Chapter 1
Harvesting, Drying and Storage of Coffee

Juarez de Sousa e Silva, Aldemar P. Moreli, Sergio Mauricio L. Donzeles, Sammy Fernandes Soares, and Douglas Gonzaga Vitor

1 General Introduction

Historically, Brazil is recognized as the major producer and exporter of coffee in the international market. In 1961, the Brazilian exportation reached 37% of world exports of coffee beans, while in 1995 it accounted for only 20% of these exports. Despite of this decrease, Brazil produced 27 million bags (60 kg each bag) of coffee in 1997, 30 million bags for the 98/99 crop and 45 million bags for the 2016/17 crop which represented around 30% of the international market.

With the current production techniques, Brazilian coffee became one of the best in the world. In addition to being the largest exporter, Brazil is also one of the major consumers behind only of the United States, which is the world's largest coffee consumer. Although the Brazilian "cerrado" has the most professionally coffee plantations, due to the appropriated topography, mechanization and the ideal climate for harvesting. Excellent coffee plantations, with an ideal climate for production of fine coffees are spread throughout the mountain forests of Espírito Santo and

J. de Sousa e Silva (✉)
Department of Agronomy, Federal University of Viçosa, Viçosa, MG, Brazil
e-mail: juarez@ufv.br

A. P. Moreli
Coffee Analysis and Research Laboratory, Federal Institute of Espírito Santo,
Venda Nova do Imigrante, ES, Brazil

S. M. L. Donzeles · D. G. Vitor
Agricultural Research Company of Minas Gerais, Viçosa, MG, Brazil
e-mail: slopes@ufv.br; douglas.vitor@ufv.br

S. F. Soares
Department of Research and Development, Brazilian Agricultural Research Corporation,
Viçosa, MG, Brazil
e-mail: sammy.soares@embrapa.br

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Minas Gerais, São Paulo, Bahia and Paraná. According to CONAB, the 2020 coffee harvest in the State of Minas Gerais showed a record of 30.7 million bags and reached almost 60% of the Brazilian production, which was 51.3 million bags produced.

For the sustainability of coffee-growing, all the producing countries have to follow a quality standard. Coffee is one of the few agricultural products whose price is based on qualitative parameters, varying significantly the value with the improvement of its quality. Details about the quality of coffee are seen in Chap. 3 (soil microorganisms and quality of the coffee beverage). Thus, extensive knowledge of high-quality coffee production techniques is indispensable for modern coffee growing. Therefore, quality with sustainability will be the main subjects discussed in this chapter.

Coffee quality, which is related to grain characteristics, such as color, appearance, number of defects, aroma and taste of the beverage. These characteristics depend on several factors, among them can mentioned:

(a) Preparation and storage process;
(b) Roasting; and,
(c) Beverage preparation.

The first topic is the purpose of this chapter and it is, with the ripe fruit, at the ideal harvest point, the ideal raw material to obtain good quality coffee. To maintain this quality, it is necessary to use special and careful techniques throughout the preparation steps. From harvesting to storage, the coffee goes through a series of operations that well executed, will provide a product within consumer standards.

2 Harvesting and Cleaning Coffee Beans

In this topic we will talk about harvesting and cleaning the coffee beans. The reader may question: why cleaning if the fruits come straight from the plant? It turns out that when you take the fruits out of the plant, even with the greatest care, other materials such as leaf, peduncles and pieces of branches can come together with the fruits. If these materials are not removed, they make the drying and peeling hulling processes more difficult.

Harvesting coffee is a complex operation, it has several stages and demands around 30% of the production cost. Besides 40% of the labor employed in the coffee plantations is concentrated in a relatively short period of time on the coffee farm.

In the last few years, there is a great mechanization expansion of the harvesting operations and is becoming an irreversible process, which aims, above all, the valorization of the labor and the maximization of the harvest results. The traditional mechanization methods have only been possible to be applied in land with slopes of up to 20%. Which combined with other operational and economic restrictions show that coffee farm mechanization always depends on human labor.

In addition, the machines require operators, maintenance staff and technical assistance, which is provide by skilled labor. Also, coffee harvesting is comparatively more difficult to execute than other products, due to the height and architecture of the plant, the uneven maturity and the fruits moisture content.

As previously mentioned, coffee harvesting takes place in a short period of time, no more than three consecutive months. In Brazil, generally starting in April and May in regions with higher temperatures. Other regions such as Araponga—MG and Venda Nova do Imigrante—ES the harvesting may extend until October and November for properties located at high altitudes.

The quantity of fruits in the plant, the number of fruits fallen in the soil, and the harvest season duration are factors to be considered to start the coffee harvesting. It is important that all production factors are suitable according to the requirement of the crop, because the price of the coffee beans is based on qualitative parameters, therefore, farmers will not reach good results, if they do not fit all parameters, even using good harvesting practices.

The coffee harvesting should be started when most fruits (90%) are ripe and before fruits drop begins. Normally, the harvest period occurs, on average, 7 months after flowering and that happens with the first rains (September to November in Brazil).

In a single coffee crop, several blooms can occur and this fact does not result in a harvest with homogeneous maturation (Table 1.1). The general rule is that the coffee harvest period varies from region to region and four basic harvesting systems are used: (1) single-pass stripping: all branches bearing fruit are harvested at once, thus collecting unripe, ripe and overripe cherries altogether and it is the most common practice in Brazil; (2) multi-pass stripping: only branches bearing mainly ripe cherries are harvested; a method that relies mainly on the ability of the worker; (3) multi-pass selective picking (finger picking): only ripe cherries are harvested; and (4) mechanical harvesting: different types of machines are used to harvest all fruits at once. Therefore, it is important to have knowledge about all harvest operations, such as: cleaning under the tree, manual or selective harvesting, manual or mechanized single-pass stripping, handpicking, dirt sieving and winnowing, and transportation.

Once started, the harvest can be completed in a few weeks or up to 3 months, depending on the conditions of flowering, fruit growth and maturation. However, these conditions depend on altitude, latitude and climate. The longer the coffee

Table 1.1 Moisture content of different types of fruits during coffee harvest

Types of fruits	Moisture content (% w.b.)
Unripe	60–70
Cherry	45–55
Over ripe	30–40
Partially dry	20–30
After pulped	50–55

remains in the tree or on the ground, after maturation, the greater the incidence of black and burned grains, and they are considered, together with unripe fruits, the worst coffee defects.

2.1 Cleaning Around and Under the Tree

The cleaning operation consists of removing loose soil, weeds and debris that must be heaped between the rows of coffee trees. It should be done before the fruits begin to fall on the ground and can be carried out basically in three ways (manual, mechanical and chemical) or an association between them. Manual cleaning and heaping are done using appropriate tools. It has as advantage the good quality of the service and disadvantage the low work performance and high operational cost.

The mechanical cleaning and heaping consist of the use of machines coupled to the tractor. These machines may have blades or blowers, or even an association of these equipment's. The advantage of mechanical heaping is the high yield, low operating cost and good quality of service and the disadvantage is the damages of the coffee root system.

2.2 Single-Pass Stripping

Harvesting by Single-pass stripping for the production of natural coffee should begin when part of the fruit has passed from the mature stage and with a small amount of unripe fruits. At this point, fruits that are relatively dry on the surface are easy to handle. However, a good proportion of partially dried fruits, depending on the weather conditions, fall on the soil.

In order to solve this problem, the soil under the coffee tree must be previously cleaned by any operation previously described and in such a way that the fruit fallen on the ground can be easily collected after the first harvest. In the case of the marketing of freshly harvested and unprocessed coffee (fresh fruit), it may be considered that 480 L of clean fruits (cherry) will result in 60 kg of green or processed coffee. At the end, a careful harvesting of remaining fruits in the tree or soil should be done to avoid the proliferation of the insect known as the coffee borer.

Harvesting by the Single-pass stripping system, usually part of the coffee is partially dry, a significant amount is unripe, ripe or over-ripe. The proportions change as the harvest progresses. Although most farmers harvest in a single pass stripping, they should perform the harvest in two or more passes in each tree, as a matter of quality and avoiding damages to the coffee trees.

Appropriate facilities and techniques (clean water, canals, tanks and pulping machine), can reduce defects from inadequate harvesting, which can be done by separation in water.

Colombia has climate conditions more propitious for harvesting by hand-picking, the period extends for more than 6 months during the year and basically 100% of the coffee produced is washed coffee.

In the manual striping, the workers run their hands, partially closed, along the branches collecting all types of fruits and avoiding leaves of being removed. Although, some leaves are removed, it is unavoidable, the worker should be trained or receive a prize in order to remove as few leaves as possible. The stripping of the coffee cherries can be done on the soil, previously prepared, or on plastic or cloth sheets placed under the coffee trees. Even if you have a well-built structure, the stripping on soil should never be recommended, because it demands a lot of strength from the workers.

If the harvested coffee is mixed with dirt, leaves and branches, as usually happen during the stripping on the soil process, it must be pre-cleaned before being packed for transportation and volume checking. The farmer should provide some training, especially for young workers, so they can develop skills to gain efficiency and productivity in the pre-cleaning process.

To increase yield, avoid excessive leaf withdrawal and facilitate the stripping operation, the worker should begin harvesting the fruits by the end of the branch and not at the beginning, also avoiding any insertion point of the branch.

2.3 Sweep and Collect

Stripping and the collection are very important operations in the Brazilian coffee farms. Sweeping is the operation of piling up and picking up coffee that has fallen on the soil, this operation is not recommended when quality is a priority. Sweeping is done first to separate the fallen coffee from the stripped coffee. For stripping on the cloth, sweeping is done later. Sweeping can be done manually or mechanically. There are also mechanical blowers, which can facilitate the coffee harvesting, minimizing the physical work.

2.4 Winnowing

When coffee beans are not handpicked, they should be as quickly as possible, transported to the separation processes before further operations. Separation of unwanted foreign material can be achieved by sieving—manual winnowing. Coffee cleaning can also be done with a tractor-powered machine or hand-powered machines.

The aim of pre-cleaning is to pack clean coffee and leave the organic waste in the field. A good shaking eliminates most of the problems in the post-harvest operations, avoiding contamination by microorganisms and their consequences.

The elimination of unwanted materials will avoid constant interruptions in the drying, storage and processing operations. Consequently, preventing excessive energy consumption, extra labor and unnecessary use of the equipment involved in these operations.

If the coffee beans have not been pre-cleaned in the field, they must go through the leaf separator and the sieve system, located upstream of the coffee washer machine. The rest of the unwanted materials are separated and directed into an appropriate open tube and eliminated, by a proper device of each coffee washer, as it will be seen further on.

Manual pre-cleaning with sieves, as shown in Fig. 1.1. Different ways of cleaning, and bagged clean coffee waiting for transportis a low-yielding, exhausting and unhealthy operation in case of coffee being harvested by Single-pass stripping on the soil or when the swept coffee is collected. Another drawback is the lack of natural ventilation, which assists in the elimination of leaves and light foreign materials, barks, branches and lights. Regardless of whether it is performed by a man or a woman, traditional sieving is painful work: in addition to physical endurance, also requires a lot of skill to execute it. The machines used to separate the unwanted materials in the field, greatly facilitate the work that comes after the harvest operation. Pre-cleaning prior to the washing system can result in a significant reduction in water consumption by the coffee washer. Also, increasing the separation efficiency of the washer or hydraulic separator.

In selective harvesting especially finger picking, some of the previous problems are eliminated. In these harvesting systems, the coffee is practically clean before entering the pre-processing unit.

Fig. 1.1 Different ways of cleaning, and bagged clean coffee waiting for transport. Source: Silva et al. (2018)

2.4.1 Motorized Pre-Cleaning Coffee Machine

Due to the difficulties pointed out and the need to increase worker productivity by manual harvest, a hand powered machine was developed to shake and separate the fruits from foreign materials. The machine is portable, low cost, and easy to operate. In the case of a larger coffee-growing, one machine can be used by ten workers. For big coffee farms, there are excellent motorized equipment produced by the Brazilian industry (Fig. 1.2).

The manual coffee pre-cleaning machine (Fig. 1.3) is an equipment consisting of two oscillating sieves and a fixed one (optional), arranged to separate larger impurities (leaves and sticks) and very small fruits from high qualities coffee fruits.

The sieves vibration is created by a crank or an electric motor and a set of pulleys. Charging is done in the hopper located on the top of the machine. From the hopper, the material (coffee + unwanted materials) passes through the upper sieve, where larger materials (leaves, sticks, etc.) are retained. Then they are directed towards the channel, located at the end of the sieves. The waste (small fruit) can be collected in the fixed screen (optional) located on the bottom of the machine.

Fig. 1.2 Motorized Pre-cleaning coffee machine produced by Pinhalense. Source: Pinhalense (2013)


(a) (b)

Fig. 1.3 Side view (**a**) e frontal view (**b**) of the manual pre-cleaning machine with one fixed sieve. Source: Silva et al. (2018)

2.5 Selective Harvest or Finger picking

At picking or selective harvesting, only the ripe fruits are collected, and can be placed in a basket, sieve screen or cloth under the coffee tree. This harvesting technique is common in places where fruit maturation occurs in more than 6 months in a year (in the range close to the equator).

As the demand for special coffee (higher quality coffee) is growing, many Brazilian farmers, mainly family farmers, have been adopting this harvest system with great success. With better price and special market, it is worth the appropriate technology, despite the great need of manpower.

As previously mentioned, it is important to harvest and collect all coffee, because the fruit remaining in the soil until the next harvest season facilitates the propagation of pests and diseases, particularly the coffee borer that significantly changes the final type and quality of the beverage.

Whatever the harvesting process, the coffee must finally be measured, bagged and transported to the pre-processing unit. It is extremely important to transport the coffee in the same day of its harvest. When for some reason the transportation cannot be done in the same day, avoid air-tight containers such as plastic bag. If the pre-processing has to be started in the next day, the coffee should be placed in the hopper or reception tank and submerged in running water to avoid heating due to both the breathing and the beginning of the fermentation process.

2.6 Mechanized Harvesting

Mechanized harvest (Fig. 1.4), despite being developed and applied in regions with flat topography, it is a good option only for big coffee producers. Even using rental machines, the high yield during harvesting season do not fit with small producers pre-processing system. Which means, this technology is used only for a few farms in Brazil, where most of the harvesting is done by the hand striping system, due to the farm size and mountain topography.

Nowadays, with the difficulty of hiring labor (less problematic in family coffee-growing), the natural tendency is the expansion of the mixed system, which is, a balanced amount of labor and small machines, especially in mountain regions, due to a lack of appropriate technology for these areas.

2.7 Coffee Transportation to the Pre-Processing Unit

The transport of coffee beans is the conducing operation of the fruits already harvested and collected from the field to the pre-processing unit, where the post-harvest operations must be continued. Whenever is possible, the production should be transported at the same day of harvesting. If the farm manager needs to wait until the next day to transport the production, the coffee beans should be bagged in open containers so they can breathe, avoiding fermentation, then the transportation can be done with appropriate bags or in bulk.

Fig. 1.4 Mechanized harvesting details. Source: Authors

As previously said, occurring failure to start the pre-processing operation, on the same day of harvesting, the production must be stored in clean and cold water or with forced ventilation system. The adoption of a small sprinkler over the receiving hopper with a drainage system is a good solution to keep the coffee fruits cool overnight. The following photos (Fig. 1.5) illustrate how to hold, transport, unload and maintain coffee in clean water in the pre-processing unit.

3 Pre-Processing of the Coffee Beans

In Brazil, because of the harvest method used, the production is composed of a mixture of unripe, ripe (cherry and greenish), and dried fruits, leaves and branches. Also, when coffee beans are harvested directly on the ground, they can contain soil and stones, which must be cleaned and separated into their various fractions so they can be dried separately. All these operations are called pre-processing and they can be performed by a dry way or drying the entire fruit, this way the final product will be called natural coffee. The fruits can also be processed by the wet way, which consists of drying the fruits without the pericarp or without pericarp and mucilage. In this case, the final product is called "Peeled Cherry" and "pulped coffee" or washed coffee, respectively. Regardless of the harvest techniques or pre-processing, all coffee beans should pass through the washing system and also by the density separation system.

Fig. 1.5 Waiting periods for the transport, unloading and maintenance of the coffee beans before pre-processing. Source: Authors

3.1 Washing and Separation of Coffee

The coffee grower who intends to produce high quality coffee should never forget that, even removing all impurities (sticks, dirt, stones, leaves, etc.) during the pre-cleaning process in the field, the coffee must necessarily pass through the coffee washer to separate fine material stuck to the coffee beans surface and the separation of coffee beans from unwanted materials by density difference (Fig. 1.6).

