Introduction to Coffee Drying

1. General Introduction:

The drying of coffee is a step in coffee processing that is required, as for many other food crops, to stabilise an otherwise unstable product. It is not in any way a trivial processing step, regardless of the degree of technology employed, and quality can easily be lost by drying that is too slow, too fast or otherwise inappropriate. Depending on the processing method employed, the whole fruit, the crushed fruit, parchments (bean enclosed by the inner integument), or naked beans may be dried.

Coffee processing begins with harvesting and this may be done according to one of several methods from mechanical 'strip' picking to the selective 'finger picking' of ripe cherries *(see: op.cit.)*. Different harvest methods provide different profiles of ripeness to the subsequent processing steps *(see: 'Stage of maturity of cherries at harvest and OTA risk' [.pdf], found in the Support Documentation area of Section 3, 'Good hygiene practices in the primary production of coffee')*. Drying can be initiated, as is, directly after harvest or the crop can be sorted in one way or another before drying. Only ripe cherries are appropriate for the wet-processing of coffee (represented by several methods that share the step of separating the seeds from fruit tissues before drying).

Cherry drying in the sun requires energy to the extent of about 17000 KJ/kg (about 400000 Kcal/kg) of fresh coffee cherry assuming a layer thickness of about 4 to 6cm (25-30kg/m^2). Removal of fruit tissues in the pulping step of wet-processing reduces this energy requirement by mechanically removing water and by removing tissues that inhibit water loss. However, the decision as to which processing system to apply is much more complex than mere consideration of drying efficiency.

Several different approaches to mechanical drying are represented by a plethora of equipment designed specifically for coffee. The energy requirement can be reduced from that indicated by sun drying by features designed to enhance heat transfer and mixing, so the time required to achieve dryness is very much reduced. Problems associated with a long residence out of doors as in sun drying are eliminated. However, such equipment is typically expensive, and often expensive to run, and does not accept fully wet coffee. Thus in addition to the mechanical drying facility some form of pre-drying equipment, typically a sun drying terrace, must also be provided.

Sun drying was, at one time, considered to be required for producing coffee of the best quality. Broadly speaking, this is no longer considered to be the case and mechanical drying has become much more common, at least with larger farms in regions that are not reliably dry during the harvest period. Whether for sun or mechanical drying there are cost differentials and technical advantages / disadvantages to consider in deciding how to dry. Beyond the technical considerations of cost, efficiency and suitability, each method has implications for the growth and development of fungi and, by extension, for the presence of OTA.

1.1 Functional differences between drying parchment and cherry coffee:

The coffee fruit or ‘cherry’ provides an additional degree of physical protection to the beans. Cherry coffee, however, requires more time and energy to dry since it has approximately twice the quantity of water per unit of dry product as does parchment. In addition, removal of the fruit tissues reduces the microbiological load but the process of doing so is considerably more expensive in capital costs, in harvesting costs and processing costs. In terms of taste, the products of these two processing methods are different, so the choice of processing method depends heavily on market considerations. Choice of processing method is also often dictated by custom and practice according to growing region.

1.2 Considerations in selecting a drying method:

This decision is based on the perception of the producer as he considers the balance between affordability and practicality. Given a processing method, the choice of drying technology hinges on affordability of alternative dryers and the degree to which it is difficult to consistently produce taint-free coffee using them. Sun drying is generally used where good drying conditions prevail during harvest season or where the scale of the farms precludes acquisition of expensive drying technology. Usually a farm will have invested in alternative methods such as ground and tables, or cement patios and mechanical dryers, or tables and conditioning bins or carros and silo dryers. In these cases, it is not economic to build and run all the required capacity in the more expensive technology so this is used only in peak season. Alternatively, one method may be used preferentially during spells of good weather. Also, pre-drying (partial sun drying) is required for most mechanical dryers so even in production areas where this technology is applied there must be a capacity to sun dry all coffee for some 3 to 5 days.

The choice of the most appropriate drying technology to be applied in any given situaiotn is quite complex and contingent on the production and maximum rate of production, value of the product and market factors, availability and cost of labour, affordability of capital and operational costs of alternative drying technologies. A technology that dries slowly may have lower unit costs but more units will be required to compensate for a longer residence time in the dryer. A wide array of drying equipment has been demonstrated to produce coffee of good quality when conditions for drying are good but many regions are marginal in this respect so there can be serious repercussions in unfavourable years.

2. Overview of Methods Employed to Dry Coffee:

2.1 Sun drying[1]:

The bulk of the energy for sun drying comes from incident solar radiation. This rate, called the solar constant, is 1.37 kW/m^2 at the edge of the atmosphere. In clear conditions this is attenuated to a maximum of 0.8 to 1 kW/m^2 at the earth’s surface depending on latitude. This is equivalent to 3200 to 3600 kJ/h/m^2 thus the 17000 kJ/kg referred to above implies about 19 x 6h days. The ambient

[1] More detail can found in Section 4 of this document.

conditions of air relative humidity and atmospheric pressure also influence water loss rates and other energy inputs are also critical in efficient solar drying, stirring and airflow. The avoidance of the addition of water through contact with rain or overnight dew are important management factors.

Facilities for sun drying consist primarily of the surface used. Bare earth is widely used especially in robusta production, whereas cement or brick are widely used in arabica production. The structure and location of these facilities has a great influence on their performance. Tables with wire mesh, sisal or bamboo mats are used commonly in certain origins, and other surfaces such as asphalt or wood are also known and commonly applied in certain regions.

