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Solar Drying of Tropical Agricultural Crops: A Caribbean Perspective

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Abstract: Drying continues to be an important operation in the processing, preservation and marketing of tropical agricultural crops. While sun drying is still widely practiced, the use of solar dryers present a viable alternative to counteract the disadvantages of sun drying, while offsetting the high costs associated with conventional drying systems. This review describes the various solar systems that have been designed, built and tested to successfully dry a wide range of tropical crops. These include simple, low-cost natural convection cabinet and wire basket dryers suitable for small farmers/processors of both a direct and indirect type; cabinet dryers which incorporate separate air heaters and employing the natural and forced convection and larger, mixed-mode or hybrid dryers, that are more dependable and suitable for industrial use; and dryers, which incorporate a supplementary oil and/or biomass burner so as to facilitate drying at nights or in periods of inclement weather. Converting the roofs of processing stations to provide solar heat for drying large volumes of crops is also described as a method. The drying of herbs, fruits, cocoa, coconut, nutmeg, root crops, timber and fish along with drying curves and drying behavior are included. The processing considerations to enhance principally the quality and marketability of the dried product are noted. Given the imperative to integrate the drying process into the food processing chain, marketing and quality considerations are explored.

Key words: Solar dryers, natural and forced convection, mixed mode, roof dryers, tropical commodities, drying behavior, pre-processing, quality, marketing.

Drying is a process of water removal from a product in order to reach a desired moisture content. It is one of the oldest techniques to preserve agricultural crops and is based on the fact that the reduction in moisture content, is usually one that allows for safe crop storage or further processing. It is therefore an energy intensive process as sensible heat is converted to latent heat through water evaporation. In drying, the reduction in moisture content below a certain level inhibits the growth of microorganisms and many chemical reactions responsible for spoilage of foods. For some spices such as chilli and pepper, drying is not only for preservation purposes, but also for modifying the taste and flavor in order to increase market value (Janjai and Tung, 2005) and to support processing such as grinding to a fine powder. The traditional method for crop drying in the tropics is sun drying. Some advantages and disadvantages of sun drying are shown in Table 1. For many Caribbean crops, a desirable moisture content on drying is between 8-12% (wb) (Table 2). On a large scale, such as the sun drying of paddy in Guyana, large tracts of concrete drying floors are built and the grain spread in a thin layer of 2-3 cm deep, is exposed to direct sunlight. Regular, manual turning and heaping with covering are necessary to ensure even drying and to protect the grain from rainfall. However, such drying systems utilize much labor and help to sustain rural communities. Solar drying is often differentiated from sun drying by the use of equipment (i) to collect the sun's radiation in order to harness the radiative energy for drying applications (Chua and Chou, 2003), and (ii) for holding the crop in a protective, drying chamber. Solar drying provides higher air temperatures and lower humidities, which are conducive to improve drying rates and lower moisture content in the final product. Escalating petroleum prices, depleting fossil fuels and the need for environmental-friendly sources of energy have led

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Table 1. Advantages and disadvantages of sun drying

Advantages	Disadvantages
Negligible capital investment on a small scale	Slow drying and requires large surface area
Reduction in crop weight and bulk	Animal/Insect infestation
Reduces shipping costs and food supply costs	Unreliable, variable climatic conditions
Simplicity	Excessive handling
Environmentally friendly	Uneven drying and consistency in quality
Rural employment	High labor requirements on large scale

to increased emphasis on using solar energy as an alternative energy source in developing countries (Sreekumar, 2010). Use of a solar drying system therefore presents a good alternative to sun drying and reduces the high operational costs especially of energy of conventional dryers. The main advantages of solar drying (Chua and Chou, 2003) include: (a) it is cheaper using freely available solar energy instead of conventional fuels, (b) environmentally-friendly, and (c) faster, efficient, cleaner, healthier and offers better quality than the open-air drying

Table 2. Moisture content requirements for the drying of selected tropical crops (Sankat, 2004)

Crop	Moisture content (% wet basis)	
	Initial MC	Final MC
Rice (paddy)	22	11
Coconut (copra)	50	8
Sorrel	88	8
Cocoa beans	65	12
Nutmegs	35	8
Cassava	65	10

The disadvantage, like sun drying is that it is very dependent upon the availability of clear, sunny skies and therefore in the wet season of the year can be problematic.

The dry season conditions in the Caribbean during the months of January to May are very favorable to both sun and solar drying. The islands enjoy a tropical climate with good sunshine and average maximum temperature of 32°C. Figure 1 shows typical daily solar insolation values in one of the dry months of the year (Sankat and Rolle, 1991). Peak insolation is usually 1000 W/m^2 near to midday and an average daily value for the dry months of the year was estimated at 18.5 MJ m^{-2} day or 428 W m^{-2} for 12 hours of the day.

Drying Theory

Drying is an energy intensive process in which energy, in the form of heat, is used to vaporize the moisture from the material; evaporating 1 kg of water technically requires 2258 kJ of energy. The drying behavior, or the way that a material loses moisture during drying, is influenced by the drying parameters like air temperature, humidity and air velocity as well as by the physical characteristics of the crop. Not only is the quantity of water removed important, but the quality of a dried product is judged by the degree of physical and biochemical degradation occurring during the dehydration process. This has formed the basis for many drying studies aimed at determining drying rates, mechanisms and optimum drying parameters for specific crops using different drying methods and equipments. Different crops dry differently and quality attributes are important and also specific. It is therefore useful to understand some of the basic principles associated with drying.

The drying behavior of different crops depends to a large extent on the physical characteristics of the crop, e.g. particle size, internal structure and composition. These characteristics are crop

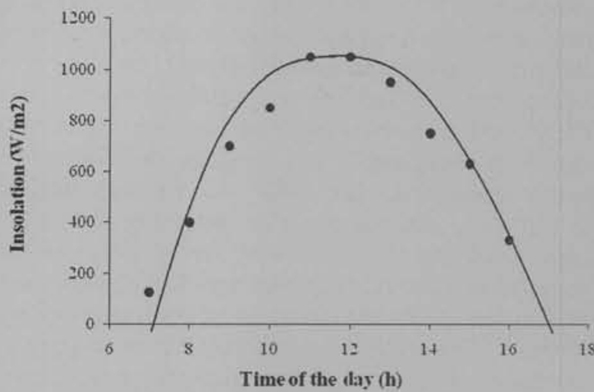


Fig. 1. Typical daily insolation pattern in Trinidad during the month of March (Sankat and Rolle, 1991).

specific and so the drying behavior of crops is usually different. Crops like cassava and the other tubers with a porous internal structure dry quickly as moisture movement from the inside of the crop to its surface is not as hindered, while crops like coconuts with a dense internal structure dry slowly. Crop drying characteristics are normally determined by passing heated air through a single layer of the material and measuring the moisture change with time until the equilibrium is approached. For effective drying, air should be hot, dry and moving, but high air temperatures must be limited by the crop and its specific usage.

Moisture content is expressed as a percentage either on a wet basis or a dry basis (Equations 1 and 2):

$$M_{wb} = [Wt_w \ / \ (Wt_w + Wt_{dm})] \times 100 \qquad ...(1)$$

$$M_{db} = [Wt_w \ / \ Wt_{dm}] \times 100 \qquad ...(2)$$

where, $M_{wb, db}$ = moisture content on a % wet basis or % dry basis; $Wt_{w, dm}$= weight of water or weight of dry matter.

For most practical and commercial purposes, moisture content is expressed on a % wet basis. During drying, the moisture content of the product is decreased and water loss during drying is usually accompanied by shrinkage. The dry matter weight of the crop is expected to remain unchanged during drying (Sankat, 2004).

The drying curve, which is a plot of crop moisture content against drying time, is used to describe moisture loss (or drying behavior) of crops during the drying process. Drying curves are used to show the influence of the factors which affect the rate of drying, e.g. temperature, air velocity, particle size and thickness. Typically, the moisture content (M) falls from the initial value (M_o) with drying time (t). As drying progresses the drying rate falls steadily and tends to zero as the moisture content approaches the equilibrium value (M_e). Generally as the drying air temperature increases, the drying rate will also be increased. Increased air velocity has no profound effect, except for thin, leafy crops that exhibit large surface areas. A drying rate curve usually reveals that there are two stages in a typical drying process: the "constant rate" period and a "falling rate" period. The first stage is the removal of "surface moisture"; the second stage is the removal of "internal moisture" from within the solid material. Drying in the falling rate period, which is usually the dominant period of crop drying, is assumed to be a moisture diffusion process. Most drying studies use the analytical solution to Fick's Law of diffusion to calculate the drying rate constants and diffusion coefficients (Henderson and Perry, 1976). The usual practice for studying the drying behavior of crops is to plot the experimental data of moisture content (usually as a moisture ratio) versus time on semi-logarithmic coordinates. From this procedure, drying constants and apparent moisture diffusivities may be established.

$$\ln M_r = \ln A - kt \qquad ...(3)$$

where, k (drying rate constant) = $\pi^2 D/4L^2$ (h^{-1}), M_r = Moisture Ratio = $(M - M_e) \ / \ (M_i - M_e)$, M_i = initial moisture content (db), D = apparent moisture diffusivity (m^2/h), L = half thickness (m).

Water activity (a_w) is also an important consideration in the drying process. The water activity is the relative availability of water in a product, defined as the vapor pressure p of water in the material divided by that of pure water p_o at the same temperature.

$$a_w = p/po = RH/100 \qquad ...(4)$$

The water activity of a material corresponds to the relative humidity (RH) of the air in the immediate vicinity of the sample. The RH and moisture content of the drying material are interrelated and with moisture content reaching equilibrium at constant temperature. Microorganisms develop at RH 70%. Since the activity of decomposing enzymes is also enhanced by increasing water activity, a threshold of RH 60% can be used for storage of some crops (Müller and Heindl, 2006). Hence dried fruits of a_w of 0.5-0.6 can be used as a safe, rule of thumb.