It is in the hydraulic separator that, depending on the density of the coffee beans, separates them. The fruits called floats (dried, brocaded, malformed and immature) floating in the water are separated from the perfect fruits (ripe and greenish), after that, they must be pre-processed, dried and stored separately.

Even using the pre-cleaning operation in the field, it is desirable that before entering the coffee washer, a cleaning machine will improve the overall pre-processing system and subsequent operations, such as pulping, drying and hulling as it will be seen later, in this chapter.

If it is possible, it would be desirable that after passing through the cleaning system, a size sorter be adapted so that after washing, the coffee can be processed into, at least, two more homogeneous batches.

Even producer that does not want to produce peeled coffee must adopt a coffee washer machine for technical and economic reasons. With this equipment, the size of the drying system and manpower will be reduced and above all, it will produce

Fig. 1.6 Mechanical system for coffee washing and separation. Source: Silva et al. (2011)

two differentiated portions (high density coffees and float coffee). It will require a smaller terrace dryer and it is estimated that farmers will earn more money during the commercialization of the differentiated coffee portions, an additional over 10% to the value that would earn for the coffee that did not go through washing and separation processes.

Considering that a farm has produced 2100 bags and got an additional average of $7.00 per bag, due to the segregation of portions (cherries, floats and unripe fruits), the profit from this operation would be a total of $15,700 above the sale price of the mixed coffee. Currently, in just one harvest season, the farmer pays off the investment made in a good washing and separation system, which can be done with the money earned through the graded coffee.

Nowadays, the Brazilian industry provides excellent medium to large capacity coffee washing machines. However, it is very difficult to find a coffee washing machine that fits family coffee production. There are few models, despite the size, that may fit family farmers (power 1 HP and 2000 L/H capacity). This model has the advantage of having a pre-cleaning system, which later on will facilitate subsequent work.

For those who are unable to purchase a mechanized coffee washer or for those who have the ability and the conditions to build their own equipment, we suggest the models illustrated in Fig. 1.7.

Fig. 1.7 Mobile coffee washer with tilting system to unload high density coffee beans. Source: Silva et al. (2014)

The two models can be easily constructed in a small metallurgical industry or on the farm itself. They are ideal for small productions and consist simply of two tanks, the first one holding the washing water. They can be constructed of metal sheet and fixed on wheels (portable coffee washer), or with the water tank built in masonry and fixed on the ground (fixed coffee washer). In both models, the second tank is tilting and constructed with perforated plate, which is used to retain the high-density coffee beans.

After the low-density coffee beans are withdrawn, by a common sieve, the heavy coffee beans are unloaded by the tilting system and transported to the next operation.

Ideally for the operation in this type of coffee washer is to have continuous feed (½ inch tubing) with clean water. If there is insufficient running water for continuous renewal of the coffee washing water, the water in the tank must be changed at each wash of 500 L of coffee beans (1 L of water per liter of coffee would be reasonable).

Another relatively well-functioning coffee washing system, though a bit more demanding is the box washer shown in Fig. 1.8. This system seems to be the best option for a small farmer who wants to improve coffee production.

Some models can be replaced by the tilt system with an endless thread with perforated sheet conductor tube to facilitate water flow. Remember that the bottom of the water tank is tilted to facilitate the heavy removal of coffee. Due to the price of the auger, it must be adapted to be withdrawn after the harvest season.

One type of coffee washer that can be built on the farm is the traditional "Maravilha" (Brazilian name for the coffee washer). The "Maravilha" basically consists of a tank and a metal gutter with branched outlet in which is adapted a pressure-injected water system to separate the heavy fruits from the stones and to direct the cherry coffee to the appropriate gutter. The dry fruits and light material

Fig. 1.8 Rustic homemade coffee washer using water box and shade screen to separate the high-density coffee. Source: Silva et al. (2014)

pass freely over the false bottom and are unloaded at the end of the floats gutter. This gutter is nothing more than the continuity of the main one it came out from the hopper.

In the past, it was used when clean water was not a limiting factor, this kind of equipment was gradually being replaced by mechanical models. The great disadvantage of the “Maravilha” coffee washer is the excessive consumption of water, which depending on the construction form and coffee beans dirtiness may exceed 10 L of water for each liter of cleaned coffee. The high-water consumption of the coffee washer is due to the fact that much of the water is used to transport the coffee through the separation gutters.

If water is available and everything is taken care of to avoid compromising the environment, the “Maravilha” can be built to wash up to 10,000 L of coffee beans per hour. To save water, the washer can be built with a total or partial recirculation system for the washing water. In this case, after each day worked, the water must be used for irrigation or sent to infiltration ponds.

The “Maravilha” coffee washer with water recirculation consists of a hopper tank, a receiving tank (washer/separator) and recirculating tank with chicanes for decantation of the waste from washing water. A semi-open rotor pump for effluent recirculation and outflow is used to supply water for transportation in the gutters.

In addition to the lower water consumption and less use of hand labor, mechanical coffee washers are compact, require less space and can be rearranged or marketed in case of withdrawal from coffee activity. On the other hand, the “Maravilha” has the same characteristics as the mechanical washer, if mobility is not considered.

After cleaning and washing, regardless of the type of coffee washer, the coffee can be sent to the dry process, which consists of drying the whole fruit “natural coffee”. If the wet process will be used, the coffee must be subjected to the peeling, with removal of the mucilage or not and washing (optional) before the drying process, which is referred to “peeled” or “washed” coffees.

3.2 Pre-processing by “Dry Way”

In the “dry way” coffee processing, the grower must prepare the coffee beans to dry the fruits in their integral form and separated from the unwanted materials, and optionally separated by density right after harvesting.

In order to save time, energy and improve coffee quality, the farmer who wishes to process his coffee through the dry way process should be advised to do so by separating the low-density materials, such as unripe, malformed and brocaded from high density materials, ripe and greenish fruits. Coffee beans with high density have better quality characteristics. After being separated, fruits with high and low densities, they must be dried, stored, processed and marketed separately.

Although the process discussed is referred to as a “dry way”, the first operation after pre-cleaning is to separate the production by density in the coffee washer. The coffee washer, besides removing fine dirt adhered to the fruits, simultaneously performs the separation between floats from high density coffee beans. Therefore, the coffee washer/separator is an essential equipment in the coffee pre-processing.

With the well-separated and high-density fruits, in the washing process, they must be brought in their entire form to the drying process in isolated batches and forming what we call natural coffee. It is expected that if the drying process is executed correctly, the high-density fruits will produce a great coffee highly appreciated in the special coffee market.

For the floating fruits, this expectation does not prevail. The producer must make analysis and hope that the product that originated the floats is also of good quality. In fact, due to the incidence of many brocaded, unripe and fermented fruits, it is extremely hard to produce good quality coffee. In order to improve the commercialization, it is recommended that the coffee beans, once they have been processed, they should be submitted to a reprocessing operation and after that an electronic selection to eliminate defects. Therefore, the transformation of ripe cherry fruits, in their entire form into dry fruit, is called “dry way” processing.

Although produced according to good harvesting and preparation methods, it produces a coffee with the true natural taste and highly desired by the consumer. When the production is harvested by stripping on the soil, hardly provides a higher quality coffee.

Drying, storage and processing of dried coffee beans require a longer drying time, greater energy consumption, more space for storage and greater machines maintenance. The “dry way” is, based on the mentioned facts, the most expensive process of coffee processing.

Although the coffee has been washed and separated in water, the process has been called the ‘dry way“ to differentiate the process that received the name “wet way” due to the fact that after passing by the same operations previously seen, the coffee beans, before being sent to the drying operation, must go through up to four operations that uses water intensely.

The differentiation from the “dry way” process is that the coffee beans that pass through the wet way process are taken to the drying process in the form of seeds with parchment, after that, the fruits are subjected to the peeling or pulping, which is made by machines that use water to facilitate the outer skin removal and separation.

Although it is known as a coffee producer using the “dry way” process, there is good conditions in Brazil for washed coffee production, mainly in the mountainous regions where it is easy to find family work and plenty of clean water supply. However, nowadays the production of only peeled coffee has grown steadily, showing a well prepared, full bodied and naturally flavored coffee as its advantage.

To facilitate the understanding of the ‘wet way” process without going into detail, it must consider that coffee fruits are composed simply of the following parts: outer skin, pulp, parchment, silver film and seeds.

The coffee seeds, also known as coffee beans or “green coffee beans”, are exported or sold directly to the domestic roasting industry. Therefore, it is not possible to mistake the unroasted coffee beans, which they are greenish in color, with the immature fruits (green and low-density fruits). They are separated in the coffee washing machine and together with the partially dried or brocaded coffees are called buoy or floats coffees. Another type of fruit that is not fully ripe and termed as greenish fruits are separated from the ripe ones during peeling.

The coffee pulping operation consists in removing the outer skin from the ripe fruits by a mechanical peeler and, optionally, subsequent mucilage fermentation and grain washing. Peeled coffee has the advantage of requiring considerably less drying terrace area and less drying time. The required volumes of dryers, silos and bag storage can also be reduced by up to 50% if compared with coffee processed by the "dry way". These advantages are due to the uniformity and the low moisture content, around 50% w.b., when compared to the drying of the integral fruit. In the same way, we can also obtain the simply peeled coffee, which differs from the pulped ones because it does not go through the fermentation step and remains with a good part of the mucilage during and after the drying process.

The removal of mucilage by natural fermentation is a process of solubilization and digestion of the product by microorganisms present in the environment. If poorly conducted it may jeopardize the quality and acceptance of coffee in the international market. The ideal fermentation time is very variable and depends on the environment temperature. The type and degree of tanks hygiene, the maturation stage of the fruits, the quality of the water used, the time elapsed between harvesting, peeling and beginning of the pulping operation. Generally, it varies between 15 and 20 h.

To speed up the mucilage removal process, the farmers may choose to add small amounts of special enzymes, which under environment conditions can complete the mucilage digestion in approximately 7 h. The ideal fermentation process for high quality coffee can be seen in Chap. 6.

Peeled coffees when well prepared are always classified as high-value commercial drinks. The mucilage is considered by farmers as a deterrent to the initial drying process and can be mechanically removed with great success. For this operation, the Brazilian market offers excellent machines that consume small volume of water per litter of peeled coffee.

In the mucilage remove machine (optional), the wet parchment coffee enters the base in a cylinder with a helicoid and an internal axis with nozzles that raise the grains to the top, where they leave practically without the mucilage. During this operation, the shaft and nozzles must be closed by a cylinder made of perforated metal sheet where the mucilage is discarded.

The first image of Fig. 1.9a, shows a traditional machine without the cap and with part of the cylinder being opened to show the helicoid and the nozzle system. During displacement, the mucilage is removed by water passing between the perforated cylinder and the shaft.

The processed coffee in this form is called Peeled Cherry. This traditional fermentation and washing processes are widely used in Colombia and Central American countries, grains are kept in a reservoir, immersed in water. In the fermentation tank (Fig. 1.9b) the coffee remains, for an enough period of time, so the microorganisms can consume the mucilage. After biological mucilage removal the coffee should be washed with clean water and sent to one of the drying processes. Coffee processed this way, receives the commercial name of "washed coffee".

Fig. 1.9 Mucilage extractor machine (**a**) in detail and in operation and part (**b**), Peeled Coffee, fermentation tank and wash channels after fermentation. Source: Authors

3.3 Reuse and Application of Processing Waters

Regardless of the process of preparing the coffee by “dry way” or, especially, by “wet way” a great amount of water is used.

If the option is for the traditional peeled cherry coffee process, a high-water consumption is required, about 3–5 L of water per liter of processed fruits. Also, during the washing, peeling and mucilage removal processes, fragments of leaves, branches, fruits, mucilage and many other wastes that had adhered to the so-called “ field coffee”, join the water of pre-processing forming the coffee processing water.

Due to the nutritional potential of these waste the coffee processing water cannot be released into the rivers or lakes without proper treatment. Therefore, that meets the conditions and standards for discharging effluents, as provided in Resolution 430, of May 2011, of CONAMA (Brazil 2011).

4 Drying

Knowing the techniques and equipment for coffee pre-processing that can be bought in the commerce or built in the farm (see equipment construction manual). In the same way, the next step is to know how to maintain or to minimize the reduction of coffee quality during the drying process.

As there are several possibilities to perform coffee drying, the coffee grower, in order to implement a project should be aware of the possibilities to choose the best option in each situation. The farmer must decide to purchase an industrialized equipment or build a drying system where efficiency, economy and quality are priorities.

As will be seen later on this topic, not always the most used technology means the best option; the reader will conclude that coffee drying is comparatively harder to perform than other products. In addition to the high sugar content in the mucilage and the initial moisture content, generally around 62% w.b., the deterioration rate shortly after harvesting is high.

If the aim is high quality coffee, the coffee grower needs to know that only in the first 3 days are possible to avoid a reduction in the quality obtained during the harvest, since the maximum quality is with the ripe fruit in the plant. Thus, whatever the drying system used; the following aspects are emphasized for the success of the coffee processing:

(a) Avoid undesirable fermentations before harvesting, pre-processing and during drying;
(b) Excessively high temperatures should be avoided. Coffee tolerates 40 °C for 1 or 2 days, 50 °C for a few hours and 60 °C for less than 1 h, without damage;
(c) Dry the fruits or the peeled cherry, avoiding the harmful effects of temperature, in the shortest time up to the moisture content of 18% w.b. (below this moisture content coffee is less susceptible to rapid deterioration); and
(d) Find a way to obtain a product with uniform color, size and density.

To understand how drying takes place and how to control the process, the coffee grower and his coworkers need to be trained to properly perform all post-harvest operations. It is fundamental that they understand the relationships between the environment air and the coffee that is under the drying and storage processes. They should be aware of how the changes in environment air (dry and humid) and improper management of drying system affect coffee quality. The coffee grower must understand that, as in nature the environment conditions (dry or humid) influence the drying process.

In nature, the coffee fruit, when ripe, dries on the plant, falls on the ground and germinates. Good drying does not damage the seed germination. The speed at where drying takes place will depend on the air conditions. The drier the air, faster the drying process. If there is no time control, the coffee may dry more than necessary, depending on air temperature and humidity. In face of that, causing damage during grain processing and unnecessary energy, labor and coffee weight loss.

For a better understanding of the drying process, one can start with a series of questions:

1. To what extent should the coffee grower dry his coffee?
   (a) The drying or removal of excess moisture must be done in such a way that the product enters in equilibrium (does not lose or gain water) with the environment air where it will be stored; and.
   (b) It must be made in such a way as to preserve the appearance, the organoleptic quality in case of roasting grains, and seed viability for new coffee plantations.
2. What to do to better understand the drying process?
   (a) To understand how drying takes place, it is essential to understand the relationship between the drying air conditions (temperature and relative

humidity) and the coffee. As in nature, it is the environment air conditions (dry or humid) that cause drying or damage.

(b) Drying in the plant may or may not damage seeds germination. The drying time will depend on the air conditions. The drier and hotter the air, faster the drying process and greater the chances of damage to the product and equipment.

3. What is relative humidity?
The air that naturally dries out the coffee is the same air we breathe and is composed, roughly, of Nitrogen, Oxygen, Carbon Gas and also Water Vapor. Humidity is important because it humidify our nasal mucous membranes and lungs. For each temperature condition, the air may contain a maximum amount of water vapor. When this happens, we say that the air is saturated or with 100% Relative Humidity. When the air is saturated, any small temperature dropping leads to the condensation of the air humidity or the steam passing to the water liquid form. As the saturated air cannot receive more moisture, it is not able to dry any product.
If the system operators do not fully understand what Relative Humidity means, they will have difficult to understand the drying process. For example, at 22 °C, 1 kg of air may contain a maximum of 17 g of water vapor. If the air contains only 8.5 g of water vapor, we say that the relative humidity is 50%. The relative humidity equals the amount of water the air contains, divided by the maximum amount of water it could contain multiplied per 100. Therefore, the relative humidity of our example would be: $(8.5/17) \times 100 = 50\%$.
If it is difficult to understand the theoretical meaning, they should try to understand through sensitivity. Very dry air makes breathing difficult because of dryness of the nasal mucous membranes. On the other hand, very humid air hinders perspiration (much sweat) on the skin. Generally, the ideal environment air is the one where we feel comfortable and we say that the climate is pleasant. In this situation, the air temperature is around 20 °C and the relative humidity, around 62%. In general, relative humidity is lower during the day and higher at night. It can also be said that during the day the air is drier and at night it is more humid. In an environment with an average relative humidity of 62% and an average temperature of 22 °C, the coffee will dry up to 12.5% moisture and remain at that value for as long as it is exposed to that air. On the other hand, if the average conditions are 50% relative humidity and 22 °C temperature, the coffee will dry up to 11% moisture. If the relative humidity is 40%, the coffee will dry up to 9.5% moisture. In another scenario, if the average relative humidity is 80%, the coffee will only dry up to 16% moisture. This happens a lot with the coffee dried in table dryer or suspended terrace in mountain regions. If the conditions above remain unchanged, the coffee will equilibrate with the air and will not lose or gain moisture.
4. Why do the mechanical dryers dry faster than the solar terrace drying?

