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DEVELOPMENT AND USE OF SOLAR DRYING TECHNOLOGIES

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ABSTRACT

A critical review of solar drying relevant to countries in Africa is presented in this paper, pointing out achievements and failures, and explanations why they may have occured. Available technical information suggests that solar drying technologies are available for a range of foodstuffs, but they need to be adapted to the local environment. Several technologies that may be suitable for rural and industrial uses are reviewed. The greatest challenge is concerned with technologies for rural farmers who at present have very little income to acquire improved solar drying technologies. It is argued that solar drying has not yet taken hold in the agricultural sector due to several reasons such as the orientation of research and development workers, promoters of related technologies, and lack of favorable national policies. Some guidelines that can be used for developing and ensuring the effective use of solar dryers are presented.

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1. INTRODUCTION

1.1 Traditional Drying and Losses

The use of the sun to preserve foodstuffs is perhaps the oldest method of food preservation known to man. Open air sun drying is practiced by the majority of people in developing countries, where other forms of energy are expensive to use or are unavailable. Traditional methods, which consist mainly of spreading the commodity on the ground or on some other surface, are known to cause several losses due to:

(a) contamination by dust, rodents and other animals;
(b) infestation by insects;
(c) the growth of molds and development of toxins;
(d) inappropriate drying rates;
(e) soaking by rain;
(f) theft and vandalism.

Since agriculture is the main preoccupation of rural dwellers who account for over 80% of the population in many African countries, and since foodstuffs need to be conserved at the farm level, drying is considered an important factor in achieving food security in many countries. However, due to certain inadequacies of traditional drying, there are besides the losses in weight of agricultural products, losses in their quality, due to health hazards such as aflatoxins. Losses in the nutritional quality of dried products is another important consideration in traditional drying.

Many efforts have been made to improve solar drying in developing countries. In Africa, very little success has been achieved in using improved solar dryers on a meaningful scale, due to technical, social and economic constraints. Work however continues unabated to develop dryers that can reduce losses and improve the quality of dried foodstuffs.

1.2 Aim of Paper

The main purpose of this paper is to present a framework for solar drying research and development based on lessons learned from previous work. It is intended to present a critical review of the general literature pertaining to the rural environment of Africa where the majority of drying activities take place. An attempt will be made to show the importance of integrating problem identification, technology development, social, economic and political issues, within the general framework of a campaign to successfully implement improved dryers. The analysis and discussions will be limited to solar food drying technologies such as natural flow dryers that have the greatest potential of being used in the near future in the poorer rural areas of Africa. As a result, dryers that predominantly use fuels such as wood and oil, will not be treated in this paper.

2. SOME COMMODITIES THAT NEED DRYING

Drying needs of a given country depend on the types of commodities being produced for local consumption as well as for export. Table 1 shows the range of commodities that require drying in some countries in Africa, consisting of foodstuffs such as cereals, vegetables, fruits, fish and meat, spices, grain legumes, roots, tubers, and cash crops for export. In semi-arid regions, where ambient temperatures are high and relative humidities are low during a significant portion of the year, drying of some staple foodstuffs such as sorghum, millet and maize can be satisfactorily achieved by traditional open air methods. Nevertheless, even in these regions, the relative humidity during certain periods create conditions that encourage the development of toxic molds. In the more humid coastal regions, drying of cereals, which are staples for many, is more difficult. For example in Mauritius, maize can only be dried to a moisture content of about 15 to 16 percent by sun drying; artificial methods are needed to dry the crop to a safe moisture content of 12% [1].

Losses associated with sun drying of some cereals are substantial. In Sierra Leone, for example, studies have shown that the combined losses incurred during field drying and drying after threshing rice can be as high as 18%. Such losses are mainly due to the lack of other drying methods which would permit early harvest of the crop at a higher moisture content.

Leafy vegetables are eaten in many countries and contribute substantially to the protein intake of the populations. Due to their seasonality, it is desirable to dry them for safe storage. Sun drying is inadequate in many instances due to poor hygienic conditions and the poor quality of the product. In some cases some of these leafy vegetables are exported for consumption by africans living outside Africa. The grower can derive substantial benefits by adopting improvements to traditional methods.

In countries, e.g. Nigeria, where root and tubers are consumed, there is an increasing need to dry commodities such as cassava and yam, before transforming them into flour. Advantages of processing are many; the shelf life of the crop is lenghtened, food preparation is made easier for women, and prices may be more stable since there is less risk associated to storage. Plantain, which is an important staple in countries such as Cameroon and Cote D'Ivoire, can be conserved for longer periods by drying. Losses due to its rapid deterioration in quality after harvest is about 40% in Cote D'Ivoire.

Fruit production is very high in many African countries. Unfortunately large quantities become spoilt due to the inexistence of adequate post-harvest facilities; transportation facilities are inadequate, refrigeration systems are generally not available due to high capital costs and lack of reliable electricity supply, traditional sun drying generally does not give products of acceptable organoleptic and nutritional quality.

Table 1. The range of commodities that need drying in some countries of Africa.

Country	Commodities
Nigeria	Millet, maize, soghum, rice, soyabeans, cowpeas, groundnut, cassava, yam, potaotes, onions, tomatoes, pepper, egusi (melon seeds).
Sierra Leone	Rice, coffee, cacao, groundnuts, sorghum, millet, beans, maize, sesame seeds, pepper, okra, cassava, egusi, piassava, fish.
Cameroon	Coffee, cacao, maize, tobacco, groundnut, sorghum, plantain, leafy vegetables, egusi.
Senegal	Millet, sorghum, maize, rice, cowpeas, fish, groundnut, tomatoes, onions, mangoes.
Gambia	Fish, millet.
Kenya	Maize, cassava, peas, beans, onions, pepper, tobacco, pyrethrum, tea.
Mali	Millet, sorghum, groundnuts, tobacco, onions, pepper, okra, tomatoes, fish, meat.
Mauritius	Maize, rice, onions, groundnuts, ginger, beans, peas, tumeric, chillies, coffee.
Niger	Onions, tomatoes, cucumber, okra, meat.
Togo	Maize, fish, okra, yam, cassava.

Vegetables are increasingly being dried in many countries by rural populations. In Sahelian countries for example, vegetables are abundantly grown during the dry months, but there is very little production during the rest of the year, resulting in malnutrition and related health problems. In these countries, women in villages dry some vegetables such as, tomatoes and onions, which are used during the difficult periods. These activities are considered to be very desirable but the main constraint is the lack of appropriate drying systems.

Fish is widely sun-dried. It is processed in some countries by fermentation and drying, e.g. in Senegal and Mauritania. However, due to unsanitary conditions of drying, the fish is usually infested with insects which cause losses in weight of up to about 40%, not to mention the associated health hazards. In addition the fish processors are paid less for the kilo due to the poorer quality of this product. In countries e.g., Mali, Guinea and Sierra Leone, where fish is smoke-dried, it is often necessary to further reduce its moisture content to acceptable levels to minimize the possibility of insect infestation and spoilage during storage. Better quality processed fish can thus be obtained by improved solar drying techniques.

Preservation of meat is carried out by either slicing it into small thin pieces followed by sun drying (as done in Niger), or by smoke-drying bigger chunks (as is the case in Nigeria).

Crops for export, such as cacao, coffee, ginger, pyrethrum, and tobacco, all need to be carefully dried in order to meet international standards. Some losses are presently being experienced by farmers due to the use of inadequate drying techniques.

3. DRYING CONDITIONS FOR CROPS

One of the factors responsible for the slow pace of adoption of improved solar drying is the difficulty of designing dryers which can be used for various crops, since each crop has its optimum drying conditions. Typical drying requirements for various crops such as their initial moisture contents, desired final moisture contents, maximum drying temperatures and the basic pre-treatment required are shown in Table 2.

This table indicates the wide range of initial and final moisture contents of the various crops and the relative order of magnitudes of drying temperatures. Immediately obvious is the lower range of drying temperatures for cereals compared to those for vegetables. Initial moisture contents for cereal grains are substantially lower than those for vegetables. Final moisture contents for vegetables are lower compared to those for grains. These differences are partly responsible for difficulties experienced in developing cheap dryers that can be used for a wide range of crops.