The control parameters comprise stirring frequency, layer thickness and covering routines. With moderate layer thickness, stirring up to four times per day dramatically improves drying rates. Of course, the thinner the layer of coffee, the faster drying proceeds, but space to spread the harvest is a major constraint. About 4cm for parchment and 5 to 6cm for cherry coffee (equivalent to about $30kg/m^2$) can be taken as near optimum compromise loading rates. The area has to be sufficient to account for coffee harvesting rates at peak harvest, a parameter much affected by harvesting technology and labour availability. This factor has often not been fully accommodated where mechanical harvesting has been introduced. Rule-of-thumb formulae to estimate drying area requirements given manual harvest and any given yield are available.

Tables or other technologies that allow for a rapid and convenient method of protection from rain are found in regions where showers are frequent during harvest. Movable roofs, movable floors or plastic tarpaulins are employed in this regard.

2.2 Solar or solar-assisted drying[2]

This technology seeks to increase drying rates by inducing higher temperatures and sometimes convective air-flow using the sun as the source of energy and the greenhouse effect created. It includes solar collection devices, displaced from the coffee layer, and air (either fan driven or convective) as the conductive fluid. Normally some kind of greenhouse effect is exploited and, in more ambitious designs, an air-flow is induced by establishing a temperature gradient. Addition of fan circulation produces much better drying performance but an electric supply is required. In these designs air can be heated 5 to $7^{o}C$ above ambient at a flow rate of $1m^3/min/m^2$ of surface.

Relatively few solar designs have proved efficacious in the field and there is an open question as to the impact of some designs on coffee quality during periods of little or no insolation.

[2] More detail can found in Section 5 of this document.

2.3 Mechanical drying[3]

Generically there are three common types of mechanical dryers used in coffee processing:

- Static bed or silo dryers where hot air is forced through a bed of coffee;
- Contra-flow or vertical dryers where the coffee is cycled from bottom to top and allowed to flow downward through a stream of hot air; and
- Horizontal dryers where the hot air is introduced through a central shaft and forced outward through a rotating, perforated cylinder oriented horizontally which shares features of contra and concurrent flow. There are several new designs which promise higher drying efficiencies as measured by kJ/kg of coffee required to effect drying.

Mechanical drying requires pre-drying so, with the exception of some arrangements of silo dryers, partial drying in the sun is also required where mechanical drying is applied. Heat exchangers are commonly employed to protect the coffee from acquiring a taint but where clean burning materials such as charcoal or propane are used, direct heating can be applied. In addition to these, wood (often from shade trees or coffee prunings), coffee husk, dried sugar cane, fuel oil and kerosene are used.

Control parameters include loading, duration and operating temperature – normally air flow is fixed, though this may vary with back-pressure. Many mechanical dryers, horizontal designs in particular, only dry efficiently when fully loaded, others are more flexible. Typical drying times are from 12 to 24h depending on input moisture content, technology and operating temperature. If duration is insufficient the product will not be stable and if too great the producer loses money due to a loss both of quality and of weight. Uniformity of drying is an aspect that has received little attention but there is no reason to believe that rapid drying will result in a population of uniformly dried particles since the migration of water through the bean and fruit tissues is quite slow. The air temperature is usually controlled at the inlet and is critical since temperatures in the grain above 45^{o}C can damage coffee quality and a proportion of immature beans will become black and thereby lose much of their commercial value.

2.4 Hybrid drying systems[4]

This new method adds a non-solar thermal source to drying on a traditional terrace by pushing heated air through perforated ducting around which the coffee is heaped. The heaps can be spread during the day to take advantage of solar input and heaped under a plastic tarpaulin over night where it continues to dry as the warm air is conducted through it. There is little experience of the system in the field, but experimental results have been promising.

[3] More detail can found in Section 6 of this document.
[4] More detail can found in Section 7 of this document.

3. Effect of Drying on Fungal Growth:

The physical conditions from top to bottom of a layer of coffee drying in the sun are far from homogeneous and they cycle daily, with stirring and progressively during the drying period. A general pattern does emerge: hydrophilic fungi perish during drying and mesophiles (this includes OTA-producing species) and xerophiles may increase. Parameters such as initial loading, speciation, drying rate and, possibly, maximum temperatures attained in the coffee layer, affect this outcome. The source of these fungi is largely the coffee itself as it comes from the field or the previous processing step onto the drying yard.

This picture is based on analyses of bean infection and there is no data on actual fungal biomass. An 'increase' thus represents *denovo* infection – grains free from fungi come to contain them. In cherry drying it is likely that this is from fungi established in the fruit tissue at the time of harvest that grow into the bean during drying as the fruit tissue changes from a metabolically active plant organ to a metabolically inert substrate. In both cherry and parchment drying, hyphal extension is likely to be the most potent mechanism of infection and with particle-to-particle infection this is more likely during the night in the absence of stirring. Hyphal extension from an established mycelium can be very rapid whereas conidial dispersal requires 9 to 15h for germination followed by some days of feeble growth in most cases.

OTA production is not concomitant with growth but established biomass of the producing fungus and growth is necessary for it to occur. This is because there are many independent factors affecting the expression of this trait. A corollary of this fact is that the range of physical conditions under which OTA production occurs is narrower than that which supports growth.