The coffee grower and his assistants should be instructed to understand a little bit more about the drying process and the relationship between Relative Humidity and Drying Air Temperature.

To facilitate, first let's understand how the drying process in terrace dryer happens. Drying occurs with the terrace surface heating by solar rays and natural ventilation to facilitate the removal of steam. Only after heating, at about nine o'clock in the morning the coffee should be spread in the terrace, with a coffee layer about 4 cm thick. Then, with a suitable tool, small lines should be made in the direction of the operator's shade and should be changed its position once the exposed part of the terrace has heated up again. The coffee lines should be changed each hour, preferably.

After the fourth or fifth day of drying, the coffee should be piled up at three o'clock in the afternoon. The coffee yet heated needs to be covered with a system of tarpaulin with thermal insulation to avoid getting humidification at night. The next day, at nine o'clock in the morning, the coffee should be spread and stirred as explained above and repeated until the end of drying process.

The exclusive use of solar terrace drying by many coffee growers is mainly because of the non-care with the product qualitative characteristics after drying or because of economic and technical level of the property. Therefore, sunny and windy areas should be chosen for the solar terrace dryer construction.

In most producing regions, drying in solar terrace facilitates the development of microorganisms on the surface of the fruits, fruit breathing and temperature increasing, which are factors that accelerate the fermentation process. Despite these risks, small and medium-size producers intensively use solar terrace drying as the only step for coffee drying.

If the climate conditions are propitious and the drying operation is done within the technical recommendations, the natural coffee will be dry in 15–20 days and the parchment coffee between 10 and 15 days.

Coffee drying in solar terrace drier is influenced by environment conditions (insolation, ventilation and rainfall) and by handling operations. In the other hand, coffee drying in the drier mechanized system has other influences, because of that, the operator must understand that every time he heats the air (by furnaces or burners), the heat will reduce the relative humidity of that air. Therefore, at the entrance of the dryer it will be blowing warmer and drier air. With hot and dry conditions, the air will have a greater capacity to remove water from the coffee, even in unfavorable environmental conditions. So, artificial drying substantially reduces the drying time.

The coffee drying process with hot air dryers is very similar to what happens with hair drying, and in both of this cases, coffee and human hair, great care must be taken with the air and temperature. Thus, if the air has a greater capacity of drying, observing the maximum temperature that the product can support, less time will be necessary to remove the extra water and leave the coffee with the ideal humidity for commercialization.

5. What is the purpose of stirring the layer of coffee during the drying process?

This issue is like the previous ones, very important, not only for coffee, but for cocoa and many other types of “grains”. To be realistic about the subject, the only way to dry coffee fruit without proper stirring is when it is in the plant. In this case, the drying is characterized as field drying and has its disadvantages.

One way to work with drying in the plant would be to spread properly the coffee on a suspended screen. In this case, the height of the layer would be equivalent to the diameter of the coffee fruits. The suspended screen must have natural ventilation as in the field. On the other hand, a lack of homogeneity in drying will be noticed in some way by a professional grader.

To simplify the drying theory, we can say that a layer of coffee dries as if it were composed by a superposition of several thin layers. Also, a thin layer of coffee can be considered to be one whose thickness corresponds to the diameter of the coffee fruit or the grain thickness of the coffee parchment.

Assuming that the cherry coffee has a diameter of 1.0 cm and the coffee parchment a thickness of 0.5 cm, a “Fixed bed “ type dryer containing a 50 cm layer of the product should be analyzed as if was composed of 50 thin layers of coffee fruit or approximately 100 thin layers of parchment coffee.

In this “drying layer”, the drying air (heated or at environment temperature) enters the lower part through the first thin layer, which is on the false floor (perforated plate) and is released into the environment (exhaust) after passing through the thin layer (layer 50 for coffee fruits or layer 100 for parchment grain, in the given example).

When drying in a “fixed or stationary layer” dryer, the air enters hot and dry, then is exhausted cold (less hot) and moist from the upper surface of the coffee layer. Simplifying a little bit more, the air goes through the entire layer of coffee and passes through each thin layer, this way the air is cooled and humidified by the water released from the grains of the previous thin layer.

If you understood what it was exposed so far, you may think that it is not necessary to stir the coffee inside a dryer, since all the coffee is dry with the same moisture content. This statement is the big problem; all the coffee hit the equilibrium moisture with drying air at high temperature and low relative humidity, therefore with very dry air. To better understand what happens when we heat or cool the air, we accept that natural or heated air is the medium for drying grain. The natural air consists of a mixture of gases (nitrogen, oxygen, carbon dioxide, etc.), steam and a number of contaminants such as solid particulate matter and other gases.

Dry air exists when the natural air removes all steam water and contaminants. The dry air composition is relatively constant, despite small variations due to geographic location and altitude. Knowing about air humidity conditions is extremely important to many sections of human activity.

Preservation of products such as fruits, vegetables, eggs and others in refrigeration systems depends on mainly in an appropriate blend (dry air/water vapor). Storage and handling of grains, including coffee, are also limited by atmospheric conditions.

Sometimes the thermal comfort index of an atmosphere depends more on the amount of steam present in the air than on the temperature itself. Thus, an air conditioning apparatus promotes greater humidity control and only minor variations in the environment temperature value. For those reasons, the detailed study of the dry air mixture (N_2 + O_2 + CO_2 + others) and water steam became a discipline, called psychometry, which studies the relationships, from measurements of specific parameters, atmospheric behavior, mainly in reference to the mixture of dry air and water steam or moist air. A study on psychometry is recommended.

For a better understanding, suppose that in a coffee farm, during the drying season, using fixed bed dryer with the following conditions: environment temperature and relative humidity are 22 °C and 62%, respectively. If the air in this condition is passed through a 50 cm coffee layer for 250 h, for example, all coffee would be dried at moisture of 12.5%. It turns out that a moist coffee, even spending 250 h to dry, may have suffered some fermentation in the upper layers and damaged the final product quality. To speed up the drying process, the best solution is to increase the drying air temperature.

Now imagine that the coffee grower decided to raise the drying temperature to 40 °C. In this case, the relative humidity of the drying air becomes 25%. This way, after a certain time, the mass of coffee will be dried and reached a final moisture content humidity of 7%. All the coffee mass is homogeneous in temperature and moisture content; however, in this situation the coffee beans are very dry and they may break while processing, causing great financial loss due to the loss of weight and energy consumption.

To solve part of the fixed bed drying problem, the engineer must plan the size of the maximum height of the grain layer equal to the thickness of the drying front and tolerating gradients of temperature and moisture content for a particular grain. The most common grain, allowing a gradual variation in the moisture content is field corn and higher than three percentage points between the driest and the wettest layers for an average final moisture content of 14% w.b.

Unfortunately, for a quality coffee, the maximum tolerance is an average 0.5 percentage points from an average moisture content of 12% w.b. and can be measured by a good moisture meter. If the moisture variation between the grains increases, the coffee will present one of the most serious defects, which is the "bad roast".

Thus, it is almost impossible to dry coffee and some types of grains without the proper stirring of the layers, especially if the temperature of the drying air is 5 °C above environment temperature and the relative humidity is well below 50%. Therefore, the coffee must be continuously stirred in special dryers or depending on the temperature and airflow, every 2 h in the maximum.

For a better understanding, assume that the "fixed bed" dryer is operated with air at 40 °C in environment conditions (22 °C and 62% relative humidity). At 40 °C, the relative humidity of the drying air will be 25%. After a period of time (10 h for instance), the coffee in the first thin layer will have reached a final moisture of 7% and in this time the upper thin layers will still be drying.

If the operator stops the dryer for samples withdrawn because the upper layers have reached 12% moisture, it will discharge the dryer with the coffee mass having an average moisture content of 9.5% under a moisture gradient of five points between the first and last thin layer.

Now imagine that the operator takes samples from different layers of the coffee bed and stops drying when the average moisture content reaches 12%. In this case, the upper layers may be more than 17% w.b. e and the first layer 7%. Drying is a physical process, and, in that way, it cannot be simplified without something wrong happening.

We must remember that the grains moisture content classification does not measure the moisture of each grain, individually. It provides the average value of the sample. Inadequate drying will only be noticed during the processing and, especially, in the coffee roasting for beverage classification.

Depending on the drying air temperature, airflow, initial moisture and the height of the layer inside the drying chamber, the process takes place on a band or front that moves from the bottom upwards. The dryer designers call this band as drying front, indicating that, after several hours of drying, the drying front has formed and it has already moved. Below the drying front, the entire product is dry and in equilibrium with the drying air and below the front there is no more drying.

As drying time passes (50 h, for example), the drying front will have passed through the entire grain layer and the whole product will be dried with the same moisture content or at equilibrium with the drying air. Therefore, to avoid overdrying of the grain bed or to avoid large gradients of moisture, it is necessary that the grain layer is not too deep or that a stirring is done every 3 h of drying at least.

In Brazil, according to technological aspects involved, basically two methods are used to dry coffee: in terrace drying, the product is spread on floors, which can be built with cement, brick, and asphalt or similar; in mechanical drying, the heated air is forced to pass through the mass of grains.

For drying, with most of the traditional coffee dryers, the initial moisture and exudation of the mucilage by the fruits stop the operation of stirring the product inside the dryer. To solve this problem, a pre-drying in solar terrace pre-dryers is necessary.

More recently, drying in combination (pre-dryer/dryer and silo-dryer) has been studied and applied in specific locations of the Zona da Mata in Minas Gerais (Brazil). In those drying combination, the coffee it is pre-dried in solar terrace pre-dryers and the complementary drying in silo with natural ventilation or with the slightly heated air. All these systems will be detailed, later, in order to serve as alternatives to be adopted in different regions.

It must be remembered that at harvesting time, coffee presents 100% of its quality potential and that it is during the first 3 days after harvest that special care must be taken. If the harvested coffee is well maintained until the third day after harvesting and further operations have been carried out correctly, it will maintain high quality until it reaches the consumer. On the other hand, coffee where in the third or fourth day after harvest, had reduced its potential quality in 15%, continues to deteriorate until the product reaches safe storage moisture content. From the point of drying, the two types of coffee had proportionally, the same variation in quality reduction. Therefore, if the coffee is dried to a safe moisture level by the third day after harvesting, the coffee grower can deliver a quality product to the final costumer. A safe humidity is 18% w.b. at this moisture level coffee can be dried slowly with air and at low temperatures during the storage period in the farm.

In most coffee producing regions, drying in solar terrace facilitates the development of microorganisms, increasing temperature and breathing of the product, which accelerates the fermentation process. Despite of these risks, small and medium-sized coffee producers intensively use solar terrace drying as the only drying technique.

However, if the climate conditions are suitable and the operation of the terrace is done within the technical recommendations, the natural coffee will be dry in 15–20 days and the peeled cherry coffee between 10 and 15 days. Therefore, drying systems that safely dry the product at 18% moisture content, within 3 days or 50 h of drying, must be adopted.

Drying with efficient techniques presents the following advantages:

(a) Allows better harvest control;
(b) Allows storage for longer periods, without the danger of deterioration or quality loss;
(c) In case of coffee seed production, low temperature drying keeps the germination for longer periods of time;
(d) Prevents the development of microorganisms and insects; and,
(e) Minimizes the loss of the product on the trees or in solar terraces during rainy days.

As we know drying affects the product and is a process involving the heat transferring and moisture between the coffee and drying air. The reader should review the basic elements of psychometry, grain water content, equilibrium moisture content, air flow rate, drying speed, grading and coffee quality, in order to take full advantage of drying techniques and reduce production costs.

Because is too difficult to address all the points above in a single chapter, we will deal with some of the most important:

5 Coffee Moisture Content

The concept of moisture content (water content) is due to the fact that both fruits and grains are composed of solid substances and a certain amount of water, under many forms. For harvesting, drying and storage operations, the product is considered to consist only of dry matter and water. Thus, water or moisture content is the amount of water present in the coffee or grain in general.

The water content is considered the most important factor that acts in the deterioration process of stored grains. It is necessary to know the moisture content of coffee beans since harvest until the final processing. We must know that, with the removal of the protective layers, the coffee is very susceptible to the absorption of odors. As the drying air in the coffee dryers is generally heated by wood burning, the removal of excess water from the pre-processed coffee is an operation that can contaminate the product with smoke. Also, because of the necessity to obtain a homogeneous product, it is not possible to mix coffees with different moisture content in same dryers and at the same time. Thus, the operator needs to be careful to dry the coffee only till the needed moisture content level. Otherwise, excess of water removal will cause breakage problems in the hulling process.

It is very important to know the coffee moisture content before hulling. If the product has excess of moisture, it must be dried to approximately 12% w.b. In case of over drying, the product should go through a ventilation by a vented bin at night to absorb water until moisture content of 12% w.b.

Therefore, from the harvest until the final processing, knowing the water content of the coffee is extremely important. The purchase of a product with excess moisture content represents losses for the buyer, who will be paying for excess water and in possible danger for the final quality of the product during storage. Selling below ideal moisture will cause losses for seller as he experiences unnecessary energy costs and equipment use, also affecting coffee quality.

As a process applied to biologically active materials, coffee drying can be defined as a universal method of conditioning the product (coffee or grains in general) by removing the water to a level that keeps them in balance with the storage environment. In the same way preserving the appearance and quality for the roasting industry, and the viability as seed.

As a hygroscopic material, the coffee beans contain liquid water, which is in direct contact with the cellular structure, but is easily evaporated in the presence of air with low relative humidity. This water is known as “free water”. Another portion of water, called water of constitution, also composing the cellular structure, is chemically attached to the material.

During drying, most of the evaporated water is “free water.” To make it easy to understand, it will be considered here that the coffee beans are composed only of dry matter and free water.

The grains moisture content is expressed by the ratio between the quantities of water and dry matter that form the product. Lower moisture content is the most important factor in preventing the deterioration of stored coffee. Keeping the water or moisture content and coffee temperature low, it will prevent microorganism attacks and breathing will have their effects minimized.

The operator must always be aware that at the end of drying the product does not lose excess water, causing problems in handling, processing and marketing.

Ideally, moisture content should be determined prior to each subsequent drying operation. If there is problem with moisture content when starting a new operation, use the solutions previously advised.

5.1 Coffee Moisture Content Calculation

As said earlier, the amount of water contained in the grains is designated based on the weight of the water and is generally expressed as a percentage. There are two ways to express the moisture contained in a product, that is, wet basis (w.b.) and dry basis (d.b.).

The grain moisture contained in the wet basis is the ratio of the water weight (Pa) present in the sample to the total weight (Pt) of this sample:

$$U = 100\left(Pa / Pt\right) \quad (1.1)$$

$$Pt = \left(Pms + Pa\right) = \text{total weight} \quad (1.2)$$

Where:

U = moisture content. % w.b.
Pa = Water weight;
Pt = Total weight of the sample;
Pms = Dry matter weight.

The percentage of the moisture content in dry basis is determined by the ratio of water weight (Pa) and dry matter weight (Pms):

$$U' = 100\left(Pa / Pms\right) \quad (1.3)$$

$$U' = \text{Moisture content on dry basis}\left(\text{d.b.}\right)$$

From the equations, it is clear that the moisture content expressed in dry basis is numerically higher than the moisture content on the wet basis (U′ > U). This is because in the second case (U′), with only Pms, the denominator is lower than in the first case (U), where it represents the total grain weight (Pa + Pms), and in both cases, the numerator remains constant (the water weight).

Usually, the wet basis percentage is used in commercial designations and pricing. On the other hand, the moisture content in dry basis (decimal) is commonly used in research and in specific calculations.

