact being more significant at higher ones. Graphically, the differences in terms of distance between the thermal curves are shown on average starting from 400 seconds, to then stabilize at the end of the process. In general, the parameters of sphericity, circularity, mass loss, surface expansion and volumetric expansion show linear increases over time.

KEY WORDS: Roasting-Physical properties-Orthogonal axes-Temperature.

RESUMO

A torrefação é um dos processos mais importantes em relação à qualidade final e às propriedades físicas do café. Este trabalho foi realizado com o objetivo de analisar as alterações nas propriedades físicas do café durante o processo de torrefação. Mais especificamente, foram analisadas as variações dos eixos ortogonais, a circularidade, a esfericidade, a perda de massa e as expansões superficial e volumétrica dos grãos de café submetidos ao processo de torrefação. A variedade de café arábica foi classificada em forma e tamanho usando uma peneira. As amostras foram então armazenadas em sacos de polietileno em câmaras de refrigeração a 18 ° C para manter as características iniciais antes da torrefação.

Depois disso, a torrefação foi realizada nas temperaturas de 220, 240, 260, 280 ou 300 ° C durante um período de 600 segundos. Especificamente, a torrefadora a gás de cilindro direto, usada a 45 rpm, foi mantida por 10 minutos em uma das respectivas temperaturas de torrefação (220, 240, 260, 280, 300 ºC) em cada caso.

A temperatura do ar foi medida por um termopar tipo k posicionado dentro do cilindro e controlado manualmente com uma válvula de passagem de gás. Cinco temperaturas do ar foram definidas dentro do cilindro. A temperatura da superfície foi medida por um termômetro infravermelho (Testo 830-T1). O experimento foi realizado em 3 repetições para cada temperatura e cada amostra.

A cada 20 segundos, 10 gramas de café em grão foram retirados da torrefadora e as medições foram realizadas usando uma régua de pinça, a fim de obter as dimensões dos grãos. Em geral, os parâmetros físicos analisados foram evidentemente afetados pela temperatura, sendo o impacto mais significativo nos mais altos. Graficamente, as diferenças em termos de distância entre as curvas térmicas são mostradas em média a partir de 400 segundos, para estabilizar no final do processo. Em geral, os parâmetros de esfericidade, circularidade, perda de massa, expansão superficial e expansão volumétrica mostram aumentos lineares ao longo do tempo.

PALAVRAS-CHAVE: Torrefação-Propriedades físicas-Eixos ortogonais-Temperatura.

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I want to thank Universidade Católica Portuguesa for giving me the wonderful opportunity to be able to live this fantastic academic experience.
I would like to express my sincerest gratitude to my thesis advisor, Professor Ana Gomes, for her availability, humanity, patience, humility and professionalism.
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CONTENTS

1. INTRODUCTION

Coffee is one of the oldest products par excellence, related to a myriad of stories dating back to the last millennium and which has spread throughout the world in different extents. Worldwide, experts estimate that people consume around 2.25 billion cups of coffee per day. Arabia was responsible for the coffee culture propagation. The most ancient manuscripts mentioning the culture of coffee date from 575 in Yemen, but only in the XVI century in Persia, the first coffee beans were toasted to be turned into the drink that we know today (Neves1974).

Coffee began to be savored in Europe in 1615, brought by travelers. Germans, Frenchmen, and Italians were looking for a way of developing the plantation of coffee in their colonies. But it was the Dutchmen who got the first seedlings and who cultivated them in the greenhouses of the botanical garden of Amsterdam, a fact that made the drink one of the most consumed in the old continent and making it become a definitive part of the habits of the Europeans.

Later, the Frenchmen were given a plant of coffee by the mayor of Amsterdam, and they began to cultivate coffee in the islands of Sandwich and Bourbon (Neves 1974).

When we think about coffee, we tend to imagine it as an efficient energizer. However, the scientific community is pointing out some other important health benefits related to its consumption, such as a lower risk of liver cancer, type 2 diabetes, and heart failure.

Coffee is a good antioxidant as it is rich in polyphenols, it is often used as a digestive after meals, it has a very low caloric impact and it contains nutritional elements which are very useful to our body such as riboflavin, magnesium, potassium and niacin.

Beyond its nutritional properties, coffee encapsulates a history, that covers the eighteenth-century coffee period, the period of colonialism and slavery on coffee plantations, the period of economic expansion in Brazil due to large exports of coffee, up to the present day dominated by the huge multinational coffee companies like Caribou Coffee, Coffee Beanery, Starbucks Coffee, McCafe, Costa Coffee and Lavazza.

Coffee is one of the most consumed products in the world regardless of the culture we are considering as it represents a moment of socio-cultural union and it is therefore automatically associated with positive events in our daily life. For this reason, coffee is adequate in all circumstances and it is seen as a fuel to help face daily life.

Historically, coffee is mostly produced in Brazil, which has managed to increase the gross domestic product exponentially and consequently led to the absorption of a huge quantity of workers. Nevertheless, other major coffee producers are: Vietnam, Colombia, Indonesia, Honduras and Ethiopia. Before a cup of coffee is made, freshly harvested coffee berries have to undergo various processes in the post-harvest operation. Then, the coffee beans will undergo roasting, grinding, packaging and transportation processes, which require knowledge of basic physical properties data of the coffee beans.

Hence, the basic information on physical properties of coffee berries and the green coffee beans are crucial in the design of the coffee processing machinery, and in the development of a mechanised coffee processing system (Ghosh & Gacanja 1970). The coffee berries' size, density, and crushing strength are important in classification of berries, and also in the design of a pulper. In designing the handling system, grading and hulling of coffee beans, the information on size, friction, angle of repose, crushing strength and bulk density is crucial (Chandrasekar & Viswanathan 1999).

1.1 COFFEE PRODUCTION AND EXPORTATION

Coffee is nowadays produced in a large number of countries worldwide..

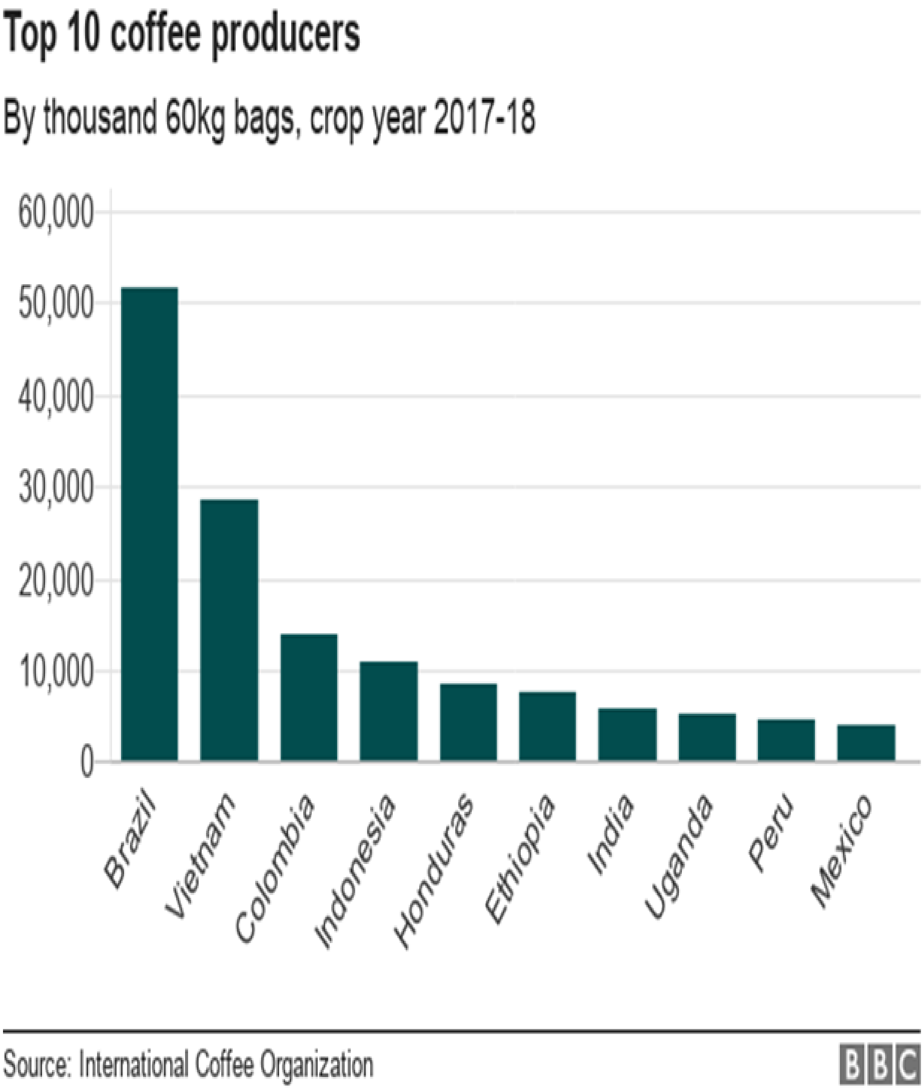

Image 1.1. Production of coffee (in thousand 60 kg bags) by the top ten producers in the year 2017-2018. (BBC, 2018)

Nevertheless, the ten largest coffee-producing countries are responsible for approximately 80% of the world production.

Of this percentage, South America participates with around 43%, Asia with 24%, Central America 18%, and Africa with 16%. Brazil, Vietnam, and Colombia are respectively the first, second, and third largest world producers, responsible for more than half of the world supply of coffee. Despite these several coffee-producing countries across continents, this section will focus essentially on coffee production in Brazil. Indeed, Brazil is currently considered a world leader in the field of agricultural exports and especially in the production of coffee; the Brazil Coffee Annual (May 2019) reports a production of 59.30 million 60-kg bags, a 5.5 million bags drop compared to record historical production in the former season (64.8 million bags).

In spite of good weather conditions in the majority of growing regions, Arabica coffee trees are mostly in the off-year of the biennial production cycle, thus producing less. Coffee exports for 2018/19 are estimated at 39.72 million bags, reaching again historical export levels, due to large production levels and steady competitiveness of the Brazilian product.

The main Brazilian coffee producing states are: Minas Gerais, Sao Paulo, Paraná, Espirito Santo, Bahia and Rondônia. *Cofea arabica* production is concentrated mainly in Minas Gerais, São Paulo and Espírito Santo, and this state is also the major producer of *C. canephora* of the conilon variety (popularly called Robusta). Brazil is the largest coffee producer in the world with an estimated production for 2015, between 44.11 and 46.61 million bags of 60 kg of processed product, with 73.7% corresponding to the Arabica species and the rest to the Robusta species.

This estimate represents a reduction of 2.7% and a growth of 2.8%, respectively, when compared to the production of 45.34 million bags obtained in the previous crop (CONAB 2015).

Regarding the exportation, the quantity of coffee worldwide exported has been on average at 90.0 million bags of 60 kg per year, with Brazil leading exportations with a share of 28% of this market (Solange I., Mussatto et al., March 2011).

One variable driving coffee production and consumption is price. Today, the price for a pound of commodity coffee is set in the stock exchanges of New York City and London, where the beans are traded. This makes the price prone to sudden spikes and dips (Bacon et al, 2008).