Some mycotoxins are produced predominantly before harvest, such as the *Fusarium* toxins, aflatoxin in peanuts and the ergot alkaloids, and most have a potential for field production. This seems ***not*** to be the case with OTA in coffee where rare instances show that field production can occur but most serious problems arise during processing and subsequent storage. During drying, the OTA-producer is subject to the changing physical conditions but also to the biological context of community adaptation to the changing conditions. At high water activity levels (A_w above about 0.95), the hydrophiles success tends to prevent much development of mesophiles. As the A_w falls below this level, mesophiles begin to prosper and OTA production can begin. This may continue until an A_w of about 0.82 to 0.80 where OTA production ceases and 0.78 where growth ceases. If the period of time spent in this window is less than four days, the indication is that coffee is protected. Though these aspects are quite well understood, the complexity of the system means that the system has a low predictability and is difficult to replicate.

4. Sun Drying: Facilities, Procedures and Control of drying:

Sun drying can be an economical and effective method, producing high quality coffee, for coffee drying under good ambient conditions. In poor drying conditions it can be impossible to produce good coffee by this method, and in many climates the harvesting season coincides with unreliable weather. There are numerous other technologies, of varying capital and running cost implications, and these will be discussed below. However, especially in the predominant smallholder sector, sun drying is the only feasible approach for economic reasons.

A range of surfaces are used in producing countries for the sun-drying of coffee (see Fig. 1 a-h, below).

4.1 Facilities for sun-drying

4.1.1 Cement or brick drying terraces

A comprehensive discussion of terrace drying is provided elsewhere in this training resource (*see: 'Terrace Drying in Brazil: Facilities and Control of Quality and Safety during Drying' [.pdf], found in the Support Documentation area of this Section*). Although some of the specific detail in that document is peculiar to Brazil, the main points are relevant to hygienic handling of drying operations on any terrace in any country.

Fig. 1: a. Brick tile (Brazil); b. Cement (Brazil); c. Compacted soil (Brazil); d. Mesh tables (Kenya); e. Bamboo mat tables (Côte d'Ivoire); f. Carros - the drying surface is withdrawn under cover (Colombia); g. Elbas - the roof is moved to provide cover (Colombia); h. Plastic tarpaulin (Indonesia).

4.1.2 Drying tables

Drying tables covered in mesh or mat are used where frequent showers can be expected during the harvesting period because this system simplifies protection of the crop from re-wetting. Built of wood, they are expensive to maintain due to the combination of high rainfall (required for coffee cultivation), wood-rotting fungi and termites. Poorly maintained mesh tables characteristically sag with the result that layer thickness, and consequently drying rates, are not uniform.

In good drying conditions terraces perform better than tables because of higher temperatures but in periods of rain the table is superior because the open lower surface prevents condensation and allows drying to continue slowly. They also may perform better where humidity is low and wind plentiful since tables present two surfaces for moisture loss.

4.1.3 Movable terraces

Another approach to protecting coffee from re-wetting in showery regions is to make solid drying surfaces or their roofs movable. The Colombian '*carros*' and '*elbas*' represent this approach. The surface of the *carros* is wood so to reduce the weight of the structure though some workers have reported a build-up of fungi on the wood after periods of heavy use. Steel tracks are required since the loaded weight is considerable. The *elbas'* drying surface is normally cement covered with a movable corrugated roof. This form of covering is superior to the use of plastic tarpaulin since there is a significant air space above the coffee minimising the risk of condensation during periods of rain.

One early Brazilian version of this system was patented in November of 1889 by Corrêia de Silva. It consisted of several meshed trays that contain the coffee. The trays with appropriate dimensions are mounted over rails, and the system is housed under a fixed covering for protection from rain.

4.1.4 Soil surfaces

Compacted earth is widely used in cherry coffee processing even though it is considered inappropriate for parchment drying. The drying period on soil is generally somewhat longer than other surfaces. Drying rates when the coffee is relatively wet, however, are comparable and the divergence in performance is principally in the late stages of drying. Under good drying conditions these surfaces can produce good coffee but the onset of rain causes significant problems. From the perspective of OTA accumulation, risk of *de novo* contamination is probably generally slight since it is known that coffee from the field bears a large microbial load including, in many cases, OTA-producers. But this may change toward the end of the season, particularly a wet season, if the surface has been more or less continually covered with coffee at various moisture contents. Given the potential problems associated with drying on this surface, and its negative image, the practice of direct drying of coffee on soil is strongly discouraged.

4.1.5 Plastic tarpaulin

Using plastic tarpaulins as a drying surface simplifies the protection of coffee from rain since the coffee can be quickly rolled into it. Although it prevents excessive contact with the soil, it may not provide much protection from cross contamination toward the end of a season for similar reasons as wood and soil. In good drying conditions, however, the performance has been poor with respect to taste and in some tests, OTA accumulation. This is likely to be attributable to the accumulation of liquid water beneath the coffee layer as it evaporates in the hot upper regions of the layer and condenses on the cooler impervious surface.

4.2 Control parameters

Control of operation of sun drying apparatus varies with the device, but they all share the same list of considerations. These include (see also Fig. 2 a-d, below):

- Covering the coffee overnight;
- Uncovering early in the morning;
- Stirring frequency;
- Protection from fouling of the product by domestic animals;
- Ensuring protection from daytime rain;
- Maintaining separation of different lots; and
- Monitoring of moisture.