Table 2. Drying requirements for various crops (Based on [2] and [3]).

Commodity	Moisture Content (%)		Drying Temperature (C)	Pre-treatment
	Initial	Final		
Rice (raw)	20-25	13	40-50	*
Rice (parboiled)	30-35	13	40-70	parboiling
Maize	25-35	12-15	60-80	*
Millet	21	14	---	*
Green peas	80	5	65	blanching
Onions, garlic	80	4	55	slicing
Carrots	70	5	75	slice/blanch
Green beans	70	5	75	blanching
Irish potatoes	75	13	70	slicing
Sweet potatoes	75	7	75	slicing
Cassava	62	17	70	slicing
Banana	80	15	70	slicing
Leafy vegetables	80	10	---	*
Peppers	---	5	65	*
Guavas	---	7	65	*
Coffee	50	11	---	fermentation
Cacao	50	7	---	fermentation
Cotton Seed	---	8	---	*
Copra	30	5	---	*
Groundnut	40	9	---	*

Moisture content is in dry basis.
--- Information not available.
* Not applicable.
Note: Initial moisture contents given may vary depending on agronomic conditions.

In general it is necessary to understand the physical and biochemical characteristics of the crops being dried. There are some gaps in the literature regarding crops grown in Africa. Optimum drying temperatures, pre-treatment required, physical characteristics of the crop and its optimal drying rate, nutritional advantages and disadvantages of drying, all need to be carefully studied and documented for important crops. Collaboration between food scientists, technologists and engineers is therefore necessary to obtain efficient drying systems.

4. STUDIES ON SOLAR DRYING

4.1 Scope and Interest

A review of the literature reveals that a significant number of work relevant to the African situation on small- to medium-sized farms have been carried out. However, the author feels that adequate efforts have not been made to tackle important aspects of solar drying that are crucial to its successful development and implementation in Africa. Unlike other fields of solar energy, solar drying does not appear to have received adequate in-depth and critical studies, as reflected in the literature.

For example, over 2200 papers have been published in the Journal of Solar Energy of the International Solar Energy Society, between 1957 and 1987. Of these, only 23 papers have been published in the area of solar drying [4]. Furthermore, only 5 of these 23 papers were very relevant to drying problems being experienced by the majority of farmers in Africa. A study of several Proceedings of international conferences outside Africa similarly indicates that drying systems appropriate to Africa have not been of interest to researchers who have better financial and material resources required to solve pending problems. A further indication of the relatively little interest in the general area of solar drying is demonstrated by the lack of a review paper in the Journal of Solar Energy.

On the other hand, solar drying is of interest to many researchers in Africa as reflected by the numbers of publications in this area by africans. For example, out of the 70 papers published in the Proceedings of a major conference on renewable energy in Africa, about 15 of them were concerned with drying systems [5]. Other publications on solar energy research show strong interest in solar drying in Africa [12, 22, 30, 31].

Other developing countries in Asia and Latin America which have similar agricultural and socio-economic conditions to those in Africa have done substantial work on solar drying. It is however noted that none of these developing countries have so far succeeded in routinely using solar dryers in their day to day post harvest activities.

Reasons for the different levels of interest in solar drying systems relevant to Africa is, of course, due to the needs of the various countries and available resources. In developed countries, for example, funds available for research are aimed at solving problems of local interest. Therefore, work on drying systems that would be economically, socially and culturally viable under African conditions are not carried out in developed countries. On the other hand even though the manpower may be available in several African countries to obtain breakthrough results, the material resources are generally unavailable. This is reflected in the results obtained in Africa.

4.2 Results of Some Research and Development Studies

4.2.1 Open Air Drying

Despite various disadvantages of open air drying mentioned earlier, this activity which is carried out on the ground or on raised platforms, is predominantly being used. It is straightforword to use, cheap and does not require any special user skills.

A review of principles involved in sun drying have been presented in [6], outlining interactions between ambient temperature, relative humidity of the air, wind and solar radiation. Direct exposure to the sun has the advantage of producing higher temperatures and vapor pressures in the commodity being dried, compared to convection drying, which induces higher evaporation rates (see Figure 1). However, overheating can occur in the final stages of sun drying and water resorption can occur at high ambient relative humidities, under extreme weather conditions.

There is, in the author's opinion inadequate information on open air drying on the ground. It would be of interest to know the contribution to drying by direct radiation from the sun, convection, and heat transfer from the ground. The relative performance of various surfaces such as plain mud, concrete, mat, etc, need to be studied in order to provide information on the relative economic and technical advantages and disadvantages of various drying activities. It would appear that in general, sufficient efforts have not been made to understand traditional drying methods before attempting to develop improvements to them.

Considering the importance of the capacity of the commodity being dried to absorb heat during open air drying, it is of interest to have access to data on solar radiative properties of various crops, such as their solar absorptance. Hemispherical solar absorptance for several cereal and grain legumes (wheat, brown rice, white rice, brown beans, yellow corn, unshelled groundnuts, black-eyed beans) have been determined and are reported in [7]. With the exception of white rice, all the crops tested have solar absorptances greater than 0.8, indicating that they are good absorbers and can be used as solar collectors. (As a matter of comparison, the solar absorptance of flat black paint is 0.94). Similar studies should be extended to other commodities such as fruits and vegetables which are dried in Africa.

4.2.2 Classification of Solar Dryers

As mentioned earlier, this paper is mainly concerned with various types of solar dryers. Thus dryers using electricity, wood and other fuels, will not be considered even though they may play a significant role in some sectors. Solar dryers of interest here are those which have the potential of being used in most rural african environments. They can be classified as; direct dryers, indirect dryers, mixed mode dryers and hybrid dryers.

Direct solar dryers basically consist of an enclosure with transparent top covers; the side walls may also be made of a transparent material. The interior surfaces of the dryer are painted black, inlet and outlet holes are located so as to facilitate the entry of ambient drier air, and the exit of warmer moist air, respectively. Crops are placed in the dryers, on porous shelfs where they are heated by the green house effect in the cabinet.

Indirect dryers usually consist of three main components; a solar air heater, a drying chamber and a chimney. Solar energy is collected by the greenhouse effect in the collector which consists of a transparent top cover and an absorber surface, insulated to minimize heat losses to the ambient air. Air heated in the collector is circulated through the dryer by means of a fan or by the effects of buoyancy. The warm air flows over and through the crops on trays in the drying chamber after which the moist air flows out of the dryer through a chimney.

Mixed mode dryers are combinations of direct and indirect dryers. They normally are indirect dryers with transparent tops or/and sides, with the crops located such that they receive direct heating from the sun as well as being dried by the air heated in the collector.

Hybrid dryers are those that use solar energy and another fuel as a heat source. Fuels that may be used are wood, gas, electricity, etc. Solar energy and the fuel may individually or simultaneously be used to heat the drying air, depending on the design of the dryer.

4.2.3 Direct Solar Dryers

A typical dryer of this type is the cabinet dryer [8] shown in Figure 2. It can be made from materials such as wood or sheet metal with sawdust, wood shavings or straw being used as the insulating material. The transparent material can be glass or plastic film and the tray made from wire mesh or string. It has been tested for example in India and Syria [8], Sierra Leone [9], and Cameroon [10]. Typical results showing the performance of direct dryers on plantains, okra, prunes and cauliflower are shown compared to open air drying in Figure 3. It is noted that for these dryers which operate at up to about 30 C above ambient temperatures, drying rates are faster compared to open air drying. They are useful for vegetables, fruits, meats, fish and other crops that need elevated temperatures.

One of the disadvantages of direct dryers is the difficulty of controlling the rate of moisture removal and internal dryer temperatures. At the start of the drying process, it is often necessary to close all the outlet air holes to allow the temperature of the air in the dryer to increase. Water evaporates from the crop and condenses on the inside of the transparent cover, reducing the amount of solar radiation transmitted to the interior of the dryer. This condition is subsequently improved by opening the outlet vent holes but in turn causes the temperature in the dryer to fall. Operators of these dryers therefore need to be adequately trained to ensure that good drying rates and good quality products are obtained.

