Solar Drying: Fundamentals, Applications and Innovations

Editors
C.L. Hii, S.V. Jangam, S.P. Ong and A.S. Mujumdar

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PREFACE

Drying using solar radiation, i.e. drying under direct sunlight, is one of the oldest techniques used by mankind to preserve agriculture based food and non-food products. This form of energy is free, renewable and abundant in any part of the world especially in tropical countries. However, in order to maximize its advantage and optimize the efficiency of drying using solar radiation, appropriate technology need to be applied in order to keep this technique a sustainable one. Such technology is known as solar drying and is becoming a popular option to replace mechanical thermal dryers owing to the high cost of fossil fuels which is growing in demand but dwindling in supply. For sustainability and climate change concerns it is important to use renewable sources of energy as much as possible.

Various topics in sun and solar drying are discussed in many scientific reports, research manuscripts and books. Readers are advised to refer to several published articles available in the Drying Technology – An international Journal and drying books as well as handbooks edited by Professor Arun S. Mujumdar. A series of e-books have been initiated by Professor Mujumdar, which is made available for free download at http://serve.me.nus.edu.sg/arun/. The main objective of these e-books is to make useful technical literature available for the public, especially for those that have limited access to expensive reading materials. Such books can also be used by students, academics, industrial experts and researchers for teaching, learning and research purposes. Free access to all parts of the globe is expected to enhance the use of renewable energy resources.

This e-book entitled “Solar drying: Fundamentals, Applications and Innovations”, is the latest addition to the current collection of this unique e-book series, is a joint effort initiated between the Centre of Food and Bio-product Processing, University of Nottingham, Malaysia Campus and the Transport Phenomena (TPR) Group, National University of Singapore. We would like to express our sincere appreciation to the contributing authors, which are listed following the preface, in their support and commitment in making this e-book successfully published and available freely on-line. The content of this e-book can be improved and added with new chapters from time to time. We welcome any feedback from readers and suggestion from potential authors to include new chapters in this e-book.

We invite readers to inform their contacts about this free professional service.

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Chapter 1
Principles, Classification and Selection of Solar Dryers

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Contents

1.1. INTRODUCTION

Preservation of fruits, vegetables, and food are essential for keeping them for a long time without further deterioration in the quality of the product. Several process technologies have been employed on an industrial scale to preserve food products; the major ones are canning, freezing, and dehydration. Among these, drying is especially suited for developing countries with poorly established low-temperature and thermal processing facilities. It offers a highly effective and practical means of preservation to reduce post-harvest losses and offset the shortages in supply. Drying is a simple process of moisture removal from a product in order to reach the desired moisture content and is an energy intensive operation. The prime objective of drying apart from extended storage life can also be quality enhancement, ease of handling, further processing and sanitation and is probably the oldest method of food preservation practiced by humankind (Mujumdar, 2007). Drying involves the application of heat to vaporize moisture and some means of removing water vapor after its separation from the food products. It is thus a combined and simultaneous heat and mass transfer operation for which energy must be supplied. The removal of moisture prevents the growth and reproduction of microorganisms like bacteria, yeasts and molds causing decay and minimizes many of the moisture-mediated deteriorative reactions. It brings about substantial reduction in weight and volume, minimizing packing, storage, and transportation costs and enables storability of the product under ambient temperatures. These features are especially important for developing countries, in military feeding and space food formulations (vanArsdel, 1965).

Drying in earlier times was done primarily in the sun, now many types of sophisticated equipments and methods are used to dehydrate foods. During the past few decades, considerable efforts have been made to understand some of the chemical and biochemical changes that occur during dehydration and to develop methods for preventing undesirable quality losses. The widest among drying methods is convective drying, i.e. drying by blowing heated air circulating either over the upper side, bottom side or both, or across the products. Hot air heats up the product and conveys released moisture to atmosphere. In direct solar drying called ``sun drying'' the product is heated directly by the sun's rays and moisture is removed by natural circulation of air due to density differences.

Solar radiation in the form of solar thermal energy, is an alternative source of energy for drying especially to dry fruits, vegetables, agricultural grains and other kinds of material, such as wood. This procedure is especially applicable in the so-called “sunny belt” world-wide, i.e. in the regions where the intensity of solar radiation is high and sunshine duration is long. It is estimated that in developing countries there exist significant post-harvest losses of agricultural products, due to lack of other preservation means. Drying by solar energy is a rather economical procedure for agricultural products, especially for medium to small amounts of products. It is still used from domestic upto small commercial size drying of crops, agricultural products and foodstuff, such as fruits, vegetables, aromatic herbs, wood, etc. contributing thus significantly to the economy of small agricultural communities and farms.