Having a list of considerations, however is not sufficient. There must also be routines and an overt assignment of responsibilities to the staff whether these are family members, temporary labour or salaried employees. The responsible persons must be trained and understand why their function is important in order to provide motivation. The use of checklists where the completion of tasks can be recorded serves as both a contemporary and permanent record.

Of course, coordination of harvesting, any other processing steps and any complementary drying methods with drying yard progress and activities must be maintained. Given the very different drying rates that can obtain in different weather conditions, this coordination of activities can be difficult and uncertain. Certainly, a degree of flexibility has to be built into the system.

Purely from the aspect of preventing mould growth and OTA accumulation, the control parameters should be designed to maximize drying rate, and eliminate inappropriate intermixing and re-wetting.

In practice, however, there are other considerations that arise requiring the drying rate to be moderated. The discussion above referred to the treatment of green cherry and the late drying period is described where drying is purposely inhibited to prevent formation of black beans and an unhomogeneously dried product, respectively. In equatorial areas it is generally recommended that after initial drying the parchment should be covered for 2 to 3 hours over the noon period to prevent splitting of the parch.

Fig. 2: a. Heaping and stirring on cement patio (Brazil); b. Heaping parchment (India); c. Covering coffee at the end of the day (India); d. Stirring parchment on tables (Kenya).

4.3 Structure and Location

The drying terrace should be located in an open, well drained, sunny, and ventilated area, avoiding humid areas, proximity of dams, shaded places with trees or adjacent buildings. It should lie at a level below the reception and preparations facilities and above the level of the storage and hulling facilities. Solar drying terraces can be built in beaten soil or be paved with bricks, asphalt or concrete. However, concrete floors present better drying results and are more durable, easier to handle, and with better sanitation characteristics.

Whenever possible, the drying terrace should be divided in blocks, in order to facilitate the drying of different lots according to origin, moisture content, and quality. To facilitate rain water drainage, the drying terrace should be built with a steepness in the range of 0.5 to 1.5% with drains located in the lower part of the terrace. The drains, measuring 0.4 x 0.25 m, should be built in steel plate with 50% perforation, and 4mm squared holes, in order to impede the passage of coffee beans in case of heavy rain. In the case of adopting circular perforations, the same perforation percentage should be used, with holes of smaller dimensions (with a maximum diameter of 2 mm).

The terrace should have raised borders with permanent and movable drying area separators (without sharp corners), the outer walls measuring 0.25 m high and 0.15 m thick around the drying terrace so as to avoid losses, or mixtures of different types of coffee. Inside the yard, circular or semicircular barriers or crowns can be built - small walls no more than 5 cm high and 3 cm diameter. The purpose of these barriers is to serve as a place to pile up the coffee, to avoided rain water flowing under the plastic sheets.

For successful terrace drying, operators must do periodic maintenance e.g. of the drying surface, and of the drainage system. Even with a good terrace drying system, to consistently produce a high quality coffee free of contamination, it is of fundamental importance that the terrace is managed correctly, and that adequate sanitation procedures are followed.

The area of the drying surface must be in scale to the maximum rate of harvest, a parameter related to yield, amount of labour engaged and harvesting method.

4.4 Estimating Required Drying Yard Size

One rule-of-thumb, in several units, for cherry drying is:

$$\mathbf{S = 5 \times 10^{-4}\, Q.T}$$

Where:

S = area required for drying in m^2/1000 trees if
Q = annual average yield of cherry coffee, in litres/1000 trees

Or:

S = area required for drying in m^2/ha if
Q = annual average yield of cherry coffee in litres/ha

Alternatively:

$$S = 7.9 \times 10^{-4}\ Q.T$$

Where:

S = area required for drying in m^2/ha if
Q = annual average yield of cherry coffee in kg/ha

And:

T = average drying time in days

To accomplish only partial drying (from 60% moisture content to approximately 30% b.u.), and in order to use complementary mechanical drying, drying terrace area can be reduced to ⅓ of the original value.

A second rule-of-thumb is as follows:

The rationale here is that harvest rate approximates a bell-shaped curve that peaks at about 2% of the total harvest brought in per day. This notion is combined with an assumed residence time on the yard (i.e. time required to achieve dryness) of three weeks for cherry, and two weeks for parchment coffee.

It is also tied to a loading rate of 30kg/m^2. It should be pointed out that thickening of the layer during the later drying stages; methods such as the use of conditioning bins or mechanical drying; and rapid harvesting methods such as stripping (especially mechanical harvesting), would throw off the estimate. It is thus best adapted for family farms.

$$S = Q \times (0.02 \times D) / L$$

Where:

S = area required for drying in m^2/ha of plantation
Q = annual average yield of cherry coffee in kg/ha
D = average drying period (days), nominally 21 days for cherry and 14 days for parchment
L = loading rate on the yard, nominally taken to be 30kg/m^2 cherry or 40kg/m^2 parchment

5. Solar or Solar-Assisted Drying:

Solar dryers utilize the greenhouse effect to maximize the development of a temperature differential from the ambient which accelerates drying rates.

In some designs the bed of coffee serves as the solar collector, and in others a separate collector is used. Despite the sun being the primary source of energy, its energy density is such that it can only be used for grain drying in deep layers in low temperature drying systems, i.e. where temperature is elevated less than about 20°C above the ambient. The collector size required to reach a temperature difference greater than 20°C above ambient, which characterizes high temperature drying, is not economically viable.