Green bean coffee price crises are not uncommon. In the 1960s, the International Coffee Organization created a series of regulations, known as the International Coffee Agreements, or the ICAs, to help prevent such price fluctuation, including export quotas, which restricted how much coffee a single country may export, so as not to flood the market and cause a price crash (Bartels, 2009).

In 1989, however, these agreements broke down, and the standing ICA was dissolved. The dissolution of the ICA had many effects on the coffee market. Without export quotas, coffee-producing countries almost immediately flooded the market and the price per pound plummeted below production costs (Bacon et al, 2008).

A series of coffee price crisis followed, from 1999 to 2005, corresponding with a rise in production in Vietnam and Brazil, as well the introduction of a new technology that allowed for the use of poorer quality coffee beans without significantly reducing cup coffee quality. Also following the dissolution of the ICA, the percentage of profit received by producing countries dropped from 20% to 13% over the course of the 1980s.

Because production takes place for almost 100% in 57 tropical developing countries and consumption for some 75% in 43 developed ones, international trade is an essential linkage of the coffee chain. The major importers of coffee are the United States, Germany, Japan and France with shares of 25, 19, 8 and 6% respectively.

Major exporters are Brazil (29%), Vietnam (15%), Colombia (11%) and Indonesia (7%). This implies the presence of concentration ratios (biggest four) of 0.58 for both importing and producing countries.

But if we put the two trading blocks EU (25) and US together, they will count for almost three quarters of all coffee imports. Mention should also be made of re-exports by importing countries, which have been increasing continuously from about 19% of the total exports in 1999 to 30% in 2005.

Countries like Germany and the US rank fourth and seventh as exporters. A considerable part of their exports are processed coffees. For 2004 and 2005 almost all (93%) of the re-exports from the EU to non-EU destinations were decaffeinated, roasted and soluble coffees. This has increased the value added share of re-exports compared to exports (Pelupessy, 2007).

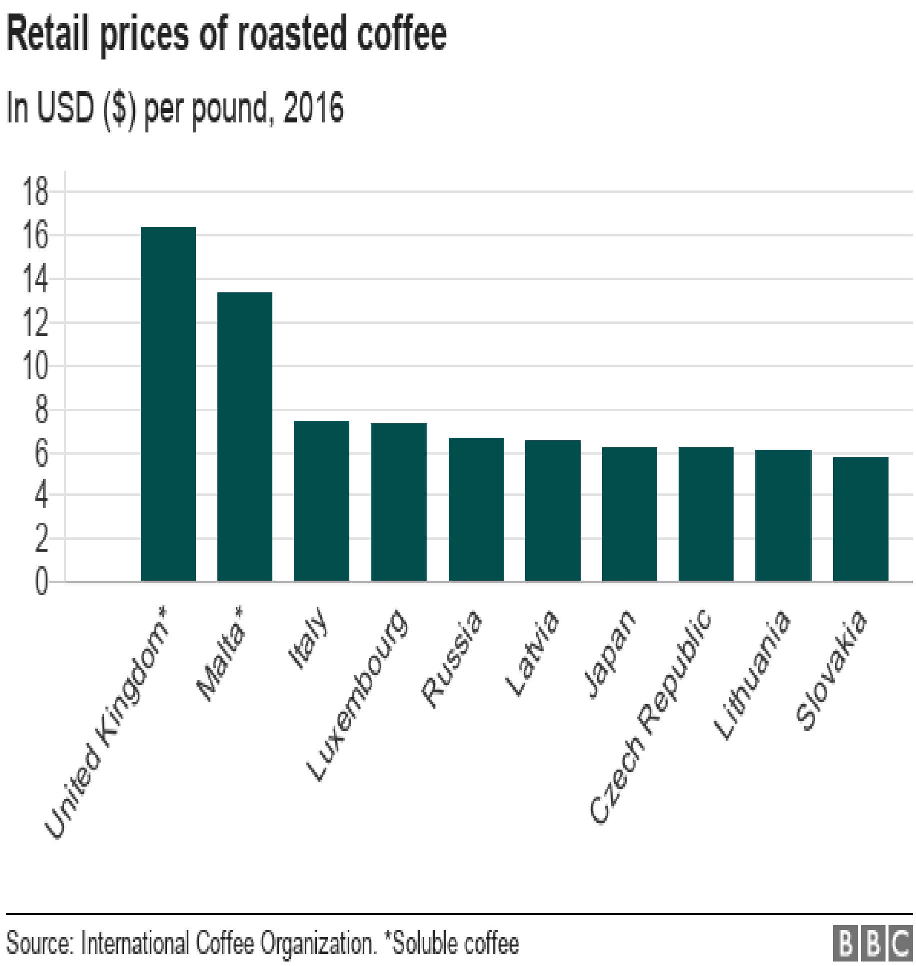

Image 1.2. Retailed price of roasted coffee in USD per pound (BBC, 2018)

1.2 THE COFFEE PLANT

When we talk about any type of coffee plant, we always return to the large Rubiacae family, which includes more than 100 diploid species (with the exception of *Coffea arabica* which is allotetroploide instead). Both from an economic and commercial point of view, the two most important species are certainly the *Coffea arabica*, the *Coffea canephora* (better known as Robusta).

Arabica (Coffea arabica):

Coffea Arabica is the most appreciated in terms of quality, opening a range of well-known varieties such as "Bourboun" and "Typica".
It is often appreciated for its aromatic characteristics, its aftertaste and slight bitterness. The Coffea Arabica plant is generally composed of dark green oval leaves and has the ability to self-pollinate (autogamy).

Image 1.3.
Plant of *Coffea Arabica*
([https://it.wikipedia.org/wiki/Coffea_arabica)](https://it.wikipedia.org/wiki/Coffea_arabica)

They are evergreen shrubs or small trees that may grow 5 m tall when unpruned. The leaves are dark green and glossy, usually 10–15 cm (4–6 in) long and 6 cm (2-4 in) wide.
The flowers are axillary, and clusters of fragrant white flowers bloom simultaneously and are followed by oval berries of about 1,5 cm. Green when immature, they ripen to yellow, then crimson, before turning black on drying. Each berry usually contains two seeds, but 5–10% of the cherries have only one; these are called peaberries. Cherries ripen in seven to nine months (G. Mastronardi, 2011-2012).

Image 1.4 *Coffea Arabica* flowers

(https://en.wikipedia.org/wiki/Coffea_arabica)

Image 1.5 *Coffea Arabica* fruit

(https://en.wikipedia.org/wiki/Coffea_arabica)

Robusta (Coffea canephora):

Coffea Robusta has a less sweet taste that is often mitigated by chemical aids and is used more frequently in powdered coffee blends.
It is more resistant to diseases and is already growing at an altitude of 700 meters above sea level even in hostile weather conditions.
This species is very common in the western region of Africa, in Vietnam, in Indonesia and in some areas of Brazil.
The species Coffea canephora is cross-pollinated and the cultivars are propagated by seed. Genetic selections are aimed at increasing yield and quality. Robusta requires warm and humid climates, with averages around 25 °C and never below 10 °C and rainfall of at least 2000 mm. In general, coffee requires deep and draining, fertile and slightly acid soil (pH 5-6) with at least 2% organic material. (Domaschi, 2012).

The flowers are white and have an average of 5 petals or slightly more. The flowers can be fertilized only through pollen that comes from other specimens, unlike the Arabica species which is able to pollinate itself. The fruits are drupes of red color and elongated inside which there are two seeds wrapped in a silver film and enclosed in a membrane.

Image 1.6 *Coffea Canephora (Robusta)* flowers
(https://en.wikipedia.org/wiki/Coffea_arabica)

Image 1.7 *Coffea Canephora (Robusta)* fruit
(https://it.wikipedia.org/wiki/Coffea_canephora)

1.3 COFFEE PROCESSING

Coffee cherries are the raw fruit of the coffee plant, which are composed of two coffee beans covered by a thin parchment like hull and further surrounded by pulp. These cherries are usually harvested after 5 years of coffee trees plantation and when the bear fruit turns red (Arya and Rao 2007).

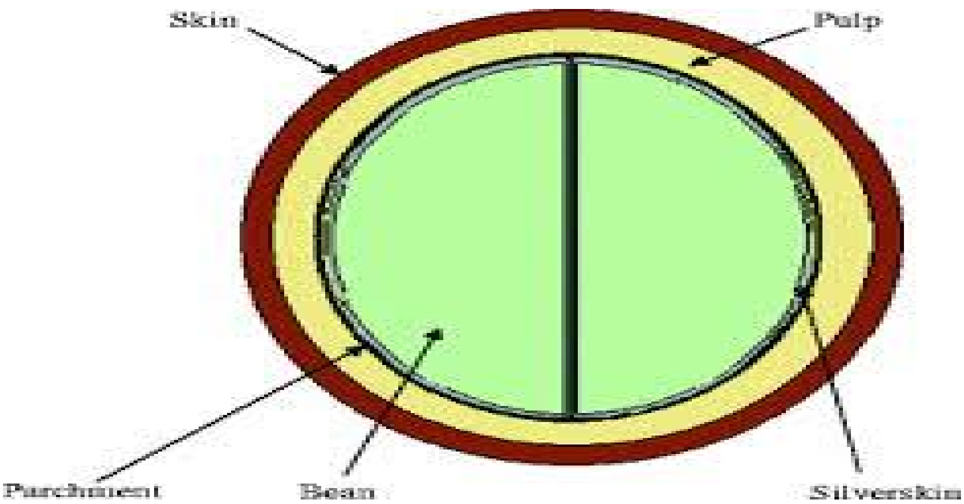

Image 1.8 Longitudinal cross section of the coffee – cherry (adapted from https://www.slideshare.net/zohaibkhan404/coffee-63469648)

The processing of coffee initiates with the conversion of coffee cherries into green coffee beans, and starts with the removal of both the pulp and hull using either a wet or dry method. Depending on the method of coffee cherries processing, i.e., wet or dry process, the solid residues obtained have different terminologies: pulp or husk, respectively (Pandey et al. 2000).

The choice of the method of coffee processing greatly impacts the profitability of coffee production and depends on several factors, such as climatic conditions; capital availability; technology and equipment; consumer-market requirements regarding product characteristics; water availability; and technology for the treatment of wastewater (Malta, 2011).

The final quality of the coffee produced is directly influenced by two decidedly relevant phases: processing and drying.

Processing is an operation carried out after the drying of the coffee and constitutes the separation of beans, bark and impurities by peeling the coconut coffee and separating the bark and parchment, thereby eliminating most of the impurities. This procedure must be conducted correctly and carefully, otherwise impurities remain in the middle of the processed beans which is considered a defect and adversely affects the classification of the coffee by type (Silva; Alves, 2013).

The fruits can be processed in two different ways immediately after harvesting: the wet method and the dry method. Wet preparation is the process by which, after passage through washers, the exocarp and/or mucilage of the fruit is removed, reducing the risk of fermentation and allowing faster drying, which generally results in good quality (Malta, 2011).

Wet preparation is a common practice among producers in Mexico, Colombia and Kenya, but in Brazil, a little pulp is still used. This method is recommended for areas where the post-harvest period occurs under conditions of high relative humidity (Nogueira; Roberto; Sampaio, 2014).