1.2. DRYING PRINCIPLES

Drying is basically a phenomena of removal of liquid by evaporation from a solid. Mechanical methods for separating a liquid from a solid are not generally considered drying. In the following section an attempt is made to provide a concise overview of the fundamental principles of drying process for agricultural products. These principles are applied, in general, to mechanical conventional drying and here concerned mainly with solar drying. However in general, must be noted that conventional drying principles and phenomena are independent of the type of energy used. Ekechukwu and Norton (1999) and Mujumdar, 2007 gives a comprehensive review of fundamental principles and theories governing the drying process. A major part of energy consumption during drying is for the evaporation of liquid water in to its vapour (2258 kJ/kg at 101.3 kPa). The water may be contained in the solid in various forms like free moisture or bound form which directly affects the drying rate. The commonly encountered terminologies in psychrometry and drying are briefly tabulated in **Table 1.1**. Moisture content is expressed either on dry or wet basis, e.g. moisture content in wet (X_w) basis is the weight of moisture per unit of wet material.

$$\boldsymbol{X_w} = \frac{\boldsymbol{m_w}}{\boldsymbol{m_w + m_d}}, \text{ kg per kg of mixture} \qquad (1.1)$$

and on dry basis (X_d), is expressed as the ratio of water content to the weight of dry material:

$$X_d = \frac{m_w}{m_d} \qquad (1.2)$$

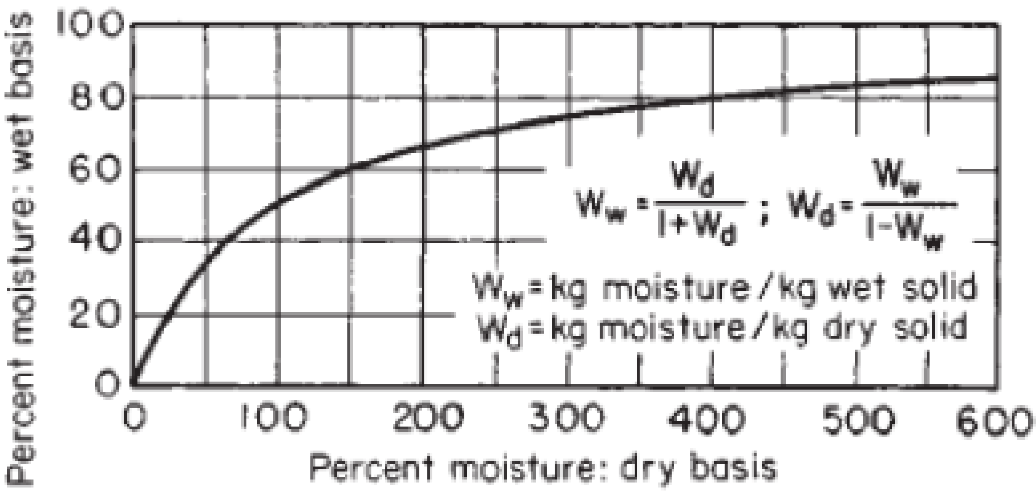

Figure 1.1. Relationship between wet-weight and dry-weight basis (Perry 2007)

Although the most convenient way to express moisture for mathematical calculations is on dry basis but for agricultural products moisture content normally is expressed in wet basis. Figure 1.1 shows the plot of relationship between the dry and wet-weight basis.

Table 1.1. Commonly encountered terms in psychrometry and drying (Perry 2007)