5.1.1 Moisture Content Base Changing

A conversion table is useful and precise when it is desired to change from the dry base to the wet base and vice versa. The table can be constructed using the following equations:

(a) Changing from w.b. for d.b.

$$U' = \left[U / \left(100 - U\right)\right]100 \quad (1.4)$$

Where:

$$U = \%\text{w.b. and } U' = \%\text{d.b.}$$

Example: if U = 13% w.b., what will be the value of U′?

$$U' = \left[13/\left(100 - 13\right)\right]100 = 14.9\% \text{ or } 0.149 \text{ d.b.}$$

(b) Changing from d.b. to w.b.

$$U = \left[U'/\left(100 + U'\right)\right]100 \quad (1.5)$$

Example: if U′ = 0.13 or 13% d.b., what is the value of U?

$$U = \left[13/\left(100 + 13\right)\right]100 = 11.5\% \text{w.b.}$$

5.2 Moisture Content Determination methods

There are two methods group for grain moisture content determination: (a) direct or basic (oven, distillation, evaporation, infrared radiation) and (b) indirect (electrical methods, calibrated according to standard oven method or other direct method).

5.2.1 Direct or Basic Methods

By direct methods, the mass of water extracted from the product is related to the mass of dry matter (moisture content, dry basis) or to the total mass of the original material (moisture content, wet basis). Although they are considered standard methods, the direct methods require a longer time and meticulous work for their execution. Commonly used in quality control laboratory analysis the main ones are the oven, distillation, evaporation (dweob) and infrared methods.

Oven

The determination of the moisture content by the oven method (under atmospheric pressure or vacuum) is done by drying a sample of grains of known mass, calculating the moisture content through the mass lost during drying. The ratio between the sample mass loss taken from the oven and its original mass, multiplied by 100, gives the moisture content in percentage, wet basis (Eq. 1.1).

The drying time and the oven temperature are variable and depend on the type and product conditions and the type of oven. To use of the standard method, the reader should consult the manual “Rules for Seed Analysis”, which should be edited by the responsible departments of each producing country.

Distillation

The grain moisture is removed by boiling a small sample in a vegetable oil bath or in toluene, whose boiling temperature is much higher than the water. The water steam from the sample is condensed, collected, and its weight or volume determined. There are two distillation methods: Toluene and Brown-Duvel. The Brown-Duvel is the most common, it will be described below and is one of the standard methods in the United States of America. The equipment can be made of several modules and the moisture is determined by the distillation process.

Sample size, temperature and exposure time change with grain type. It is therefore it is advised to consult the equipment manual before performing the moisture determination.

The water is removed by heating a mixture of grains and vegetable oil until to the boiling point. The boiling temperature of the oil is a lot higher than the water. The water steam from the sample distillation is condensed and its volume determined.

Considering the water density as 1.0 g/cm^3, the mass of the water withdrawn is equal to the volume measured by a graduated cylinder. Commercial Brown Duvel has a thermometric system that automatically shuts down the heating source when the oil reaches a specific temperature for each type of product.

Despite the many types of moisture meters (direct or indirect) available in the market, they are relatively expensive and often suppliers do not provide appropriate technical assistance. Due to this fact the DWEOB (Direct water Evaporation in Oil Bath) was developed. This method is nothing more than a simplification of Brown Duvel. It is inexpensive and has the same precision of the standard method. Figure 1.10 shows a simplified scheme of the DWEOB method, which can be built with regular and laboratory tools such as thermometer and a scale with a capacity of 500 g with an accuracy of 0.5 g, or better, and actually putting together the DWEOB system.

In order to determine humidity through DWEOB, the operator needs to follow the following steps according to the next examples:

Example 1: Determine the moisture content of a coffee sample using the DWEOB. Procedures:

(a) Sampling the coffee production correctly;
(b) Weigh 100 g of the coffee and place it in a high temperature resistant container with 10 cm diameter and 20 cm high, and a perforated lid (screen type) with a larger hole to insert a graduated thermometer up to 200 °C;
(c) Add soybean oil until it covers the coffee layer;
(d) Weigh the container + product (coffee sample) + oil + thermometer and take a note of the initial mass (Mi);

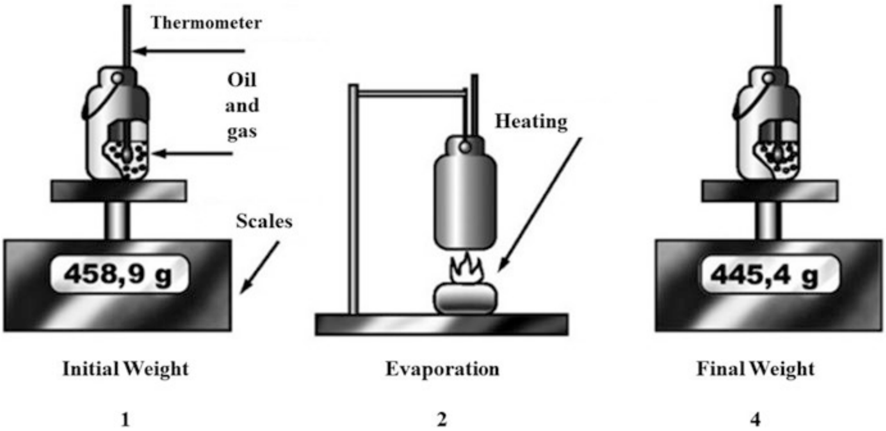

Fig. 1.10 Schematic of a DWEOB (moisture meter) with gas flame. Source: Authors

Table 1.2 Temperature for moisture content determination by the DWEOB method

Product	Temp. (°C)	Product	Temp. (°C)
Beans	175	Corn	195
Rougth rice	200	Soybean	135
Hulled rice	195	Sorghum	195
Dry coffee fruit	200	Wheat	190
Hulled coffee	190		

(e) Heat the container for approximately 15 min until it reaches the temperature indicated in Table 1.2 (in the case of the hulled coffee, 190 °C). Then remove the heat source, wait for the bubbling to cease and perform the weighing to obtain the final mass (Mf); and.

(f) The result of Mi – Mf is the moisture content in percentage, wet basis. For example, if Mi = 458.9 g and M f = 445.4 g;

$$\text{Ma} = \text{Mi} - \text{Mf} = 13.5\,\text{g}.$$

i.e., the moisture content of the coffee batch is 13.5% w.b.

Example 2: represent, in decimal dry basis (d.b.), the moisture content found in wet basis percentage (w.b.) in the previous problem.

Solution: According to Eq. (1.4):

$$U'(\%) = ?$$

$$U(\%) = 13.5\%.$$

$$U'(\%) = [13.5/(100 - 13.5)].100 = 15.6\% \text{or} \, 0.156 \, \text{d.b.}$$

5.2.2 Sources of Error with Direct Methods of Moisture Content Determination

Considered primary or secondary standards, direct methods are subject to errors. The main ones are:

- Incomplete drying;
- Oxidation of the material;
- Sampling errors;
- Weighing errors; and.
- Observation errors.

Figure 1.11 shows the weight variation of the sample using a direct method. Three phases are identified to illustrate the first two types of errors. In the first stage, the grains gradually lose water, while in the second drying phase (the sample weight remains constant) because all the "free water" has been removed.

Prolonging the time after the second phase, new weight loss begins to occur due to sample oxidation. If the process is interrupted in the first or third phase, an error will happen. Therefore, the interruption needs to take place in the second phase, when there is no change in the sample weight.

Sampling Errors: The purpose of a sample is to represent a population or a big amount of certain product. If sampling is not performed according to proper techniques, the value obtained will be not reliable even using the most reliable method.

Weighing errors: The use of inappropriate or inaccurate scales leads to errors while determining moisture. The weighing of samples yet hot, causes convection currents and really affect the final result.

In order to better characterize the product moisture content, the samples weighing and the reading in the equipment must be made by a single person. Depending on the equipment type, a reading between two known values done by different people will hardly have the same value.

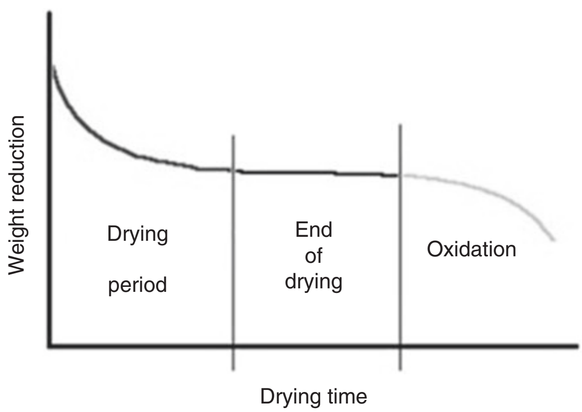

Fig. 1.11 Sample weight variation, in function of the time, by direct methods. Source: Authors

5.3 Indirect Methods for Moisture Content Determination

The most important are the electrical methods. The equipment classified in this category uses a grain property that varies with its moisture content and is always calibrated according to a direct method adopted as the official standard.

Because of high speed of the moisture content measurement, electrical or electronic moisture meters are used in the control of drying, storage and in commercial transactions. This equipment provides the value of the moisture content on a wet basis. It shows the percentage relation between the amount of water and the total mass of the sample, according to Eq. (1.1).

5.3.1 Electrical Resistance Method

The electrical conductivity of a biological material varies with its moisture content. In the case of grains, the moisture content (U) is inversely proportional to the logarithm of the resistance they offer to the passage of an electric flowing. In a given moisture range, the moisture contained in a grain sample can be given by Eq. (1.6).

$$\mathrm{U} = \mathrm{K}\left(1/\log \mathrm{R}\right) \tag{1.6}$$

On what:
U = moisture content;
K = constant depending on the material; and.
R = electrical resistance.

It is known that the electrical resistance of a material varies according to its temperature and that, unlike metals, an increase in temperature promotes a decrease in electrical resistance in the carbon. Since the grains are basically composed of carbon, measuring with equipment based on the principle of electrical resistance, the operator needs to take care of the sample temperatures. High temperatures can induce errors (high temperature results in a low electrical resistance, which in turn means high humidity). Therefore, it is necessary to make the temperature correction.

The electrical resistance also depends on the pressure made by the electrodes on the grain sample. The higher the pressure over sample, the lower the electrical resistance, which will influence the correct value of the moisture content. That way, each type of grain, using the same moisture meter, must be subjected to a specific pressure (read the equipment catalog).

Usually, commercial tools show better results for samples with low moisture content (10–20% w.b.).

When using equipment based on electrical resistance, the following points should be observed:

1. Refer to the equipment manual. Each type of grain requires a specific technique and the reading cannot be repeated with the same sample. Once passed by measuring it is damaged by the compression system.

2. Sampling techniques must be followed.
3. At each determination the electrodes must go thorough cleaning.
4. Periodically adjust the compression system. It is subject to relatively high efforts and may suffer serious malfunctions.
5. Beware of hot samples. To avoid errors, it is important to keep the samples in repose for some time (homogenizing the moisture inside the beans) and wait until their temperature is close to the moisture meter temperature.
6. In case of grains with wet surface by condensation or rain, it will have moisture content above the real value.
7. Moisture meters shall be periodically evaluated and, if necessary, re-calibrated using a direct method.

5.3.2 Dielectric Method

The dielectric properties of biological materials depend on their moisture content. The capacitance of a capacitor is influenced by the dielectric properties of the materials placed between its plates. Thus, by determining the variations of the capacitor electric capacitance, whose dielectric is represented by a mass of grains, one can indirectly determine its moisture content.

The variation of the dielectric capacity (D) and the moisture content (U) of the grains are given by Eq. (1.7).

$$U = D \times C \tag{1.7}$$

On what
D = dielectric;
C = constant depending on the equipment, material etc.; and,
U = moisture content.

The moisture meter based on this principle are quick and easy to operate. Unlike electrical resistance systems, they do not damage grain samples.

To properly use a dielectric or capacitive moisture meter, the operator must pay attention to the following recommendations:

1. Since some moisture meters also measure a small electrical resistance, they are considered more accurate in the determination of lower moisture contents. This method allows measuring the samples moisture content, even hot, due to the effect of temperature is lower than that observed in the electric resistance method.
2. Sampling techniques must be followed.
3. Proper sample temperature correction is required.
4. Damping the sample into the moisture meter chamber must be made from the same height and with care. There are moisture meters that have automatic devices for weighing and loading samples.
5. Voltage fluctuations can harm the operation and the equipment should be standardized frequently according to the equipment manual.

6. Moisture meters shall be periodically evaluated and, if necessary, calibrated by a direct method.
7. For each type of grain there is a specific table for moisture content evaluation.
8. The manufacturer's instructions must be followed correctly.

6 Equilibrium Moisture Content

The concept of Equilibrium Moisture content is important because it is directly related to the coffee drying and storage also other agricultural products. It is useful in order to know if the coffee will gain or lose moisture, depending on the temperature and relative humidity of the drying air or the environment where it is stored. When the rate of moisture loss from the product to the environment is equal the grain to the environment, it is said that the product is in equilibrium with the air. The moisture of the product, when in equilibrium with the environment, is called equilibrium moisture content or hygroscopic equilibrium. The equilibrium moisture is, therefore, the moisture that is observed after the grains are exposed for long period of time to a certain environmental condition.

The equilibrium moisture content of a coffee sample is a function of temperature, relative humidity and the physical conditions of the product. For example, the dried coffee fruit, parchment coffee and hulled coffee have different equilibrium moisture contents for the same environmental conditions.

The relationship between the moisture of a given product and the corresponding equilibrium relative humidity for a given temperature can be expressed by the curves (Fig. 1.12a). In Fig. 1.12b, we can observe the representation of the hysteresis phenomenon, where it is verified that the values of the equilibrium moisture content are not equal when the coffee gain water (adsorption) and when water is lost (desorption).

The rate of adsorption of water by the coffee is a lot slower than the rate of desorption, which causes the phenomenon of hysteresis to happen between the drying curve and the product rewetting.

The mathematical relation most used to represent the equilibrium isotherms is given by Eq. (1.8):

$$1 - \mathrm{UR} = \exp.\left(-\mathrm{C}\,\mathrm{T}\left(\mathrm{Ue}\right)\mathrm{n}\right) \tag{1.8}$$

Where:

UR—relative humidity, decimal;
exp. – ln base = 2718;
T—Absolute temperature, K;
Ue—equilibrium moisture % d.b.; and,
C and n—constants that depend on the material.

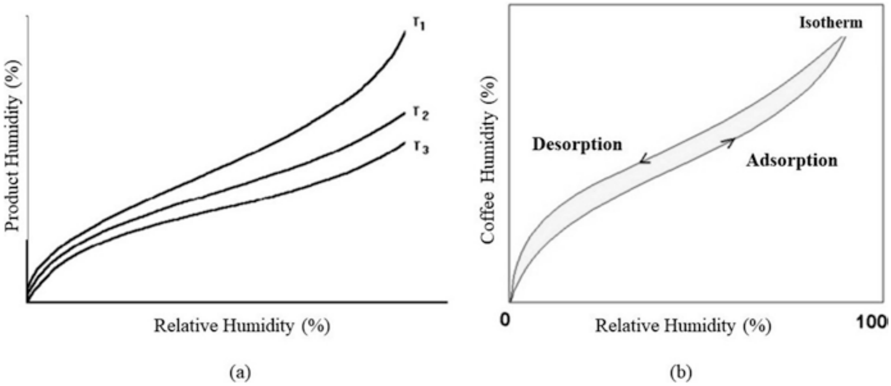

Fig. 1.12 Equilibrium isotherms with T1 < T2 < T3 (**a**) and Hysteresis phenomenon (**b**). Source: Authors

From Eq. (1.8) and Fig. 1.12a it is observed that:

- The equilibrium "moisture content" is zero for relative humidity equal to zero;
- The equilibrium "relative humidity" is close to 100% when the product moisture content increases to 100%; and.
- The slope of the curve tends to infinity when the humidity tends to 100%.

The relation between the Ueq value and the air conditions (temperature and relative humidity) can also be represented by the following Equation:

$$\mathrm{Ueq} = \mathrm{a} - \mathrm{b}\left\{\ln\left[-\left(\mathrm{T} + \mathrm{c}\right)\ln \mathrm{RH}\right]\right\} \tag{1.9}$$

Where:

a, b and c = constants that depend on the product (Table 1.3);
T = air temperature (°C);
RH = relative humidity (decimal); and,
Ueq = equilibrium moisture content (decimal, d.b.).

7 Airflow

When the grains lose moisture during the drying process, the water, in form of steam, is carried by the airflow that passes through the grains layer. To properly design and operate a coffee drying system, the fundamental principles of air movement need to be understood, especially those related to static pressure, fan characteristics and system operating conditions.