Furthermore, the intensity of the sun is both periodic and intermittent. Medium capacity mechanical dryers require 120,000 to 300,000 kJ/h which, at a solar input of 3200 kJ/h/m^2 (0.8kW/m^2), implies solar collectors of between 37 to 94m^2 even assuming 100% efficiency of collection/transmission. Solar energy could be used to defray fuel usage of conventional fuel in appropriately designed small scale dryers. If a 56m^2 collector was coupled to the furnace, it could save up to 100kg of firewood during the day without stopping drying operation by operating the furnace by burning firewood during the night, in the absence of solar radiation.

5.1 Systems with coffee bed collectors

5.1.1 Parabolicos, marquesina

These systems are basically greenhouses adapted for drying. There is no convective circulation due to the large head-space but there is temperature elevation. Field tests have failed to confirm any significant or consistent drying rate improvement with the parabolicos though it does provide protection against rain which is an advantage in wet regions.

Fig. 3: a. The marquesina is typically constructed in steel and glass so is expensive; b. The parabolicos was designed to be built with local materials such as bamboo, and is aimed at smallholder farmers.

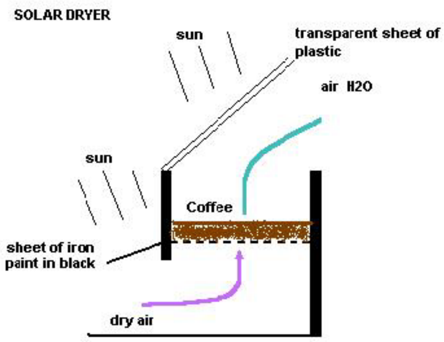
5.1.2 ITIPAT dryer

Coffee is laid on a wire tray support and the dryer is kept covered by a transparent plastic sheet. Heat accumulates between the coffee and the plastic and the air starts to circulate. This dryer is mounted on a pivot so it can be turned towards the sun.

Field trials have returned disappointing results using this design. Condensation was noted on the plastic sheet which suggests that there is insufficient convective air flow. In warm cloudy weather there is insufficient temperature development and the commodity tends to sweat.

Fig. 4: Views of the ITIPAT dryer

Variation of the convective circulation design:



Here the dry air inlet has to be pointed towards the prevailing wind. The air is slightly heated by the sun, and circulates through the mass of coffee. The coffee should be in very thin layers, and is also heated from above.

Fig. 5: Diagrammatic representation of convective airflow in simple solar dryer

5.2 Systems using solar energy collectors

Despite a lot of similarities, there is a great variety of solar collectors types in the specialist literature. The collector must be oriented in such a way to receive the maximum of solar energy. The 'solar roof collector' should be of the type shown in Fig. 6, with the llong side oriented east-west, and the absorbing surface facing north for (southern hemisphere) or facing south (northern hemisphere).

The horizontal inclination of degrees off the horizontal is best adjusted to equal the latitude of the location. Of course, within several degrees of the equator the sun is in the south and north almost equally so a horizontal roof would provide the best average performance.

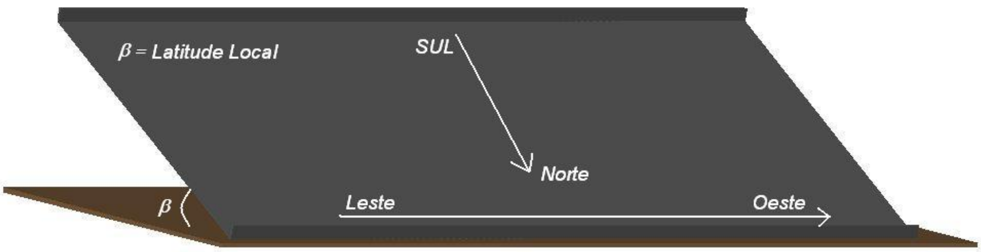


Fig. 6: Ideal fixed inclination for the solar energy 'roof collector' - about 20^o latitude.

A great advantage of the 'roof collector' is that it will absorb both direct incident radiation from the sun and also diffuse radiation, that reflected or scattered by the earth and by clouds.

A second advantage is that, depending on design, the roof could serve to protect the coffee from rain. With the 'roof collector' it is possible to augment ambient air temperature by up to 30°C at very low airflow rates and high sun intensity. An increment of 7 to 10°C is considered a good value to obtain reasonable efficiency of the system.

As the collector can be designed to serve as the roof of the drying facility, the total cost of the system won't be very high. The 'roof collector' itself is of relatively simple construction and of lower cost than other types of solar collectors.

There are several models of plane collectors, but all of them have two basic characteristics:

- A black plate, to absorb solar energy; and
- A circulating fluid (ambient air) used to remove the heat from the black plate and transfer it to a chamber that contains the grains to be dried.

A 'roof collector' can be built with metal or cement-asbestos tiles, painted flat black. The tiles should form clear channels with the roof structure and the covering plastic through which the drying air will be forced to pass. The covering transparent plastic is supported by chicken wire and attached to the ridges of the roof work thus defining channels. The plastic contributes greenhouse heating as well as channeling the airflow efficiently (see Fig. 7 below).