Sr no.	Term	Meaning/ Definition
1.	*Bound moisture*	is that in a solid liquid, which exerts a vapor pressure less than that of the pure liquid at the given temperature.
2.	*Capillary flow*	is the flow of liquid through the interstices and over the surface of a solid, caused by liquid-solid molecular attraction.
3.	*Constant-rate period*	is that drying period during which the rate of water removal per unit of drying surface is constant.
4.	*Critical moisture content*	is the average moisture content when the constant-rate period ends.
5.	*Dry-weight basis*	expresses the moisture content of wet solid as kilograms of water per kilogram of bone-dry solid.
6.	*Equilibrium moisture content*	is the limiting moisture to which a given material can be dried under specific conditions of air temperature and humidity.
7.	*Falling-rate period*	is a drying period during which the instantaneous drying rate continually decreases.
8.	*Free-moisture content*	is that liquid which is removable at a given temperature and humidity, may include bound/unbound moisture.
9.	*Funicular state*	is that condition in drying a porous body when capillary suction results in air being sucked into the pores.
10.	*Hygroscopic material*	is material that may contain bound moisture.
11.	*Initial moisture distribution*	refers to the moisture distribution throughout a solid at the start of drying.
12.	*Internal diffusion*	may be defined as the movement of liquid or vapor through a solid as the result of a concentration difference.
13.	*Moisture content*	of a solid is usually expressed as moisture quantity per unit weight of the dry or wet solid.
14.	*Moisture gradient*	refers to the distribution of water in a solid at a given moment in the drying process.
15.	*Non-hygroscopic material*	is material that can contain no bound moisture.
16.	*Pendular state*	is that state of a liquid in a porous solid when a continuous film of liquid no longer exists around and between discrete particles so that flow by capillary cannot occur.
17.	*Unaccomplished moisture change*	is the ratio of the free moisture present at any time to that initially present.
18.	*Unbound moisture*	in a hygroscopic material, is that moisture in excess of the equilibrium moisture content corresponding to saturation humidity.
19.	*Wet-weight basis*	expresses the moisture in a material as a percentage of the weight of the wet solid.

1.2.1. Psychrometry in Drying

In drying phenomena the psychrometry is of importance as it refers to the properties of air-vapor mixture that controls the rate of drying. When an adequate supply of heat is provided for drying, the temperature and rate at which the liquid vaporization occurs will depend on the vapour concentration in the surrounding atmosphere. When a free liquid or wetted surface is present, drying will occur at the saturation temperature, just as free water at 101.325 kPa vaporizes in a 100 percent steam atmosphere at 100 °C. On the other hand, when evolved vapor is purged from the dryer environment by using a second (inert) gas, the temperature at which vaporization occurs will depend on the concentration of vapor in the surrounding gas.

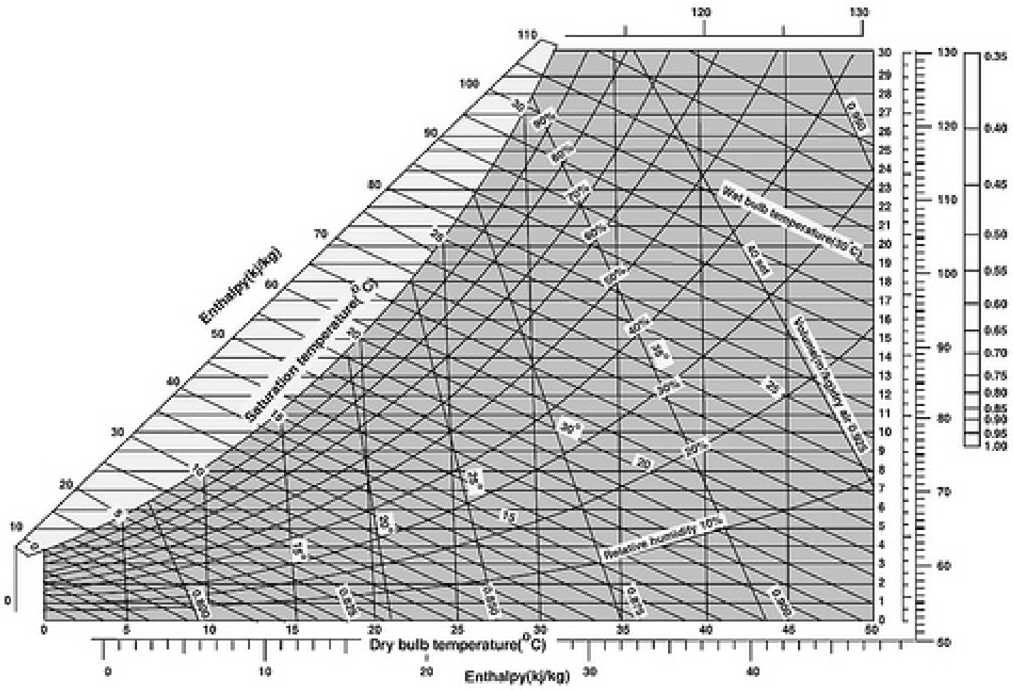

Figure 1.2. Psychrometric chart: properties of air and water-vapor mixtures

In effect, the liquid must be heated to a temperature at which its vapor pressure equals or exceeds the partial pressure of vapor in the purge gas, while in the reverse situation condensation occurs. In most drying operations, water is the liquid evaporated and air is the normally employed purge gas. For drying purposes, a psychrometric chart found very useful is that reproduced in Figure 1.2 and can be explained as follows (Perry 2007 and Treybal 1980):