Table 1.3 Constants a, b and c for the calculation of grain moisture content equilibrium, according to Eq. (1.9)

Product	a	b	c
Coffee	0.3	0.05	50.55
Corn	0.339	0.059	30,205
Paddy rice	0.294	0.046	35,703
Soybean	0.416	0.072	100,288
Wheat (hard)	0.356	0.057	50,998

Table 1.4 Constant (a) and (b) for Eq. (1.10)

Product	a	b
Dry coffee fruit	0.017	3.9
Parchment coffee	For lack of data, use soybean values	
Shelled corn	0.583	0.512
Rougth rice	0.722	0.197
Soybean	0.333	0.302
Wheat	0.825	0.164

7.1 Static Pressure

The static pressure of a grain drying system is related to the resistance of the grains to the passage of air. Generally, the static pressure variation (PV) per unit height of the grain layer (mmca/m) is expressed, and can be calculated according to the following Eq. (1.10).

$$PV = (a\,Q\,2) / \ln(1 + bQ) \tag{1.10}$$

Where (a) and (b) are constants that depend on the product and Q is the airflow in m^3 per minute per m^2 area of the grain layer. Values of the constants (a) and (b) for some grain types are shown in Table 1.4. In a well-designed grain drying system, more than 90% of the airflow resistance happens in the grain layer and less than 10% in the distribution channels of air and perforated floor. The characteristic curve of the system is a graph showing the variation of the total static pressure of the system as a function of the airflow.

8 Fans

During drying and grain aeration forced ventilation systems are required. Also, other systems such as separation, cleaning and transportation machines require a component to create an energy gradient that promotes air movement through the elements of the system and the product. In grain drying, the air carries the product evaporated water out of the dryer. In the aeration, the purpose of air is to only cool the grains mass, although sometimes carrying small amounts of evaporated water.

Fans are machines that work by rotating a rotor provided with properly distributed blades and motor driven, enable the mechanical energy of the rotor to be converted into potential energy forms of pressure and electric energy. Due to the energy produced, the air becomes capable of overcoming the resistances offered by the distribution system and by the grain mass, so that it can be dried, cooled, separated, cleaned and transported.

8.1 Fans Classification

There are different criteria that can be used to classify fans. It will be mentioned the most used in the subjects included in this chapter. Also, which ones are the most used for drying and storage of agricultural products such as coffee:

According to the energy level of pressure that they reach, the fans can be:

- Low pressure: up to 2.0 kPa (200 mmwc) and are widely used in aeration of small and medium silos;
- Medium pressure: between 2.0 and 8.0 kPa (200–800 mmwc) used for aeration in taller silos and also in high temperature dryers;
- High pressure: between 8.0 and 25 kPa (800–2500 mmwc). Widely used for pneumatic conveying.

Above 25 kPa the fans are classified as compressors. Except for pneumatic conveying that must be from medium to high pressure, the fans used in the operations of drying, cleaning, separating, sorting and coffee aeration and other types of grain are usually done by most medium pressure.

According to the constructive modality they can be classified as:

- Axial: the rotor resembles a propeller. Air enters and exits the fan parallel to the fan axis;
- Centrifugal: In this fan type, the air enters the casing or volute, parallel to the drive shaft then is unloaded perpendicular to the air inlet direction. The rotor can be produced and have backward, forward or radial options with straight blades.

The characteristics of a fan can be obtained either in tables or by the characteristic curves provided by the factories.

Axial flow fans normally have a higher airflow than centrifugal fans of the same power for static pressures below 1 kPa (10 mbar). If a coffee ventilation system has to operate at static pressures greater than 1.2 kPa, a centrifugal fan will provide a higher airflow. An axial flow fan, although it is less expensive than an equivalent centrifugal fan, it has a higher noise pollution index.

8.2 The Use of Fans for Drying

The drying rate of a batch of coffee depends on the drying system and drying characteristics of each grain, individually. In general, the drying rate for small grains is higher than for large ones. Peeled Cherry coffee dries faster than natural coffee fruits. Because of the protective layer, grains of rice in the husk, dry out more slowly than the grains of wheat. In the same way, comparisons can be made with the coffee beans. If not properly separated by maturation stage such as size and the same physical conditions, it will be difficult to obtain a final product with homogeneous drying and the same roast point.

There are two ways to reduce the agricultural products drying time:

(a) Increasing the airflow passing through the product increases the amount of evaporated water. The drying rate is, to a certain extent, proportional to the airflow; and.
(b) Increasing the temperature of the drying air increases its drying potential.

In drying systems using low temperatures, the drying must take place in a time that it does not predispose the upper layers of the grain mass to deteriorate. The use of an auxiliary heat source can make low temperature drying systems economically impracticable, as well as causing the product to be over dried. This way, calculating the airflow and using the proper fan are the most practical and efficient ways to control the drying time.

9 Coffee Dryers

As will be discussed along this topic, not always the most used technology means the best option for coffee drying, especially, for a certain coffee grower. Also, that coffee drying is comparatively harder to perform than other agricultural products. In addition to the high sugar content in the mucilage, the initial moisture content, generally above 65% w.b., causes the rate of deterioration to be quite high shortly after harvesting.

For quality coffee, the farmers should follow some practices already mentioned in this chapter. The careful coffee grower will only have the first 3 days to avoid a large reduction in the quality achieved during the harvest operation. As already mentioned, the maximum quality is with the ripe fruit in the plant. Therefore, whatever the drying methods used, as it will be discussed ahead, we must emphasize that “Good Practices” need to be followed throughout the coffee production chain.

9.1 Terrace Coffee Drying

First, the drying in terrace happens with the heating of the terrace surface by the sun. Natural ventilation will facilitate the removal of water steam. Only after the sun's rays have warmed up the terrace at about nine o'clock in the morning, the coffee should be spread with a layer of approximately 4 cm thick. Then, with proper equipment, small heaps should form in the direction of the operator's shadow.

These heaps lines should be changed as soon as the uncovered part of the terrace is heated again. The operation of forming and changing the heaps should be done hourly, preferably.

After the fourth or fifth day of drying, the operator should follow the operating sequence as seen in item 4 and question 4 (Why do mechanical dryers dry faster than the terrace drying?).

The exclusive use of terrace drying by many coffee growers is mainly because of non-concern with the qualitative characteristics of the product after drying, or due to the financial capacity or even the low technical level of the farm.

In most producing regions, terrace drying facilitates the development of microorganisms, increasing respiration and fruit temperature, which are factors that accelerate deterioration. Despite these risks, small and medium-sized producers intensively use the terrace drying as the only step to dry coffee.

If the climate conditions are appropriate and with correct terrace management, the natural coffee will be dried in 15–20 days and the peeled cherry between 10 and 15 days.

9.1.1 Location of the Drying Terrace

A good drying terrace should be located in a flat, well drained, sunny and ventilated area. When possible, the terrace should be located at a lower level than the reception and initial preparation facilities, and superior to the storage and processing facilities.

Concrete-paved terraces provide better results, are more durable, easier to handle and have better sanitation characteristics. It is not conceivable nowadays to continue to see a large part of coffee farmers using terrace drying without proper lining. In addition to the lack of hygiene, drying is slow and usually humidifying coffee, because it does not facilitate the heating of its drying surface, which allows the translocation of soil water to coffee.

9.1.2 Types of Drying Terrace

It is very common in Brazil to see drying terrace made with asphalt technology. When used for large areas and allowing a good job of machines and the correct application of asphalt, the only inconvenience is the high temperature, which can cause serious damage to the peeled cherry coffee.

Unfortunately, there is an inadequate dissemination of a technology that, when not properly performed, leads to financial problems, frequent repairs, and quality problems due to contamination of the product. In this type of terrace, while using asphalts mud some problems were observed such as: problems such as: Asphalt layer adhesion, mechanical strength, surface unevenness, high porosity and appearance of vegetation.

Regardless of the type of pavement, one of the restrictions on the terrace drying process refers to climate problems.

Because it is considered a bottleneck for many producing regions, the conventional terrace has been considered inadequate because it exposes the product to adverse weather conditions, presents low drying efficiency and requires too much human labor.

Disregarding the high implantation costs and the labor-intensive requirement, the inconstancy of solar radiation and the possibility of rainy periods during the harvest season, make the drying terrace unfeasible for the production of quality coffees in regions of altitudes, very common in Zona da Mata de Minas, Serra do Espírito Santo, Planalto da Conquista and Chapada Diamantina (Bahia). For all this, terrace drying is considered one of the highest cost operations in coffee production. To succeed with the technique, it is mandatory periodic maintenance, such as:

Correction and rectification of the terrace floor;
Correction of the drainage system;
Correct management of the terrace, and,
Daily sanitation of the entire system.

9.1.3 Required Area for Terrace Drying

The paved area required for the terrace dryer should be calculated according to the average production of thousand trees, the total number of coffee trees and the region climate conditions.

If only the terrace is used for drying, the area calculation can be done according to Eq. (1.11).

$$S = 0.055\ QT \tag{1.11}$$

In the equation, S equals the terrace area in square meters for the production of 1000 trees, Q is equal to the average annual production of cherry coffee or the quantity of liters/1000 trees and T is the average drying time in the region, in days. When using the terrace for pre-drying to reduce the initial fruit moisture content to approximately 30% w.b, and with the additional drying being performed in mechanical dryers, the terrace area may be reduced to 1/3 of the calculated value for terrace drying only.

Whenever possible, the terrace should be divided into blocks, in order to facilitate the drying of the lots according to their origin, moisture content and quality (Fig. 1.13). Pre-drying in conventional terrace takes place in a period of 6 days.

If the use of drying terrace is mandatory, the recommended one is a good concrete paved terrace. It must be able to withstand loads and be fenced in order to prevent the entrance of animals and must be built with walls that facilitate the gathering of the coffee also allowing a good cleaning.

If it is used for coffees from different pre-processing days or different types of coffees, the terrace must have also movable partitions, when it is necessary to place different batches in a same area limited by the fixed walls. It is extremely importance that the terrace drying be done correctly, and that the daily sanitation of the system be maintained.

To protect coffee at night or in rainy days, circular or semicircular barriers can be built inside the terrace. These barriers are small walls with a triangular cross-section of 5 cm in height and 3 m in diameter, which serves as a place to pile the coffee, avoiding the entry of rainwater under the tarpaulin covering the coffee partially dried (Fig. 1.14).

Construction of terraces should be avoided in humid places near dams, in shaded places by trees or buildings and on the east and west faces. For the south hemisphere, buildings located near the north side of the terrace should also be avoided. This orientation is very difficult in mountain regions such as “Matas de Minas Gerais” and “Serra do Espírito Santo”.

Fig. 1.13 Terrace with concrete pavement, sanitized, fenced and divided into blocks. Source: Silva et al. (2018)

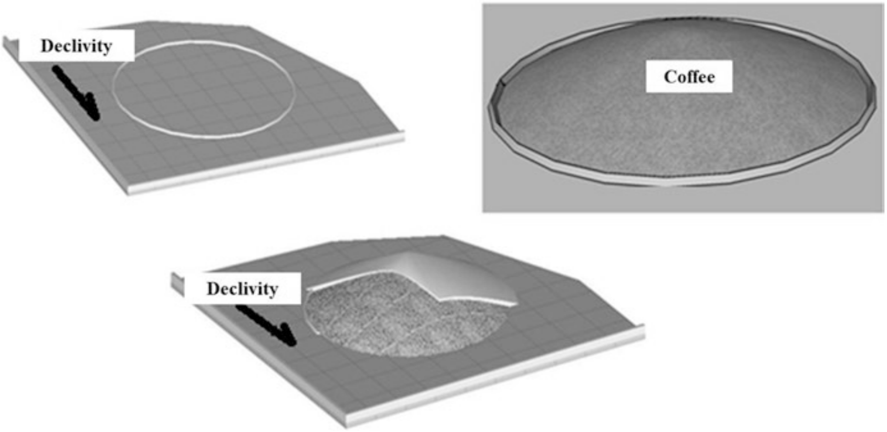

Fig. 1.14 Circular barriers to protect the partially dried coffee in rainy days. Source: Adapted from Silva et al. (2018)

9.1.4 Drying Terrace Management

As mentioned, the coffee is dried by the action of the solar rays and by the natural ventilation. It is advisable to work with homogeneous lots during the drying season, considering both the day of harvest and the maturation stage, in order to obtain a uniform final product of good quality.

At the beginning of drying, when the coffee is still wet or when it is removed from the coffee wash machine, the surface of the terrace also gets wet. If part of the terrace surface is not exposed to the immediate drying of excess water, the product becomes highly susceptible to contamination due to the high humidity in the lower part of the layer.

To do this, the coffee layer should be opened, for at least the first 5 days, to form small heaps. The heaps should be broken and redone continuously at regular periods of time, never exceeding 1 h and must be done following the shadow of the worker.

The open lanes can be made with the aid of a scraper blade or with a leaf blower after the coffee surface water has been removed. In all cases the open lanes will be dried and heated by the sunrays that indirectly will speed the coffee drying in the next turn.

As drying progresses, the product should be dried in bigger heaps during the last 5 days of drying. In this case, a more appropriate tool should be used.

After the first 5 days of drying with normal solar incidence, when the coffee is partially dry, at approximately 3 O'clock in the afternoon, it is necessary to heap the coffee in big heaps, in the direction of the terrace greater slope, which must be covered with a jute blanket and on top of it with plastic tarpaulins.

The cover, thus formed, will allow the conservation of heat absorbed by the coffee during the exposure to the solar rays, guaranteeing better uniformity and distribution of the moisture inside the coffee fruit or the peeled coffee.

In the morning of the following day, at approximately 9 O'clock, the blanket must be removed, and the coffee heaps moved from the overnight place to a dry area. Afterwards, the product should be spread over the terrace, repeating the operations made in previous days, until the ideal moisture content for storage (12% w.b.), or until the point of half-dry (35% w.b.), which is ideal to start final drying in mechanical dryers.

9.1.5 Drying Terrace Disadvantages

In order to maintain a competitive coffee production in certain aspects such as: productivity, quality and economically sustainable, the knowledge of modern production techniques is required.

For the international market it is very important that the coffee has desirable organoleptic and chemical properties and they depend on the efficiency of pre-processing operation. As mentioned before, the drying method used is the operation that has the greatest influence on the final quality of the coffee and it is during the first 3 days after harvesting that coffee growers are able to maintain the quality of the harvested product, to achieve quality standard. In an effort to reach this aim it is sufficient that, after being properly prepared, the coffee is dried to 18% before 50 h after washing or peeling.

To solve problems with quality loss in a guaranteed way and within the coffee growers' possibilities, furnaces were designed, and they will be discussed later. Also, some technologies such as "Hybrid Terrace or Terrace Dryer" are more efficient and economically correct.

Up until recently, no coffee drying system had been developed to satisfy the majority of producers, especially those producing coffee in the mountainous regions.

Terrace drying is considered a bottleneck for many producing regions; If the terrace is inadequate, it will expose the product to adverse weather conditions, it will have low drying efficiency and it will use too much labor.

Commercial mechanical dryers, as we will see later, require maintenance and energy availability, pre-drying, and if the quality is deteriorated during pre-drying, we cannot expect good qualities from mechanical drying.

A well-designed system, equipped with loading, stirring, unloading, heating and ventilation systems will produce a quality coffee if the output from pre-drying (natural or artificial), is of quality. Thus, the quality of a product in the mechanical dryer cannot be improved if it came deteriorated from the terrace pre-drying. Therefore, depending on the environmental conditions, if coffee moisture content does not reach safe levels until the third day after harvesting, a higher quality coffee cannot be expected even when the farmer uses an excellent system for complementary drying. Also, drying coffee in terraces is near to impossible to get good quality coffee, because of the high implantation and labor costs, inconstancy of solar radiation and the possibility of rainfall during harvesting.

9.1.6 Problems with the Use of Solar Energy for Coffee Drying

In terrace drying, the energy used to remove moisture from the coffee beans comes from the solar radiation and the enthalpy of the natural ventilation that carries the moisture released from the product out. Although, it is widely used by family farmers around the world to dry rice, corn and beans. Solar drying on terraces and platforms are especially used to dry coffee and cocoa, yet, there are some concerns about the product quality when talking about disadvantages of drying in terrace.

Even so, there has been great interest in the possibility of using solar energy for mechanical drying and in other applications. However, the amount of solar energy that fall in a surface perpendicular to the sun's rays is relatively diluted. In a completely clear day at a medium latitude of Brazil is approximately 20,000 kJ/day, for square meter of collecting area. That means, an absorber surface of 2.5 m^2 could, in a best scenario, only intercept a quantity of solar energy equivalent to 1 kg of diesel oil or 3 kg of charcoal per day. For a medium-sized coffee dryer, approximately 40 m^2 of collector area would be needed.