Traditionally, pulping is carried out via spontaneous fermentation in concrete tanks, removing the remaining mucilage adhered to the parchment as it is a suitable substrate for the development of microorganisms that can cause fermentation, which is detrimental to the final quality of the product. The coffee remains in these tanks with water for a period of 12 to 36 hours to eliminate the mucilage.

After this period, the beans are washed until no sign of this mucilage is detected, and then the beans are dried (Malta, 2011; Chalfoun; Fernandes, 2013; Nogueira; Roberto; Sampaio, 2014).

In the semi-wet process, the ripe fruits are mechanically husked, and part of the mucilage remains adhered to the fruit parchment. This operation is performed on husking machines based on the difference in resistance to pressure of green fruit and ripe fruit (Malta, 2011).

After pulping, demucilation is carried out in demucilating machines in order to remove the mucilage that remains adhered to the beans. The removal is mechanical and occurs due to the friction between beans and between beans and the metal cylinder. In this apparatus, water is added in small quantities for lubrication and cleaning of the mucilage (Malta, 2011).

The main advantage of using this equipment is the removal of part of the mucilage without using fermentation tanks; besides facilitating the work of movement and drying in the yard, by this method, the beans do not form agglomerates as they do in the pulped natural cherry process (Alves, et al., 2013). In the dry preparation, the coffee cherries are completely dried in yards or on patios, with pre-dryers or mechanical dryers, without the removal of the bark, giving rise to coconut coffee.

While this type of preparation is the most commonly used for Brazilian coffee, wet preparation has been considered a viable alternative to obtain coffee of higher quality (Alves et al., 2013; Nogueira; Roberto; Sampaio, 2017).

Regardless of the process used, after harvesting, the coffee fruit must be processed and spread in the shortest possible time. The fruit must never be crowded or remain in the carts, waiting for discharge, since humidity and temperature conditions in the coffee mass are highly favourable to the development of microorganisms that accelerate the fermentation process (Pimenta et al., 2008; Angélico, 2011).

Coffee beans are conventionally stored in jute bags that have the capacity to hold 60 kg of processed coffee. Storage in big bags, which have the capacity to hold 1,200 kg of coffee, has the advantages of adaptation to mechanized handling, reduction of losses associated with the loading and unloading of the coffee, and reduction of the labour required. An additional way to store coffee is bulk storage, which does not use bags, with the coffee being stored in silos or bins (Borém, 2014). On the dry process, after being washed and separated by density, the coffees are sent separately to the yards where they are fully dried.

Excellent quality coffee can be obtained as long as drying is conducted properly.

In the wet process, in turn, it is necessary to conduct the pulping mechanically or through fermentation and drying, so as to minimize the occurrence of defective grains.

The quality of water and the cleanliness of materials are equally relevant. Drying yards should have a smooth surface, be waterproof and hygienic. When drying, care for the coffee is extremely important - during the night it should be covered in the yard to avoid reabsorption of moisture. The maximum humidity in dry coffee is 12% (Gomes, 2014).

The pulp resulting from the wet drying process should be stored away from dry coffee as there is a possibility of microorganisms proliferating in the coffee pulp such as *Spindles spp*. and the *Colletotrichum Caffea. Aspergilos Niger, Penicilum spp* and *Rhizopus ssp*., Some candida yeast and *Saccharomyces* and some bacteria may also appear in a terreiro (Correia, 1990).

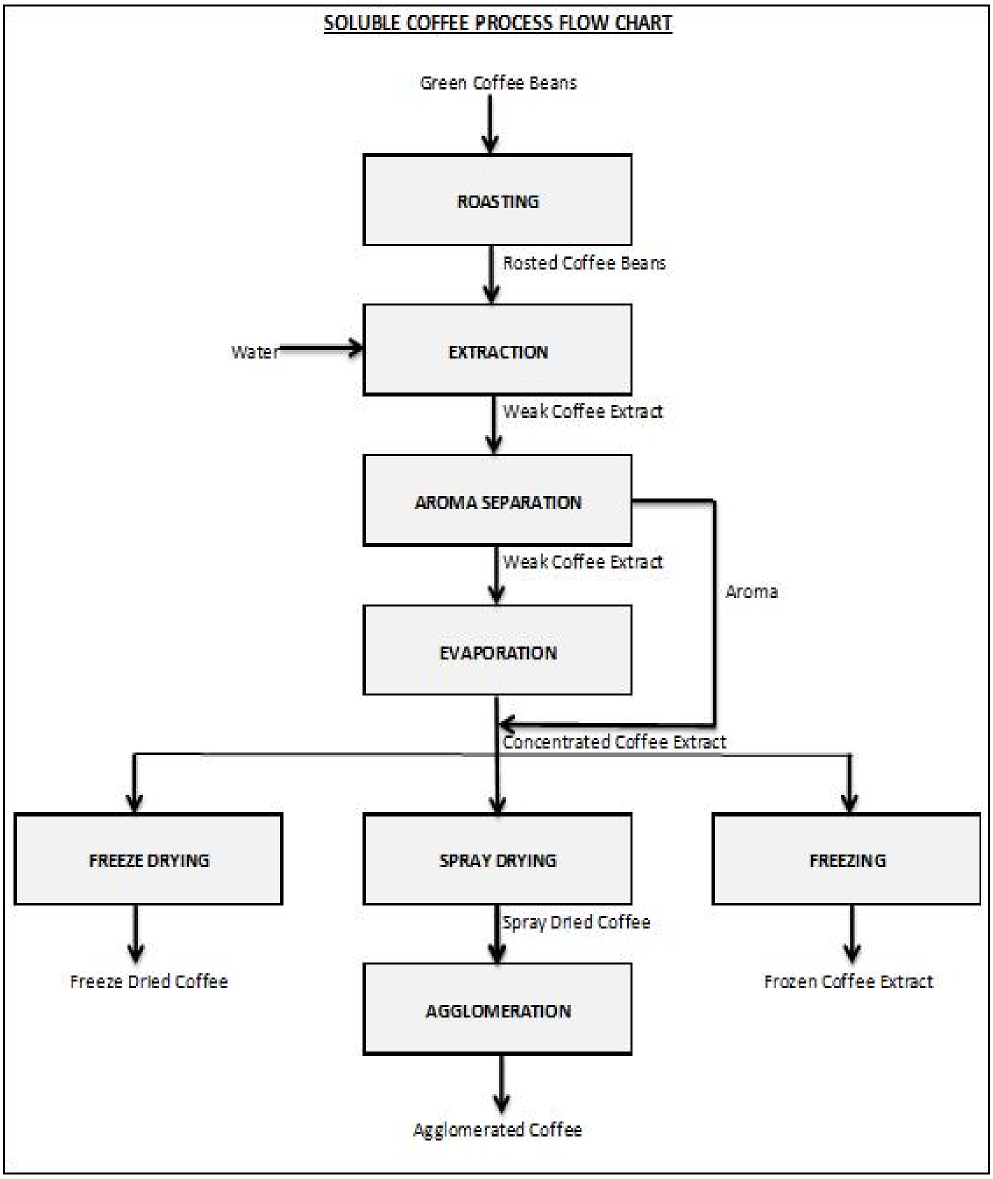

Image 1.9

Soluble coffee beans processing

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1.4 ROASTING

The roasting of coffee is a process that is considered to be of prime importance for the quality of the final product since this process consists of heating the beans at high temperatures, promoting physical and chemical changes in the beans, such as changes in colour and aroma (Putranto, C., 2012; Ruosi et al., 2012). Coffee bean roasting is indeed one of the most critical steps in coffee processing, since it controls quality and aggregated commercial value to the product. Green coffee beans provide neither the characteristic aroma nor flavour of brewed coffee until they are roasted. Moreover, the roasting process increases the value of coffee beans, by 100-300% of the raw material (Yeretzian et al. 2002). One example is Germany that is considered the world's largest re-exporter of coffee, importing predominant raw coffee from Brazil, Vietnam and Colombia and re-exporting roasted coffee mainly to the European market (OIC, 2013).

Roasting of coffee beans typically takes place at 200-240°C for different times depending on the desired characteristics of the final product. The final quality of roasted coffee is influenced by the design of the roasters and time-temperature profiles used. Although heat transfers during roasting can involve conduction, convection, and radiation, convection by far is the most important mode of heat transfer that determines the rate and uniformity of roasting (Baggenstoss et al. 2008).

Events that take place during roasting are complex, resulting in the destruction of some compounds initially present in green beans and the formation of volatile compounds that are important contributors to the characteristic of coffee's aroma.

This process is another very important step in coffee processing, since specific organoleptic properties (flavors, aromas, and color) are developed and affect the quality of the coffee and the excellence of the coffee beverage, as a consequence (Hernández et al. 2008; Franca et al.2005; Fujioka and Shibamoto 2008).

This process is time – temperature dependent and leads to several changes in the chemical composition and biological activities of coffee as a result of the transformation of naturally occurring polyphenolic constituents into a complex mixture of Maillard reaction products (Czerny et al. 1999; Sacchetti et al. 2009), as well as the formation of organic compounds resulting from pyrolysis (Daglia et al. 2000).

Sulfur compounds are also changed by oxidation, thermal degradation, and/or hydrolysis (Kumazawa and Masuda 2003), and the vanillin content increases considerably during the roasting process (Czerny and Grosch 2000). Besides the chemical reactions during coffee roasting, moisture loss and other major changes (color, volume, mass, form, pH,density, and volatile components) occur, while CO_2 is generated (Hernández et al.2008). Therefore, coffee roasting is a quite complex process considering the importance of the heat transferred to the bean (Franca et al. 2009).

After the roasting process, coffee beans should be rapidly cooled in order to stop exothermic reactions and to prevent excessive roasting, which might jeopardize the product quality (Baggenstoss et al. 2007; Dutraetal. 2001).

The roasting index of coffee grains can be measured by comparison with an end -point color standard. The Agtron Roast Color Classification System (Specialty Coffee Association of America – SCAA) assigned a number for each color according to grain reflectance in which the darkest level is classified as n° 25 and the lightest as n° 95 (ABIC, 2013).

The coloration is directly related to consumer preferences, which varies according to the region, customs and drink preparation.

According to the Brazilian standard, roasted beans can be classified between discs n° 75 and 45, which corresponds to the light and moderately dark roasting index, respectively (ABIC, 2013). Within this range, grains lose between 15 and 19% of mass during the process (França et al.; 2009; Moon et al.; 2009; Schwartzberg, 2011). Depending on the extent of heat treatment, coffee can be largely categorized as light, medium or dark roasts. Light roast process tends to give non-uniform bean color with sour, grassy, and underdeveloped flavour, while medium roast process produces a balanced taste and aroma with citrus flavour. By contrast, dark roast process produces coffee of low acidity sensory profiles (Lyman et al. 2003).

Physical characteristics such as temperature, color, and weight-loss are often used as indicators of roast degree.