Another type of direct dryer is the "chamber" dryer [8]. It consists of an inclined channel-like collector in which the height of the channel is small compared to the its length and width. The crop is placed on perforated shelves and receives solar energy directly through a transparent cover. Air entering through an inlet at the lower end of the dryer is heated in the chamber where the crop is situated and flows out through an outlet at the top.

Three versions of the chamber dryer are shown in Figure 4. The see-saw dryer (Figure 4a) was developed in Ivory Coast for drying coffee and cacao and further improved in Ghana. Crops are supported by a perforated base made of some form of netting, a plastic film (e.g.,polyvinyl chloride) is used for the top cover and the interior of the dryer is painted black. Two sections, at the base and at the top of the dryer, are separated from the rest of the dryer where the crops are spread, by wood partitions. These blackened sections are intended to help the flow of air by natural convection. The dimensions of the dryer are 3.6m long, 1.2m wide and 8cm deep. In operation, it is inclined facing east in the morning and facing west in the afternoon.

Figure 4b shows the "downdraught" dryer which is similar to the see-saw dryer. It has been used for cereal grains such as barley and wheat. Air circulated by natural or forced convection is drawn through the grain as shown. In the "crossdraught" dryer in Figure 4c, the heated flows over the crop instead of through it.

Results for three versions of the crossdraught dryer has been presented in [11] for studies in Niger on the drying of meat and tomatoes. The quality of the products were acceptable but the capital cost of the dryers made them uneconomically viable. For example one of the dryers which could only dry 6 kg of tomatoes cost 275.000 francs CFA (about $1000 US).

4.2.4 Indirect Dryers

Figure 5 shows the essential features of an indirect dryer. It should be mentioned that the main constraints on the use of this dryer are inadequate airflow (in the free convective mode) and cost. When a fan is used for air circulation, the design of the dryer is relatively straigthforward as noted in the literature [12]. Amongst the four types of dryers classified above, this is the one most prone to poor performance when operated in the natural flow mode. Air heated in the collector passes through the drying chamber where the crops are placed on a single porous tray or on several trays. It passes through the wet crop, becomes nearly saturated (which lowers its temperature to nearly that of the ambient air), and subsequently exits to the surroundings through the chimney. However, because the air above the crop is not substantially different in temperature from that of the ambient air, the resulting buoyancy forces, which are proportional to this temperature difference, are very small, and in turn produce very low airflow rates [13, 14, 15].

Extensive experimental work aimed at understanding the operation of indirect dryers have been carried out in Sierra Leone [13]. These studies showed that chimneys were in general not useful. The effect of heating the chimneys using solar energy improved the performance of the dryer but this was not substantial [16]. The complex interaction between insolation, airflow, chimney design, collector design, ambient temperatures, etc have been discussed in [17], the chimney being identified as the component limiting the performance of such dryers.

Considering the difficulty of studying the dryers experimentally under real conditions [32], other studies have been carried out on numerical modelling and experimental simulation of the dryers [18, 19, 20]. Work in [18] consisted of developing sub-models for use on a microcomputer for; generating weather data, the solar collector, the flow in the drying chamber, the rice bed, and the chimney. Results were compared to field conditions in Sierra Leone, giving good agreement for dryer temperatures, but results for drying rates were less satisfactory, indicating that the model used for the rice bed (pressure drop across the bed proportional to $V^{1.1}$, where V is the velocity of airflow through the bed) needed refinement. In order to better compare various dryer designs, controlled laboratory experiments were carried out with a heated electrical plate simulating the solar collector for various dryer designs [19]. A computer model was developed assuming that: the air above the rice bed is saturated; the pressure across the bed is the dominant pressure loss; the heat transfer rate in the collector can be given by a simple equation; and, the collector efficiency in terms of the plate temperature can be described by a simple linear relationship [20].

The predicted drying rates obtained using the model in [20] agreed very well with field results obtained in [13] (see Figure 6). Results of work in [13, 18, 19, 20] have resulted in the following recommendations for an improved natural convection indirect dryer:

1. The collector area should be at least equal to the cross-sectional area of the dryer cabinet;
2. The rice bed should be at least 1m above the collector outlet;
3. The depth of the rice bed should not exceed 5 cm;
4. A chimney should not be used since the temperatures in the chimney are close to ambient, giving rise to negligible buoyancy forces.

It is difficult to compare the performance of indirect dryers operating under different absorber plate temperatures Tp, ambient relative humidity RH and temperature Ta, and height of the packed bed B. A useful contribution presented in [19] is the parameter for comparing the drying rates, dM/dt, of various tests carried out under various conditions. This is the Standardized Drying Rate SDR defined as:

$$SDR = (dM/dt)_{measured} (60/(Tp-Ta))^{2/3} (B/3)^{5/3} (50/(100-RH)) \quad (1)$$

The above equation has not taken into account the variation of the absorber plate temperature which in real life varies with time even during a clear day and as a result of cloud cover. Ambient conditions such as relative humidity and temperatures under real conditions also vary. Neverless mean values of these parameters can be used in equation (1).

The above-mentioned studies on indirect solar dryers demonstrate the importance of carrying out numerical and controlled experimental studies in order to minimize the amount of experimental studies needed to understand the operation of solar dryers. These coupled with carefully conducted field studies can lead to the development of appropriate dryers.

4.2.5 Mixed Mode Dryers

A typical mixed mode dryer is the AIT dryer which has been developed at the Asian Institute of Technology in Thailand [21]. It is essentially an indirect natural flow dryer made of bamboo and covered with transparent plastic. The area of the collector is about three to four times the area of the drying chamber. Burnt rice husk is used as the absorber and a chimney covered with a black plastic sheet to absorb heat from the sun is attached to the drying chamber. It is reported to be designed for rice bed heights of up to 10 cm. Air is circulated by natural convection and the inlet of the collector is located to face the prevalent wind direction.

This dryer has been reported to work in some locations but not in others. In the absence of detailed experimental results to confirm the performance of this type of dryer, it is difficult to predict its effectiveness under various conditions. It is possible that the flow through the dryer is due to the wind blowing into the dryer through the collector inlet. Also, the contribution to drying by direct heating of the grain by solar radiation compared to convective effects is not known for the dryer. The effectiveness of the chimney in view of work reported in [16] and [19] is in question. In general the aspect of the design that makes it work is not clear. Considering that the AIT type dryer does not work in many cases begs the question whether the role of natural convection is significant. Since the dryer is completely covered by transparent plastic, heat losses are expected to be substantial, further contributing to a decrease in buoyancy effects.

Another dryer in this class of mixed mode dryers has been used to dry fruits and vegetables. Work outlined in [33] consists of the development and testing of a cabinet dryer with a transparent cover and translucent walls. The arrangement shown schematically in Figure 7 obtained heated air from a solar collector. In the absence of adequate solar insolation, provision was made for a butane gas heater to provide supplemental heat. (Results of tests using this auxiliary heater was not reported). A small fan provided forced air circulation through the crops that were placed on shelves. Fruits such as bell peppers and sultana grapes were dried using the heat supplied by indirect and direct solar energy in the forced convection mode. The drying rates and the quality of the dried products, judged by their color, were superior compared to open air drying.

Mention should be made of the advantages and disadvantages of mixed mode dryers. They generate higher cabinet temperatures which are useful in enhancing moisture migration from within the crop. It is however at the initial stages necessary to have adequate air flow to transport water vapor from the surface of the crop to avoid over heating and "cooking" of the product. Thus the dryer should be designed to provide adequate air flow either by free convection or by forced convection. Direct radiation helps in enhancing the color of fruits or vegetables during drying due to the breakdown in chlorophyll. Compared to the direct solar dryer, the mixed mode dryer, by virtue of the solar collector, provides a higher mass flow rate which enhances drying.

4.2.6 Hybrid Dryers

Relatively little work has been done on dryers that use solar energy and other forms of energy that are relevant to African conditions in general. Two examples which have been reported in the literature involve cabinet dryers. The dryer described in Figure 7 could be considered a hybrid dryer. Application of auxilliary heating using butane gas would however present economic difficulties for most of these farmers.