Unfortunately, the sun does not shine every day and in the absence of solar radiation, it would be necessary to use a furnace coupled to the dryer. Therefore, the use of a mixed system (furnace plus solar collector) should be taken in an economic base.

Although, there are several types of dryers that use solar energy, such as those used for small coffee production, two systems were built and tested at the Federal University of Viçosa. One of these driers resembles a horizontal fixed bed drier, having a sunroof (solar collector), a blower, a connecting duct and a drying chamber as shown in the second image.

The second is a rotary solar dryer, which is an improvement of the solar table dryer. This dryer consists only of a box formed by wooden sides, with front and backs in steel screen with square mesh of 4 mm. The box has a central axis, which is supported by two small wooden pillars, to allow easy rotation. Natural ventilation is the method that takes away heat absorbed along with moisture, as it does in traditional terrace or table dryer.

The small coffee grower or the one who wants to participate in a quality contest may opt to dry the coffee in mobile suspended table dryers, which consists of several perforated trays to retain the grains. The trays with appropriate dimensions, are constructed on a railing system. The tray set, when not exposed to the sun, is sheltered under a fixed cover to protect the product from rain or nocturnal condensation. The dryer operator has to pull the trays out to expose them under solar radiation and stir the coffee periodically. The system must be oriented in such a way that it can receive the solar incidence in the longest possible time.

Because table dryers do not contain the coffee in direct contact with the floor, they do not present cleaning and disinfection difficulties and, therefore, the product is less exposed to the contamination by undesirable microorganisms. In addition, the table dryer or suspended terrace brings some advantages, like natural ventilation and less coffee stirring operation.

A big drawback of the table dryer is at the end of drying, which is greatly influenced by dew and wet night winds. One solution that many coffee growers have found is to cover the dryers with a transparent plastic cover that allows solar radiation and protects the coffee from rain. Even with this improvement, the table dryer has slowed final drying, because of nocturnal high relative humidity of the air.

A solution would be to completely close the system around the table dryer. As Table dryers for big productions are relatively expensive, another option would be to transform the table dryer into a forced air dryer heated by an indirect heating furnace. To do this, simply build a wall with small axial fans around the table dryer. The furnace and the heat exchanger should be adapted under the dryer's floor.

The heat exchanger, formed by a 50 cm in diameter metal pipe, connects the furnace to the chimney. The function of the small fans is to remove heat from the heat exchanger and force it through the coffee layer, which must be stirred periodically.

Still using the advantage of solar radiation, as in the original model, this dryer improvement allows drying during rainy periods and in the absence of solar radiation. Based on cost, the small axial fans can be replaced by a centrifugal fan of equivalent power and forcing the air to enter the same points where the small fans would be installed.

9.2 High Temperature Drying in Mechanical Dryers

Although the modifications shown in the previous item will be classified with drying at high temperatures, they will be kept with the drying systems in terraces and table dryers for didactic reasons. The reader will understand that, in many cases, the producer will encounter problems due to the climate conditions, with consequent qualities reduction if he does not use a system that guarantees the drying even in bad climate conditions.

To obtain good quality coffee, it is necessary to use mechanical dryers to speed up the process. On the other hand, special care is also required to control the temperature of the grain mass, especially when the moisture content is <25% w.b.

For moisture contents lower than this value, depending on the drying system used, there is a tendency for the temperature of the grain mass to equal the temperature of the drying air. This tendency is caused by the difficulty of moisture migration from the innermost layers to the periphery of the grains. The maximum air temperature the coffee should be dried in a conventional crossflow or fixed bed dryer is 60 °C.

The drying operation with air at high temperatures is detrimental because coffee does not flow easily inside the dryer, primarily at the beginning of drying. While part of the product is dried in excess, the other part may not reach the ideal moisture content (11–12% w.b.). This fact brings difficulties during roasting process and the end result.

In addition to accelerating post-harvest operations, drying in mechanical dryers help the coffee grower to be less dependent on climate conditions and to have better control of the drying process.

In the Brazilian market a large variety of industrialized dryers can be found and the literature provides models that can be built on the farm.

For the proper functioning of the mechanical dryers, the mass of coffee should not have excess water, to facilitate the flow inside the dryer or to avoid blocking the perforated plates. Therefore, before bringing the coffee to the dryer, it needs to go through cleaning after pre-drying, which is usually done in conventional terrace or in pre-dryers such as the fixed bed and the hybrid terrace, as it will be seen later.

With the exception of concurrent flow dryers whose grain flow has the same airflow direction, the air temperature can be close to 120 °C. However, for conventional dryers, the drying air temperature should not exceed 65 °C. The coffee mass temperature cannot exceed 45 °C for periods exceeding 2 h, in any dryer type.

9.2.1 Fixed Bed or Fixed Layer Dryers

The fixed bed dryer has been widely used in pre-drying or in coffee drying. In this case, the recommended air temperature is 50 °C. The coffee layer, depending on the conditions of the product, can vary from a few centimeters up to 50 cm thick. In the dryer, model UFV (Fig. 1.15), the product should be stirred to homogenize the drying at each 3 h period. For a dryer with a diameter of 5.0 m, the operator must carefully stir the product and attempt to perform the operation in a time no <30 min.

Studies with the dryer, UFV model, showed that coffee drying with a 40 cm thick layer, drying air temperature of 55 °C, 120 min of stirring interval, what comes to an average 32 h of drying time to reduce the moisture content from 60% to 12% w.b.

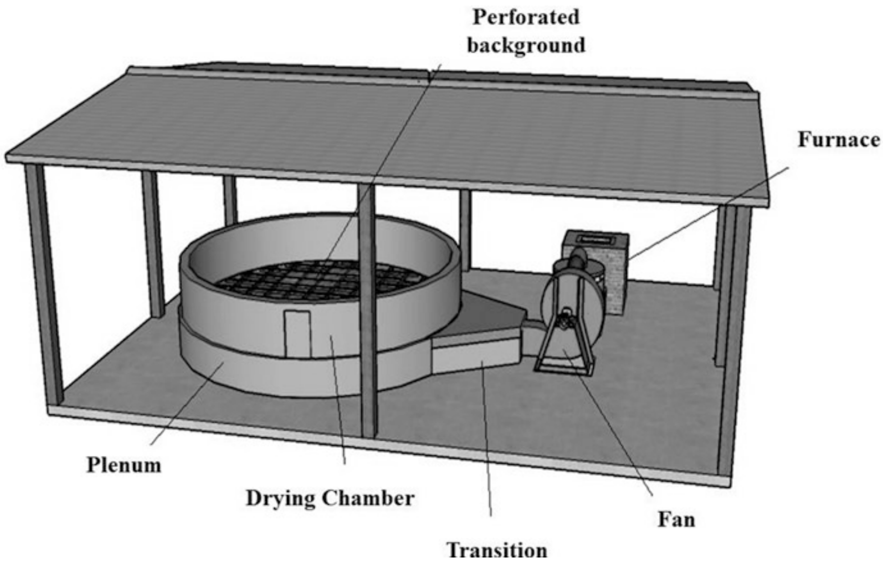

Fig. 1.15 Fixed bed dryer (UFV model). Source: Silva et al. (2018)

Under these conditions, the drying operation does not compromise the beverage quality and the type of coffee obtained is, generally, superior to the same coffee dried in conventional drying terrace. Unlike most mechanical dryers, the fixed-bed drier can dispense pre-drying in terrace when weather conditions are not favorable and can be used as a pre-dryer in more complex systems.

9.3 Concurrent Flow Dryers

Studies made at UFV, on coffee drying using concurrent flows dryer or in dryers where the drying air and the product flow in the same direction (parallel flows), using temperatures of 80, 100 and 120 °C with initial coffee moisture content of 25% w.b., showed that it is possible to obtain lower consumption of energy using the highest temperatures.

It has been found that, although the recommended temperature is 80 °C, it was possible to dry coffee with the drying air up to 120 °C, without damaging the final quality of the beverage. In order to do this, a lot of care must be taken to increase the speed of the product inside the dryer and make sure that the product is flowing evenly.

The first image of Fig. 1.16 shows the details of a concurrent flow dryer were coffee is loaded, revolved and unloaded by a bucket elevator. The second image shows a similar dryer where the above operations are performed by a pneumatic conveyor. In this dryer the stirring of the product is performed every 3 h during 5 min. For greater drying efficiency, a hybrid terrace (pre-dryer), which will be discussed later, is coupled to the dryer, and works with the same drying fan when the product is not being stirred. In this system, the single fan does the loading, stirring, unloading and ventilation operations of the two dryers.

9.4 Rotary Dryers

Coffee drying systems in Brazil remain practically the same since the first mechanical dryers appeared and even with the technological advances available in other activities, it does not appear that there will be substantial changes in the way coffee is pre-processed and dried around the world.

The traditional rotary dryer is formed by a horizontal tubular cylinder that rotates about its longitudinal axis at an angular velocity of up to 15 rpm. A very common type and used as a pre-dryer or batch coffee dryer is a horizontal, non-tilted drum in which the drying air is injected into a chamber located in the center of the cylinder and passes through the coffee mass perpendicularly to the axis of the dryer. Regardless of how they work, the rotary dryers available in the Brazilian market are very similar and have the same drying characteristics.

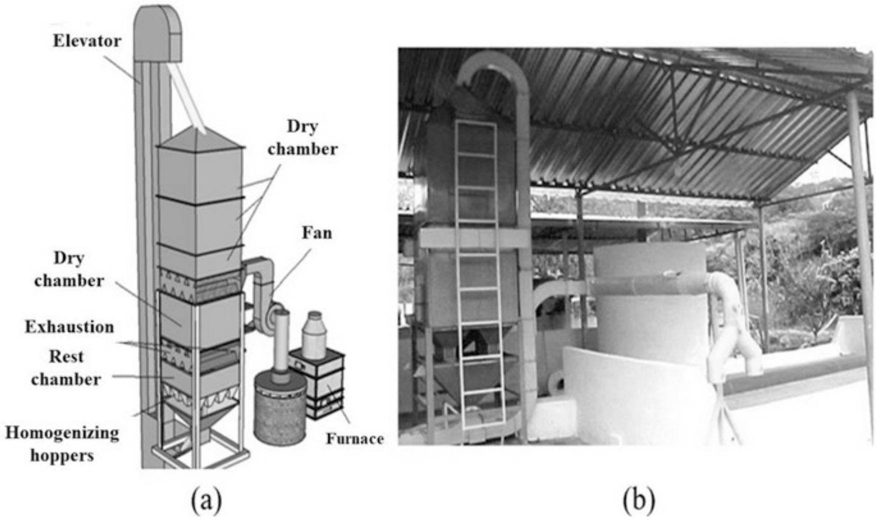

Fig. 1.16 Concurrent flow dryers (**a**) with bucket elevator and with pneumatic system (**b**). Source: Adapted from Silva et al. (2018)

As advantages, products such as pre dried coffee fruits, favoring cleaning and have good drying uniformity, when working with homogeneous products. As disadvantages, they present high energy consumption at the end of drying. Generally, they have high initial cost and, depending on the operation form can cause loss of the parchment of the peeled cherry coffee, resulting in non-uniform drying of the coffee mass. To solve this problem, it should work at a lower rpm for parchment coffee.

An alternative model for coffee drying is the intermittent rotary dryer developed at UFV. If necessary, it can be used for wet fruits or parchment coffee without passing by the terrace. The new model can also be used as a pre-dryer without the problems of closing the perforated plate holes.

Unlike the traditional model, it has airflow directed from the center to the periphery, only at the bottom. By being rotated at predetermined times and having the cylinder drilled only at the bottom, the dryer can work with half the load. The stirring or turning system of the dryer should be activated for at least 2 min every 2–3 h. For this reason, it has a very low power consumption compared to the traditional model. With simple work the traditional rotary dryer can be transformed into an intermittent rotary dryer.

9.5 Hybrid Terrace or Terrace Dryer

As the coffee quality cannot be improved in mechanical dryers, if the product was already deteriorated during pre-drying in the terrace. The solution is to adopt artificial pre-dryers to solve the problem. Therefore, a higher quality coffee cannot be expected even when the farm has an excellent system for complementary drying. As mentioned in the topic about terrace drying, the costs of construction and labor, the inconstancy of solar radiation and the possibility of rainfall during harvesting, make impossible the production of high-quality coffees, mainly in regions of altitude where in terrace drying is problematic.

To solve these problems, researchers from UFV and EPAMIG analyzed the adaptation of a ventilation system with hot air to improve performance and reduce the drying time of a conventional terrace.

Despite the use of any source of heat, the authors had chosen to heat the system with a charcoal furnace to transform a conventional terrace into high temperature dryer during the night, rainy days or in the absence of solar radiation.

The hybrid terrace occupies a small part of the conventional terrace, and for each thousand square meters of terrace, it is necessary to adapt 60 square meters in drying area at high temperatures. The hybrid terrace could have some elements such as fan, distribution channels, air inputs and walls to separate different batches of coffee, for simultaneous drying.

As the hybrid terrace is an adaptation of the conventional terrace, the coffee grower can make this adaptation in order to obtain success with the lowest possible cost.

Although slightly more expensive, it is recommended to cover the hybrid terrace area containing the ventilation system (furnace, fan, ducts and gutters) with a permanent roof. However, to reduce costs, the system can be covered with plastic cover overnight or in rainy periods. The hybrid terrace was built above the conventional terrace floor, which avoids problems with heavy rains that can get the coffee wet. If it is decided to build on the same level, it would be ideal to build a wall.

With the conventional terrace, the energy used to remove the moisture content from the coffee comes from the solar radiation and the enthalpy of the air. It has been seen that one of the terrace disadvantages is the lack of product quality assurance. Also, it was argued that solar energy has low potential to be used in high temperature driers.

For a medium-sized coffee dryer, only 40 square meters of collection area would be needed. Unfortunately, the sun does not shine every day and in the absence of solar radiation, a furnace coupled to the system is required. Therefore, the adoption of a mixed system (furnace + solar collector) should be taken based on economic analysis.

If it is convenient, a roof solar collector can be used. In this case, it is more economical and practical to leave the product enclose during periods of solar incidence, turn off the heating source and use only the energy supplied by the roof solar collector to dry the product.

Since the roof of a hybrid terrace is approximately 100 square meters, it has the potential to produce, on sunny days, the equivalent of 12 kg of firewood per hour, which is the amount of heat that should be supplied by the furnace in the absence of solar radiation.

9.6 Drying with Natural Air in Silos and Combination Drying

In box drying in silos or drying in a deep layer (layer over a meter high) should be kept in mind that it is a slow process, requires special care, and consumes electricity for a long period of time. The cost per ton of dried coffee is inversely proportional to the size of the box and, as a limiting factor; each box can only receive a certain type of coffee. Thus, in box drying with natural air, which will be detailed later, should only be adopted if the producer chooses the production of quality coffee (Peeled Cherry). In order to achieve this goal, it is necessary, in addition to wet pre-processing equipment, efficient dryers, box or silo with perforated floor, which is an important component to complete the desired infrastructure.

Unlike corn, rice and soybeans, the coffee mass due to its high initial moisture content, part of the mucilage and fruit fragments adhered to the grains, cannot easily flow through the transport system and into the dryers during the drying period. To solve this problem, the coffee must first be passed through a pre-drying system to allow the necessary fluidity to be homogeneously dried before being transferred to the mechanical dryers. With rare exceptions and as mentioned, the traditional terraces, regardless of their form of paving, do not safely serve as pre-drying for high quality coffee.

Depending on the handling techniques applied to the fresh peeled cherry, coffee may be subject to quality loss if its moisture content is not reduced to 18% w.b. within the first 3 days after harvesting. Therefore, the use of efficient pre-dryers is the technology required to replace conventional terraces that are dependent on optimum climate conditions to produce higher quality coffees.

Thus, in addition to facilitating the flow of the coffee mass inside the mechanical dryers and allowing a homogeneous drying, the fast reduction of the initial moisture content avoids the possibilities of deterioration by microorganisms and guarantees the production of coffee with desirable commercial quality.

A pre-dryer should be used to improve the performance of the mechanical dryer (productivity with lower energy consumption) and, when all previous operations were performed using Good Practices, ensuring hygienically produced coffee with high quality and cost competitive.

A set (pre-dryer/dryer) ideal for parchment coffee should enable the reduction of the initial moisture content to 20% in 40 h or less, avoiding mechanical damages, being energy efficient and allowing the correct use of temperature and drying time.