Important processing considerations

Good preparation practices, pre-treatments, and proper packaging and storage conditions are essential to obtain a high quality, dried product that is market-ready. The drying process cannot improve the initial quality of the material being dried, therefore, the starting material should be wholesome crops, free from disease. Fruits and vegetables must be properly washed before drying and damaged parts trimmed before peeling and cutting into small, uniform pieces. Fish should be de-scaled and the skin removed in some cases, such as shark and catfish.

Pre-drying treatments such as blanching, osmotic dehydration treatments using sugar or salt and sulfating are commonly used in drying to improve product quality. Blanching reduces microflora and inactivates enzymes, which may cause undesirable changes in quality, particularly color. The simplest method for blanching is immersion for a few minutes in boiling/near boiling water. Steam blanching may also be used. Over-blanching results in loss of texture and difficulties during drying.

Immersing fruits in a sugar solution prior to drying can be used to remove some moisture, prevent product discoloration during subsequent air drying and give a tastier product of appropriate texture when dried. Typical sugar solutions of 60-66° Brix, as measured by a refractometer, are used for fruits, while immersing fish in a saturated salt solution prior to drying can be used to remove moisture and add salt. Both sugaring and salting can allow the preservation of dried products like candied fruits and fish with a higher, intermediate moisture content of 25%. The use of chemical preservatives such as citric acid or sodium metabisulphite pretreatment may also be used to enhance the color of the dried product. For example, tomatoes are soaked in a 0.1% sodium metabisulphite solution for 15-20 minutes prior to drying (FAO, 1997). The use of an oil dip for paprika fruit has been shown to hasten the water loss during drying by restructuring the epicuticular wax of the fruit's surface and possibly altering cuticle characteristics (Krajayklang *et al.*, 2001).

Pre-treated material should be drained and arranged in single layer on drying trays in the dryer to ensure maximum exposure of each piece to the surrounding drying air. Selecting the appropriate temperature for drying is very important for good product quality and this must be accompanied by good air movement through the dryer. A good, safe temperature for drying many foods is 50-60°C. Solar drying is therefore particularly attractive as solar dryers would hardly exhibit temperatures higher than those and such dryers can be classified as low temperature dryers. In most cases, the material is dried until there is no appreciable loss in weight, which indicates that the moisture content of the dried product is in equilibrium with the surrounding drying air.

The dried product, unless protected, is susceptible to physical damage, moisture re-absorption and microbial contamination during handling and storage. The dried product should therefore be properly packaged. Packaging material should be moisture-proof, insect-proof and airtight. Polyethylene and polypropylene bags or containers are often used for dried fruits and vegetables. Bags should be properly sealed, and appropriately labeled. The packaged product should be stored in a cool, dry place as this will allow for a longer storage life of the dried product.

Solar Drying Systems

Design of solar dryers

In order to select an appropriate dryer and the drying parameters, such as time and temperature, it is important to understand the drying behavior of the material to be dried. This forms the basis of many drying studies, which are conducted to determine characteristics of moisture loss as well as physical and biochemical changes. Solar dryers are generally classified based upon how the crop is exposed to solar radiation (direct/indirect dryers), or the method of airflow through the dryer (natural/forced convection). Solar dryers can be simple in design and built with local materials. A typical, simple solar dryer will have the following features:

- Drying chamber for holding and protecting the product
- Absorber plate receives and absorbs the solar radiation. Usually blackened, corrugated galvanized iron is used. The slope of this plate is important so that maximum energy can be collected when the sun's rays strike the collector perpendicularly.
- Transparent cover which is placed above the absorber plate or the drying chamber in a solar air heater design or directly above the drying chamber in a cabinet type dryer, respectively. This cover is usually made of glass with good transmissivity for visible radiation and virtually opaque to infra-red radiation, thus reducing heat loss from the absorber plate to the surroundings while also protecting the crop from inclement weather. Clear plastic that is lighter, cheaper and easy to handle, but with limited life may also be used.
- Air circulation system: Natural or forced convection may be employed to transfer the heat from the absorber plate to the airflowing over and through the dryer. Simple (passive) dryers use natural convection as warmer, less dense air rises naturally in the drying chamber. Forced convection dryers utilize axial or centrifugal electric fans.

A direct, passive dryer is one in which the crop is directly exposed to the sun's rays and air is circulated by natural convection. This type

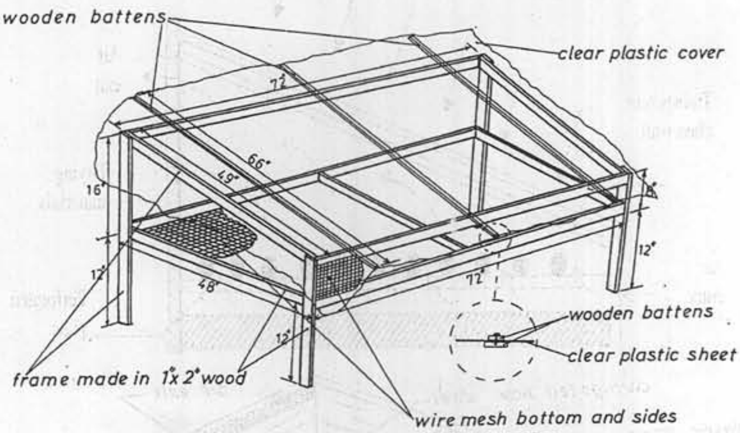


Fig. 2. The wire basket dryer (Sankat et al., 1987).

of dryer, usually of low cost, is best for drying small lots of fruits and vegetables. For large crop volumes, systems which employ forced air movement are recommended. More advanced systems, such as mixed mode dryers use a combination of solar energy and supplementary, conventional energy including gas, diesel or kerosene burners while others utilize non-conventional materials (biomass) such as coconut shells. Heat exchangers may also be employed in such hybrid dryers to improve the quality of the dried product through removal of contact of the products of combustion with the drying material. Recent studies on the development of a solar assisted, dehumidification system for heat-sensitive medicinal herbs and the integration of photovoltaic (PV) cells into a forced flow, solar dryer have shown favorable results (Yahya *et al.*, 2008; Shukla and Vishwakarma, 2009). The performance of a solar dryer with sun tracking capability to maximize the capture of solar radiation was also investigated by Mwithiga and Kigo (2006).

The wire basket dryer

An extremely simple design is the wire basket solar dryer (Sankat *et al.*, 1987). This is suited to the small farmer; it is economical in cost (approx. US$ 50) and can be used for drying in excess of 50 kg of wet crops where high ventilation rates and low temperatures (about 5-7°C above the ambient) are required. The dryer consists of a drying chamber made of wire mesh using wood as the framing material, and a removable cover made of a clear plastic sheet, and sloping at 10°C to the horizontal, while facing south (Fig. 2). The dryer has been used successfully to dry a range of fruits and forages eg. sorrel, banana, grass. The moisture content of sorrel (*Hibiscus sabdariffa)* can be reduced from 90% to 23% (wet basis) in 4 to 5 days. On a dry matter basis, this corresponds to a reduction in moisture content from 900% to 30% (Fig. 3). The horizontal portions of the curve represent nighttime, when drying usually ceases. Dried banana, ginger and forages can be obtained in 3 days (McGaw *et al.*, 1987). Balladin and Headley (1999) investigated the drying behavior of the fragrant herb, thyme (*Thymus vulgaris* Linn.) dried in a wire basket solar dryer. Herbs could be dried from an initial moisture content of about 75% to 12% (wet basis), at a temperature of about 50°C, after 12 h.

The cabinet dryer

The simple cabinet type dryers are direct, natural convection dryers. This type of dryer comprises a drying chamber that is covered by a transparent

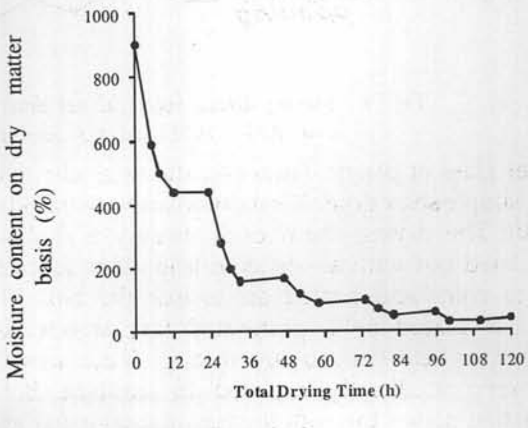


Fig. 3. Plot of moisture content versus time for sorrel calyces dried in a wire basket dryer (adapted from Sankat et al., 1987).