a. In the psychrometric chart the wet-bulb or saturation temperature line gives the maximum weight of water vapor that 1 kg of dry air can carry at the intersecting dry-bulb temperature shown on the abscissa at saturation humidity. The partial pressure of water in air equals the water vapor pressure at that temperature and the saturation humidity is defined by

$$H_s = \frac{18}{28.9} \cdot \frac{p_s}{(P-p_s)} \tag{1.3}$$

b. The percent relative humidity is defined by

$$H_R = 100 \cdot \left(\frac{p}{p_s}\right) \tag{1.4}$$

c. Humid volumes are given by the curves entitled "volume m³/kg dry air." The difference between dry-air specific volume and humid-air volume at a given temperature is the volume of water vapor.

d. Enthalpy data are given on the basis of kilojoules per kilogram of dry air. Enthalpy-at-saturation data are accurate only at the saturation temperature and humidity.

e. There are no lines for humid heats on Figure 1.2. and can be calculated by

$$C_s = 1.0 + 1.87H \quad (1.5)$$

The wet-bulb-temperature lines also represent the adiabatic saturation lines for air and water vapor only, and are based on the relationship

$$H_s - H = \left(\frac{C_s}{\lambda}\right)(T - T_s) \quad (1.6)$$

The slope of the adiabatic saturation curve is (C_s/λ). These lines show the relationship between the temperature and humidity of air passing through a continuous dryer operating adiabatically. The wet-bulb temperature is established by a dynamic equilibrium between heat and mass transfer when liquid evaporates from a small mass, such as the wet bulb of a thermometer, into a very large mass of gas such that the latter undergoes no temperature or humidity change, and is expressed by the relationship

$$h_c(T - T_w) = k_g'\lambda(H_w - H_a) \quad (1.7)$$

A given humidity chart is precise only at the pressure for which it is evaluated and most air–water-vapor charts are based on a pressure of 1 atm. Humidities read from these charts for given values of wet-bulb and dry-bulb temperature apply only at an atmospheric pressure of 760 mmHg. If the total pressure is different, the humidity at a given wet-bulb and dry-bulb temperature must be corrected according to the following relationship.

$$H_a = H_o + 0.622p_w\left(\frac{1}{P - p_w} - \frac{1}{760 - p_w}\right) \quad (1.8)$$

1.3. MECHANISM OF DRYING

Drying basically comprises of two fundamental and simultaneous processes: (i) heat is transferred to evaporate liquid, and (ii) mass is transferred as a liquid or vapor within the solid and as a vapor from the surface. The factors governing the rates of these processes determine the drying rate. The different dryers may utilize heat transfer by convection, conduction, radiation, or a combination of these. However in almost all solar dryers and other conventional dryers heat must flow to the outer surface first and then into the interior of the solid, with exception for dielectric and microwave drying.

1.3.1. Internal Mechanism of Liquid Flow

The movement of moisture within the solid result from a concentration gradient which is dependent on the characteristics of the solid, that may be porous or nonporous. Thus the structure of the solid determines the mechanism for which internal liquid flow may occur and these mechanisms can include

(a) *diffusion* in continuous, homogeneous solids,
(b) *capillary flow* in granular and porous solids,
(c) flow caused by *shrinkage* and *pressure* gradients,
(d) flow caused by *gravity*, and
(e) flow caused by a *vaporization-condensation* sequence.

In general, one mechanism predominates at any given time in a solid during drying, but it is not uncommon to find different mechanisms predominating at different times during the drying cycle. In the plots shown in Figure 1.3, the curves indicate that capillary flow is typified by a moisture gradient involving a double curvature and point of inflection (Figure 1.3a) while diffusional flow is a smooth curve, concave downwards (Figure 1.3b). They also showed that the liquid-diffusion coefficient is usually a function of moisture content which decreases with decreasing moisture (Keey, 1978 and Treybal 1980).