Another hybrid dryer is shown in Figure 8. It uses a cabinet dryer in which auxiliary heat from sawdust is supplied by a simple heat exchanger. The sawdust heats water, in a piping system, which flows through the heat exchanger pipes in the dryer cabinet [9]. The dryer is appropriate for drying during poor weather conditions. The performance of the dryer can be judged from Figure 9 where the drying rates of okra are compared with open air drying. Drying times and product quality were found to be substantially better compared to open air drying [9]. While this dryer may be useful, it needs further improvement to lower its cost and improve its performance. For example, the efficiency of the "boiler" is very low and this can be improved using local materials which in turn will lower costs. Its performance needs to be verified on various crops as the operating temperature in the dryer can be as high as 45 C above ambient temperature, depending on the combination of heating sources used.

5. SOME REASONS FOR LIMITED USE OF SOLAR DRYERS

In spite of the substantial amount of work that has taken place in various countries around the world, countries in Africa are still not using improved solar drying methods. It has been argued that one of the main reasons for the general lack of use of solar energy technologies is the inability of many African countries to properly define their problems [23]. An attempt is made in this section to outline some reasons why improved solar drying systems have not been adopted.

5.1 Inadequate Knowledge of the Drying Problem

Many solar dryers have been designed without any initial needs assessment studies having being carried. The farmers aspirations and opinions are usually not sought, quantities of crops dried at a given time, quantities sold versus those used for home consumption, marketing and distribution systems for the crops and the potential financial benefits that can be derived by improved drying, etc, are usually unknown. The importance of carrying out studies to at least appreciate the perceived needs of farmers has been outlined in [24], which presented results of a study to determine how farmers articulated their drying problems. The result of not carefully considering social, cultural and economic parameters mentioned above, has resulted in the non-adoption of solar drying technologies. For example, an impact study of the AIT dryer indicated that it did not attract strong interest amongst Thai farmers due to its small size, lack of government incentive to improve the quality of rice, and because the benefits provided by the dryer were not perceived by the farmers to be substantial enough to motivate them to use it [25]. A thorough evaluation of various aspects of the farmers' needs and wishes would have answered most of the crucial questions which affected the successful adoption of the dryer.

5.2 Poor Technical Designs

As mentioned earlier, natural convection dryers are more appropriate for rural areas in Africa. It is unusual to find designs of these dryers that work since design criteria for them are not well established. As a result, designs are often not based on engineering calculations but rather on ad hoc criteria. Most of the dryers are not effective due to poor airflow rates and this leads to them being abandoned at the lab testing stage or at the farm level.

5.3 High Cost of Improved Drying Technology

Farmers do not often have the financial means to pay for improved solar drying even though it would make a significant difference to their harvest, both in quantity and quality. Some dryers, designed using expensive materials, dry very small quantities, making their use economically unjustifiable. A typical example of this is work mentioned in [11] for a dryer which costs about $US 1000 but can only dry 6 Kg of tomatoes at a time.

5.4 Low Levels of Production

This is related to the inability of farmers to pay for improved drying. Quantities harvested are often not large enough to justify investing in a relatively expensive technology. It would appear that not all farmers will be able to acquire improved drying technologies since a substantial percentage of them cultivate small plots of land and use a significant quantity of their harvest for home consumption [24]. Thus, based on results of needs assessment studies, a conscious decision should be made regarding farmers for whom the dryers are built.

5.5 Inadequate Storage Facilities on Farms

In order that farmer derive substantial benefits from their dried crops, they must be able to store them until market prices become attractive. Storage systems on farms are however not efficient or large enough, resulting in poor quality crops or insufficient storage at the farm level. Farmers, anxious not to lose their harvest, sell the crop as fast as possible after harvest, leaving small quantities for home consumption and for seed if this is appropriate. Thus in general little extra effort is made in ensuring that good quality dried products are obtained.

5.6 Poor Transportation Facilities

Transportation is a major constraint in the agricultural sector of many African countries. There are difficulties at the farm level to transport crops to a central storage locations or markets. It is often difficult or even impossible to move farm products to local markets. Farmers have to therefore wait for buyers who come in trucks to buy their harvest at low prices. There is clearly little incentive for the farmer to be interested in improved drying if he will derive no financial benefits from having a better quality dried product.

5.7 Underdeveloped Distribution Systems

Most crops are either sold in local markets or to marketing boards which may not pay attractive prices. Farmers therefore, due to several reasons, do not have alternate methods of distributing their goods. A more lucrative market exists outside the country but transportation and government controls make this difficult. Smuggling are for many a method of obtaining more lucrative markets, but this could mean significant financial losses and possible jail, if caught.

5.8 Non-existent Government Policies to Improve Product Quality

Many governments do not have a pricing system that provides incentive for farmers to produce better quality dried crops. In some cases government policies or lack of them create disincentives. For example, many rice growing countries with a capacity to be self-sufficient in this commodity, import rice which are sold at prices substantially lower than that locally produced. There are in fact disincentives where the policy in many countries is to import rice which are sold at prices lower than that locally produced. In the case of other cereal grains for example, government marketing boards which buy grains for storage take little notice of grain quality during purchase. As mentioned in [1] for the case of Mauritius, farmers can be encouraged to produce better quality grains, using dryers, if the prices are attractive enough and incentives are given for crops sold by the farmers at moisture contents lower than that achieved by open air drying.

Farmers in general would produce more foodstuff and invest in improved drying if they perceive appreciable financial benefits in such investments.

5.9 Lack of Locally Produced Materials

Basic materials needed in the construction of solar dryers are wood, glass or plastic as transparent materials; sheet metal for the absorber and wire mesh for shelves. These materials are imported by many countries in Africa and local prices are very high as a result of taxes and exploitation by importers. Thus a very simple dryer using very basic materials becomes ridiculously expensive for adoption by farmers. The only available option is the use of locally produced materials such as bamboo, flimsy plastic which degrades rapidly and is easily torn by wind. Pressures on researchers/developers of solar drying systems are therefore very high, not only to obtain technically viable solar dryers, but also to ensure that they are extremely cheap; these two conditions are difficult to fulfil.

5.10 Inadequate Technical Expertise

This topic has already been broached in [23] where it was mentioned that developing countries lagged behind in the development of solar technologies due to lack of adequately trained researchers/developers in the field. In the case of solar drying, the situation is even more critical compared to other technologies such as distillation, refrigeration, water heating, etc, where, due to the systems' apparent sophistication, they have not generally attracted the attention of "laymen". Since solar drying is perceived by many as an area for development in post harvest technology and is considered to be very simple by many, due to its easily understood principles, it has attracted many "designers" from basically all fields in the applied sciences, pure sciences, social sciences, and the health sciences. The end result has been a proliferation of various types of dryers which no not operate satisfactorily. While these attempts by themselves should be commended, as they were carried out in the interest of improving the situation of rural farmers, they in many ways have caused many farmers to be wary of solar dryers.

5.11 Lack of Interdisciplinary Approach

Perhaps one of the most important bottleneck in the development and use of solar dryers is the lack of interdisciplinary collaboration. Solar drying involves, not necessarily in order of importance, the following disciplines; thermo-fluid sciences, meteorology, the physics of materials, food science and technology, nutrition, economics and marketing, sociology, anthropology as well as politics. There has unfortunately been little conscious effort made to include the various expertise needed to successfully implement an improved solar drying technology. As such, important elements are omitted during initial planning activities and the implementation of the project, which would have been taken into account had an interdisciplinary team been constituted at the onset of the project.

5.12 Lack of Electricity Supply

Poor airflow rates in natural convection solar dryers have been cited as a limiting factor in the design and use of solar dryers. This situation can be easily improved with the use of small fans using electric motors, but many rural areas do not have electricity.

5.13 Inadequate Financial Resources and Planning

Very few countries have any overall strategy for the improvement of post harvest technologies. Thus the development and use of solar dryers have not received any meaningful attention at the government level. Projects usually carried out often depend on the interests of individuals and funding organizations. This apparent lack of collective interest and planning only serve to disperse meagre financial and other resources and encourage duplication of efforts. Thus it is difficult to obtain funding for potentially useful projects, training personnel and setting up the minimum infrastructure required.