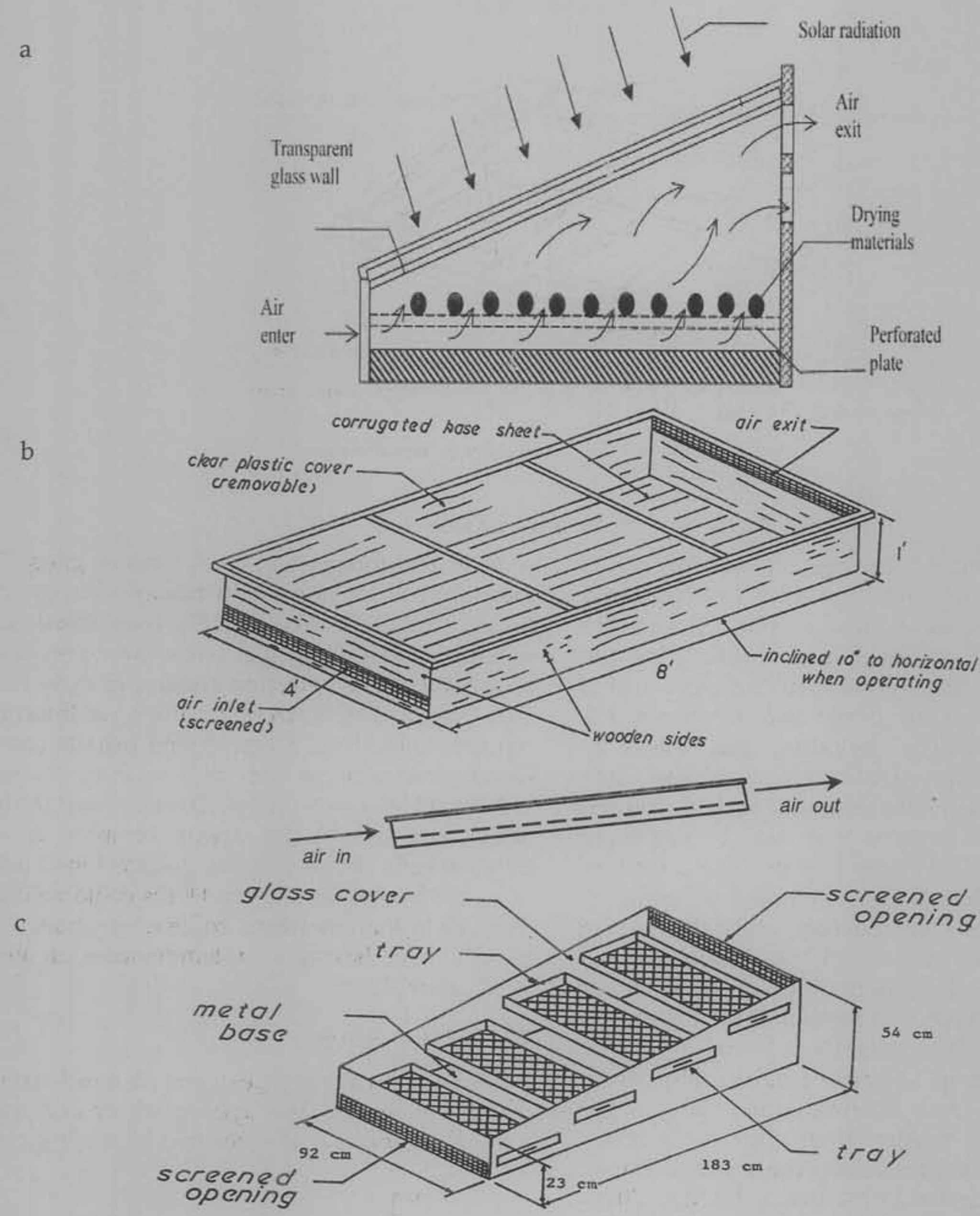


Fig. 4. Simple, direct, solar cabinet dryers (a) Grabowski and Majumbdar, 2000; (b) Sankat and Rolle, 1991 and (c) Sankat, 1984).

cover glass or plastic. Figure 4a shows a schematic of a simple solar dryer (Grabowski and Majumbdar, 2000). The drying chamber is usually a shallow, insulated box with air vents in it to allow ambient air to enter and heated air to exit the box. The crop is placed on a perforated tray which also allows the heated air to flow through it and usually the crop is directly exposed to sunlight. Solar radiation passes through the transparent cover and is converted to low grade heat when it strikes the absorber plate (Chua and Chou, 2003).

Sankat and Rolle (1991) built and tested a simple direct cabinet dryer for the drying of copra (Fig. 4b). It consists of a drying chamber with wooden sides and a corrugated metal base as absorber, and a removable, transparent cover. Screened rectangular openings along the length of the shorter

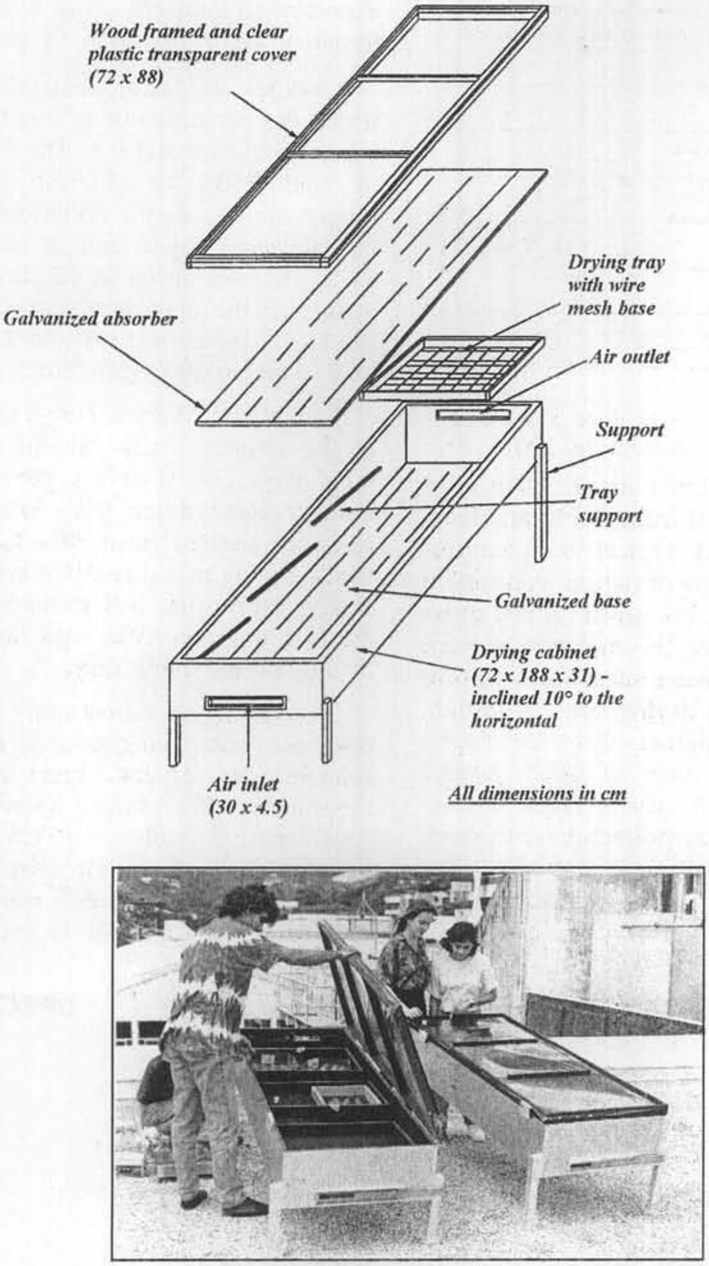


Fig. 5. A direct solar cabinet dryer with side removable drying trays.

sides provide the air inlet and exit and interior surfaces of the dryer were painted flat black. When operating in Trinidad, the air exit end of the dryer is raised and supported above the inlet side to provide a slope of 10° to the horizontal, with the cover facing the south.

Sankat (1984) investigated the use of a multi rack cabinet dryer (Fig. 4c), which consists of tiered drying trays that can be removed or inserted into the drying cabinet through rectangular slots on one side of the cabinet. Rectangular ports provide for air movement at the lower front and top of the dryer. Temperatures in the dryer can be increased or decreased by closing or opening these air inlet and exit vents. The horizontal base (absorber plate) is made of galvanized sheet and between this and the dryer support, 25 mm thick Styrofoam insulation is used. Again the dryer cover is sloped at 10° to the horizontal and the cover

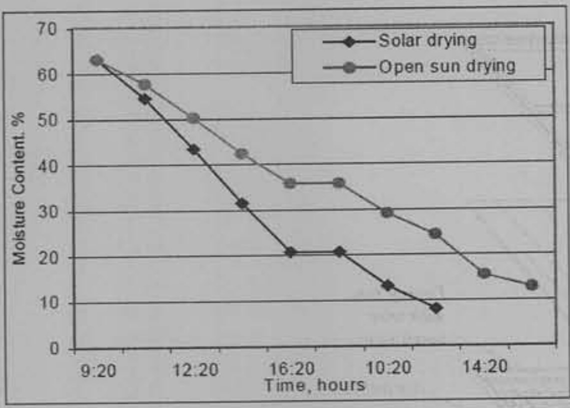


Fig. 6. Drying curves for Jackfruit dried in a cabinet dryer (Cheapok and Pornnareay, 2000).

faces south. The solar cabinet dryers have been used to dry various tropical fruits, herbs and leafy vegetables, and fish and typical temperatures experienced inside this type of natural convection dryer range from 40-60°C. The direct cabinet dryer has been shown to reduce the moisture content of osmotically treated banana slices from 66% to 18% in 6 days with 7-8 h drying per day (Smith, 1992). Osmotically dehydrated slices develop a beautiful yellow-orange color of good texture (Sankat *et al.*, 1996). Both dryers (Figs. 4b, 4c) may also be converted to an indirect dryer through the insertion of a blackened, galvanized plate directly beneath the clear glass/plastic cover as shown in Fig. 5. Such dryers have the advantage of removing the crop to be dried from direct exposure to sunlight. This is often beneficial in terms of color retention in particular.

Cheapok and Pornnareay (2000) developed and tested the performance of a cabinet dryer to dry banana, jackfruit and fish. The dryer was designed to hold 20-35 kg of fresh material and the temperature inside the dryer reached 57°C at noon. Jackfruit was dried from a moisture content of 65 to 5% (wet basis) in 1.5 days compared with 3 days in the open sun (Fig. 6). Fish was dried from 75% moisture to 5% in 2.5 days compared to 3 days in the open sun.

Sankat and Maharaj (1994) showed that drying of the aromatic herb 'Shado beni' or 'cilantro' for 5 days (7-8 h drying per day) in a simple, indirect solar dryer (Fig. 5) could reduce the moisture content from 89% to 17% (wet basis). While drying in a direct dryer was faster, indirect drying and prior hot water blanching reduced the loss of green color typically seen during sun drying of the herb (Fig. 7).