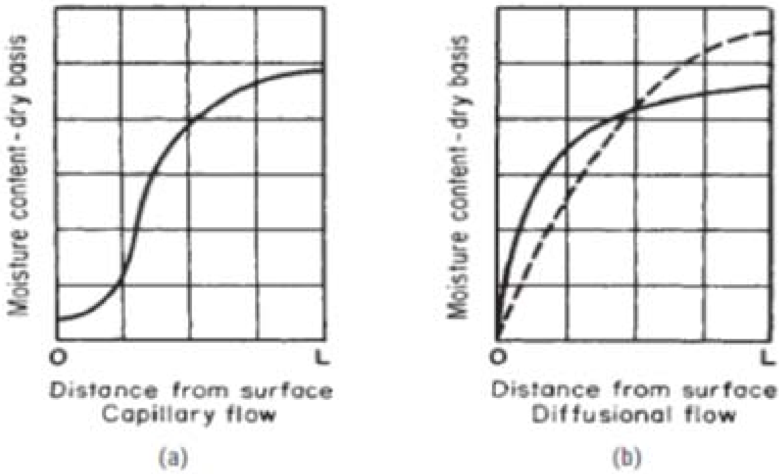

Figure 1.3. Two types of internal moisture gradients in solid drying (Perry 2007)

1.3.2. Periods of Drying

Figure 1.4 shows a plot of moisture content (X) versus time (θ) generally obtained by experimentally drying a solid. This curve represents a typical case when a wet solid loses moisture initially by evaporation from a saturated surface on a solid, followed by a period of evaporation from a saturated surface on a solid, followed by a period of evaporation from a saturated surface of gradually decreasing area and finally when the latter evaporated in the interior of the solid. Figure 1.4a indicates that the drying rate is subject to variation with time or moisture content, further better illustrated by graphically or numerically differentiating the curve and plotting $dX/d\theta$ versus W, as shown in Figure 1.4b, or as $dX/d\theta$ versus θ, as shown in Figure 1.4c. These rate curves illustrate that the drying process is not a smooth, continuous one in which a single mechanism controls throughout. Figure 1.4*c* has the advantage of showing how long each drying period lasts.

The section *AB* on each curve represents a warming-up period of the solids. Section *BC* on each curve represents the constant-rate period. Point *C*, where the constant rate ends and the drying rate begins falling, is termed the critical-moisture content. The curved portion *CD* on Figure 1.4a is termed the falling-rate period and, as shown in Figure 1.4*b* and *c*, is typified by a continuously changing rate throughout the remainder of the drying cycle. Point *E* (Figure 1.4b) represents the point at which all the exposed surface becomes completely unsaturated and marks the start of that portion of the drying cycle during which the rate of internal moisture movement controls the drying rate. Portion *CE* in Figure 1.4b is usually defined as the first falling-rate drying period; and portion *DE*, as the second falling-rate period (Perry 2007).

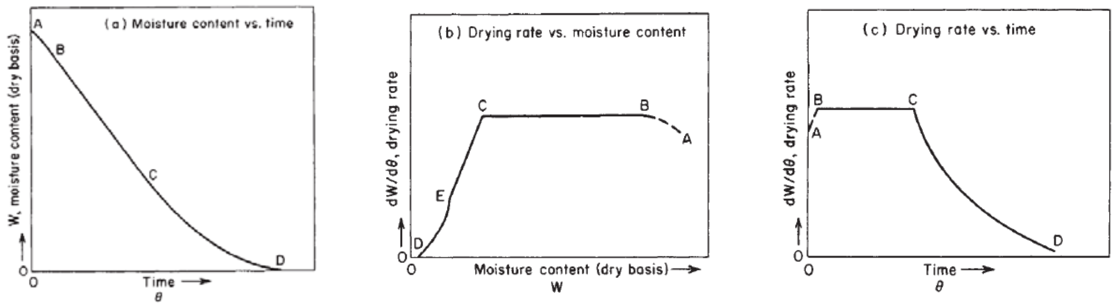

Figure 1.4. Drying period curves (Perry 2007)

1.3.2.1. Constant-Rate Period

In the constant-rate period moisture movement within the solid is rapid enough to maintain a saturated condition at the surface, and the rate of drying is controlled by the rate of heat transferred to the evaporating surface. Drying proceeds by diffusion of vapor from the saturated surface of the material across a stagnant air film into the environment and as the rate of mass transfer balances heat transfer, the temperature of saturated surface remains constant. If the heat supplied for drying is solely by convection, the surface temperature approaches the boiling point temperature rather than the wet bulb temperature. This mode of heat transfer is typically seen in indirect dryers. Radiation is an effective mode of heat transfer as it increases the constant rate by augmenting the convection heat transfer and raising the surface temperature above the wet bulb temperature.

The magnitude of the constant rate depends upon three factors:

- The heat or mass transfer coefficient
- The area exposed to the drying medium
- The difference in temperature or humidity between the gas stream and the wet surface of the solid.

All these factors are the external variables. The internal mechanism of liquid flow does not affect the constant rate (Keey, 1980).