However, these parameters only allow assessment of the flavour profile for coffee roasted under narrow process conditions (Sivetz 1991; Illy & Viani 1995). Roasting causes a net loss of matters in the forms of CO2, water vapor, and volatile compounds. Moreover, degradation of polysaccharides, sugars, amino acids and chlorogenic acids also occur, resulting in the formation of caramelization and condensation products.

Overall, there is an increase in organic acids and lipids, while caffeine and trigonelline (N-methyl nicotinic acid) contents remain almost unchanged (Buffo & Cardelli-Freire 2004).

The reaction products formed are highly dependent on the roasting time-temperature profile used. Excessive roasting produces more bitter coffee lacking satisfactory aroma, whereas very short roasting time may be insufficient to develop full organoleptic characteristics (Yeretzian et al. 2002; Lyman et al. 2003; Buffo & Cardelli-Freire 2004).

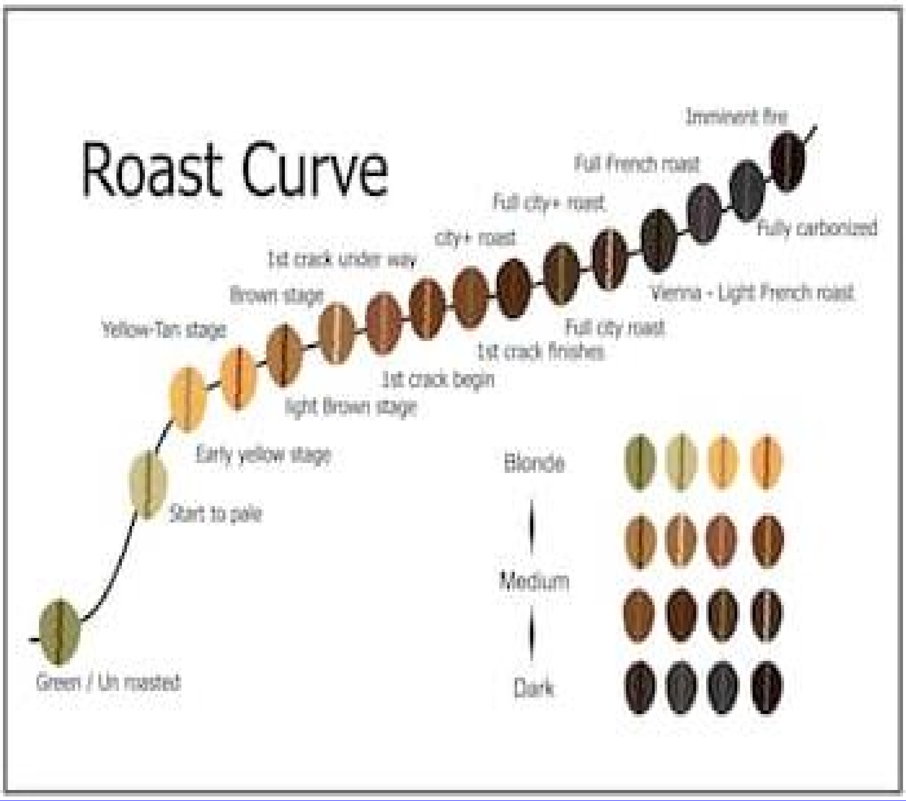

Image 1.10 Roast Curve

1.5 QUALITY OF COFFEE BEANS

The overall quality and chemical composition of green coffee beans are affected by many factors, such as the composition of the soil and its fertilization, the altitude and weather of the plantation, and the final cultivation and drying methods used.

Caffeine is the most known component of coffee beans. In raw Arabica coffee, caffeine can be found in values varying between 0.8% and 1.4% (w/w), while for the Robusta variety these values vary between 1.7% and 4.0% (w/w) (Belitz et al.2009). However, the coffee bean is constituted by several other components, including cellulose, minerals, sugars, lipids, tannin, and polyphenols. Minerals include potassium, magnesium, calcium, sodium, iron, manganese, rubidium, zinc, copper, strontium, chromium, vanadium, barium, nickel, cobalt, lead, molybdenum, titanium, and cadmium.

Among the sugars, sucrose, glucose, fructose, arabinose, galactose, and mannose are present. Several amino acids such as alanine, arginine, asparagine, cysteine, glutamic acid, glycine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, proline, serine, threonine, tyrosine, and valine can also be found in these beans (Belitz et al.2009; Grembecka et al. 2007; Santos and Oliveira 2001). Additionally, coffee beans contain vitamins from complex B - niacin (vitamin B3 and PP), and chlorogenic acid in proportions that may vary from 7% to 12%, three to five times more than the caffeine (Belitz et al.2009; Lima 2003; Trugo 2003; Trugo and Macrae 1984).

These fruit contain volatile compounds that are responsible for the characteristic flavour and aroma of coffee and are present at very low sensory values in green fruit, the values increasing gradually with maturation, with cherry fruit assuming optimal values (Pimenta et al., 2008). It has been observed that fruit in the cherry stage exhibit better drinking patterns as this phase corresponds to the ideal point of maturation of the fruit, in which the bark, pulp and seed have a suitable chemical composition, which leads to fruit of the highest quality. It should however be highlighted that the best type of beverage is produced from coffee cherries, provided that the fruit is properly processed; however, because crop concentration occurs at the same time, some growers tend to anticipate the coffee cherries when the percentage of green fruit is 5% higher than the recommended value (Chalfoun).

In addition, in the cherry stage, the coffee fruit presents a smaller detachment force, which facilitates harvesting (Silva et al., 2013; Santinato et al., 2015). Obtaining high maturation uniformity is a major challenge in the coffee sector and is a procedure that provides consistent quality.

Matching the species/cultivar to the best cultivation site followed by appropriate agricultural treatment has been shown to be decisive in the reduction of unevenness in maturation uniformity.

It is important to note that the climatic conditions in year of growth can change the number of flowering plants, which will directly affect the desired maturation uniformity (Pimenta et al., 2008).

The determination of the best time to harvest a majority of the fruits in the cherry stage, along with other factors, is essential for obtaining a coffee with adequate chemical composition and minor undesirable chemical modifications and detriments to the quality of the product.

1.6 ORGANOLEPTIC QUALITY OF COFFEE

The aroma profile of roasted ground coffee is related to the origin and variety of the beans. In general, blends with greater Arabica content tend to carry more fruity notes due to the aldehydes, acetaldehyde, and propanal, while the pyrazines give the earthy odor. In comparison, Robusta beans carry stronger “roasty” and “sulphury” note due to the presence of greater amount of sulphur-containing compounds (Sanz et al. 2002).

Thus, Arabica is often added for the aroma effect while Robusta is used for enhancing the body, earthy and phenolic notes of the coffee blend (Parliment & Stahl 1995).

Mazzafera compared the chemical composition of defective beans and non-defective beans. The researcher found that non-defective beans were heavier, had higher water activity, and lower titratable acidity than the defective beans. The content of sucrose, protein, 5-caffeoylquinic acid, and soluble phenols were also higher in non-defective coffee beans (Mazzafera 1999).

Nevertheless, the antioxidant level in the defective beans, especially chlorogenic acids, remains high which may be a good source of antioxidant or radical scavenger for other food applications (Nagaraju et al. 1997).

The definition of the quality of coffee as a beverage is quite broad, being dependent on the chemical composition of the beans, which is determined by genetic, environmental and cultural factors; harvesting, processing and storage methods; and roasting and preparation of the beverage.

To obtain superior coffee, harvesting care and post-harvest management have become fundamental for commercialization and to increase the coffee grower’s profit (Coradi; Borém; Oliveira, 2008; Santinato et al., 2015).

Therefore, it is essential that the harvested coffee be prepared and then subjected to drying to avoid fermentation processes, which will damage the quality of the beverage (Bozza et al., 2009; Compri et al., 2016).

The quality parameters of commercial Arabica coffee are evaluated according to commercial characteristics, namely:

a) Type of separation of defects and impurities;

b) Definition of the size of the coffee, separating a sample of beans by size and shape;

(c) organoleptic characteristics as assessed by expert evidence based on basic tastes: sweet, bitter, sour and salty;

(d) health-related nutritional characteristics assessing the chemical and nutritional compounds contained in coffee beans: alkaloids, mainly caffeine, trigonellin, antioxidants (chlorogenic acids), serotonins, vitamins and minerals totals (Gomes, 2014).

Quality factors are a necessity for consumers to set their price, so quality control of green coffee aims to obtain a commercial coffee, a quality drink and also seeks to ensure a high-quality processed product.

In obtaining green coffee, there are risks in various stages, from planting, harvesting, post - harvest processing of the fruit, to storage. Late harvest quality increases the quality of the ripe fruit as well as the incidence of black and burnt grains resulting from contact with the ground which gives rise to the action of microorganisms on the grains that are the worst defects in green coffee. This is also an economic detriment to the of the beverage.

Harvesting should be as short as possible, labor availability should ensure harvesting is completed within 6 months (Gomes, 2014).

Prolonging the harvest may increase the likelihood of rainfall occurring during harvesting and drying, thus increasing the risk of compromising quality.

The separation of the fruits by different densities allows two layers of coffee to be obtained: a denser layer containing mainly the ideal ripe fruits, and another layer consisting of lighter floating fruits, essentially the fruits that have dried on the plant and those with some abnormalities during its formation and ripening such as malformed and punctured fruits.

This uniformity operation is very important in pulping to decrease the quality of fragmented beans that also constitute a green coffee defect.

1.7 CUPPING

Coffee is a product that lends itself to differentiation. There is a wide diversity of flavors and aromas that emerge from different coffee growing soils and climates, tree varieties and cultivation and processing methods.
Flavors and aromas constitute the coffee 'sensory attributes' because they refer to quality aspects that are perceived by the senses. Similar to grapes, the genetic strain of the coffee plant and its unique adaptation to the environment profoundly influence the character of the final product (Arvidson, 2003; Davids, 2004). Coffee sensory attributes are evaluated through cupping which is the sensing of aromas, flavors and body through olfaction, gustation and mouthfeel, respectively (Lingle, 2001). Because of the shorter time required respect to instrumental methods and because it allows to determine coexisting characteristics, sensory analysis is most frequently used to estimate aroma, taste, and flavor of coffee brews (Nebesny and Budryn, 2006; Alvarado & Linnemann, 2010).
In coffee beverages, the presence of several hundreds of volatile compounds can make drastically difficult to find the correlation between single substances and sensory attributes (Sanz et al., 2002). Industries such as coffee, perfume, tea, and tobacco use trained panelists for descriptive analysis and expert tasters for flavor evaluation and quality control assessment process. Perceptive abilities such as the recognition of volatiles, can be enhanced in trained assessors or person that, having a reasonable sensory acuity and ability to focus their attention on specific sensory stimuli, are exposed to an appropriate series of products (Lawless, 1984). Lawless categorizes assessors that are not trained panelists in person having a longstanding experience with a specific product, more used for quality control, and persons who, as their profession, develop new products such as perfumers and flavor chemists.
These types of assessors can further be defined as persons that accumulate, year after year, wide knowledge about a specific product, and are involved in the decision-making process by companies (Gatchalian, 1981).
Professional coffee judges are widely used all over the world. These experts can be very sensitive to any change in the characteristics of the product

(Feria-Morales, 2002). However, the use of experts for this scope cannot always be a proper and complete evaluation tool.