The drying of salted shark slabs dried in the open air (sun drying) and in natural convection solar cabinet dryers (direct and indirect) was investigated in Trinidad (Sankat and Mujaffar, 2004). Shark slabs (10 cm x 5 cm x 1 cm) pre-treated with a citric acid dip and osmotically dehydrated in a saturated salt solution were dried in a direct solar dryer for 2 days to reduce the moisture

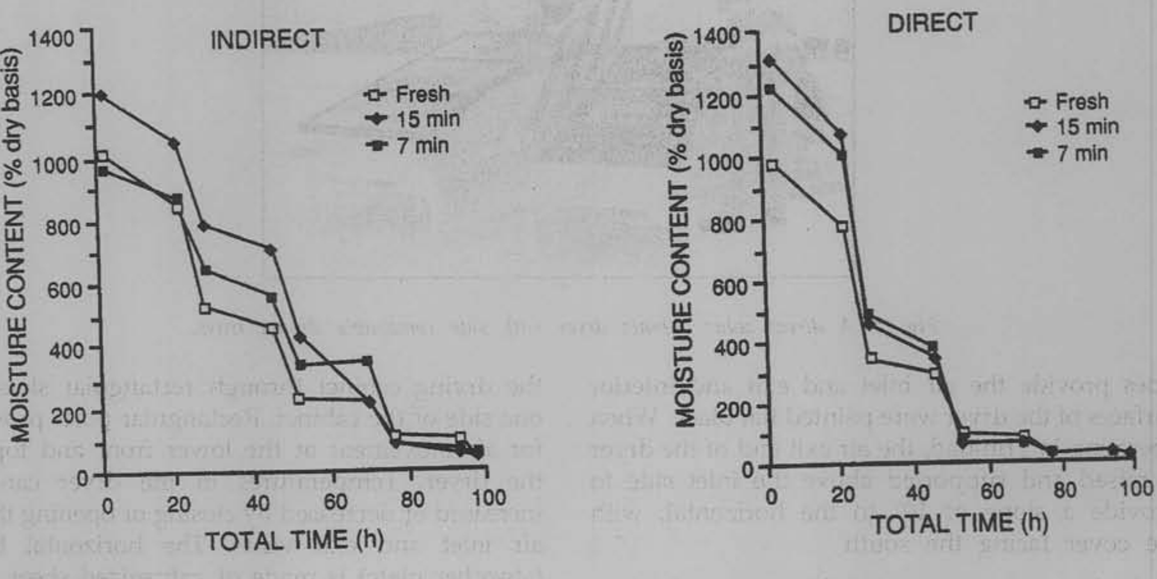


Fig. 7. The effect of blanching time on the drying behavior of Shado Beni in the direct and indirect solar cabinet dryers (Sankat and Maharaj, 1994).

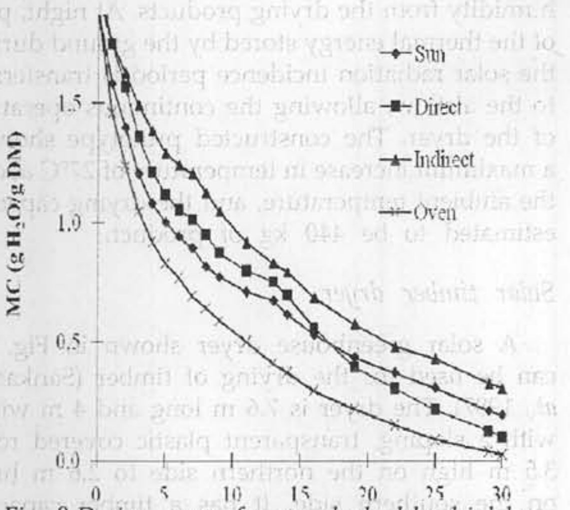


Fig. 8. Drying curves for sun shark slabs dried by different methods: sun drying, direct and indirect solar dryers and oven dried at 50°C (Sankat and Mujaffar, 2004).

content (MC) from 62% to 40% (wet basis) and give a product with a pleasing and even color and aroma. Figure 8 shows the drying curves on a dry matter basis and drying time adjusted to actual drying time while Table 3 gives the drying rate constants (k) for the first four hours of dehydration for sun, solar and oven dried shark slabs (Sankat and Mujaffar, 2004).

Table 3. The drying constants (k) for shark slabs dried using different drying methods (Sankat and Mujaffar, 2004)

Drying Method	Rate Constants (k) (h^{-1})	Correlation Coefficient (r^2)
Sun Drying	0.1381	0.9946
Direct Solar Dryer	0.1264	0.9981
Indirect Solar Dryer	0.0838	0.9962
Oven (50°C)	0.1890	0.9936

Kalra and Bhardwaj (1981) described a natural convection, 'shelf-type' cabinet dryer with separate air heater for fruit and vegetable products of the type shown schematically in Fig. 9. The solar air heater is a parallel pass type, with air moving by natural convection on either side of a blackened, corrugated metal surface, which is positioned between a glass cover and an insulated (25 mm thick Styrofoam) plywood bottom. The wooden drying chamber is designed to hold four trays stacked vertically. Hot air from the air heater rises through the stack of trays and leaves the dryer through a rectangular opening at the top of the rear panel of the drying chamber. Experience has shown that if the drying trays are in any way over-packed, airflow is obstructed and crop spoilage occurs. Also, for larger amounts of material, a tall chimney will be required to induce air movement, but dryers of this type must be used with care. An exhaust fan, fitted at the top of the cabinet or the use of a chimney with a ventilator can facilitate air movement through such dryers.

The thin-layer drying of mango, cassava and plantain was investigated by Koua *et al.* (2009) using a direct solar dryer with a chimney (Fig. 10). The decline in mango moisture content is given in Fig. 11. It was noted that drying occurred in the constant rate and falling rate periods and diffusion coefficients were found to be dependent on the initial moisture content of the food. Ferriera *et al.* (2008) also assessed the technical feasibility of a solar chimney to dry coffee grains, whole bananas and tomatoes. The solar chimney is

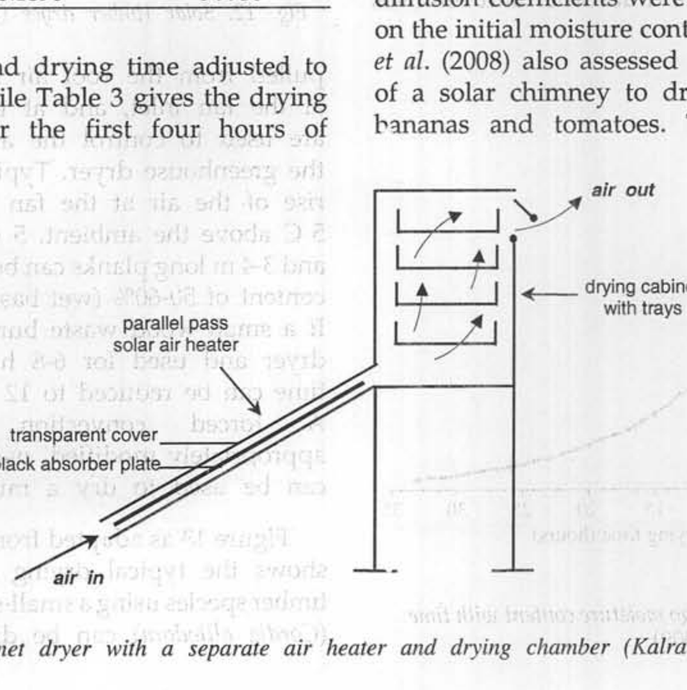
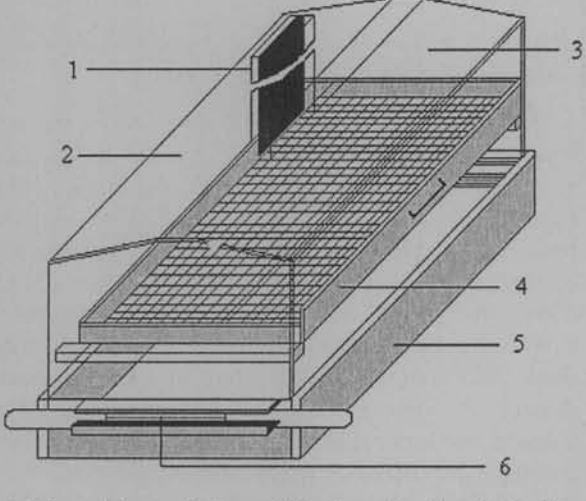


Fig. 9. A solar cabinet dryer with a separate air heater and drying chamber (Kalra and Bhardwaj, 1981).



1-Solar chimney 2-Cover 3-Drying chamber 4-Hurdle 5-Box 6-Ambient air inlet

Fig. 10. Direct solar dryer using a chimney (Koua et al., 2009).

composed of a central tubular tower fixed to a translucent circular cover, opened at the edges. A 12.3 m high tower was constructed with sheets of wood and covered by fiberglass. During the solar radiation incidence period, a fraction of the incident solar radiation on the cover is absorbed by the ground and the drying product, which is then converted into thermal energy. The heat is transferred by convection through the air and in turn to the product. The hot airflow enters the tower and creates an up draught from buoyant forces. The ambient airflows from the periphery to the center of the circular collector. In the process, it is heated by the ground absorber and removes

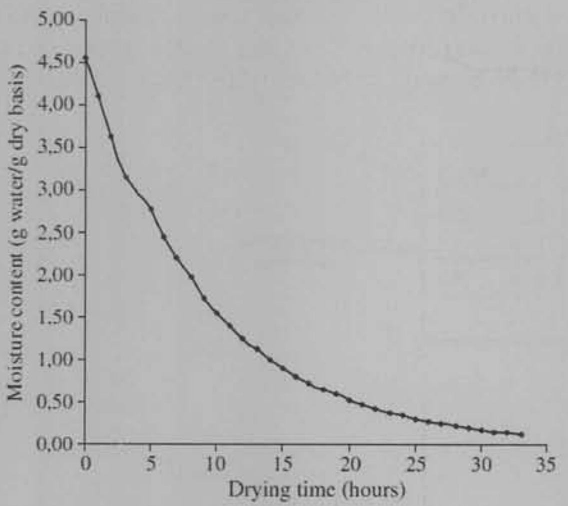


Fig. 11. Variation in mango moisture content with time (Koua et al., 2009).

humidity from the drying products. At night, part of the thermal energy stored by the ground during the solar radiation incidence period is transferred to the airflow, allowing the continuous operation of the dryer. The constructed prototype showed a maximum increase in temperature of 27°C above the ambient temperature, and the drying capacity estimated to be 440 kg of product.