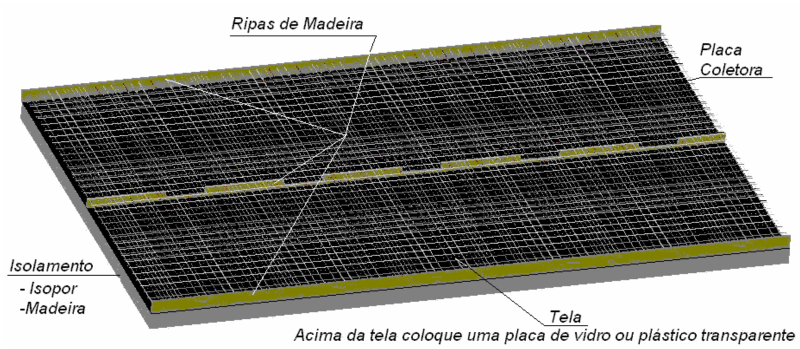


Fig. 7: Structural details of solar energy roof collector

There are different ways to improve the collector efficiency, but the calculation of cost/benefit for such higher costs have yet to be done. For example, is the addition of insulation of the bottom of the collector cost effective?

Usually, the most efficient collectors are also the most expensive. The desirable characteristics of a solar energy collector are to:

- Absorb the maximum of the solar radiation;
- Lose the minimum of heat to the atmosphere; and
- Transfer the absorbed heat easily to the circulating air.

Painting the roof black will absorb more radiant energy than any other colour. A flat black surface can absorb up to 95% of the radiation that passes through a transparent covering. When the collector is not in operation, or if the fan is turned off, the temperature can reach over 80°C. So it is advisable to cover the collector to avoid damage caused by those high temperatures and, if possible, remove the transparent cover when the collector is not in use over the growing season.

These dryers require an additional source of energy to circulate the air within the mass to be dried. They are also more difficult to construct and more expensive.

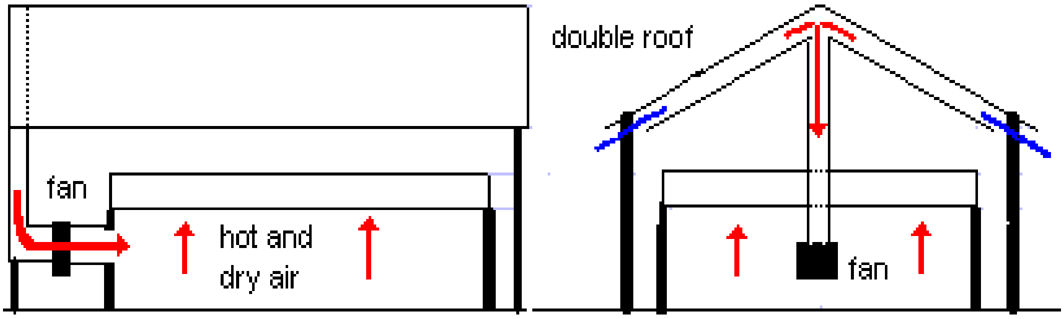


Fig. 8: This consists of a double roof in which the air is heated by the sun. A large diameter pipe recovers hot air at the top and it is blown by a fan towards the drying trays on which the coffee is placed.

6. Mechanical Drying:

6.1 Fixed-bed or silo dryers

For small scale operations, drying coffee on a fixed bed has become one of the most widely used techniques in Zona da Mata, Minas Gerais in Brazil. Something like half of farms in the Caldas region of Colombia also use silo dryers. In Brazil, strip-picked coffee with a wide range of initial moisture content is placed in the dryer and heated air is passed up through the coffee using a power-driven fan.

Loading and unloading are generally done by hand. Traditionally, as in cross flow dryers, the air temperature must be kept at moderate levels (below 50°C) in order to minimize over drying in those layers close to the input air side of the dryer. Generally, the drying is stopped when the average moisture content of the whole grain layer has reached the required level for safe storage. By this time, the grain close to the exhaust air side of the dryer is still under dried.

Stirring the coffee is a problem in thick layers and allowances for redistribution of moisture in the coffee bed must be made. During operation a moisture gradient in parallel with the temperature gradient will be established such that coffee near the bottom is over-dried and that near to the outlet, under dried. Bed depth and equilibration time are two additional control parameters. Usually these dryers are not stirred but if they are the fan must be turned off to protect workers. So far very little research on coffee-stirring devices has been done to determine the extent of mechanical damage to the product. However, the introduction of stirring devices increases both the fixed and operating costs of the dryer.

The coffee must be pre-dried and this can be efficiently done on the roof of the facility utilizing the heat lost in the drying operation. Pre-dryed in this way for 24h yields parchment coffee with an A_w of about 0.92. The drying chamber itself, a furnace, heat exchanger and fan comprise the structure (see Fig. 9a). A typical routine would be for the furnace to be run overnight but the dry coffee not unloaded until late in the afternoon to provide an equilibration period. Immediately the pre-dried coffee is loaded through the roof (a bunged hole built in for this purpose), and the freshly washed coffee is loaded onto the roof (see Fig. 9b).

Silva & Lacerda Filho (1984, *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*) designed and built a fixed bed dryer to dry natural, washed and pulped coffee (Fig. 10). The dryer has been widely adopted by small and medium scale coffee farms and has been eventually used to dry other agricultural products such as beans and corn.

Fig. 9: a. Silo dryer; b. Pre-drying of wet parchment on the roof of a silo dryer

The dryer can be built with a drying chamber up to 5 m in diameter and 0.6 m high. The plenum chamber with the same height results in a total dryer height of 1.2 m. The walls consisted of one brick layer 0.15 m thick covered with plastering on both surfaces. Production of heat takes place in one stage in a downdraft direct combustion furnace using wood or coal as a fuel source.