6. CORRECTIVE MEASURES TO PROMOTE IMPROVED SOLAR DRYING

6.1 Appropriate and Adequate Needs Assessment Studies

Even though it is generally accepted that it is very important to understand the drying problem before developing a drying technology which solves that problem, this strategy is often not followed during a project. Key elements to consider during needs assessment studies have been discussed in several technology development and technology introduction articles, some of them being specific to drying and relevant to Africa [12, 24, 26].

Of utmost importance is the methodology used to carry out a needs assessment survey. Classical methods of developing detailed questionnaires and sampling large numbers of people are being questioned in view of cost, human resources, expensive data analysis, and the accuracy and usefulness of some of the data collected. Rapid Rural Appraisal Methods, which involve interdisciplinary teams interacting with substantially smaller numbers of people in a more personal atmosphere have been shown to be fast to implement, quite accurate and cost effective, compared to extensive surveys [27]. This technique is recommended for use when dealing with farmers who tend to vary their response depending on the questioner.

Certains questions which should be answered by such a survey include

a) the availability of solar energy resources;
b) effectiveness of traditional drying methods,
c) the range of crops that need to be dried, quantities, and at what times of the year drying takes place,
d) drying problems being faced and traditional methods of storage;
e) existing drying systems and results that can be exploited;
f) income obtained from dried crops and potential gains to be made by improving drying;
g) marketing channels for dried crops;
h) willingness to pay for improvements to drying and up to what level;
i) an approximate economic analysis to determine the minimum production/utilization level that makes a dryer economically viable,
j) the existence or implementation of policies that will encourage the use of dryers.

Such studies should be carried out taking into account the dynamic situation that exists in developing countries. Deteriorating economic and climatic conditions create unstable situations, which render present conclusions invalid with time due to inflation, inavailability of materials, drop in production levels, etc.

Follow-up studies therefore have to be made when significant changes occur in the social and/or economic environment.

6.2 Development of Drying of Systems

Solar drying can be pursued from various fronts. Activities that can contribute to the future adoption of drying systems are: a) research on traditional open air drying; b) understanding the mechanisms involved in the operation of various types of dryers; c) reducing the cost of construction materials; d) improving the efficiency of dryers; e) development of reliable testing procedures; f) studying and modelling the mechanism of moisture loss from various crops; g) developing better design procedures. Suggestions are presented below regarding research which if pursued would significantly improve solar drying in Africa.

6.2.1 Traditional Open Air Drying

Traditional open air drying has been taken for granted. The mechanisms involved are generally known but details of the contributions of various factors such as effect of wind, solar radiation, ambient temperature and relative humidity, conduction from the ground, surface condition, etc are not well documented. It is the author's opinion that a thorough understanding of open air drying will permit workers to properly compare open air and solar drying.

6.2.2 Understanding Operation of Solar Dryers

Work of the type reported in [16-19] should be carried out to experimentally study various types of dryers in order to understand the effects of their various components. In view of the experience gained so far, it is advisable to adopt a strategy involving a combination of laboratory simulated experiments [13] and outdoor experiments [19]. In view of their importance in grain drying, indirect dryers deserve continued attention. Direct and mixed mode dryers are can significantly contribute to the drying of fish, meat, vegetables and fruits in the future and should therefore be studied in order to define their performance on various classes of commodities. Prototypes of potentially useful designs ought to be studied in order to choose appropriate designs or make changes to improve on a design.

6.2.3 Construction Materials

In view of the various failures experienced with solar drying, it can be concluded that materials used for dryers are generally not appropriate to the needs of the farmer since the cost of the dryers are high. Research should concentrate in the area of developing efficient but cheap air collectors, due to their high cost compared to the other parts of dryers. Materials such as galvanized iron, surfaces made from mud, carbonized waste materials, waste sheet metal, etc, should be used as absorber surfaces in order to lower construction costs. Results using mud as the material for the cabinet of indirect dryers in Sierra Leone have indicated its potential advantage; it is easy to use by farmers who traditionally use them for building houses, and serves as a thermal storage material. Results of tests indicate that the mud dryer performed better than open air drying over a 24 hour period; the dryer continued to dry at night compared to the open air dried product which absorbed moisture [28]. Transparent materials pose one of the greatest problems. Glass is expensive and breaks easily. Plastics are relatively cheaper but they tear and degrade easily.

One option is to develop air collectors that would reduce the amount of transparent cover needed. It would appear from recent work [28] that collector areas equal to the area of the crop bed, in the case of rice, may give satisfactory drying rates.

It has been observed that insulating the sides of the drying chamber of an indirect dryer increases the drying rate significantly due to the reduction of heat losses [19]. The cost of insulating material can be reduced by using local materials such as straw, wood shavings, and other fibres, for all the insulation work needed.

6.2.4 Improving Drying Efficiency

Increasing the efficiency of drying systems implies the reduction of heat losses, the efficient transport of moisture from the crop and the incorporation of thermal storage, in order to increase drying rates compared to open air drying. In the context of rural areas, dryers should have adequate air circulation without the use of fans, indicating the need for studies aimed at improving airflow but at the same time ensuring that the air temperature is sufficiently high for efficient drying.

6.2.5 Testing Procedures

The development of testing procedures in solar dryer design is an area that needs substantial effort. The range of dryers, test locations and experimental methodologies make it difficult to compare results of various studies. The following are suggested as the minimum measurements that should be made during the testing of a solar drying system:

* Moisture content of the crop as a function of time, care being taken to minimize errors due to improper sampling of the crop which gives an oscillating variation (the maximum interval between two readings should be two hours);

* Ambient temperature, temperature above the crop in the dryer, absorber temperature, depending on the type of dryer (the maximum interval between readings should be 15 minutes);

* Relative humidity of the ambient air and that of the moist air above the crop (maximum interval between readings should be two hours);

* Intensity of solar radiation with time on the plane of the collector (maximum interval between readings should be 15 minutes), and/or total integrated solar energy on collector.

The comparison of the performance of two dryers can pose enormous problems considering the amount of work involved in taking experimental data, especially if data acquisition systems are not available. It is however difficult to compare the performance of two dryers under outdoor conditions without testing them side by side. This procedure is suggested if accurate results are needed to determine the effect of a certain design parameter. The development of parameters such as the Standardized Drying Rate [19] shown in equation (1) will help in the comparison of experimental data.

Performance of dryers overnight are not traditionally reported. This should be done as the dryer's performance at night will affect the period needed to dry the crop to the required moisture content. For example, the work in [23] showed the superiority of the mud cabinet dryer at night due to heat storage, compared to open air drying. Knowledge of the performance of dryers during a typical 24-hour period will allow steps to be recommended for proper management during their use.

It is impossible to obtain clear cut generalized testing procedures. Difficulties usually occur regarding the duration of drying. Some outdoor testing may start in the morning at 0900 hours with the crop in the dryer. Others may have the dryer heated up till 1100 hours before loading it with the crop. It is therefore important to specify the initial conditions of the drying tests when results are being presented. It is advisable to load the dryer in the morning and allowing the dryer and crops to attain equilibrium conditions as the day progresses.

An area of confusion is the comparison of the performance of a dryer to that of open air drying. As an example consider a dryer in which a grain such as rice is packed to a height of 7 cm over an area of 1 m^2. A similar mass of rice is to be dried on the ground. The performance of open air drying will vary depending on the height of packing. What then is a area over which the rice should be spread on the ground? It is obvious that there will be many suggestions. It would appear reasonable, for comparison purposes, to spread the crop over an area of ground equal to that occupied by the dryer. Thus in comparing traditional open air drying to solar drying it is suggested that the area of the drying floor should be equal to that occupied by the dryer

6.2.6 Drying Mechanism of Crops

Difficulty is encountered in attempting to mathematically model the flow across the crop being dried. The pressure drop across the crop depends on parameters such as the type of crop, air velocity, the thickness of the bed, etc. The rate of drying of the crop depends on the rate of diffusion of water from within the crop to the surface, which in turn depends on the temperature of the crop, the flow rate and temperature of the air passing through the crop, etc. These processes are not well known for various crops under different drying conditions. As such experimental studies which would provide empirical information that can be used to describe the drying of various crop are needed.