Solar timber dryer

A solar greenhouse dryer shown in Fig. 12 can be used for the drying of timber (Sankat *et al.*, 1987). The dryer is 7.6 m long and 4 m wide, with a sloping, transparent plastic covered roof, 3.5 m high on the northern side to 2.6 m high on the southern side. It has a timber capacity of 18 m^3. Two axial flow fans blow air from the plenum chamber through the timber stacks, with the plenum chamber being supplied by hot air

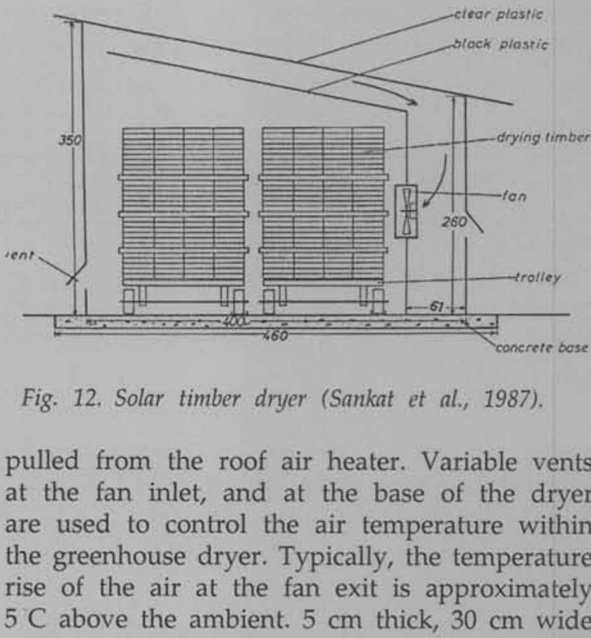


Fig. 12. Solar timber dryer (Sankat et al., 1987).

pulled from the roof air heater. Variable vents at the fan inlet, and at the base of the dryer are used to control the air temperature within the greenhouse dryer. Typically, the temperature rise of the air at the fan exit is approximately 5 C above the ambient. 5 cm thick, 30 cm wide and 3-4 m long planks can be dried from a moisture content of 50-60% (wet basis) to 16% in 3 weeks. If a small wood waste burner is attached to the dryer and used for 6-8 h per day, the drying time can be reduced to 12 days (Headley, 1986). A forced convection greenhouse dryer appropriately modified, using trays for example, can be used to dry a multitude of crops.

Figure 13 as adapted from Tang Kai *et al.* (1993) shows the typical drying curves for Caribbean timber species using a small-scale solar dryer. Cypre (*Cordia alliodora*) can be dried from a moisture

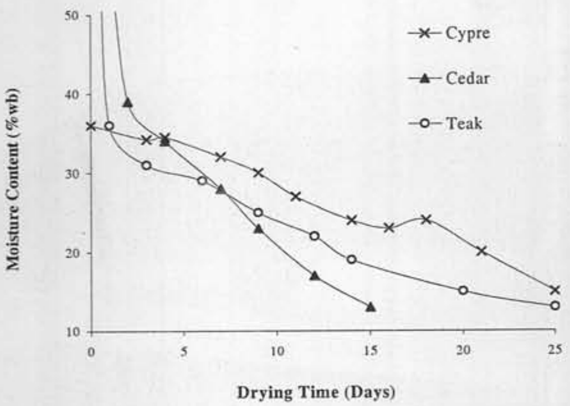


Fig. 13. Plots of moisture content versus time for local timber (Tang Kai et al., 1993).

content of 35.9% to 16.3% (wet basis) in 25 days, cedar (*Cedrela odorata*) dried from over 50% to 13.9% in 15 days and teak (*Tectona grandis*) from over 50% moisture to 15% in 18 days.

Mixed mode/hybrid dryers

Mixed-mode drying systems utilize conventional heating sources (hydrocarbon fuel or biomass) and are used to ensure that drying continues in the solar dryer during rainy spells or at night, or when large quantities of material are being dried. In a hybrid solar dryer, drying is continued during off-sunshine hours by back-up heat energy or stored heat energy using for example a rock bed storage. This ensures that the drying continues and that the product is saved from possible deterioration.

Fagunwa *et al*. (2009) developed a cabinet solar dryer with thermal energy storage for the intermittent drying of cocoa beans in Nigeria. This dryer consists of three major components: the solar collector, the drying chamber and a heat storage chamber (Fig. 14). The solar collector is basically a top-open, wooden box inclined at an angle of 15° to the horizontal. The collector is connected to one end of the drying chamber via an air duct, while the other three sides of the collector are partitioned internally to form heat storage chambers. The chambers are completely filled with gravel to absorb heat during the day and release it at night. The surfaces of the collector, the drying chamber and heat storage chambers are covered separately with glass doors and a five-speed axial flow fan is located inside the air duct. The prototype was designed to hold 50 kg of wet cocoa beans. The moisture content of the beans was reduced from 53.4 to 3.6% in a 72-hour intermittent drying process against ambient conditions (24-30°C, 58-98% relative humidity).

A hybrid solar dryer was designed and tested by Amer *et al*. (2010) in Germany for the drying of ripe bananas. The dryer consisted of a solar collector, drying chamber, heat exchanger and heat storage unit (Fig. 15). The heat exchanger consisted of a 15 mm diameter copper tubes placed inside the solar collector. Two ends of the copper tubes were connected to the 500 e insulated, water storage tank and water was circulated using a small water pump at 20 L h^{-1}. The heat exchanger gave a part of the heat collected during the hours of the sun-shine, which was carried by air inside the solar collector, to the water inside the copper tubes. The water traveled slowly inside the pipes. The temperature of this water could also be raised by using 6 kW water heaters located inside the tank to reach a desired temperature for drying during the night as well as in adverse weather for maintaining the temperature and the humidity throughout the drying process. The air temperature could be raised up to 40°C above ambient temperature. The dryer could be used to dry about 30 kg of banana slices in 8 h from an initial moisture content of 82% to a final value of 8% (wet basis). The efficiency of the solar dryer could be raised by recycling about 65% of the drying air in the dryer.

McGaw *et al*. (1988) developed a mixed mode, packed-bed dryer, which has a solar air pre-heater and a hydrocarbon fuel or kerosene burner (Fig. 16). The dryer was developed through the coupling of two main components: a parallel flow, flat plate air heater with a wooden support which provides a 10° slope to the horizontal and a packed bed, commercial dryer consisting of a drying bin, a fan and a kerosene burner with a maximum fuel consumption rate of 3 L h^{-1}. The air heater also serves as the protective roof of the dryer.

The mixed mode dryer was used to dry sliced, cassava tubers using solar heated air only and supplemental heat. Cassava tubers were chipped mechanically (3-4 mm thick) and dried at a bed-depth of approximately 7 cm (McGaw *et al*., 1988). When using kerosene to heat the drying air, the air temperature in the plenum chamber was maintained at approximately 40°C ± 2°C over a four day period. The time taken to dry the top layer to less than 0.15 kg H_2O kg^{-1} DM was approximately 75 h using solar heated air only.

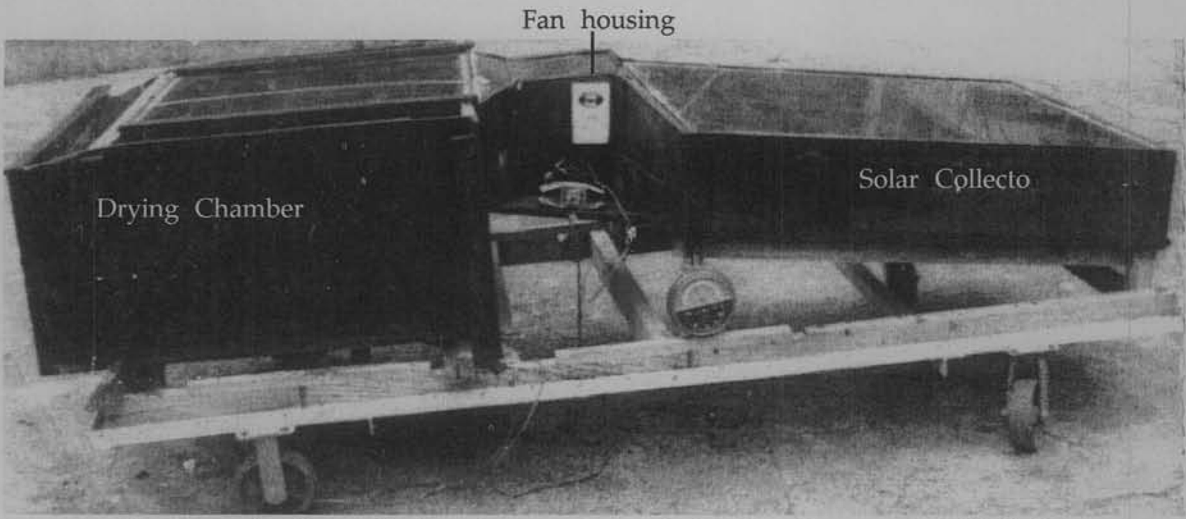


Fig. 14. A solar dryer with thermal energy storage developed by Fagunwa et al. (2009) for the drying of cocoa beans.

This time was reduced to less than half when kerosene fuel was utilized in the night period only.

A commercial, mixed mode dryer was designed and built in Trinidad and is recommended for multipurpose industrial drying for foods that are placed in trays as shown in Fig. 17. The roof-integrated solar dryer consists of a solar air heater, a drying cabinet, a commercial propane, gas burner and a 1-hp exhaust fan of 48″ in diameter. The fan pulls air between the roof and the ceiling and this serves as the solar air heater. The heated air moves through the drying trays and then out to the surroundings. In periods of rainfall or at night, the air is heated using the gas burner and its temperature is controlled by a thermostat.