The inside of the furnace is lined with insulating firebricks and a paste of sand, molasses and soil is plastered on the exposed surfaces of the furnace wall. The use of molasses in the mortar prevents the formation of cracks in the furnace.

The furnace is equipped with a cyclone chamber where the ash is trapped and where natural air is mixed with the flue gases to obtain the proper drying air temperature. The cyclone chamber is made with bricks and consists of a cylinder having height and diameter of 1.2 and 1.0 m, respectively. As the gases are drawn through the cyclone by negative pressure generated by a single centrifugal fan located between the dryer and cyclone, air mixes with the hot gases. The fan must be selected based on previous calculations to provide the amount of excess air needed both for a complete combustion and a clear burning. Not only particulate emissions must be below acceptable levels, but the dried coffee must be free of odor and harmful contaminants (nitrogen oxides and polycyclic aromatic hydrocarbons).

Fig. 10: General view of a fixed bed dryer
(model designed at the Federal Univesity of Viçosa, Brazil).

Drying runs have consistently shown that the fixed-bed dryer is capable of reducing the moisture content of a 0.4 m high layer of natural coffee from 60% to 12% w.b. in 48 h, provided the drying air temperature is kept at 55°C and the coffee bed is stirred at intervals of 2 h.

The amount of energy (6,600 kJ kg^{-1}) consumed during the drying of a 0.5 m deep natural coffee bed is approximately 65% higher than the amount (4,100 kJ kg^{-1}) consumed during the drying of washed coffee. These values were obtained for coffee originally at 52% w.b., and subsequently dried to about 14% w.b. with an airflow rate of 12 m^3 min^{-1} m^{-2}, drying air temperature of 60°C, and a stirring interval of 3 h. Dryer output increases from 9.8 (natural coffee) to 18.7 kg h^{-1} m^{-2} (washed coffee) for those same drying conditions.

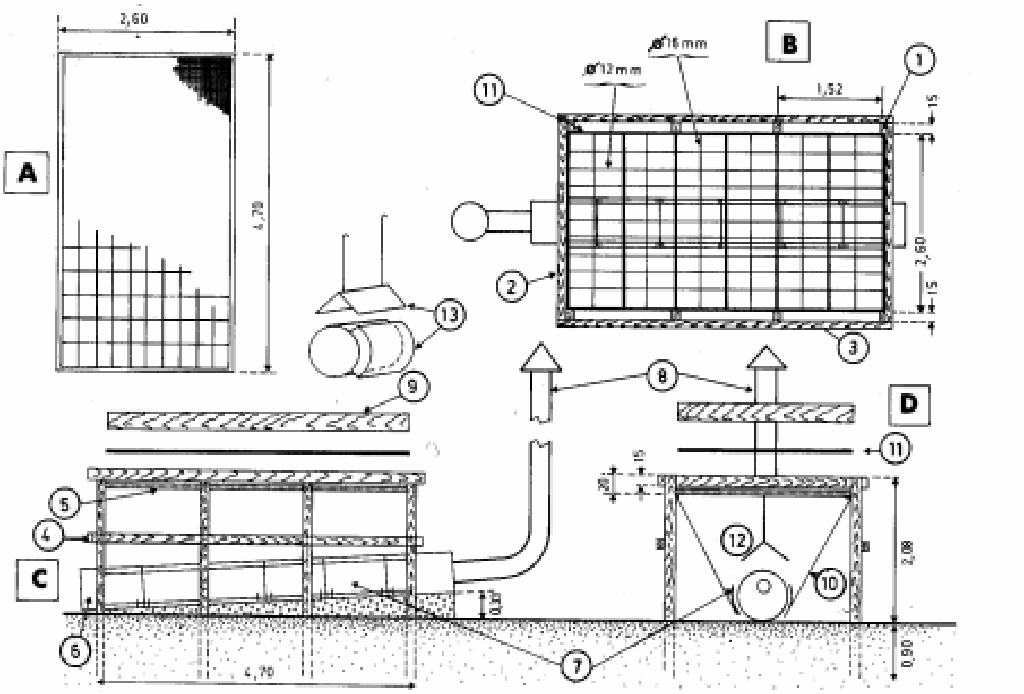
6.2 Natural convection dryers

Air moved by natural convection is an alternative to solve drying problems on small coffee farms that do not have an electric power supply. This type of dryer does not need fans, can be built with easily found materials, and needs little specialized labour for its construction.

Fig. 11 below shows one such natural convection dryer that uses one heat exchanger to transfer heat from combustion to the drying air that enters through openings in the lower sections of the dryer walls. The movement of the air that crosses the coffee layer is due to pressure gradients produced by the temperature difference between the drying air and the ambient air. A natural convection dryer has the following key characteristics:

- Does not require fans;
- Has a low initial cost;
- Non-specialized labour for its construction;
- Low thermal efficiency as compared with forced convection dryers;
- Uneven temperature and air distributions for inadequate plenum chamber project; and
- Risks of smoke contamination in case of perforations or leaks in the heat exchanger.