1.3.2.2. Falling-Rate Period

The falling-rate period begins at the critical moisture content when the constant-rate period ends. This is generally divided into two zones viz., (i) the zone of unsaturated surface drying and (ii) the zone where internal moisture movement controls. In the first zone, the entire evaporating surface can no longer be maintained and saturated by moisture movement within the solid. The drying rate decreases from the unsaturated portion, and hence the rate for the total surface decreases. Generally, the drying rate depends on factors affecting the diffusion of moisture away from the evaporating surface and those affecting the rate of internal moisture movement. As drying proceeds, the point is reached where the evaporating surface is unsaturated. The point of evaporation moves into the solid, and the dry process enters the second falling-rate period. The drying rate is now governed by the rate of internal moisture movement; the influence of external variables diminishes. This period usually predominates in determining the overall drying time to lower moisture content (Treybal 1980).

1.3.2.3. Estimations for Total Drying Time

Estimates of both the constant-rate (θ_c) and the falling-rate periods (θ_f) are needed to estimate the total drying time (θ_t) for a given drying operation as

$$\theta_t = \theta_c + \theta_f \tag{1.9}$$

1.4. WATER ACTIVITY, {αw}

The ratio of the equilibrium vapor pressure to the saturation vapor pressure is known as the equilibrium relative humidity (ERH), or water activity. Water activity α_w, is of great importance for food preservation as it is a measure and a criterion of microorganism growth and probably toxin release, of enzymatic and non-enzymatic browning development.

$$\alpha_w = \left(\frac{p_w}{p_w^*}\right)_T \approx \varphi \tag{1.10}$$

For every food or agricultural product there exists an activity limit below which microorganisms stop growing. Beuchat (1981) refers that the vast majority of bacteria will grow at about $\alpha_w = 0.85$, mold and yeast about $\alpha_w = 0.61$, fungi at $\alpha_w < 0.70$, etc. In these cases water activity is regulated in detail, after drying by the addition of some solutions of sugars, starch, etc. Water in food and agricultural crops, is in the form of a solution which contains salts, sugars, carbohydrates, proteins, etc., which at constant temperature are in thermodynamic equilibrium. The water activity is then given by the following equation:

1.5. EQUILIBRIUM MOISTURE CONTENT

A wet solid exposed to a continuous supply of fresh gas continues to lose moisture until the vapor pressure of the moisture in the solid is equal to the partial pressure of the vapor in the gas. The solid and gas are then said to be in equilibrium, and the moisture content of the solid is called the equilibrium moisture content under the prevailing conditions. Further exposure to this air for indefinitely long periods will not bring about any additional loss of moisture. The moisture content in the solid could be reduced further by exposing it to air of lower relative humidity. This means that moisture desorption from the product is in dynamic equilibrium with the absorption of the environmental air moisture contain. Relative humidity at this point is known as the “equilibrium relative humidity”, and is characterized by the curves of moisture content plots against equilibrium humidity known as moisture equilibrium isotherms.

1.6. SORPTION ISOTHERMS

Various changes in physical, chemical and biological characteristics of foodstuffs occur during processing, storage and distribution therefore the knowledge of water sorption isotherm is necessary to evaluate their stability (Roca et al., 2006). Moisture sorption isotherms, an important tool for predicting the interactions of water and food components, describes the relationship between water activity and the equilibrium moisture content of a foodstuff. These are graphical representations of the relationship between moisture content at the corresponding water activity α_w, over a range of values at constant temperature. Figure 1.5 presents the absorption and desorption isotherms. It is obvious that it has a slight hysteresis in re-absorbing water when the product has been dried. There exist numerous mathematical models, theoretical, empirical and semi-empirical relationships, developed for various agricultural products, crops, grains, etc. The three models most widely used in food drying are described here.

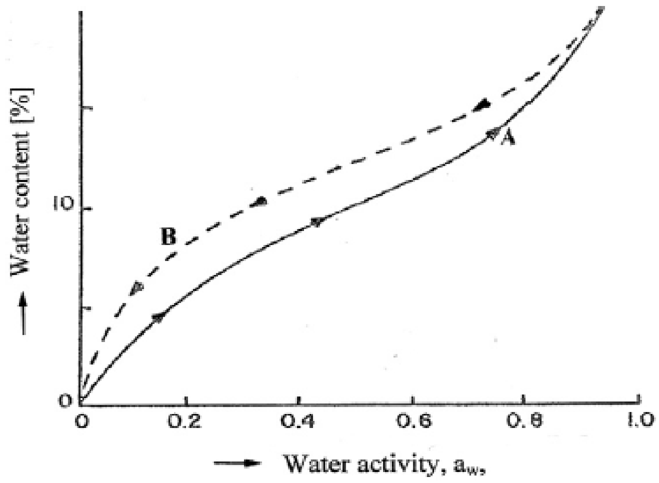

Figure 1.5. Sorption Isotherm (A) Absorption curve (B) Desorption curve (Belessiotis and Delyannis, 2011)