Roof integrated solar dryers

As noted by Janjai and Tung (2005), farmers in areas of high solar radiation, such as those situated near the equator, tend to carry out various farming activities in structures with galvanized roofing sheets. Therefore, it is feasible to use this type of roof to assist in the production of hot air for drying crops. This type of drying system will provide space for the solar collectors and reduce the total investment cost. They developed a solar drying system for use in Thailand, using hot air from roof-integrated solar collectors for drying herbs and spices (Fig. 18).

The farmhouse (8 x 9 m) was oriented in the east-west direction. Sixteen solar collectors, each 1.0 x 4.5 m, were constructed to function both

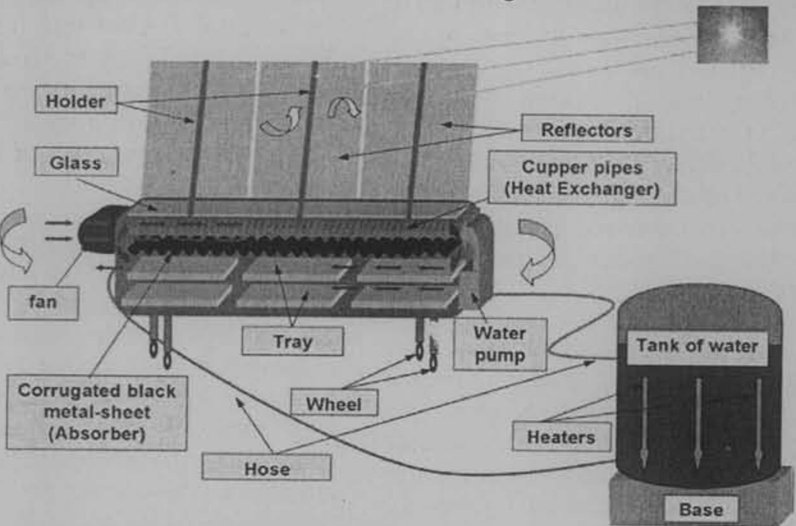


Fig. 15. Schematic diagram of a solar hybrid dryer (Amer et al., 2010).

as a hot air generator and a roof of the farmhouse. Each solar collector consists of iron frames, a back insulator and a transparent corrugated fiberglass cover. The back insulator is made of glass wool sandwiched between two galvanized iron sheets. The upper sheets of the insulator are painted black to absorb solar radiation. Ambient air is sucked to pass through an air channel between the back insulator and the cover. A rectangular air duct is placed horizontally at the middle of the roof to collect hot air from the two arrays of the solar collectors. Another cylindrical air duct is vertically connected to the middle of the rectangular air duct to transport the air from the solar collectors to the air distributor box of the dryer. The bottom side of the bin-type dryer is made of a rectangular perforated plastic plate and the top side is open for loading the products to be dried and for allowing moist air to leave the dryer. To obtain a uniform airflow distribution, a 2-hp axial flow fan is installed. The walls of the dryer are made of high-density foam, sandwiched between two aluminium sheets to reduce heat losses. With this dryer, 200 kg of rosella flowers (a medicinal herb) and lemon grass (a spice) can be dried within 4 and 3 days, respectively. The average daily efficiency of the collectors is 35%. The investment rate of return (IRR) and the pay-back period (PBP) of this dryer was estimated to be 70.3% and 3.9 years, respectively (Fig. 18).

Grenada in the Caribbean is the second largest producer of nutmegs (*Myristica fragrans*) in the world. Nutmeg seeds are dried through natural convection, in large drying trays, which are removed from direct sunlight. Usually such trays are on the top floor of the receiving/ processing stations, directly under the metal roof. The drying trays are attached in stacked tiers, 7 to 10 trays per tier, with trays 15 cm deep (approximately 6 seeds). Seeds are dried from 30-35% moisture content to 8-9%, in 6 to 8 weeks. McGaw and Sankat (1984) showed that the drying time may be halved by simply passing sufficient air through the bed of seeds, and if the air was heated to 37°C (about 5°C above ambient), the drying time may be about 7 days. Solar drying with forced convection therefore is ideally suited for such drying, as higher drying air temperatures can significantly reduce the quality of nutmegs, through the loss of its aromatic components. To achieve this objective, a receiving/drying station in the town of Beaulieu in Grenada was modified to become a solar assisted, drying station. As shown in Fig. 19, ambient air was pulled and heated under the blackened, metal roof of the station, directed through the stack of trays and exhausted to the station's exterior through eight, 2-hp axial flow fans. Preliminary drying results were promising, however, the drying station in Beaulieu was never commissioned, as the roof was blown away and much of the building was destroyed by hurricane Ivan in 2004.

Sreekumar (2010) conducted a techno-economic analysis of a roof-integrated solar air heater for drying pineapples. Baffles placed along the solar air heater forced the air to flow a winding path, thereby doubling the length of the air passage through the collector. A centrifugal blower was used to suck hot air from the air heater and four axial fans provided for uniform circulation and recirculation of hot air through the dryer. Dried pineapple was found to be of good color, as it was not directly exposed to the solar radiation. Drying of 200 kg of pineapple took 8 h. The cost of drying pineapple was about 20% of the cost of drying it in an electric dryer.

Solar tunnel dryers

A tunnel dryer is so called because the drying chamber is tunnel-shaped. For example, the Silpakorn type solar tunnel dryer (Fig. 20) was developed by Janjai *et al.* (2006) for drying fruits and vegetables in Thailand. It consists of a solar collector and a solar tunnel. The collector and the drying tunnel have the area of 1.22 x 1.95 m and 1.22 x 8 m, respectively. The drying tunnel has a 100 kg capacity. Both parts have a similar structure and they are connected directly without

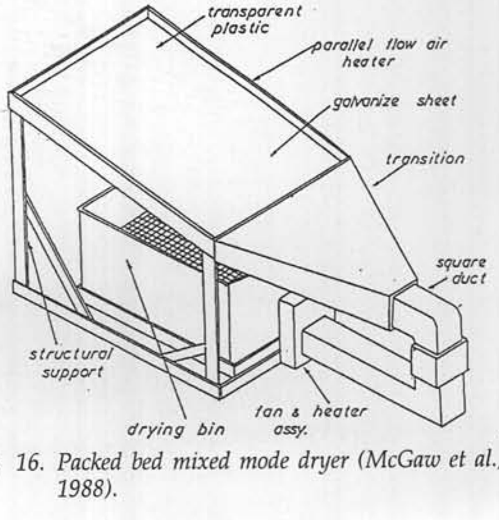


Fig. 16. Packed bed mixed mode dryer (McGaw et al., 1988).

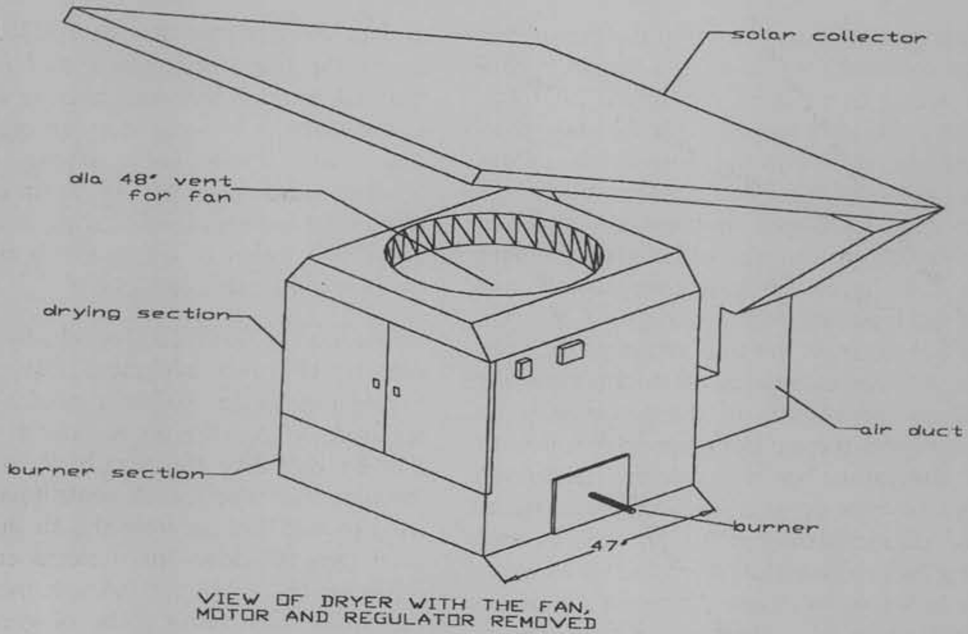
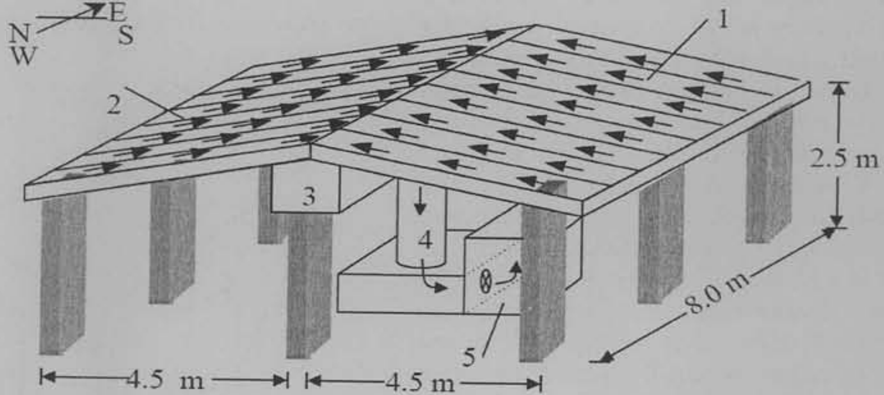


Fig. 17. Industrial, mixed-mode dryer in Trinidad.

any air ducts as shown. The collector and the drying tunnel are covered by glass plates with a tilted angle of 5° for drainage of water in case of rain. The product to be dried is loaded and unloaded through the windows at a side wall of the drying tunnel. A DC-fan powered by a 15-watt solar cell module is used to draw ambient air into the collector tunnel and it is blown through the drying tunnel. The dryer was used to dry 70 kg of chillies in 3 days, compared to 5 days needed for natural sun drying.