Problems like bias, the influence of external factors, change in perceptiveness of the individuals, and the long time that can be necessary to develop this kind of professional figure, could discourage their use as sole evaluation tool.

Totally different can be the case using trained sensory panelists, whose utilization is increasing, for example, for a detailed evaluation of the raw materials following to a rapid initial assessment by the experts (Feria - Morales, 2002). At the same time expert coffee tasters like ‘cuppers’, trained to distinguish among small differences of coffee beverages, use a larger vocabulary than experienced untrained people.

Conventional sensory analysis of coffee using well-trained panelists tends as well to evaluate intrinsic quality characteristic and descriptors, trying to deconstruct coffee flavor contrarily to a holistic perception (Narain et al., 2003).

As previously mentioned, the most used method, now as well as in the past to evaluate coffee quality in the cup is called 'cupping'. The grading system developed by the Speciality Coffee Association of America (SCAA) includes a list of standard attributes, such as Body and Acidity, to be scored in order to describe the product. However, one of the problems in coffee evaluation by expert 'cuppers' is the lack of a common language and a consistent vocabulary.

This could help in better describing and comparing notes essential in discriminating among different coffee beverages beyond the main defects (Castle, 1986).

This phase may be a critical point during quality assessment of the products. Vocabularies (ICO, 2010) and handbooks (Castle, 1986; Lingle, 2001) have been developed to list terms that can describe sensory properties of coffee.

Often these vocabularies focus on trying to develop terms influenced by specific cultural and linguistic aspects in order to be also recognized by local consumers of a given country (Hayakawa et al., 2010; Seo et al.,2009).

1.8 PHYSICAL PROPERTIES OF COFFEE

Studying the physical properties of roasted coffee beans is important due to potential market conditions. Furthermore, only qualitative coffee quality evaluations through raw and organoleptic monitorization are not enough to describe the effects of harvesting and postharvest processing on quality of roasted coffee. Thus the knowledge of the descriptive physical quality analysis of roasted beans is recommended (Nebesny and Budryn, 2006).

Additionally, in recent years, the quest of knowledge regarding physical quality of roasted coffee is spreading due to the growing appreciation of coffee since, quality of coffee beverage is closely related to the physical appearance of the roasted beans, which, in turn, is affected by the composition of green beans and postharvest processing conditions (Franca et al., 2005a; Illy and Viani, 2005).

Physical changes in coffee during roasting include reduction in mass due to loss of moisture and decomposition of carbohydrates, increase in volume of coffee beans, lowering of density due to puffing and increase in brittleness (Mwithiga and Jindal, 2003; Noor-Aliah et al., 2015).

It is well known that during roasting, coffee beans lose their strength and toughness and become brittle and fragile (Pittia et al., 2007).

Such parameters like weight loss, volume change and density can be used to control the coffee bean roasting quality (Schenker et al., 2000; Pittia et al., 2001; Alessandrini et al., 2008). In terms of volume Franca et al. (2005a) demonstrated that the volume increase of non-defective beans was higher than for black beans.

The total weight loss of green coffee beans after roasting can be one of the criteria for determining the degree of roasting (Jokanovića et al., 2012) and measure the efficiency of green bean preparation.

Bulk density changes are implied in bean expansion and in the formation of a characteristic porous structure of the roasted coffee bean (Pittia et al., 2001).

Structural characteristics (defined by heat treatment) can directly affect the physicochemical, functional, technological and even nutritional properties of food products (LAVERSE et al., 2012). Roasted coffee at higher temperatures has greater volumetric expansion and larger pores, facilitating oil migration and oxidation during storage (Schenker et al., 2000; Geiger, 2004) facts that contribute to decrease the quality of beverage. Around 15% of grain is related to dry matter content and higher values of this property reflect in better quality grains. Structural characteristics (defined by heat treatment) can directly affect the physicochemical, functional, technological and even nutritional properties of food products (LAVERSE et al., 2012). The expansion mechanism can be studied as a balanced process between the formation of gas (water vapor and CO2) as the driving force, and the state transitions of the cell wall material as the resistance force (GEIGER, 2004).

Schenker (2000) studied the transitions from vitreous to elastic state during roasting, finding that the grain remains longer in the elastic state during roasting at high temperatures, which contributes to the greater expansion capacity under these conditions.

According to Pittia et al. (2001), the increase in coffee volume during the roasting can be quantified by measuring its three main axes. One of the ways to evaluate the transformations occurred is through mathematical modeling, which is very important for data prediction.

This evaluation through modeling can provide parameters used for the study of heat and mass transfer during drying processes; for sizing roasters; besides allowing greater practicality regarding the prediction of the quality of the final product.

2. GENERAL OBJECTIVE

Based on the rationale described above, the main objective of this research work was to analyze the physical properties of coffee beans during the roasting process in order to assess its impact on coffee bean quality.

2.1 SPECIFIC OBJECTIVES

The major objective will be fulfilled by developing a set of specific objectives based on the analysis of the variations of the following physical properties during roasting:

- Variations of the axes a, b and c,
-Sphericity,
-Circularity,
- Mass loss,
-Volumetric expansion,
-Surface area expansion;

3. MATERIALS AND METHODS

This work was developed at the Laboratory of Physical Properties and Quality of Agricultural Products belonging to the National Center for Training in Storage (CENTREINAR), located on the campus of the Federal University of Viçosa (UFV), Viçosa - Minas Gerais (MG).

3.1 RAW MATERIAL:

Coffea arabica sieved coffee beans, above the size of sieve 18, were used, derived from a coffee processing plant located in Viçosa, Minas Gerais.
The grains were submitted to a previous classification (manual) in order to remove impurities such as broken husks and grains. After this process, the flat grains were separated from the maize by the use of plaques. The beans were separated by shape and size due to the shape and size of their sieves.

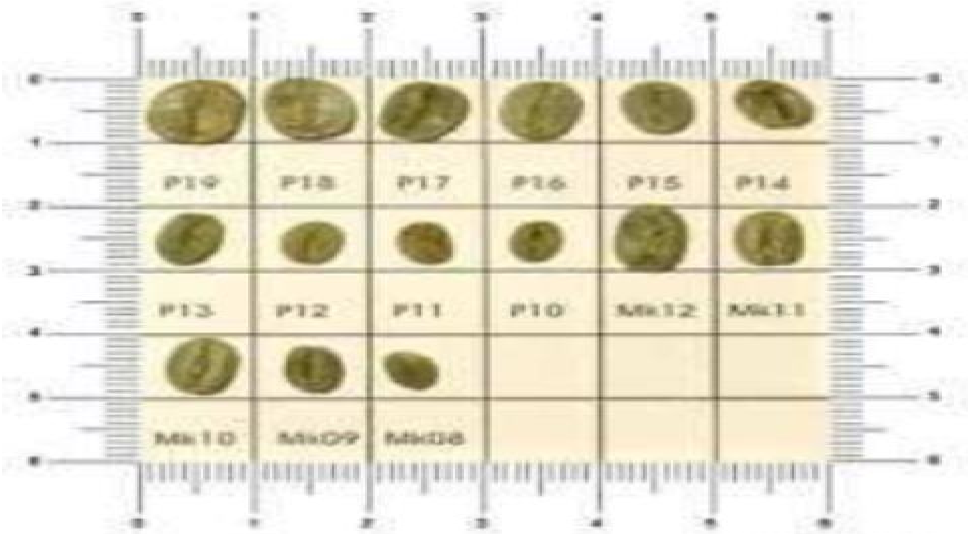

Image 3.1
Size of sieves used for sieve separation
(Unicafé, 2004)

The samples were placed in polyethylene bags and stored in a temperature controlled chamber at 20 ºC. For the roasting process, the samples were taken from the chamber and exposed to the environment for approximately 12 h to achieve thermal equilibrium and minimize variations related to the initial temperature and maintain the initial characteristics until the roasting process.

3.2 ROASTING PROCESS

250 grams of mocha coffee (ovoid) were exposed to the environment for a period of 12 hours in order to reach a thermal balance.

After that, roasting was carried out at the respective temperatures of 220, 240, 260, 280, 300 ºC over a period of 600 seconds. Specifically, the Roaster was held for 10 min at one of the roasting temperatures (220, 240, 260, 280, 300 ºC) in each case.

A rotary cylinder direct gas firing roaster at 45 rpm was used. The air temperature was measured by a type k thermocouple positioned inside the cylinder and controlled manually with a gas step valve. Five air temperatures were set inside the cylinder.

In the literature Shenker (2000) defined a range of optimal temperatures (220 up to 260 ºC) for light, medium and dark roasting levels respectively. The beans were roasted in a unitary way and were held in the center of the drum by the thermocouple.

Convection and radiation were the types of heat transfer that dominated the process. The roasting time was set at 600 seconds to ensure the dark roasting level for all temperatures.

Image 3.2 A *Drum Roaster*
(https://beans.at/en/kaffeewissen/kaffeeroestung/kaffeeroestvorgang)

The surface temperature was measured by an infrared thermometer (Testo 830-T1). The experiment was performed in triplicate for each temperature and each sample. Every 20 seconds 10 grams of coffee beans were taken from the roaster and measurements were taken using a caliper rule, in order to obtain the dimensions of the beans.

They have a concave, round and a straight phase. So we obtained the 3 measurements: *a, b* and *c* respectively. Through these measurements it is possible to calculate the volume, surface expansion, sphericity and circularity.

3.3 VOLUME

The coffee beans volume was determined by approximating the shape to a semi-ellipsoid and measuring the axes a, b and c (Mohsenin, 1986) (Equation 3.1) with a 0.01 mm precision digital caliper. The unit volume of 10 beans was determined before roasting and after each time interval of 20 s and then the volumetric expansion index (ψ) for each (Equation 3.2) was calculated. Finally, the average index of the 10 beans for each time interval was calculated.

$$V = \frac{\pi abc}{6} \quad 3.1$$

$$\psi = \frac{V_f}{V_0} \quad 3.2$$

In which:

a, b and *c* = Length of orthogonal axes (m);

V_f = Beans volume at the end of the time interval (m^3);

V_0 = Beans volume before roasting (m^3).

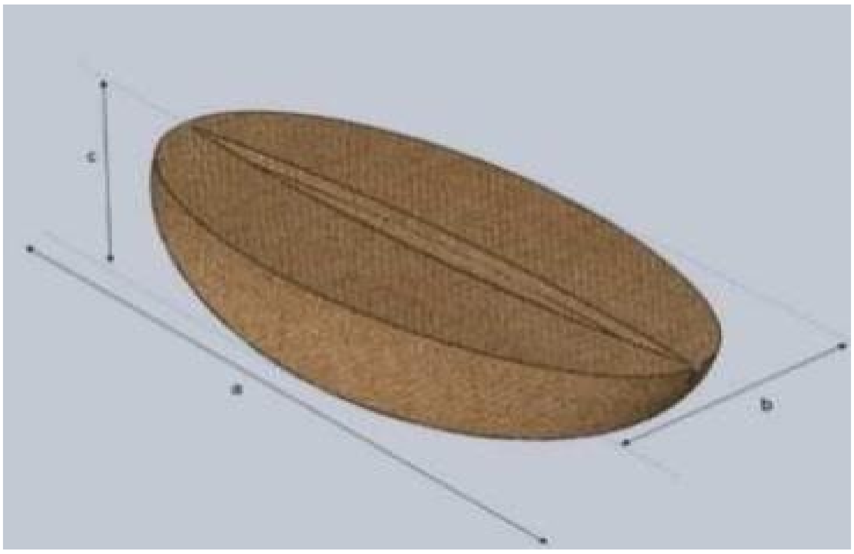

Image 3.3

Geometry of the coffee bean

(Bustos Vanegas,2015)

3.4 COFFEE BEANS SURFACE AREA

The coffee beans surface area was determined using the model cited by Mohsenin (1986) (Eq. 2.3), measuring the axes a, b and c with a 0.01 mm precision digital caliper.