1.6.1. Sorption Equations

A number of mathematical equations have been proposed to describe the sorption phenomena but only the BET and GAB equations are widely accepted especially for crops. These are based on the theory of water molecular layers absorbed onto the materials surface, a modification for multi-layer absorption, of the Langmuir's (1918) water molecular mono-layer equation:

$$\alpha_w \left(\frac{1}{X} - \frac{1}{X_{mon}}\right) = \frac{1}{C \cdot X} \tag{1.11}$$

where are: X, the moisture content at the observation time period, X_{mon}, the mono-layer moisture content and is the Langmuir's constant. As shown in the schematic model of Kei on Figure 1.6 (Toei, 1996), it is assumed that, with respect to the externally exposed molecules on each layer within the multi-layer, dynamic equilibrium between Langmuir's adsorption– desorption rates still holds for the exposed molecules on each layer.

The isotherm models used to fit the data were BET (Brunauer et al., 1938) (Eq. 1) and GAB models (Van den Berg, 1984) (Eq. 1.12):

$$X_e = \frac{X_m C_{GAB} K_{GAB} a_w}{[(1 - K_{GAB} a_w)(1 - K_{GAB} a_w + C_{GAB} K_{GAB} a_w)]} \tag{1.12}$$

where X_e is the equilibrium moisture content (g water/g solids); X_m is the monolayer moisture content (g water/g solids); n is the number of layers; C_{BET}, C_{GAB} and K_{GAB} are the constants.

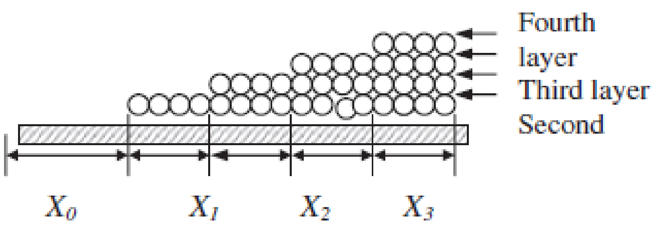

Figure 1.6. Schematic model of BET theory (Belessiotis and Delyannis, 2011)

1.6.2. The Bet Equation

The BET (Brunauer et al., 1938), equation is a modification of the previous Lagmuir equation, widely accepted for foods. The BET equation is:

$$M_w = \frac{M_b B a_w}{(1-a_w)[1+(B-1)a_w]} \tag{1.13}$$

where *Mw* is the water content (kg water/kg dry solids), *Mb* is the BET monolayer water content (kg water/kg dry solids) and *B* is a constant related to the net heat of sorption. The BET isotherm holds well between water activities of 0.05 and 0.45, an adequate range for the calculation of parameters *Mb* and *B* (Rahman, 1995).

1.6.3. GAB Equation

The GAB (Guggenheim, 1966; Anderson, 1946; de Boer, 1953) equation is the most widely accepted isotherm model as it fits isotherms of products in a range of water activities from aw = 0 up to aw = 0.99 (Van der Berg, 1981).
The GAB equation is:

$$M_w = \frac{M_g C K a_w}{[(1-Ka_w)(1-Ka_w+CKa_w)]} \tag{1.14}$$

where M_g is the GAB monolayer water content (dry basis). C is a constant related to the monolayer heat of sorption and K is a factor related to the heat of sorption of the multilayer. BET and GAB models are the most commonly used models to fit sorption data of food materials. The GAB isotherm equation is an extension of the BET model taking into account the modified properties of the sorbate in the multilayer region and the bulk liquid water properties through the introduction of a third constant K. Estimation of three parameters in GAB using two variables (i.e. water content and water activity) leads to a non-linear optimization. The BET monolayer value is more acceptable than that of GAB monolayer value, although the GAB model provides accurate prediction over the water activity range up to 0.90 (Rahman, 1995).

1.7. THIN LAYER DRYING AND DEEP BED DRYING

Drying rate is controlled by the external process factors of the process and the internal diffusion mechanisms. Apart from the external factors, the type and size of the product also affect the drying rate. Thus many products, i.e. fruits, vegetables, sliced fruits, are better to be dried in thin layers, but grains, i.e. corn, beans, etc., can be dried in deep beds, in dryers, or into bins.