6.2.7 Development of Design Procedures

The development of better design procedures is crucial in the development of dryers. It is highly desirable that design packages be developed for various dryers. A procedure which gives a first approximation of the indirect dryer has been presented in [29] which makes use of a simple model for indirect natural flow dryers. A more refined but simple model [20] is available for the the same class of dryers that agrees quite well with field results and can be used to design indirect dryers. Similar computer models of direct, mixed mode and other dryers should be developed as design tools.

6.3 Field Testing

An accepted strategy for the successful adoption of any technology is the participation of the intended beneficiary, from the problem definition stage to the field testing stage [23]. Assuming that the farmer had been aware of the development of a new solar drying system, the field testing phase must at least involve close collaboration between the farmer, technologist, social scientist and extension agents. The following are some guidelines which have been found useful in practice in various projects.

If the dryer is made from local materials, the farmers should be involved in its construction or should at least see how it is being made. Installation of the dryer should take place in locations where crops are available for drying and where the enthusiasm of the intended users is high. Farmers should receive thorough training on how to use the dryers since they will be the operators during field trials. During the initial drying tests, it is advisable to encourage the farmers to dry samples of his crop in the dryer as well as using traditional methods in order to compare results. They should be clearly informed and made to believe that they are part of a team involved in solving their own problems. Thus successes and failures should be shared by all concerned.

Follow-up of the field testing activities is best done by three key groups of people; the extension personel, the socio-economist and the technologist. The extension agents will be responsible for the nearly daily visit to the farms during drying activities. They will gather information such as quantities dried of crops dried, duration of drying, advantages and disadvantages of the dryers, complaints and appreciation of the farmers regarding the dryers. Samples of the dried product should also be taken for closer examination by the researchers. These findings will be passed on to the socio-economist and technologist who should visit the project at least once a week during the drying activities. From informal and semi-formal interviews, they in turn will be able to assess the technical and socio-economic viability of the dryers.

There should be no hesitation in correcting designs which are unacceptable to the farmers, if this is technically feasible and no significant costs are involved. If this is not done the farmers will only put the dryer aside and carry on with their old methods.

Since the aim of such field tests is to encourage farmers to use the developed solar dryers, sound but simple economic advice regarding acquiring and using the dryers ought to be provided by competent persons within the project, and all efforts should be made to pass on the wider introduction of the dryers to extension services who hopefully will be actively involved in the field work.

An assessment of the impact of the introduced dryer would help provide useful information for future use of the results. This should contain a clear outline of technical constraints and benefits of the dryer and its potential technical viability. Likewise, the economic viability of the dryer should be included in the assessment.

6.4 Information Sharing and Collaboration

Effective work on drying depends on having access to information and collaboration. African workers often start and complete a project without discussing results with peers. Some efforts have been made by the Commonwealth Science Council (CSC) in England, the Groupes de recherches et d'echanges technologiques (GRET) in France, the International Development

Research Centre (IDRC) in Canada, among others, to develop modalities for collaboration and information exchange between various African workers.

The main contribution of the CSC was the setting up and suppport for the African Energy Programme which had solar drying as on of its three sub-programs. A network of projects were supported in Gambia, Ghana, Kenya, Mauritius, Uganda, Tanzania and Zimbabwe between 1979 and 1985. Various meetings were organized for exchanging information. Results of various work on solar drying have been published in "The African Energy Programme Research Report Series". Books useful to solar drying workers have also been published [5, 12].

The IDRC has in the past supported research on food drying in the following African countries; Egypt, Kenya, Mali, Niger, Sierra Leone and Zambia. There is presently a network of projects on solar drying aimed at developing dryers suitable for rural use. Involved in the collaborative activity are Cameroon, Nigeria, Senegal, Sierra Leone, Togo and Canada. IDRC has organized several meetings on drying and books of interest have been published in english and french [22, 30].

GRET has collaborated with several countries in the general area of solar energy. Of particular interest is a practical book on solar drying which treats socio-economic and technical issues in solar drying [31].

Conscious effort is needed to create the atmosphere that will encourage solar drying research and development activities. Contacts should be established by researchers at both national and international levels; nationally to sensitize potential users, extension workers and policy makers, and internationally to share information and improve the quality of research results. The process is understandably long and needs innovative ideas and patience.

7. SOME POLICY ISSUES

The above technical discussions on possible methods of promoting the use of solar dryers cannot be separated from the policy issues concerning national governments and the international community.

In the case of individual countries, institutions where work is being carried out must have the required human and material resources. Many institutions lack these resources and the situation is becoming worse due to economic crises that affect nearly every country in Africa. Policy makers have the tendency to drastically reduce funds for research and development as one of the first measures taken to upgrade the economy, and still expect improvements in, for example, the agricultural sector. This is however, at times, self defeating as improvement in agriculture cannot take place without improvements in post-harvest technology. Even if it is necessary to reduce research funding in general, some work should continue to be supported in the development of drying systems.

As mentioned earlier, some government policies or lack of them do not encourage the use of post-harvest processing such as drying. There are often little or no price incentives for better quality dried crops. As such, farmers are not interested in improving their traditional drying practices. Considering the uncertainty of food production in many countries from year to year, many governments are interested in maintaining reserves and stabilizing prices. The

development of policies aimed at penalizing farmers for poor quality crops will create the awareness and need for better drying, and ensure that the population will have access to good quality food products.

In relation to the above, standards for various dried products should be developed with respect to drying methods, product quality, packaging and storage.

Governments should, through research and extension agencies, encourage an increase in crop production. The higher the production, the more the need for drying, and the more the use of dryers would become economically feasible. Efforts should be concentrated on the major commodities that are consumed locally. A concerted effort should be made to provide better storage systems at the farm level to allow good quality crops to be safely stored until they are sold.

Since a constraint to the utilization of solar dryers is the high prices of imported materials, costs must be lowered. This may be made possible by controlling prices of materials which may perhaps not be politically desirable. It may be more effective for government to give subsidies to farmers using solar dryers. These may be in the form of soft loans.

It is the responsibility of people working on solar drying to make proposals to policy makers at all government levels and to influence the decision making process, for without positive government reaction, all efforts made in the development of solar dryers may be in vain.

8. CONCLUSIONS

a. Solar drying is a technology that can be exploited in Africa in the light of increasing population and the need to produce more food that can be safely stored for food security.

b. Technololgies in existence can be used by selected producers, the limiting factors being cost and production levels on farms.

c. Due to the unavailability of electricity in most rural areas, natural flow dryers appear to be the most appropriate for most rural farmers.

d. A significant amount of research is needed to develop efficient solar dryers and design procedures. Activities of this kind can be accelerated by close collaboration between workers in the field.

e. Governments can contribute to the rapid development and use of solar dryers by adopting policies, regarding post harvest technologies, aimed at strengthening research efforts on one hand and creating incentives that will make solar drying attractive to farmers.

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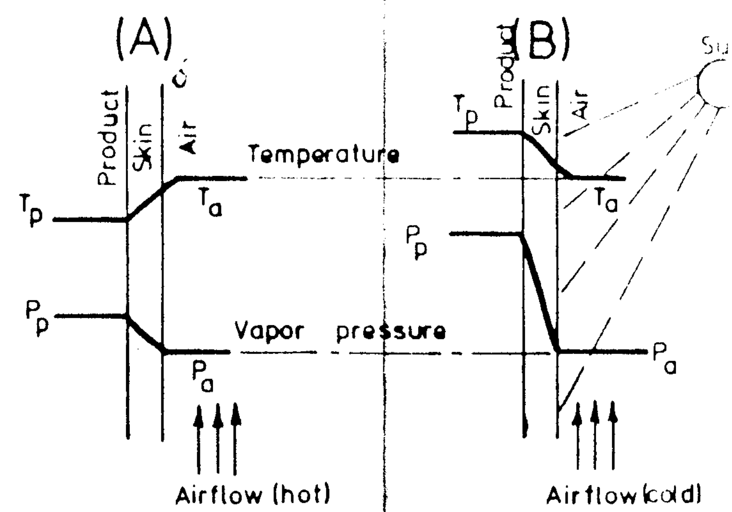


Figure 1. Temperature and Vapor pressure at the product - air inte when heat is supplied by hot air (A) and by direct solai radiation (B)[6].