The unit surface area of 10 beans was determined before roasting and after each 60 s time interval and then the surface expansion index (ΔS) (Equation 2.4) was calculated. Then the average index of the 10 grains for each time interval was calculated.

$$A = \left[\left(\frac{\pi B^2}{2} + \frac{\pi a B}{2e}\sin^{-1} e\right)/2\right] + \left(\frac{\pi a b}{4}\right) \qquad 3.3$$

Where:

$B = (2bc)^{1/2}$; $e = \sqrt{1 - \left(\frac{B}{a}\right)^2}$

and

$$\Delta S = \frac{A_f}{A_0} \qquad 3.4$$

In which:

A_f = Coffee beans surface area at the end of the time interval (m^2)

$A_{0=}$ Coffee beans surface area before roasting (m^2)

a, b and c = Characteristic dimensions of coffee (mm).

3.5 MASS LOSS

The coffee beans mass was determined on an analytical balance of 0.001 g accuracy. The 10-bean unit mass was determined before roasting and after each 20 s time interval and then the mass loss (RL) (Equation 2.5) was calculated.

$$RL(\%) = \frac{m_0 - m_f}{m_0} x100 \quad 3.5$$

In which:

RL = mass loss (%);

m_0 = initial mass of the bean (g);

mf = mass of the beans at the end of the roasting time interval (g).

3.6 SPHERICITY AND CIRCULARITY

The mocha bean was approximated to an ellipsoid (Figure 2.4) and the flat grain to a semi-ellipsoid, with the characteristic dimensions “a”, “b” and “c”, where “a” corresponds to the largest size of the bean, followed by “b” and the smallest size “c”.

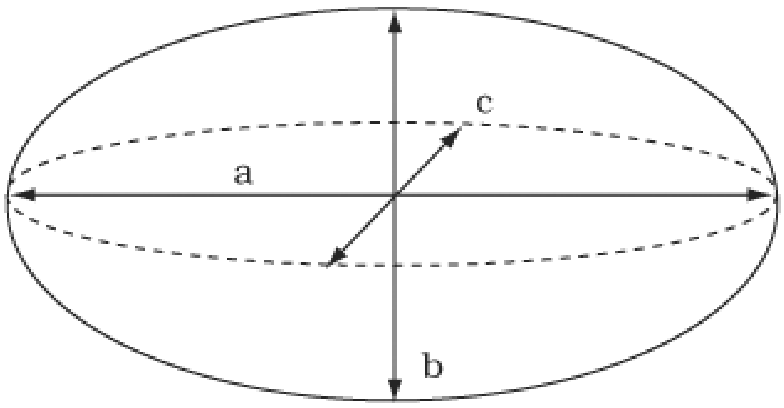

Image 3.4 Representation of the coffee beans dimensions a.b and c.

The shape of the mocha bean was characterized by Sphericity (Eq. 2.6) And Circularity (Eq. 2-7), calculated using the following expressions (Mohsenin, 1986).

$$Es = \left(\frac{(abc)^{1/3}}{a}\right)100 \qquad 3.6$$

$$C = \left(\frac{b}{a}\right)100 \qquad 3.7$$

In which:

Es= Sphericity (%);

C= Circularity (%);

a = largest characteristic dimension (mm);

b = intermediate characteristic dimension (mm);

c = smallest characteristic dimension (mm).

4. RESULTS AND DISCUSSION

4.1 VARIATIONS OF THE ORTHOGONAL AXES

The main parameters to be measured, which are the basis for calculating all the other derived parameters, are *a*, *b* and *c*. The evolution of these dimensions during roasting is closely related to the increase in temperature over time, showing proportional increases. The expansion may be considered isotropic.

The following graphs, Figures 3.1 to 3.3, show an increase in the values of the a, b and c axes respectively, following the five thermal patterns over time.

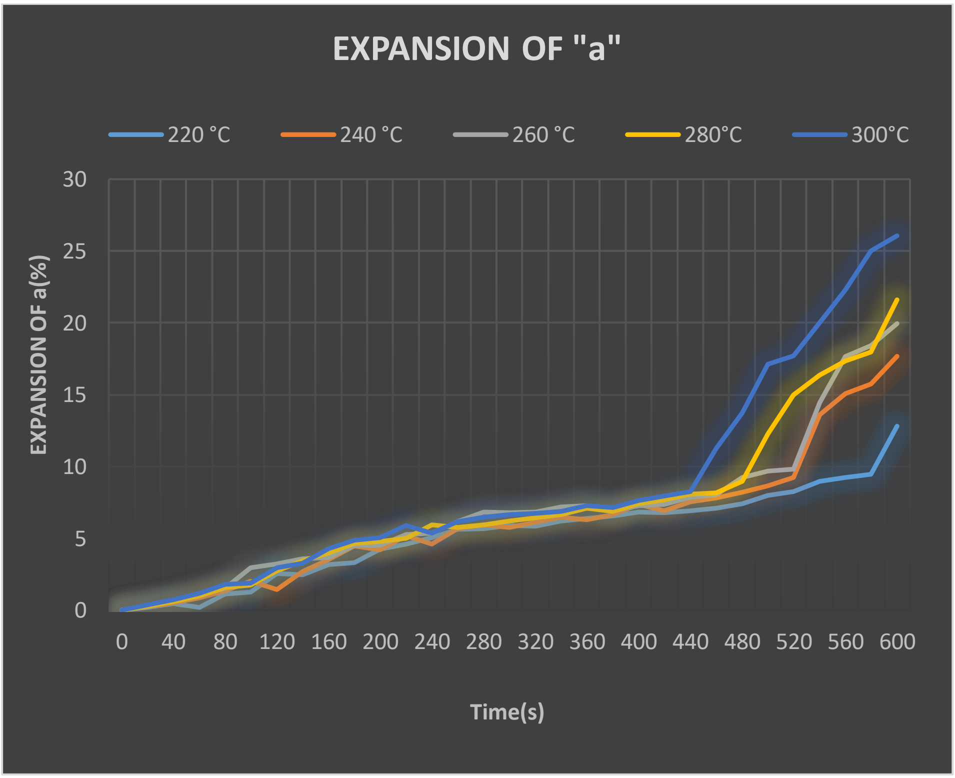

Figure 4.1

Increase of “a” axis at different roasting temperatures over time

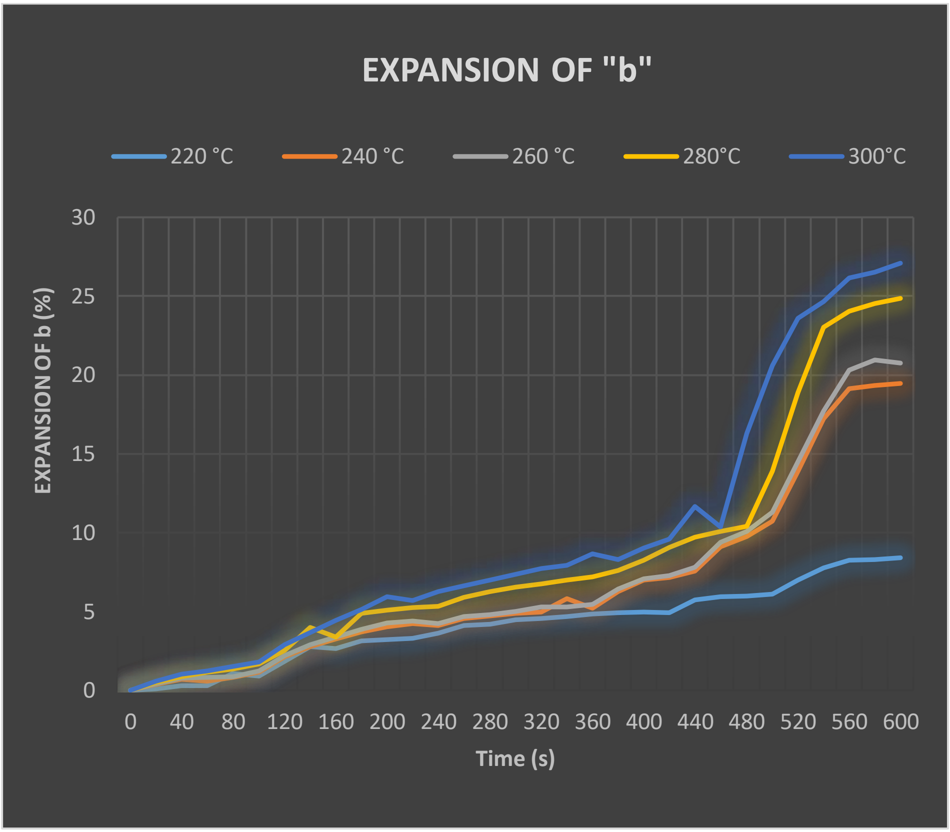

Figure 4.2

Increase of "b" axis at different roasting temperatures over time

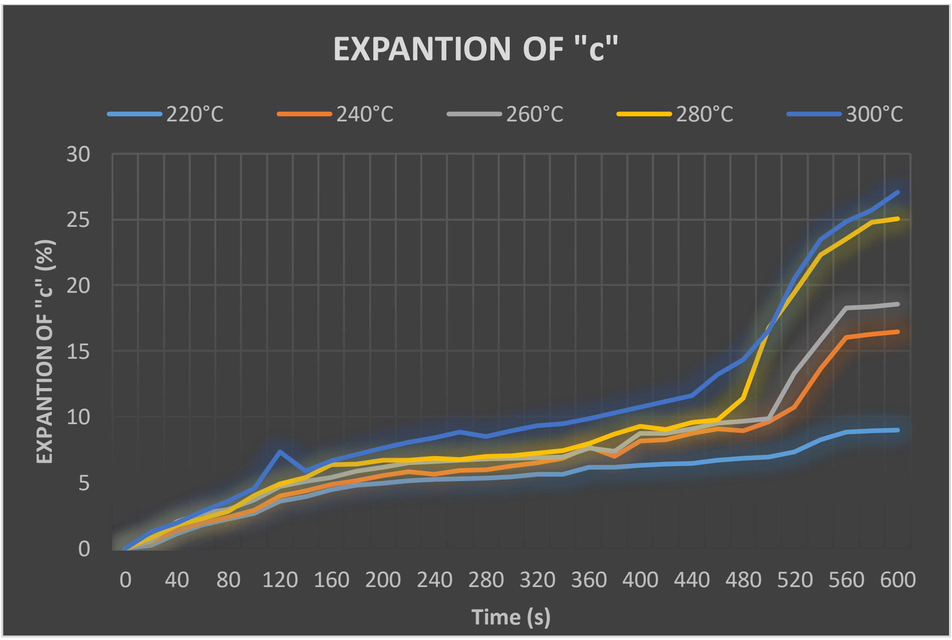

Figure 4.3

Increase of "c" axis at different roasting temperatures over time

From what can be seen from the graphs, there is a visible increase in the parametric increments, b and c which increase proportionally with increasing roasting temperatures.