Modern tunnel solar dryers are used for larger amounts of material. Such dryers consist of a transparent roof and side walls, mainly in a hemi-spherical configuration. The material to be dried is spread onto trays, which are stacked onto racks, which may be wheeled. The photograph shown in Fig. 21 is a natural convection walk-in type dryer for bulk drying of agricultural and agro industrial products developed as part of the All India Coordinated Research Project on Renewable Sources of Energy for Agriculture and Agro-Based Industries (Indian Council of



(1) south-facing solar collectors (2) north-facing solar collectors (3) horizontal air duct (4) vertical air duct (5) dryer.

Fig. 18. Schematic diagram of a solar dryer using hot air from a roof-integrated solar collector (Janjai and Tung, 2005).

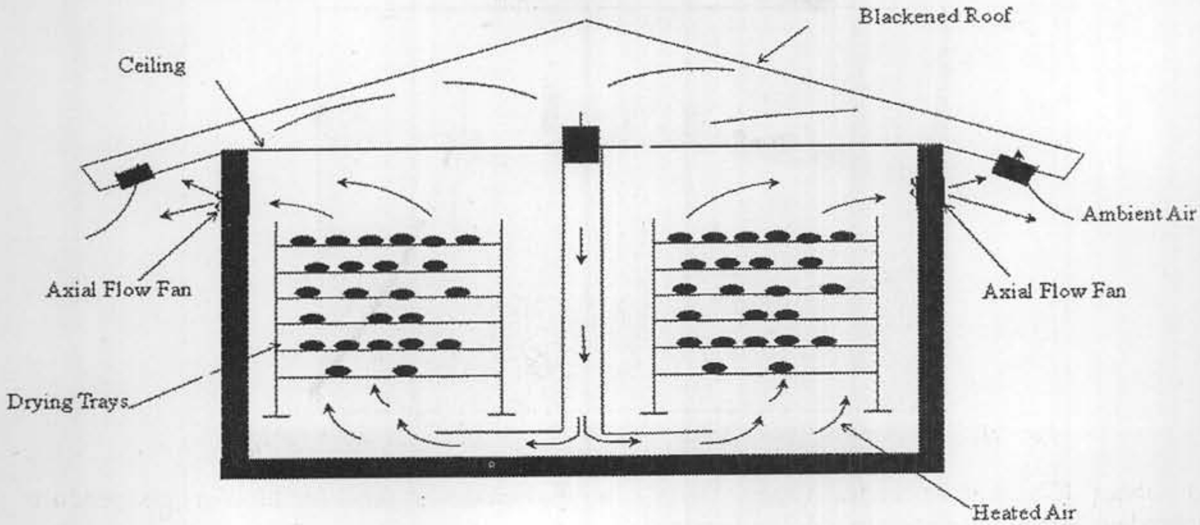


Fig. 19. Solar drying of nutmegs using a roof air heater in Beaulieu, Grenada.

Agricultural Research, 2010). The dryer consists of a semi-cylindrical metallic frame of 3.75 m diameter and 2.0 m height and covered with UV stabilized, transparent 200 micron thick polythene sheet. A slope of 10-15° is provided along the length of the tunnel. An exhaust fan at the upper end of the tunnel, and a few chimneys (number of chimney depends on the amount of moisture to be removed) on the top of the tunnel are provided to remove the moist air. An insulated wall on the north side is provided to reduce the heat loss. The average temperature inside the tunnel was found to be 15-20°C higher than the ambient temperature. The cost may vary depending upon the application and size of the dryer. Approximate cost of materials and labor was about US$ 2824 for standard size (3.75 m x 21.0 m). Cost of drying is reduced by around 50% in solar tunnel dryer compared to the diesel fired, mechanical dryer.

Ayyappan and Mayilsamy (2010) developed a natural convection solar tunnel dryer for copra drying in India. The dryer was 4 m wide, 10 m long and 3 m high and was designed to dry 5000 coconuts per batch. The semi-circular portion of the dryer was covered with UV stabilized, polyethylene film. Moisture content in copra was reduced from 52.2% to 8% in 57 h under full load. The average efficiency of tunnel drying was estimated at 20% and the quality of copra was

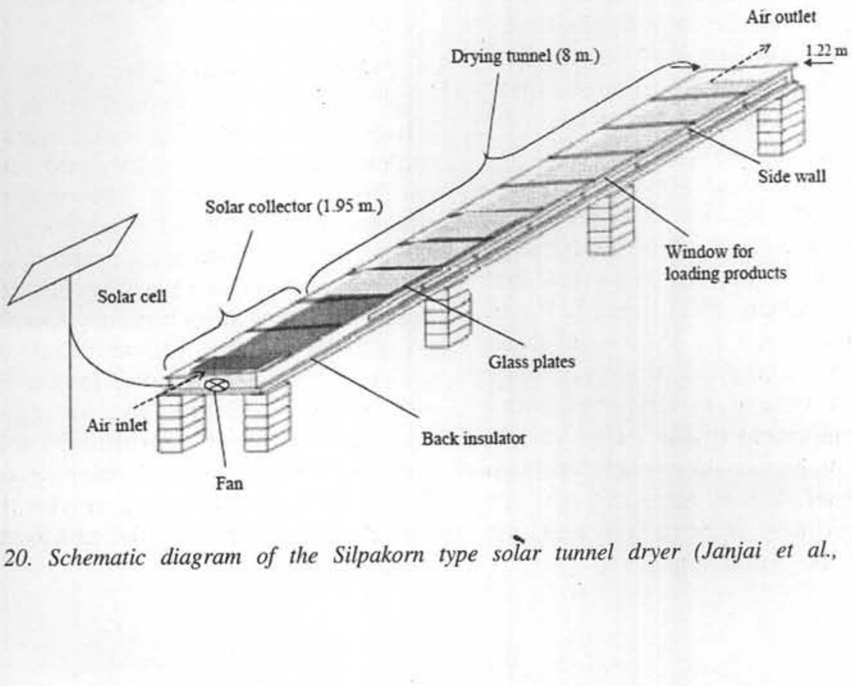


Fig. 20. Schematic diagram of the Silpakorn type solar tunnel dryer (Janjai et al., 2006).

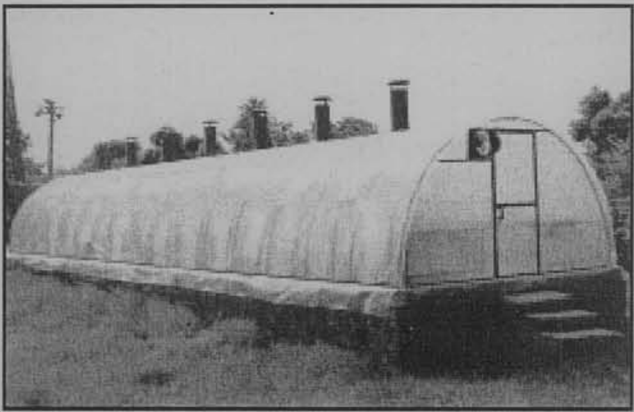


Fig 21. Solar tunnel dryer (Indian Council of Agricultural Research, 2010).

good (about 85% milling copra Grade 1) as compared with open sun drying (53%). The average thermal efficiency of the dryer was estimated at 20%, and pay back period was 5 months.

Preparing for the Market

The food markets of the world are highly competitive, and in the more developed economies these are essentially driven by market demand and legislation pressures focusing on quality. The degree to which these pressures engage are dependent on whether the market is local, regional or international. Whilst trade liberalization may be welcomed by retailers and consumers, for local producers, in developing countries the ability to compete on equal terms with imported items and the need to ensure quality of dried products including sanitary and hygienic as well as packaging and labeling requirements are of primary concern. Exporters of solar dried products have to follow the standards of the importing country and the export destination. For local farmers and companies to compete, even on the domestic front, assistance will have to be made available to encourage product development, quality and good food hygiene practices and assured distribution. Another important consideration is the delivery of updated market intelligence on a regular basis specifically to educate farmers, producers and processors of the realistic local, regional and overseas opportunities open for their solar dried products. However, for solar processing technology to provide sustainable returns, this requires careful development and placement of the technology in a fully integrated value chain stretching from producer to consumer. When accessing markets for solar dried products, information must be sought concerning the following:

- the markets available for the solar dried products
- compliance with existing and emerging technical, legislative and market requirements
- consumer acceptance of the product. This is of particular importance when solar dried product is not currently available or is unknown to the potential market
- proper innovation of new product ideas
- development of compliant plant and technology
- marketing mechanisms or organizations for bringing producer and buyer/consumer together
- the price currently obtained for the fresh (or unprocessed) commodity versus the price that can be obtained for the solar dried product
- training and human resource development in the areas of food science and technology, quality, food hygiene and the general logistics of modern food processors

Potential markets for solar dried fruits, vegetables, herbs and spices are in the industries related to production of breakfast cereals, confectionery, soups, bakery and food processors particularly for infants. The major distribution channel for solar dried products is supermarket. Many people associate marketing only with advertising, but there are other important elements in a marketing strategy besides promotion, including p icing, placement (distribution) and product. Collectively, these are called *'the four P's,'* and every new business should have a strategy for each 'P'. For solar drying of agricultural products to gain a secure footing in the developing countries, and integrated approach is needed with the technology considered an enabler only, in a larger marketing chain.