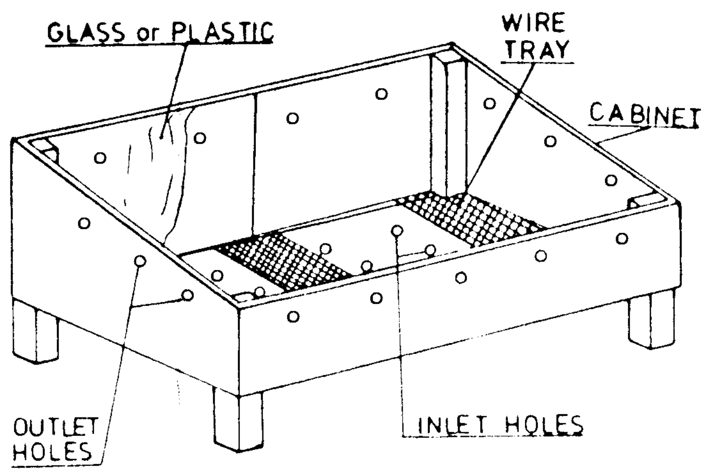


Figure 2. A solar cabinet dryer.

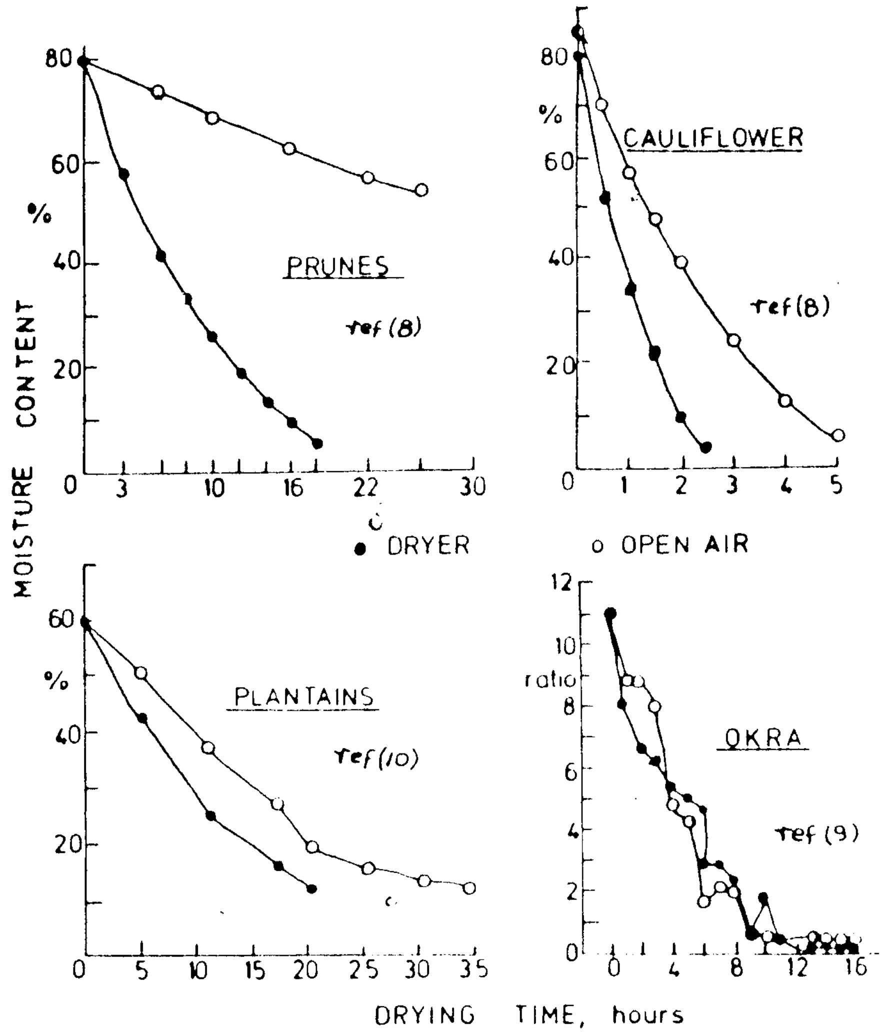
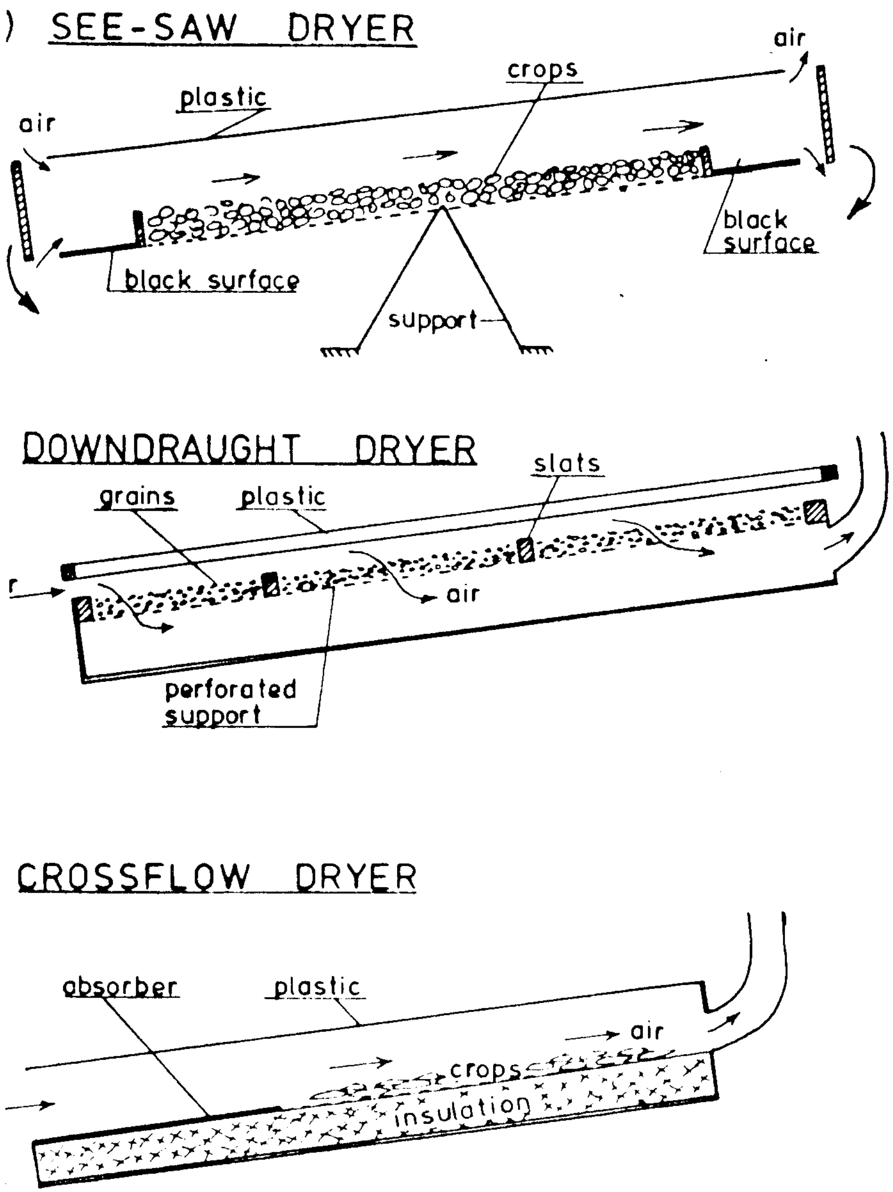


Figure 3. Drying curves for various crops using solar cabinet dryers.



gure 4. Three types of "chamber" dryers using direct solar energy.