All the thermal roasting patterns show a linear and progressive trend up to 400 seconds, after which, depending on the axis we consider, the expansion tends to increase suddenly and immediately afterwards to stabilize. The most different behavior is that of the *a* axis, which tends to expand suddenly after 400 seconds and tends less to stability at the end of treatment. The b and c axes tend to expand less quickly and more linearly, beginning to differentiate the thermal patterns a little after 400 seconds, and showing greater stability in the last 40 seconds of roasting. This difference in terms of geometric expansion is certainly due to the different axes proportions; in fact the 'a' axis is on average 1/3 greater than the 'b' axis and 1/2 greater than the 'c' axis. For this reason, however, the b and c axes tend to have a much more similar behavior both in terms of expansion and in their stability.

4.2 SPHERICITY AND CIRCULARITY

Figures 3.4 and 3.5 show how Sphericity and Circularity, respectively, were affected over time under the proposed thermal patterns.

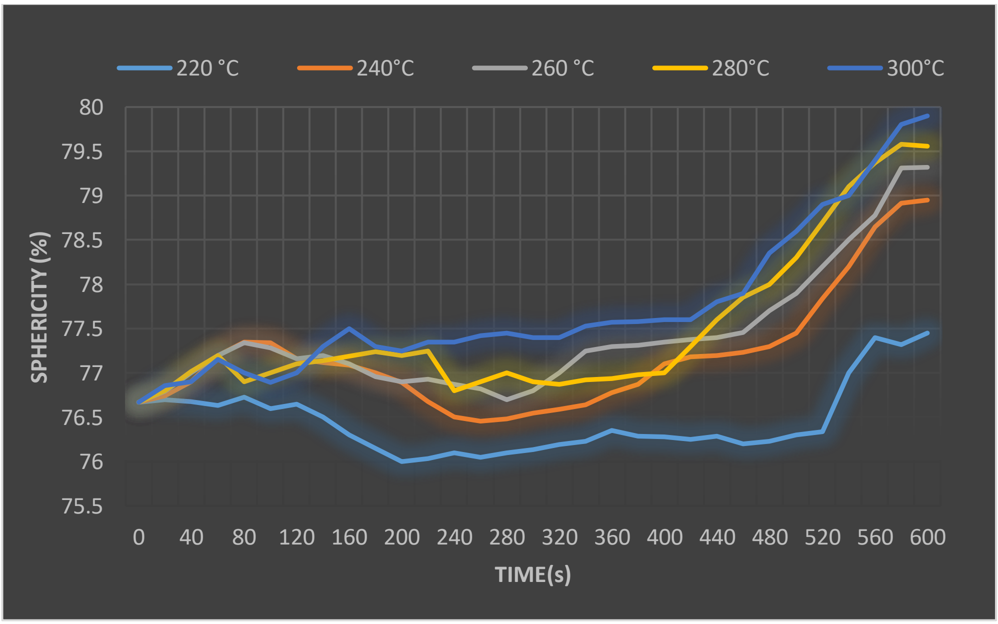

Figure 4.4

Increase of Sphericity at different roasting temperatures over time

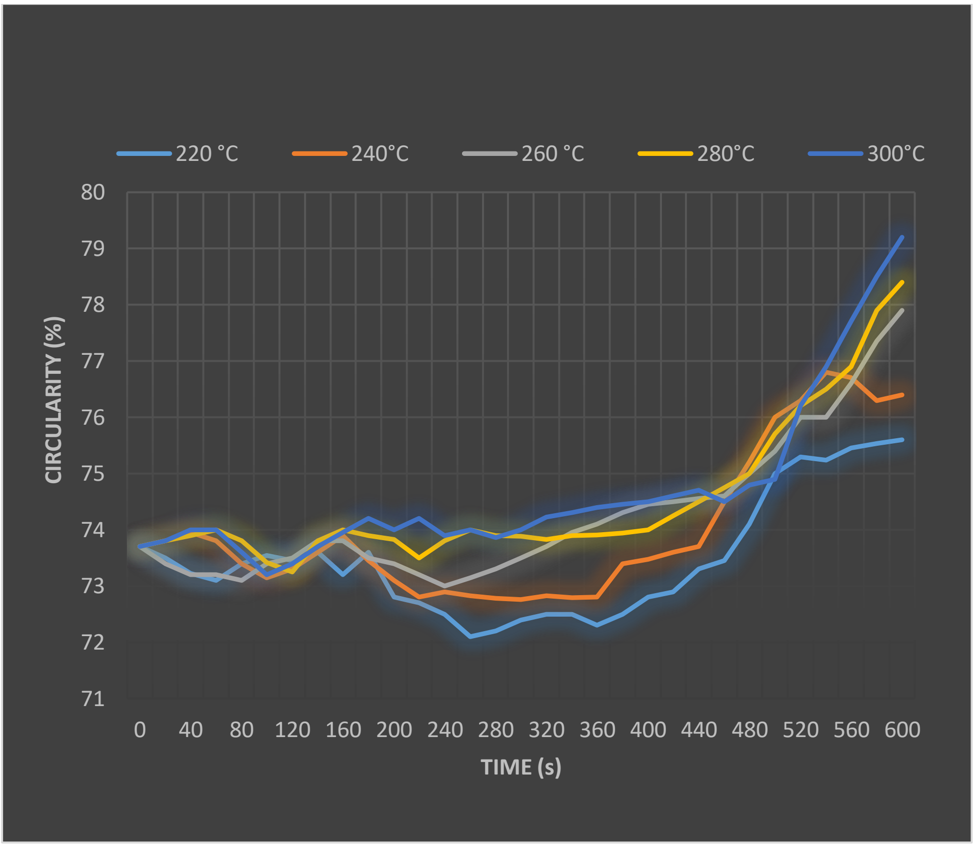

Figure 4.5 Increase of Circularity at different roasting temperatures over time

According to the graphs above, coffee beans tended to become rounder as temperatures and time increased, thus increasing its sphericity and increasing circularity. The expansion of the *b* and *c* axes during roasting showed different behaviors from the "a" axis. In fact the values of b and c were more responsible for the spherical effect which is three-dimensional opposite to the expansion of the value *a*. Even if the value of *a* was more prone to expansion in the last few seconds of roasting, the other values were more stable and above all more connected, giving more sphericity over time. The circularity was, unlike sphericity, much more linear in its behavior, probably because it takes into account only the percentage ratio between the parameters *a* and *b*, which despite the different trends, showed both increases almost at the same times and almost with the same intensity.

4.3 SURFACE AREA

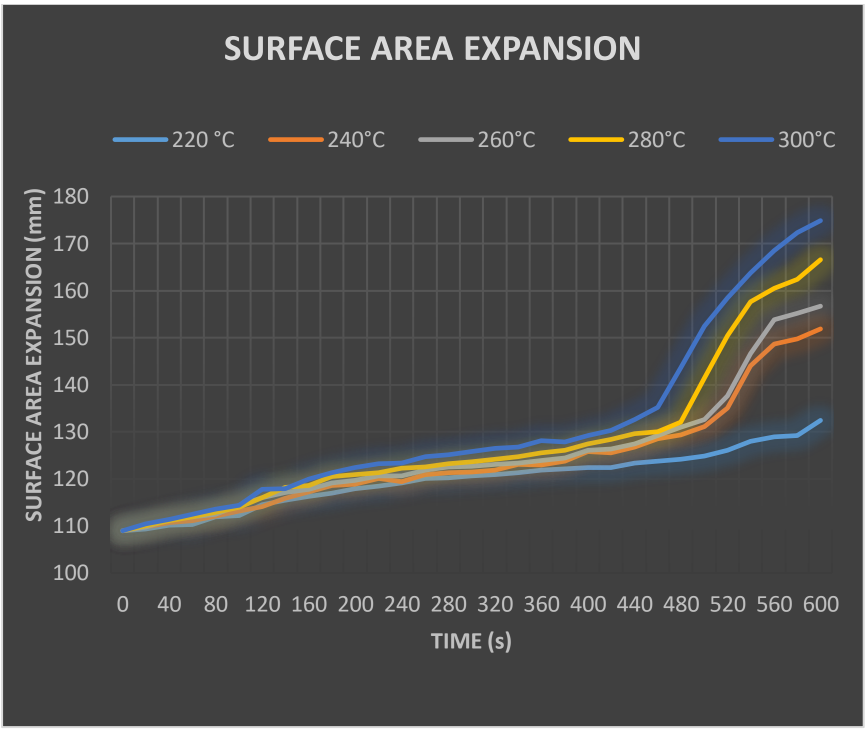

Figure 4.6 Increase of Surface Area Expansion (mm^2) at different roasting temperatures over time

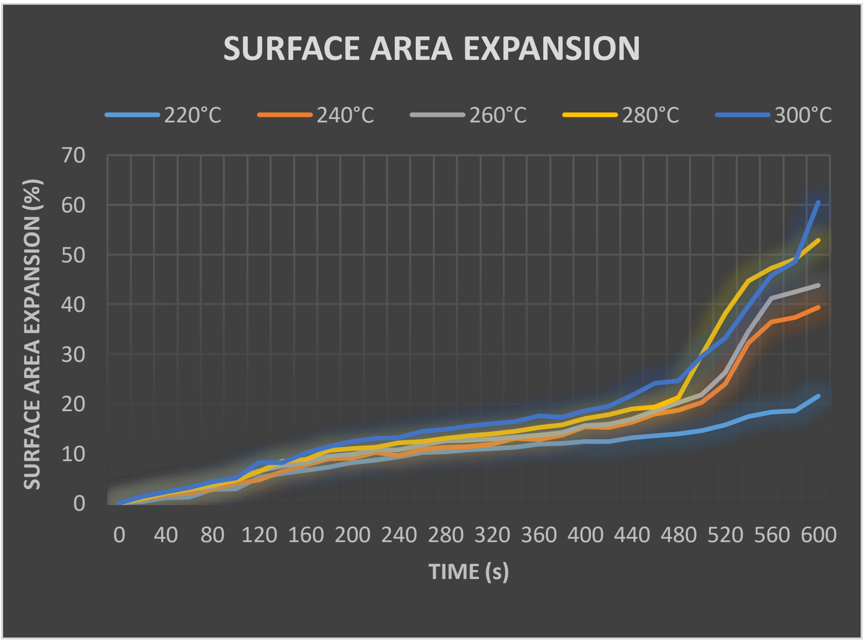

Figure 4.7 Increase of Surface Area Expansion (%) at different roasting temperatures over time.