Quality considerations

Quality has become a major issue for all levels of market. Entry into these markets require close attention to methods of production, food handling and hygiene, the conditions of the plant and premises and the quality of the food production staff. There are several factors to consider, including purchase of fresh produce of good quality, careful transport and storage, proficient preparation of produce including pre-treatments, correct loading and operation of the dryer, drying to the correct moisture content, proper packaging and storage of the dried product, achieving good product quality and efficient management of all operations to assure quality, minimize losses and maximize business profitability. Most importantly, activities must always be carried out with due diligence at all times with regard to cleanliness, hygiene and food safety aspects.

Some knowledge of the importance of quality can be gauged from the following:

- the feature of the dried product that determines its selling price i.e. appearance, color, size, shape, moisture content, purity, extractable constituent, degree of contamination, microbiological quality
- the methods by which the quality factors are evaluated, i.e. qualitative or quantitative analysis
- the relationship between product quality and selling price

It is important to minimize contamination with unwanted micro-organisms at all stages including the handling, transport and storage of raw materials and of the product during processing, packaging and subsequent storage and delivery to the buyer. It is helpful to refer to the Codes of Practice produced by the FAO and the World Health Organization (WHO) under the Joint FAQ/WHO Food Standards Programme - Codex Alimentarius Commission. Such Codes of Practice provide useful checklists for food safety (refer to Codex Alimentarius web site at http://www.codexalimentarius.net/).

Conclusion

Several solar-energy drying systems have been designed and developed for various agricultural products as alternatives to the traditional open-sun drying. Such systems are economically viable in developing countries. For the small farmers of the Caribbean, simple solar cabinet or wire basket dryers may be used. For industrial applications or drying on large estates, mixed mode dryers, which utilize solar energy and conventional fuels as well as forced convection are recommended. Such dryers have capabilities of drying many Caribbean crops eg. sorrel, sweet potatoes, mangoes, pineapples, bananas, herbs, hot peppers, cassava, coconuts, nutmegs and fish. However, the quality of the dried product is dependent upon proper pre-treatments that are crop specific such as osmotic dehydration and blanching, followed by drying in dryers operated under suitable conditions of temperature and air movement.

Drying has previously been viewed as a stand-alone process for the production of storable, primary crops in the Caribbean – cocoa, coffee, paddy, etc. Drying must now be considered in integrated, food processing operation, with technology and entrepreneurship combined to create successful businesses that promote new products from the exotic crops of the Caribbean. These products must be of attractive, consistent quality - color, texture, taste, aroma, etc., and attractively packaged so as to gain and sustain the confidence of consumers. Solar drying is about creativity and innovation – in technology, processes, products and marketing, all integrated for success.

References

Amer, B.M.A., Hossain, M.A. and Gottschalk, K. 2010. Design and performance evaluation of a new hybrid solar dryer for banana. *Energy Conversion and Management* 51: 813-820.

Ayyappan, S. and Mayilsamy, K. 2010. Experimental investigation on a solar tunnel dryer for copra drying. *Journal of Scientific and Industrial Research* 69: 635-638.

Balladin, D.A. and Headley, O. 1999. Evaluation of solar dried thyme (*Thymus vulgaris Linné*) herbs. *Renewable Energy* 17: 523-531.

Cheapok, C. and Pornnareay, P. 2000. Introducing solar drying in a developing country: The case of Cambodia. *World Renewable Energy Congress VI (WREC 2000)* (Ed. A.A.M. Sayigh), pp. 2198-2201. Elsevier Science Limited,.

Chua, K.J. and Chou, S.K. 2003. Low-cost drying methods for developing countries. *Trends in Food Science & Technology* 14: 519-528.

Fagunwa, A.O, Koya, O.A. and Faborode, M.O. 2009. Development of an intermittent solar dryer for cocoa beans. *Agricultural Engineering International: The CIGR Ejournal*. Manuscript number 1292. Vol. XI. July, 2009.

FAO 1997. *Technical Manual on Small-scale Processing of Fruits and Vegetables*. FAO Regional Office for Latin America and the Caribbean, Santiago, Chile. http:www.fao.org/DOCREP/x0209e/x0209e00.htm, 17 Dec. 2003.

Ferriera, A.G., Maia, C.B., Cortez, M.F.B. and Valle, R.M. 2008. Technical feasibility of a solar chimney for food drying. *Solar Energy* 82: 198-205.

Grabowski, S. and Mujumdar, A.S. 2000. Solar-assisted osmotic dehydration. In *Developments in drying Vol. 1: Food Dehydration* (Eds. A.S. Mujumdar and S. Suvachittanont), pp. 142-178. Kasetsart University Press, Bangkok.

Headley, O. 1986. Drying tropical woods with plastic covered solar timber dryers. In *Solar Design and Energy in Buildings* (Ed. L.F. Jesch), pp. 69-73, UK ISES, London.

Henderson, S.M. and Perry, R.I. 1976. *Agricultural Process Engineering*. Connecticut: AVI Publishing Company.

Indian Council of Agricultural Research 2010. New Dehli. *All India Coordinated Research Project on Renewable Sources of Energy for Agriculture & Agro Based Industries.* http://www1.icar.org.in/aicrponres/Solar%20tunnel.asp. Date accessed: Dec 30, 2010

Janjai, S., Intawee, P., Chaichoet, C. and Sittiamnuay, P. 2006. Field Experiments of the Silpakorn Type Solar Tunnel Dryers in Northern Thailand. *Proceedings of the International Conference on Energy for Sustainable Development: Issues and Prospects for Asia*, March 1-3, 2006, Phuket, Thailand.

Janjai, S. and Tung, P. 2005. Performance of a solar dryer using hot air from roof-integrated solar collectors for drying herbs and spices. *Renewable Energy* 30(14): 2085-2095.

Kalra, S.K. and Bhardwaj, K.C. 1981. Use of simple solar dehydrator for drying fruit and vegetable products. *Journal of Food Science and Technology* 18: 23-26.

Koua, K.B., Fassinou, W.F., Gbaha, P. and Toure, S. 2009. Mathematical modelling of the thin layer solar drying of banana, mango and cassava. *Energy* 34: 1594-1602.

Krajayklang, M., Klieber, A. and Dry, P.R. 2001. Acceleration of the drying rates of paprika fruit with drying oil and cutting. *International Journal of Food Science and Technology* 36: 207-214.

McGaw, D.R. and Sankat, C.K. 1984. The effect of air flow rate on the drying of Nutmegs. *Tropical Agriculture* 61(3): 171-173.

McGaw, D.R., Headley, O., Sankat, C.K. and Fraser, I. 1987. Crop drying for the small island states of the Eastern Caribbean. *Ciencia Interamericana* 27(1-2): 20-29.

McGaw, D.R., Sankat, C.K. and Headley, O. 1988. Mixed mode solar crop dryers for the tropics. *6th International Drying Symposium IDS'88*, pp. 93-97. Versailles, Sept. 5-8, 1988.

Müller, J. and Heindl, A. 2006. Drying of medicinal plants. In *Medicinal and Aromatic Plants* (Eds. R.J. Rogers, L.E. Craker and D. Lange), pp. 237-252. Springer, Netherlands.

Mwithiga, G. and Kigo, S.N. 2006. Performance of a solar dryer with limited sun tracking capability. *Journal of Food Engineering* 74: 247-252.

Sankat, C.K. 1984. Technical and economic parameters for the adoption of solar drying systems on small farms. *Caribbean Food Crops Society, 20th Annual Meeting, St. Croix, USVI* 20: 264-266.

Sankat, C.K. 2004. Drying technologies for Caribbean agro-industry using solar energy. In *Solar Assisted Drying Systems: Innovative Technologies for Agricultural and Marine Products* (Eds. K. Sopian, A. Sayigh and M.Y. Othman), pp. 229-254. The Islamic Educational, Scientific and Cultural Organization (ISESCO), Rabat, Kingdom of Morocco.

Sankat, C.K., Castaigne, F. and Maharaj, R. 1996. The air drying behaviour of fresh and osmotically dehydrated banana slices. *International Journal of Food Science and Technology* 31: 123-135.

Sankat, C.K. and Maharaj, V. 1994. Drying the green herb Shado Beni (*Eryngium foetidum* L.) in a natural convection cabinet and solar dryers. *ASEAN Food Journal* 9(1): 17-23.

Sankat, C.K., McGaw, D.R. and Headley, O. 1987. Solar crop dryers for the Caribbean. *Caribbean Food Crops Society, 23rd Annual Meeting, Antigua* 23: 150-161.

Sankat, C.K. and Mujaffar, S. 2004. The sun and solar drying potential of salted shark fillets. *International Drying Symposium (IDS)*, 2004. Vol. 37, p 1584-1591 Sao Paulo City, Brazil.

Sankat, C.K. and Rolle, R.A. 1991. The performance of natural convection solar dryers for copra production. *Canadian Agricultural Engineering* 33(1): 85-91.

Shukla, A.K. and Vishwakarma, S.K. 2009. Design, construction and performance study of photovoltaic integrated forced flow solar dryer. In *EnviroEnergy 2009: Proceedings of the International Conference on Energy and Environment*, Chandigarh, India, March 19-21, 2009.

Smith, S. 1992. *Solar Crop Drying, Vols. 1&2.* B.Sc. Agricultural Engineering Special Project (Unpublished), Faculty of Engineering, The University of the West Indies, St. Augustine, Trinidad, W.I.

Sreekumar, A. 2010. Techno-economic analysis of a roof-integrated solar air heating system for drying fruit and vegetables. *Energy Conversion and Management* 51: 2230-2238

Tang Kai, A., McDoom, I.A. and Headley, O. 1993. A solar timber kiln for artisans. *Proceedings of the Solar World Congress of the International Solar Energy Society* 8: 43-47.

Yahya, M., Sopian, K., Daud, W.R.W., Othman, M.Y. and Yatim, B. 2008. Performance of a solar assisted dehumidification system for *Centella Asiatica* L. *8th WSEAS International. Conference on Power Systems*, Santander, Cantabria, Spain, Sept 23-25, 2008.

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