A pre-dryer that can be successfully used is the Hybrid-Terrace described above. It is simple technology, easy to manufacture/assemble and, when conveniently installed/operated, can double the output of traditional coffee dryers.

Unlike traditional dryers where the drying air is heated to temperatures up to 70 °C with a drying time near to 50 h, the in box drying with natural air is carried out at temperatures of 3 °C above environment temperature due to the heating caused by the fan. Therefore, drying with air at low temperatures is a slow process and would not finish the coffee drying with high initial moisture content, without intense deterioration in the upper layers of the box.

With these considerations, it is suggested, as it will be seen later, one of the drying technologies in combination with in box drying, which consists of using pre-dryers and dryers at high temperatures while the product has a higher moisture content that is easy to be removed. When the moisture content of the peeled cherry coffee reaches 20% w.b., the coffee must be transferred for additional drying in the silo with natural air. In addition to the substantial fuel reduction required for drying, the combined system (Pre-dryer/dryer/in box drying) can double the dynamic capacity of conventional dryers and improve the drying thermal efficiency. The main reasons for better efficiency are:

(a) Pre-dryers and dryers will operate in a moisture range where the withdrawal of water from the product is relatively easy; and,
(b) The cooling period is eliminated; the product must be transferred for in box drying with the residual heat from the partial drying. Optionally, the ventilation system can be activated between 4 and 6 h after the addition of the coffee batch into silo.

As mentioned, drying in mixed systems reduces the total energy required by conventional drying methods and increases the dynamic capacity of the dryers and the low drying rate in the silo is due to the small air flow and the small potential of natural air drying in mountain regions. As the permissible time for storage of parchment coffee, at 18% moisture is long, it is possible to use smaller fans than in the drying of cereal grains.

Due to silo drying be a complementary process it is also understood as drying during storage, because even after drying, the product will continue to be stored in the same silo until the point of commercialization. The dryer-storage silo presents some special features that are not required for silos used for storage only: for uniform drying, the floor must be of perforated metal sheets with at least 20% perforated area. The fan should provide enough air to dry the entire grain mass without deterioration in any added layer.

The dimensions of the silo (diameter and height) and the type of product that will be stored define the power of the fan to be used. As the small amount of air per unit mass of coffee makes the process slow and low air temperatures decrease the ability to evaporate water from the product, the process may present difficulties in regions with average high relative humidity. To fix the problem, the operator should use a supplementary heating source that is reliable and with low cost. The adaptation of a humidistat and a thermostat to the silo plenum, will control the heating source operation.

In drying with natural air, the drying potential of the air and the small amount of heating caused by the fan (3 °C above room temperature) are enough to provide the recommended final moisture content for safe storage in the wide majority of coffee producing regions. Drying systems with natural or slightly heated air (maximum 10 °C above the environment temperature) properly designed and managed are economical and technically efficient methods.

In the proposed system, silo-drier without the stirring device, the drying starts in the lower layer and progresses until reaching the last layer, in the upper part of the silo. After a drying time, three layers or bands of moisture are distinguished.

The first band, which is formed by dry grains, has already reached equilibrium with drying air and all grains in this band have the same moisture content, which is known as equilibrium moisture (for most coffee producers' regions, around 12%). Values of average relative humidity below 50% are very frequent in the Cerrado regions, during coffee harvesting. However, solutions to avoid excess in coffee drying are of low cost and easily manageable.

In the second band, called "drying front" and that moves slowly during the drying process, the moisture transferred from product to the drying air is still happening. The thickness of this band varies around 3 cm and depends on the conditions established for the project such as airflow, environmental conditions, type of product and its moisture content when added into the silo.

The grains that are not in drying process form the third band. The coffee moisture content in this band is equivalent to the initial one, when it was added into silo and by going through this layer the air had its drying capacity depleted in the "drying front". As the drying progresses the dry product depth grows and the wet product wide decreases. When the base of the drying front reaches the top of the last layer, the process is finished and the coffee is ready for commercialization or may remain stored in the silo with the ventilation turned off.

Calculation of the drying airflow rate and the choice of equipment should be made carefully. The flow rate must allow the base of the drying front to reach the last layers in a time set by calculations. For Peeled cherry coffee it should be provided that the base of the drying front reaches the last layer no more than one week after the end of harvest.

For coffee drying in a combined system (pre-drying at high temperatures and silo-dryer, with natural air), proceed as follows:

- Peeled cherries or parchment coffee should be transferred to the partial drying system (pre-dryer/dryer) as soon as possible and have their water content reduced to a pre-set value, according to temperature and relative humidity during harvesting); in the most common cases, for a moisture content of 18%;
- During the operations with the pre-dryer/dryer, the coffee mass temperature should not be exceeded 40 °C;
- Optionally, 4–6 h after the transfer of the first coffee lot into the silo, the ventilation system must be started and kept on. Finally, the fan will only be turned off when the product on the top of the last layer added in the silo reaches moisture content of about 16% w.b.; below this value, the fan will remain on, only during periods when the relative humidity is between 60 and 70%. The ideal would be to couple a controller to the ventilation system, so that it is automatically triggered for the established relative humidity range; and.

- Ventilation should be avoided when moisture in the last layer reaches equilibrium moisture content (close to 12% w.b.).

When in silo drying is performed with the air at high temperatures or when the average relative humidity of the drying air is below 50%, one of the following options must be adopted:

(a) Work with batch drying with a fixed layer of 0.6 m in height (Fig. 1.17) and, after drying, transport the product for drying in silos with natural air. Drying with high temperature without coffee stirring should not be used. To reduce costs, the silo-dryer should be used as a storage unit at the end of harvest season. As with any high temperature dryer, it is possible to adopt additional drying during storage at low temperatures, if necessary;
(b) Work with the full silo (load completed in up to 5 days). In order to avoid the formation of the drying front and consequently with excess drying of the lower layers, the silo must be equipped with a stirring system similar to the "STIRRING DEVICE" system. In addition to revolving the entire grain layer, the equipment facilitates the passage of the drying air stream (Silva and Lacerda Filho 1990).

The "STIRRING DEVICE" mixing equipment can be constructed with one or more vertical helicoids, which move radially from the center to the silo wall and vice versa, mixing the product vertically. Besides the high cost and losing part of the static capacity of the silo, due to adaptation of the mixer the system, depending on the type of energy for heating the air, results in high drying cost when the product is dried to 12% w.b. (Silva and Lacerda Filho 1990).

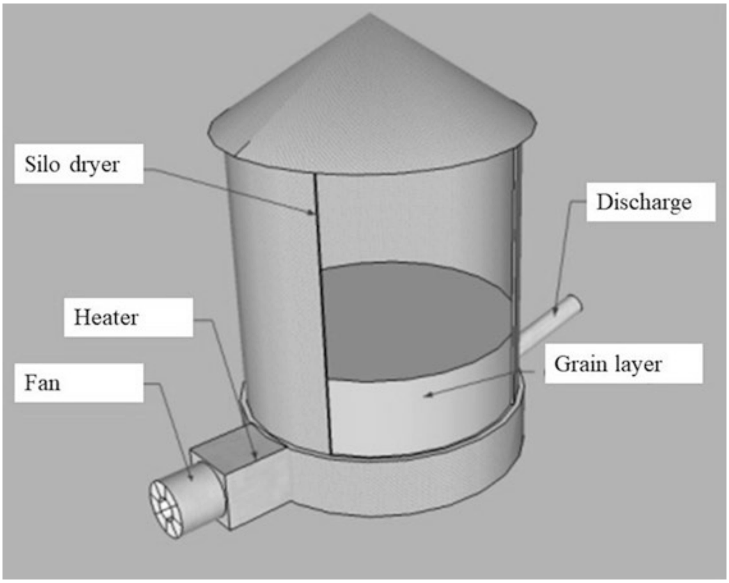

Fig. 1.17 In silo drying with air at high temperatures. Source: Authors

9.6.1 Coffee Drying with Seven Silos System

The system consists in the adoption of seven silos-dryers or ventilated boxes (metal, wood or masonry), which will be weekly charged with a layer of coffee. The silos should be planned to receive, each week, a certain amount of product with a preset initial moisture content.

Each silo shall have until the end of harvest, its loading capacity completed. When the last layer is added to the last silo, it means that all the others will be dried and in equilibrium with the environment. The moisture content on the upper surface of the last coffee load should monitor the end of drying. From this point on, the ventilation system can be switched off. The silo 7 should be considered a reserve, so it should always be empty to solve eventual problems during the harvest period (Silva, 2008).

For simplicity, imagine the first harvest day happens on a Monday. Thus, the coffee, after being pre-processed and pre-dried at 18% moisture content (w.b.), should be immediately dumped into silo 1 and the ventilation system turned on. On Tuesday, the second day of harvest, the product must be taken to silo 2, with the same treatment. With this routine, we will arrive at the Saturday, the sixth day of harvest, which must be placed in silo 6.

So, in the second week of harvest, which will begin on Monday, silo 1, which received the coffee from the first harvesting day, will have dried the first layer and will be ready to receive the coffee from the seventh day of harvest. Therefore, the eighth day of harvest should go to silo 2 and so on, successively, until the harvest is over. Thus, it can be concluded that, one week after the end of the harvest, all the peeled cherries will be dry and can remain stored until commercialization.

9.7 Combination of Drying Systems

Now that the different types of coffee drying have been shown, the reader can from now on analyze and combine different dryers to take advantage of the advantages of each dryer.

The combination of systems consists basically of using two or more drying systems to perform coffee drying with quality and energy efficiency. As said before, if part of the drying is performed in silos, dryers are used at high temperatures while the product has higher moisture content and, from the point of safe moisture, transfer the coffee to have final drying during storage.

In addition to the substantial energy reduction required for drying, the combination of dryers can facilitate the process and also increase the thermal efficiency and dynamic capacity of each dryer. The main reasons for this increased efficiency are: dryers operate with products in a range of humidity where is more recommended for each coffee type and using less energy, time and labor.

9.7.1 Combination (Conventional Terrace and Mechanical Dryers)

Because coffee drying is quite different from the drying of other grains, we can use different possibilities for an efficient combination for coffee drying. Even disconsidering the normal combination for other types of grain, most of coffee growers use the combination, conventional terrace and mechanical dryers.

For coffee, the combination, Terrace/Mechanical dryer, is the inverse of the combination established for other types of grains where the combination drying starts with high temperature and ends with low temperature. This fact happens because coffee is a fruit with a high moisture content, it exudes honey during handling and has little or no fluidity.

With the advent of the hybrid terrace and the intermittent rotary dryer (UFV model), which can receive the coffee directly from the coffee washer or from the peeler, it is possible to make several combinations to finish coffee drying in silos as it is made for other types of grains.

9.7.2 Combination (Terrace with Dryer Silo)

A second possible combination would be to pre-dry the parchment coffee in conventional concrete terrace and complete the drying during storage in a silo dryer.

Although the drying of parchment coffee in silos does not suffer any greater problems due to unfavorable climate conditions, they are however, very unfavorable to pre-drying in the terrace. Therefore, the combination, conventional terrace and dryer silo (Fig. 1.18a), can only be made if the weather is favorable. In this case, with 5 days of pre-drying in the sun, the coffee can be dumped into the drying silo. The variation in the coffee quality dried in the terrace during the harvesting season is a bottleneck that prevents different coffee lots from being placed into the same silo. If the above combination is adopted, the producer must be convinced that the product has the same quality or that the silo is planned to contain only one batch.

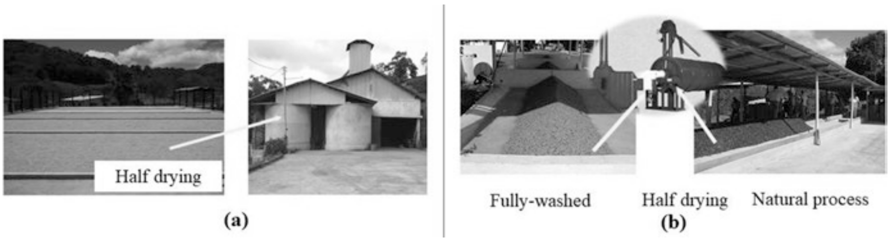

Fig. 1.18 Combination (**a**)—concreted terrace with silo-dryer—for peeled cherry coffee drying and (**b**) combination—Hybrid terrace with conventional mechanical dryer. Source: Adapted from Silva et al. (2018)

9.7.3 Combination (Hybrid Terrace with Conventional Mechanical Dryer)

A third option to combined drying would be high temperature pre-drying in hybrid terrace and final drying in mechanical dryers (rotary or flow driers).

This option is very interesting when you want high drying productivity and when working mainly with parchment coffee. This combination greatly reduces the need for mechanical dryers since the product can be transferred with a slightly lower humidity.

After 20 h of pre-drying in the Hybrid Terrace, the coffee can be transferred to the mechanical dryer (Fig. 1.18b). The total drying time will be approximately 50 h and there would be no need to use conventional terraces.

9.7.4 Combination (Hybrid Terrace with Silo-Dryer)

The combination of hybrid terrace with silo-dryer is one of the most economical options to dry peeled or parchment coffee. This combination avoids or reduce the need for large areas of conventional terrace and the coffee grower can reduce investing in additional dryers to increase drying capacity.

As the drying will be completed with natural air in the silo, there is no need for a rigid moisture content control during pre-drying. The great advantage of the in-silo drying is that all grains will have the same moisture content at the end of drying.

10 Coffee Storage in the Farm

Despite being less attacked by insects than products such as corn, wheat and beans, coffee also suffers from storage damage. In this case, the coffee grower must take into account the economic losses due to the reduction in quality and remember that the equivalent of a unit of 60 kg of coffee can occupy the same space as a product like corn. However, for the same weight, the value of the coffee is more than twenty (20) times the corn value and special care should be devoted to the coffee storage in the farm.

As most of the time coffee is sold after processing, it stays, after drying, for some time stored in the producing farm. In the case of natural or parchment coffee, the product must be stored in suitable places to avoid qualities losses.

Because natural coffee requires more storage space, it is usually packaged in 30 kg jute bags. Off season, these bags are stored in piles according to their pre-classification, preparation or origin. The storage location should be clean, well ventilated and sheltered from the sun and rain. The use of jute bags is advantageous because they are resistant and facilitate the sealing of openings made at the time of sampling.

Because of the large volume to be stored and the high cost of the storage operation, natural coffee can also be stored in bulk in labeled bins. In bin storage, despite the protection of the outer skin, there is the possibility of physical and chemical changes, especially in the upper layers of the bins. A forced ventilation system protects the product against environment humidity and rainfall problems.

For the storage of parchment coffee, preference should be given to bins or silos with ventilation or adopting the complementary drying technique during storage, in metal or masonry silos as seen in item 9.6.

11 Coffee Processing of Coffee (Hulling and Classification)

Coffee processing is a post-harvest operation that transforms the dried coffee fruit or parchment coffee into coffee beans (green coffee), by removing the dry pericarp or the grain parchment. The processing operation must be done as close as possible to the coffee marketing season, so that the product can maintain its original characteristics.

Depending on the conditions in which the coffee has been dried or even due to the changes that may happen during storage, it is advisable to carefully pass the product through a high temperature dryer to ensure a homogenization of the moisture content to an ideal value for processing. Also, care must be taken for not processing the hot product. Natural cooling prevents the incidence of broken coffee beans.

A coffee processing unit, at farm level, should have the following equipment:

(a) Vibratory cleaner:
It is formed by a group of sieves with different types of holes, to separate the coffee from light foreign materials (big and small). This machine (Fig. 1.19a) should be located between the entrance pit and the stones and metals separator machine; this machine is not necessary if there is a good pre-cleaning system before and after the dryer.