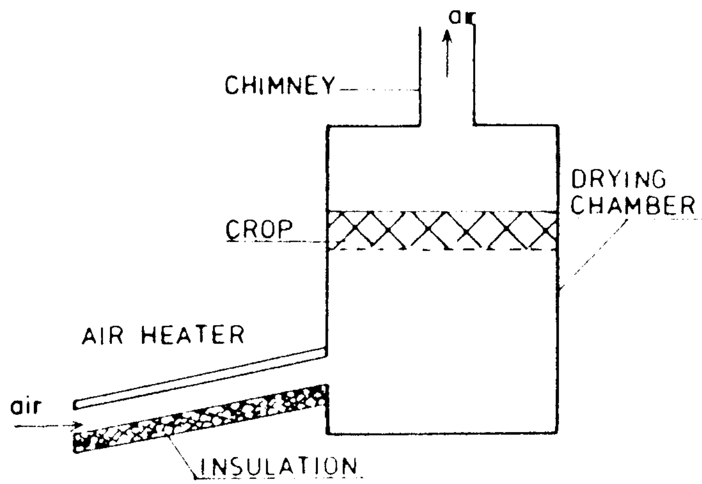


Figure 5. Typical indirect natural convection solar dryer.

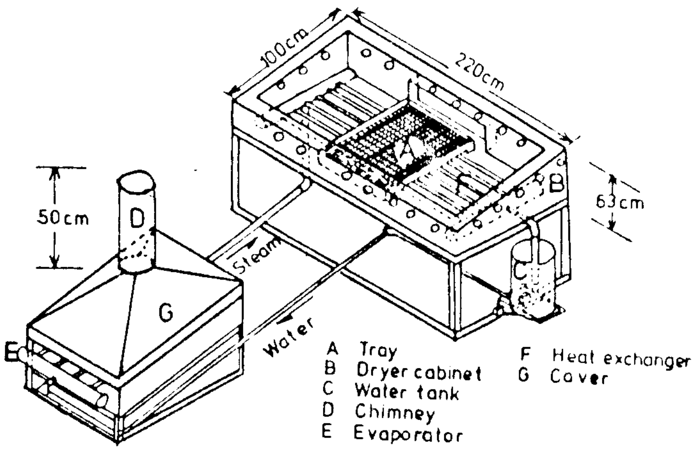


Figure 8. A hybrid dryer using solar energy and sawdust (ref [9]).

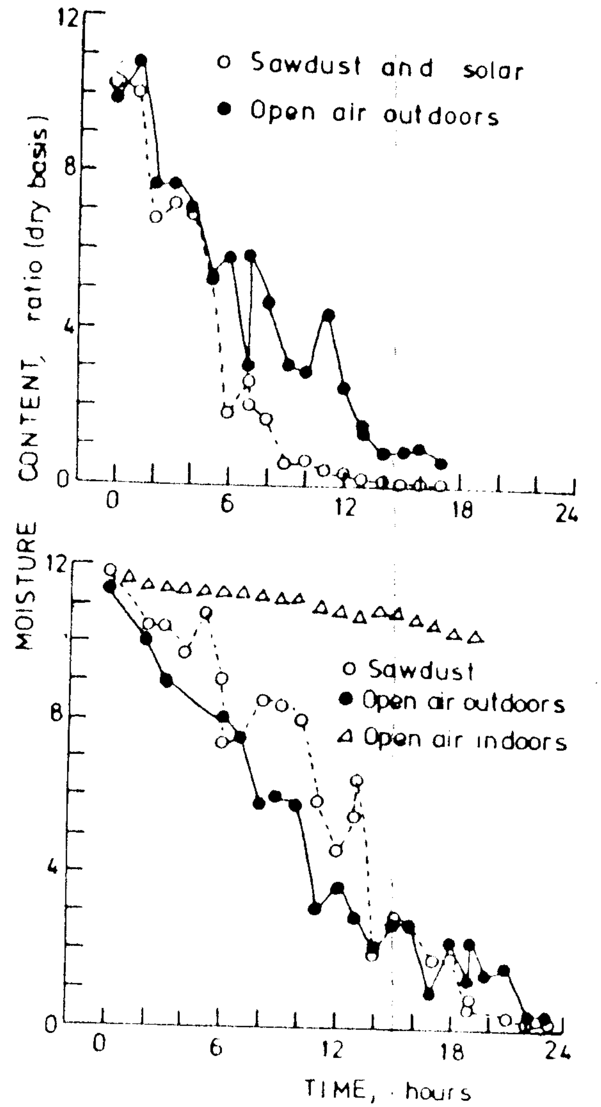


Figure 9. Drying curves for okar using the solar/sawdust hybrid dryer (ref [9]).

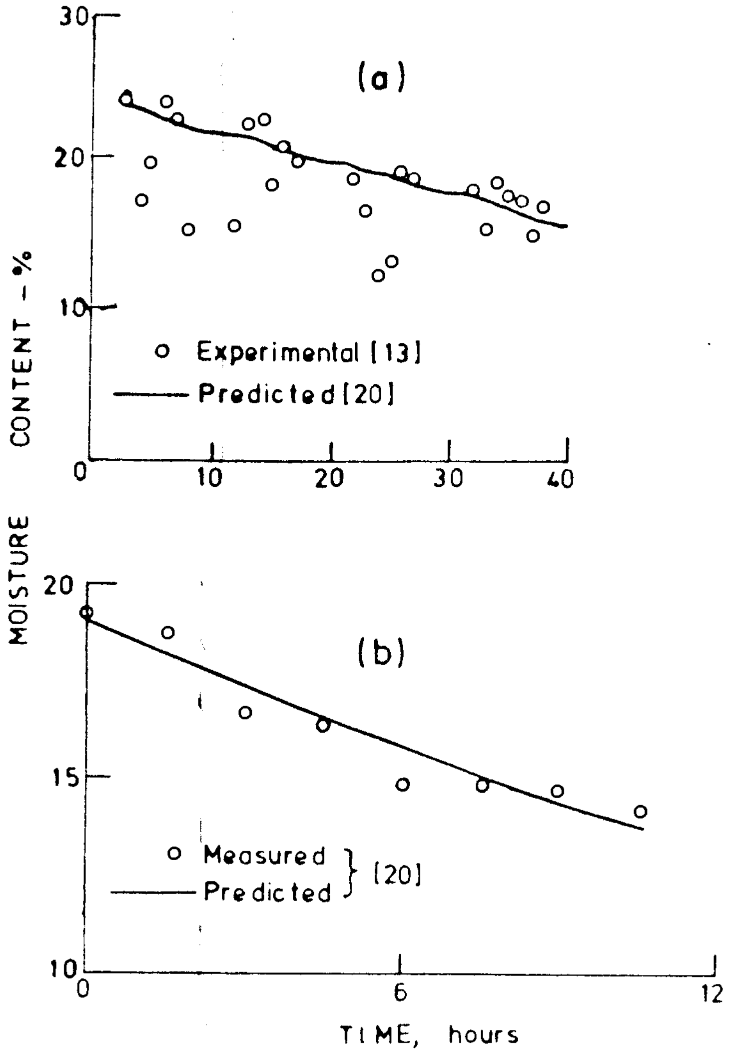


Figure 6. Comparison between Oosthuizen's model [20] for indirect natural convection dryer and measured results.

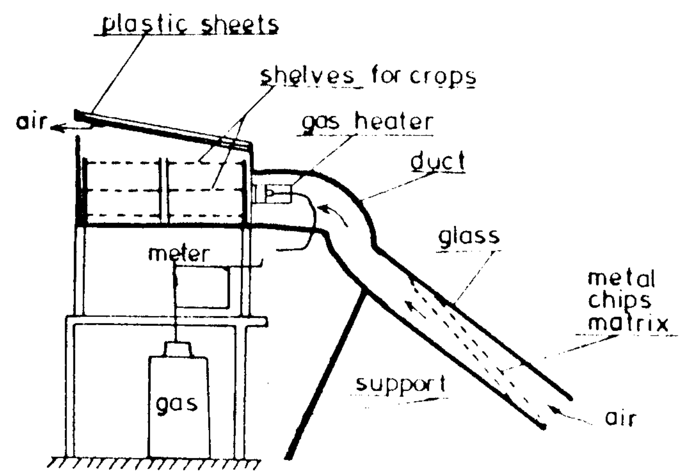


Figure 7. A cabinet dryer incorporating a solar air heater and auxiliary heating using gas (ref [33]).