The analysis of the surface area of the coffee beans gave an initial area of 109 mm2. Following roasting, the final values of the surface areas of 132,152,157,166,175 mm2 were obtained for the respective temperatures of 220, 240, 260, 280 and 300 ℃.

The graphs clearly show that, as temperature increases, there is obviously an increase in surface expansion. In percentage values (always at the temperatures of 220,240,260,280 and 300 ºC, respectively), a superficial increase of 21.5% - 39.3% - 43.8% - 52.8% - 60.5% was obtained. The difference in the behavior of the various thermal patterns occurs starting from 400 seconds (as also in the previous parameters) to then outline more marked differences between 500 and 600. As already analyzed above, the superficial expansion of the beans was higher at higher temperatures. All this is in accordance with the increase in the characteristic measures of *a* ,*b* and *c* during the roasting process.

4.4 MASS LOSS

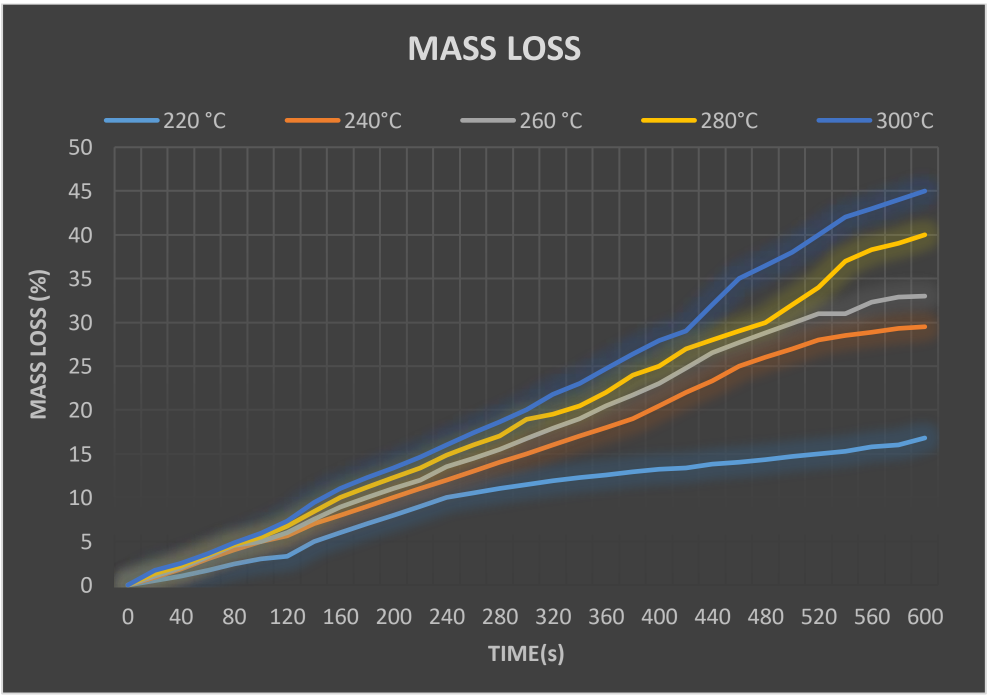

Figure 4.8 Mass Loss percentage at different roasting temperatures over time.

As regards the loss of mass, a linear behavior was observed. In the final stage of roasting, exactly as in the previous cases, a tendency to stabilization was shown (more precisely, the last minute).

The thermal patterns tended to detach from each other as the roasting time advanced, always maintaining a linear behavior. In particular, it is possible to deduce more "distances" from the graph starting from 400, especially for the lower thermal pattern (220 ° C).

About 90% of the mass loss during roasting corresponded to water and 72% corresponded to the initial moisture of the coffee bean. The other 18% corresponded to the water formed during the pyrolysis reactions.

10% of the total loss was mainly CO2 and small amounts of volatile aromatic compounds that were formed and released during the process (Illy and Viani, 1995).

During roasting of Arabica coffee, Franca et al. (2009) correlated this change in the rate of mass loss with the transition from the drying to the roasting phase and observed a greater loss in high roasting temperatures.

Wang and Lim (2013) also studied the mass loss at roasting temperatures between 220 and 250 °C by finding two separate passages from the average roasting level.

For the first step, they determined an activation energy of 53.49 kJ mol^{-1} while for the second this value was 184.15 kJ mol-1, indicating a higher temperature dependence for the second step.

Vargas-Elías (2011) instead correlated the total mass loss with the roasting levels that found a high correspondence.

4.5 VOLUMETRIC EXPANSION

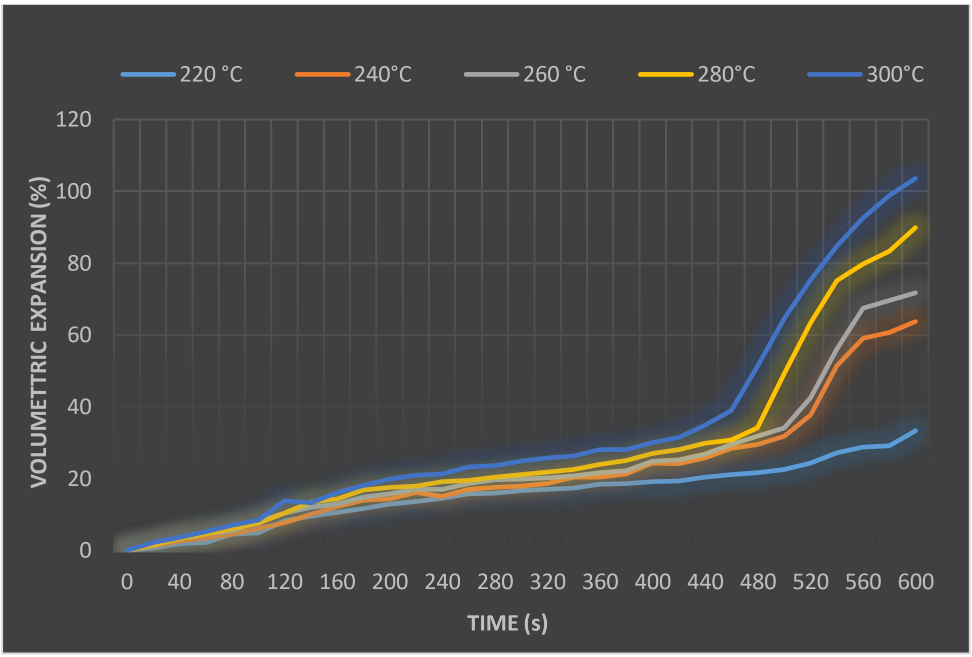

Figure 4.9 Volumetric Expansion (%) at different roasting temperatures over time.

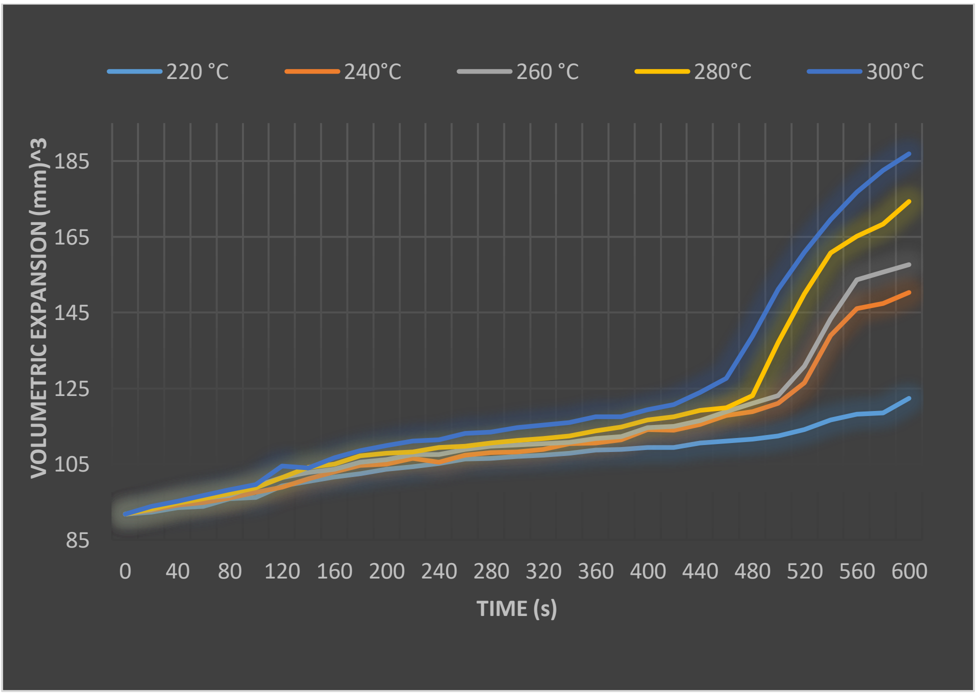

Figure 4.10 Volumetric Expansion (mm^3) at different roasting temperatures over time.

As shown in Figures 4.9 and 4.10, both in percentage terms and in numerical values, the volumetric expansion of the grains followed a trend very similar to that of the surface expansion, and therefore of the orthogonal axes *b* and *c*.

At the end of the roasting process, for the temperatures of 220, 240, 260, 280 and 300℃, the volumetric expansions reached the values of 33.3%, 63.7%, 71.7%, 89.8%, 103.5% and in absolute values, 122.37, 150.3, 157.6, 174.3, 186.9 mm^3, respectively. The graphs show that the volumetric expansion was greater at higher roasting temperatures. All of this agrees with the fact that the characteristic dimensions *a b* and *c* showed greater increments when the roasting temperature intensified.

Baggenstoss (2008) also reported that high-temperature-short-time roasting led to beans of lower density, higher volume, less roast loss, and lower moisture content as compared to the low-temperature-short time process.

According to Illy & Viani (1995), volumetric expansion is mainly a function of the pressure accumulated by the rapid formation of water vapor and CO^2 inside the grain, able to reach values between 40% and 60% due to mass losses of 18%.

5. CONCLUSIONS

The roasting process had a visual impact on the physical properties of the analyzed coffee. The main basic parameters, which made it possible to calculate and analyze the remaining derived parameters, were the orthogonal axes *a*, *b* and *c*.

In the analysis of the behavior of the three axes, axis a was the one that presented more differences and less stability in terms of expansion, while axes b and c showed very similar trends over time.

Through the latter, it was possible to calculate the impact that five thermal patterns (220, 240, 260, 280, 300 ºC) had on coffee beans over a period of 600 seconds. The temperatures generally recommended by literature in this sector, oscillate between 240 and 280 ºC, but it was decided to include the other two temperatures in order to analyze more extreme conditions.

The physical parameters analyzed were generally found to suffer an evident impact with temperatures, especially with higher ones.

Graphically, the differences in terms of distance between the thermal curves are shown on average starting from 400 seconds, to then stabilize at the end of the process.

Still in general, the parameters of sphericity, circularity, mass loss, surface expansion and volumetric expansion showed linear increases over time.

In the case of the expansions, we can define them as isotropic expansions.

In the future, it would be optimal to be able to develop industrial equipments suitable for ameliorating the physical characteristics, or to improve roasting conditions in order to reach the standards of maximum efficiency for quality.

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