Désignation des ouvrages (*Description* — Denominación de las obras)		Quantités (*Quantities* - Cantidad)
Charpente du four (*Framework* — Armazón del horno)		
Poteaux de (*Posts* — Postes de) 0,15 × 0,10	mL (m)	24,0
Basting de (*Rails* — Maderos de) 0,10 × 0,5	mL (m)	25,0
Planches de (*Planks* — Tablas de) 0,25 × 0,025	mL (m)	15,0
Lattes de (*Battens* — Listrones de) 0,03 × 0,02	mL (m)	10,0
Boulons d'assemblage (*Through-bolts* — Pernos para ensambladura) 27,5 × 12	Nbre (No.)	40
Partie chauffante (*Heater* — Elemento calefactor)		
Fûts de récupération (*Salvaged drums* — Barriles de recuperación) (6 fûts pour le foyer + 14 pour les fermetures latérales + 6 pour les déflecteurs) (*6 for oven, 14 for side and end panels, 6 for deflectors* — 6 barriles para el hogar, + 14 para los cierres laterales + 6 para los deflectores).	Nbre (No.)	26
Fer plat de (*Hoop iron lugs* — Hierro plano) 2,5 × 0,3	Nbre (No.)	6
Fer à béton de (*Reinforcing bar* — Hierro para hormigón) ∅ 12	mL (m)	5,0
Grille (*Grid* — Rejilla)		
Tube de (*Concrete bar* — Tubo de) 1"1/4	mL (m)	28,0
Fer à béton (*Reinforcing bar* — Hierro para hormigón) de ∅ 16	mL (m)	15,0
Fer à béton (*Reinforcing bar* — Hierro para hormigón) de ∅ 12	mL (m)	18,0
Grillage cacao (*Cocoa netting* — Alambrado para cacao)	m²	14,0
Fer plat de (*Hoop iron* — Hierro plano de) 4,0 × 1,0	mL (m)	1,2
Boulons à bois (*Wood bolts* — Pernos para madera) 17,5 × 12	Nbre (No.)	16
Cheminée (*Stove-pipe* — Chimenea)		
Tôle galvanisée 6/10 (*6/10 galvanized iron sheet* — Chapa galvanizada 6/10) 2,40 × 1,20	Nbre (No.)	2
Divers (*Miscellaneous* — Varios)		
Boîtes de vis avec écrous de (*Boxes nuts and bolts* — Cajas de tornillos con tuercas) 19 × 7	Nbre (No.)	24
Baguette de soudure (*Strip solder* — Varilla para soldadura) 4 mm	kg	4,0



Schelle :
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FIG. 1. — **Four à coprah à air chaud** (*Hot air copra dryer* — Horno de copra por aire caliente).
[A] : **Cadre du lit à coprah, vue de dessus** (*Coprah bed, top view* — Marco de la cama para copra, vista superior).
[B] : **Vue de dessus, tôles latérales enlevées** (*Top view, side panels removed* — Vista superior, después de quitadas las chapas laterales).
[C] : **Vue latérale, tôles latérales enlevées** (*Side view, side panels removed* — Vista de perfil, después de quitadas las chapas laterales).
[D] : **Vue de face, tôles de fermeture-avant enlevées** (*Top view, end plates removed* — Vista frontal, después de quitadas las chapas de cierre).

Fig. 11: Schematic representation of natural convention dryer

However, when well dimensioned and adequately built, these problems can be minimized. For coffee drying only the use of a heat exchanger or a flue is satisfactory. In the design above, the air is heated in contact with the flue pipe (the design is actually for a copra dryer).

6.3 Vertical & horizontal dryers

A very common type of mechanical dryer is the vertical dryer. The flow of coffee is by gravity, the rate controlled be the size of an outlet funnel (Fig. 12a). As the coffee leaves the drying chamber it is returned to the top via an elevator. Hot air is introduced near to the bottom of the chamber and flows upward against the flow of coffee, hence 'counter current dryer'. The drying chamber can be either cylindrical or rectangular (Fig. 12b). Some data on energy requirements for drying related to inlet temperature is given in the table below.

The horizontal dryer (Fig. 12c) is also very common and has aspects of both concurrent and counter current drying. The hot air is introduced through a central shaft and leaves through the tumbling mass of coffee. Performance of this type of dryer is particularly sensitive to load and an under loaded dryer works poorly since the hot air leaves with little contact with the coffee. Analysis has shown that much of the energy used in continuous rotation is not converted into faster drying, thus an interesting hand rotated prototype has been the subject of evaluation at the Federal University of Viçosa (Fig. 12d).

Fig. 12: a. Outlet funnel of vertical dryer; b. Drying chambers of vertrical dryer; c. Horizontal dryer with continuous rotation of coffee; d. Prototype horizontal dryer developed by University of Viçosa, Brazil.

Table 1: Energy requirements of counter current drying of natural coffee: effect of drying air temperature on total drying time, specific energy requirement, and throughput

Drying-air temperature (°C)	Total drying time (h)	Specific energy requirement (kJ kg^{-1})	Throughput (dry kg h^{-1})
60	21.5	8,300	50.2
80	14.2	7,550	76.1
100	10.2	6,440	105.9

Source: Silva (1991, *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*).

7. New Approaches to Coffee Drying:

The drying step in coffee processing is of critical importance for preserving the intrinsic quality characteristics of the coffee and for ensuring that food safety problems do not develop. In light of this, research institutions in coffee producing countries have spent time in the development of dryers that better suit the needs of the local industry. One institution that is heavily involved in such work is the Federal University of Viçosa (UFV) in Brazil. Several innovations in coffee drying technology that are being promoted by the UFV are outlined in a separate background document, 'New technologies for the drying of coffee' (*see: 'New technologies for the drying of coffee' [.pdf], found in the Support Documentation area of this Section*).