(b) Stones and metals separator machine:
Usually coupled with a ventilation system, the machine is used to separate the heaviest foreign materials, including heavy hulled coffee from light ones and the husks. The system has a magnetic device that retrieves metallic material (Fig. 1.19b);

(c) Coffee huller:
Coupled with a ventilation system, the huller consists of a group of regulated rotary metallic razors and a fixed one. The machine removes the peel and the parchment (Fig. 1.19c). Husks are removed by the ventilation system, and the coffee bean goes down to a pan, where the clean coffee is separated from non-hulled coffee. The clean coffee may pass to the polisher and, the non-hulled coffee returns to the huller;

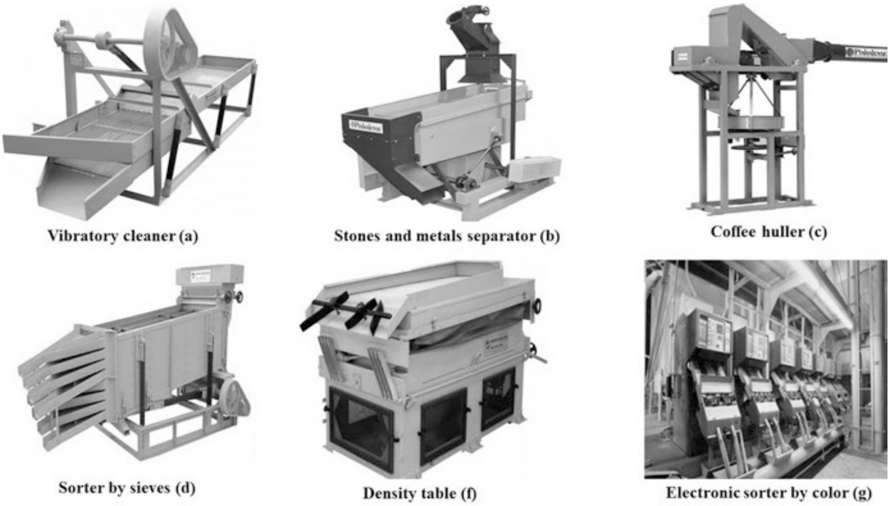

Fig. 1.19 Vibratory cleaner (**a**), Stones and metals separator (**b**). Coffee huller (**c**). Sorter by sieves (**d**), Density table (**e**) and Electronic sorter by color (**f**). Source: Pinhalense (2013)

(d) Classifying machine:
It is a system used to separate coffee beans by size, format and densities. It is constituted by a group of sieves with different sizes and types of holes. The system has a regulated air column that separates the light foreign material or poorly formed coffees beans (Fig. 1.19d).

(e) Reprocessing machines:
More sophisticated processing units also have reprocessing machines, such as the separator by density (Fig. 1.19e) and electronic sorter (Fig. 1.19f), which have the purpose of improving the coffee type, according to the market interest. The density table, besides being essential in the coffee reprocessing, greatly assists the work of the electronic sorter. Other equipment such as scales, bagging, sewing and conveyors should compose an ideal coffee processing unit.

(f) Coffee processing for small producers:
Like most small and medium-sized coffee growers, they do not have the conditions to invest in their own machines. Without the availability of the cooperative service, they generally use the mobile external service. Another processing machine for small coffee growers. In any case, some practices must be observed to avoid quality loss during coffee processing such as: Keep the beans, parchment and husks completely separate; Separately transport green coffee, parchment coffee, and natural coffee; Avoid re-wetting and; when appropriate, clean the transportation system.

12 Storing the Hulled Coffee

In producing countries, hulled coffee or green coffee beans are traditionally stored in bags instead of bulk storage. Despite the many disadvantages, the bag storage allows batch segregation. This is very important in stock assessment and quality testing. In addition to easy access to coffee lots, the natural circulation of air over the bag piles, easy inspection and sampling are important factors to consider when using conventional bag storage. Despite of little or no environmental control, it is possible to keep the product stored for relatively long periods (for more than 2 years) without the risk of serious losses, as with products such as corn or wheat.

Although the wide majority of coffee is kept in bag storage, Big Bags storage and silos with controlled ventilation are already in use. In the latter case, the product has already been classified and transformed in a large batch.

An objection to the bulk storage of coffee is the difficulties of doing accurate inventories. Any small variation in apparent density or grain mass compaction can cause large errors in the inventory evaluation, which does not happen when the coffee is maintained in bag storage.

The importance of accurate inventories of the amount stored is because coffee has a higher value than most grains. The main advantage of bulk storage is the use of mechanization that allows a large reduction in the required labor and brings good economic results due to the actual cost of the jute bag.

It can be said that: the main disadvantages of the conventional bag storage of hulled coffee are: intensive use of labor, high cost of bags and difficulties associated with pest control.

Bleaching and density reduction are other problems related to traditional bag storage. Depending on the amount of damage during storage, product price reductions can happen and go up to 40%.

Finally, during storage of bagged coffee, the amount of light incident on the bags should be carefully controlled. Under certain wavelengths, the coffee beans may suffer changes (bleaching) in the desired commercial coloration. The grain color is considered as indicative of the coffee quality. However, bag storage offers some advantages such as:

(a) It allows manipulating lots that vary in type, moisture content and product quantity;
(b) Bag storage does not require sophisticated techniques and equipment to handle the product;
(c) Storage problems that occur in one or more bags can be solved without the need of removal of all pile;
(d) Low initial cost of installation.

In the conventional bag storage, it should be taken into account some points that can increase the efficiency and the protection that the warehouse can offer to the coffee:

(a) Excess light should be avoided because it can cause changes in coffee color (bleaching);
(b) Provide the roof and floor of the warehouse walls with controllable openings protected for natural air renewal;
(c) Install fans, if possible;
(d) Waterproof the floor or build suspended floors.

13 Energy Use for Coffee Drying

The main objective of this topic is to know the systems and practice the rational use of energy in the drying operation. This will contribute to fuel economy and, obviously, to reduce the coffee drying costs. Additionally, alert for a reduction in energy availability for coffee drying. The concern is due to the shortage of natural resources used as sources of energy and the frequent increase in the GLP costs, which is also used for coffee drying.

13.1 Energy from the Biomass

Understanding and correctly managing a heating system designed to dry the coffee will cause some coffee growers to stop using heavily consumed, incorrectly sized wood burned in furnaces without proper maintenance and excessive heat loss. Most wood-fired furnaces do not have a combustion control mechanism; they are poorly operated and producing air pollution in the field, roads and in the urban centers near the coffee farms. These facts are some concerns and they make the Public Ministry and the Environmental Police close down some drying units due to the amount of pollution caused, mainly by burning the coffee husk as energy source.

To avoid problems during the harvest operation, coffee growers should stock, in advance, the heat source for their dryers. If wood will be used, it must be properly cut, dried and stored. Whenever possible keep a certain amount of prepared firewood under cover. Wet firewood decreases dryer efficiency.

If the option is the heating by charcoal, this fuel should be like the firewood, be properly prepared and stored. Although it costs more than wood the choice of charcoal is more practical and saves manpower in the operation of the drying system.

With the difficulty of using conventional fuels to heat the air, the wood has been the most important heat source. Currently the wide majority of coffee dryers are operating with this type of fuel. However, most wood-burning furnaces in use, have high energy consumption and require a lot of manpower.

Because they are not encouraged to produce firewood for coffee drying, many growers use natural wood as firewood or use coffee straw as fuel. They ignore that, with this attitude, they are against the good principles of environment conservation and still paying high cost for this option.

In order to solve part of the problems discussed, four (4) types of furnaces were designed and tested in the Department of Agricultural Engineering (Federal University of Viçosa): the first is a wood-burning furnace for indirect heating of the drying air and by the use of the chimney is thermally less efficient. The second furnace designed for direct air heating, does not have chimney and needs dry firewood and of good quality to dry peeled cherry coffee. It has lower cost of construction and high energy efficiency.

The third furnace is a boiler type under environment pressure. It consists of a small pump for recirculating water, a heat radiator and a ventilation system to draw hot air. It can work with water for drying air temperature lower than 40 °C or with thermal fluid for higher temperatures. Finally, the fourth furnace has charcoal as heat source and direct heating type. Depending on the drying temperature, the load of this furnace can last up to 10 h of operation without replenishment and without having to regulate the pre-set temperature.

All of these furnaces were designed taking into account the initial cost, the possibility of being built on the farm, the low consumption of charcoal or firewood and the preservation of the environment. It is suggested to the reader to look for some extra knowledge about fuel and combustion to obtain a good performance of a particular furnace model.

For furnaces design, combustion control and equipment design using the heat generated, it is necessary to know the supply rate of the combustion air and the characteristics of the gases generated (composition, volume, temperature, etc.). Otherwise, the drying system will consume excess fuel, need furnaces of unnecessary size, have poor heat transfer rate, require more frequent maintenance and cleaning and, above all, will produce a lot of pollution.

14 Furnaces for the Drying Air Heating

Furnaces are devices designed to ensure complete burning of the fuel, in an efficient and continuous way to allow the use of the released thermal energy to obtain the greater thermal yield. The design of a furnace for coffee drying should be based on the 3Ts of the combustion: temperature, turbulence and time. The furnace size and shape depend on the type of fuel, the device used to burn it, and the amount of energy to be released over a period of time. For complete fuel combustion to happen, a homogeneous air-fuel mixture must be done at optimum dosage and at the correct time. This results in fuel heating to its self-sustaining ignition.

14.1 Furnace Types for Coffee Drying

Depending on the way coffee fruits were pre-processed (dry way or wet way) and the quality of the combustion, two types of furnace can be used:

Furnace with direct air heating - In this type of furnace, the thermal energy from the gases resulting from the combustion are mixed with the environment air, and then they are used directly to dry the coffee. However, the mixing of part natural air with the gases resulting from the combustion may become undesirable in cases where the combustion process is incomplete, generating contaminating compounds such as carbon monoxide and smoke. With the direct use of the thermal energy of the combustion gases, the furnaces with direct heating, when under complete combustion, present a greater yield. In these furnaces, a tangential decanter or cyclone needs to be coupled, which the particles, especially the incandescent ones, they go into spiral motion and are separated from the gaseous stream by the action of the centrifugal force.

Indirect heat Furnaces - In furnaces with indirect heat system, the thermal energy from the combustion gases is fed to a heat exchanger, which is intended to indirectly heat the drying air or a second substance, for example, in a steam generator. In this category, there is loss of thermal energy by the chimney and to the system, resulting in a lower efficiency when compared to the furnace with direct heating. Furnaces with indirect heating are intended for agricultural products, which require controlled temperature during drying, such as drying seeds, cocoa and peeled cherry coffee.

Talking about firewood, it is observed that furnaces with indirect heating generally present excessive heat loss, consume large amounts of fuel, do not have precise mechanisms to control combustion and temperature of drying air and, despite of that, are the most used in conventional coffee dryers. Also, the furnace with indirect heating, when the wood has poor quality and is not adequately dried, produces smoke while is burning, causing discomfort and leaving a smell or taste in the product when the heat exchanger or one of the elements connecting the fan is damaged by the thermochemical corrosion process.

Although it is a widely used fuel, wood requires well-planned furnaces, built with durable materials and well-defined criteria for its use (size, quality, wood moisture content, etc.).

However, furnaces with indirect heating when using heat exchangers with thermal fluids have, besides other advantages, the easy temperature control of the drying air. Currently, in the coffee drying, steam boilers have been used for the indirect air heating. Although it is a technology available and results in good quality product, boilers are only accessible to large coffee growers and are recommended for those who operate two or more dryers simultaneously. The high implementation cost of a conventional boiler and the small volume of coffee produced does not allow small producers to use this technology as one of the options for improving coffee quality.

The lack of interest of the traditional industries in developing systems compatible with the production volume of small farmers is easily understood because they are equipment whose economic return is not advantageous in comparison to the big coffee processing systems. Thus, the small regional industries are that can have better conditions to serve this segment of the coffee chain.

14.2 Furnaces Use Recommendations

(a) Use wood efficiently. The use of moist firewood in furnaces is an obstacle to the production of heat. Evaporation of the water during the combustion of the wood removes heat during the firing, resulting in less energy to heat the drying air. As drier and denser is the wood, the better its use to dry. It is suggested that the extension worker or the furnace manufacturer instructs the coffee grower to provide good and dry firewood in advance and to store it in a place protected from rain. The moisture content of wood to burn in furnaces must be less than 30%.
(b) During operation, the furnace must be constantly supplied at predetermined intervals with firewood of uniform length and diameter. Although it is laborious, it should be avoided that the fire goes down too much to feed the furnace again with a lot of firewood. Since indirect heat firewood furnaces has little control, careful feeding helps maintain temperatures close to those recommended for efficient drying.
(c) The firewood shall be separated into homogeneous lots of length and diameter. The use of firewood of the same class will facilitate the combustion and better performance of the furnace.
(d) Avoid throwing wood into the combustion chamber, as this may cause cracking and contribute to reduce the furnace's life.
(e) During furnace feeding for indirect heating, the door promotes the entrance of a large excess of air, which decreases the flame temperature, reducing the availability of energy and causing great loss of sensible heat by the chimney. Therefore, avoiding unnecessarily opening of the furnace door.
(f) For efficient combustion and proper gases circulation, maintain a daily schedule for cleaning all components of the furnace and dryer.
(g) A furnace model of great interest for indirect heating of the drying air has a radiator, combustion chamber and thermal fluid heater. Cold air, when entering the radiator is heated by the circulating fluid in the fins of the radiator. The maximum temperature of the drying air is determined by the equilibrium with the boiling temperature of the circulating hot fluid and the size of the radiator. Therefore, the temperature of the drying air will never reach the boiling temperature of the hot fluid, which means, if the circulating fluid is water, it will be difficult to achieve temperatures in excess of 70 °C.
(h) The maximum drying temperature is determined by the airflow, the size of the system and the boiling temperature of the hot fluid. Besides the great durability,

by working with thermal fluid under relatively low temperatures, the furnace in question has the advantage of non-contamination of the drying air. By not working at high temperatures, the radiator will hardly be damaged. This aspect is of special attention in the coffee drying that, if it smells smoke, will be discarded by some buyers.

14.2.1 Furnaces with Direct Heating

Furnaces for direct heating can be classified, according to the flow of gases from combustion, into up flow furnaces and down flow furnaces. In the first case, the oxidizing substance enters the lower part of the combustion chamber, crosses the grate, comes into contact with the firewood, and mixes with the volatile gases. This movement of the gases inside the furnace is in ascending form. Depending on how the combustion occurs it may or may not produce smoke. In the second case, the oxidizing substance enters the upper part of the furnace, comes in contact with the firewood, crosses the grate and, mixing with the volatile gases, forming a downward flow inside the furnace. In this case, the flame resulting from the oxidation of the volatile gases is formed under the grate and, if the firewood is of good quality, it does not produce smoke.

The combustion chamber in the direct heating furnaces is confused with the furnace itself and can be divided into three distinct parts. The first is intended for loading, fuel ignition and combustion air intake. The second part comprises the space where the flame develops and where the combustion of the volatile compounds is completed. Finally, the third part of the furnace has the function of interconnecting the furnace to the cyclone and increasing the residence time of the gases in the furnace.

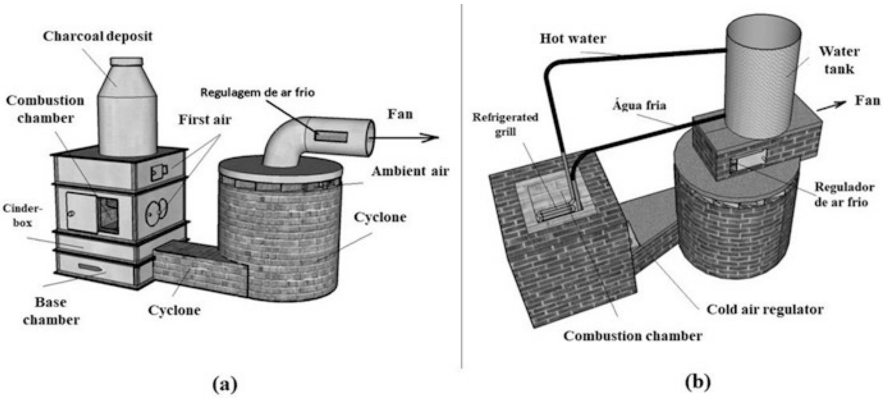

Fig. 1.20 Direct heating furnace having firewood as fuel (**a**) and Direct heating furnace with charcoal as fuel—part (**b**). Source: Adapted from Silva et al. (2018)

Below are two types of direct heating furnaces that can be built in local stores. It is recommended, however, the most common or easily found material on the farm. With this, the cost of construction or adaptation will be greatly reduced. In both types of furnaces combustion gases are mixed with ambient air and sucked by the fan and injected directly into the grain mass (Fig. 1.20a, b).

If the dryer does not have a system that can suck the air through the furnace, the proposed models cannot be executed. In this case, farmer should opt for another furnace type.

The option for direct heating is due to the fact that there is no need to build chimneys and heat exchangers that turn indirect heat furnaces inefficient and more expensive.

As the purpose of the current chapter is general information, the reader is advised to consult for constructive details of furnaces (Silva 2008).

Finally, as coffee drying is part of the coffee chain production that requires the greatest amount of energy and is responsible for maintaining the product quality after harvesting, it is advisable, especially for the extension worker, to adopt guidelines for the producer and the operator of the coffee drying system. Good practices will reduce energy and maintenance costs in an important and costly system.

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