1.7.1. Thin Layer Solar Drying

Thin layer drying models fall into the three categories, namely theoretical, semi-theoretical and empirical, contributing to the understanding of the drying characteristics of agricultural materials. The theoretical approach concerns either the diffusion equation or simultaneous heat and mass transfer equation, the semi-theoretical approach concerns approximated theoretical equations and the empirical equations are easily applied to drying simulation as they depend on experimental data. Among these models, the theoretical approaches account for only the internal resistance to moisture transfer, while the semi-theoretical and empirical approaches consider only the external resistance to moisture transfer between the product and air (Usub et al., 2010). In general they are based on the assumption that the ratio of air volume to the crop volume is infinitely large. Considering this assumption drying rate depends only on the properties of the material to be dried, its size, the drying air temperature and the moisture content. Recently, there have been many researches on the mathematical modeling and experimental studies of the thin layer solar drying process of various vegetables and fruits, such as grapes (Bala and Mondol, 2001), apricots (Banout et al., 2011; Belessiotis and Delyannis, 2011), green pepper, green bean and squash (Bena and Fuller, 2002), Eucalyptus globulus (Bennamoun and Belhamri, 2003; Beuchat, 1981), mint, verbena, and sage (Beuchat, 1981), pistachio (Ayensu and Asiedu-Bondzie1986; Baird et al., 1981), and prickly pear fruit (Boer, 1978). As an example, an empirical equation predicting drying time is given which is valid for temperatures from 60 to 80°C for solar drying, up to 140°C for conventional and hybrid solar drying (Eissen, 1985):

$$\theta = a \cdot \ln\left[\frac{X_t - X_{eq}}{X_{in} - X_{eq}}\right] + b \cdot \left(ln\left[\frac{X_t - X_{eq}}{X_{in} - X_{eq}}\right]\right)^2 \quad (1.15)$$

The parameters a and b are given by the following numerical equations:

$a = 1.86178 + 0.00488T$, $b = 427.2640e^{-0.0301T}$, where T is in degrees Celsius (°C).

1.7.2. Deep Bed Solar Drying

In deep bed drying solid phase is stationary and remains in the dryer for a certain time while gas flows through it continuously. Drying begins at the inlet end of gas and progresses through the entire bed (Ekechukwu, 1999). It is obvious that the lower zone dries rapidly. Air moves from the lower to thr upper zone and increases its moisture content and cools due to evaporation. Thus a gradient of temperature and relative humidity is formed between the lower and the upper zone, which is a measure of the drying rate. Final moisture content is the mean moisture of these zones. The critical drying factors are: air flow rate, drying air temperature and the bed's depth. By adjusting these parameters, a moderate drying operation can be achieved without over-drying in the lower material zone.

1.8. SOLAR DRYING TECHNOLOGY

Solar drying has been used since time immemorial to dry plants, seeds, fruits, meat, fish, wood, and other agricultural, forest products. In order to benefit from the free and renewable energy source provided by the sun several attempts have been made in recent years to develop solar drying mainly for preserving agricultural and forest products. However, for large-scale production the limitations of open-air drying are well known. Among these are high labour costs, large area requirement, lack of ability to control the drying process, possible degradation due to biochemical or microbiological reactions, insect infestation, and so on. The drying time required for a given commodity can be quite long and result in post-harvest losses(more than 30%) . Solar drying of agricultural products in enclosed structures by forced convection is an attractive way of reducing post-harvest losses and low quality of dried products associated with traditional open sun-drying methods (Jain and Tiwari, 2003). In many rural locations in most developing countries, grid-connected electricity and supplies of other non-renewable sources of energy are either unavailable, unreliable or, too expensive. In such conditions, solar dryers appear increasingly to be attractive as commercial propositions (Mekhilefa et al., 2011; Xingxing et al., 2012).

During the last decades, several developing countries have started to change their energy policies toward further reduction of petroleum import and to alter their energy use toward the utilization of renewable energies. With very few exceptions, the developing countries are situated in climatic zones of the world where the insolation is considerably higher than the world average of 3.82 kWh/m^2 day. In Figure 1.7 daily average horizontal insolation data and sunshine hours of some developing countries are given. An alternative to traditional drying techniques and a contribution toward the solution of the open air drying problems is the use of solar dryers. Accordingly, the availability of solar energy and the operational marketing and economy reasons offer a good opportunity for using solar drying all over the world.

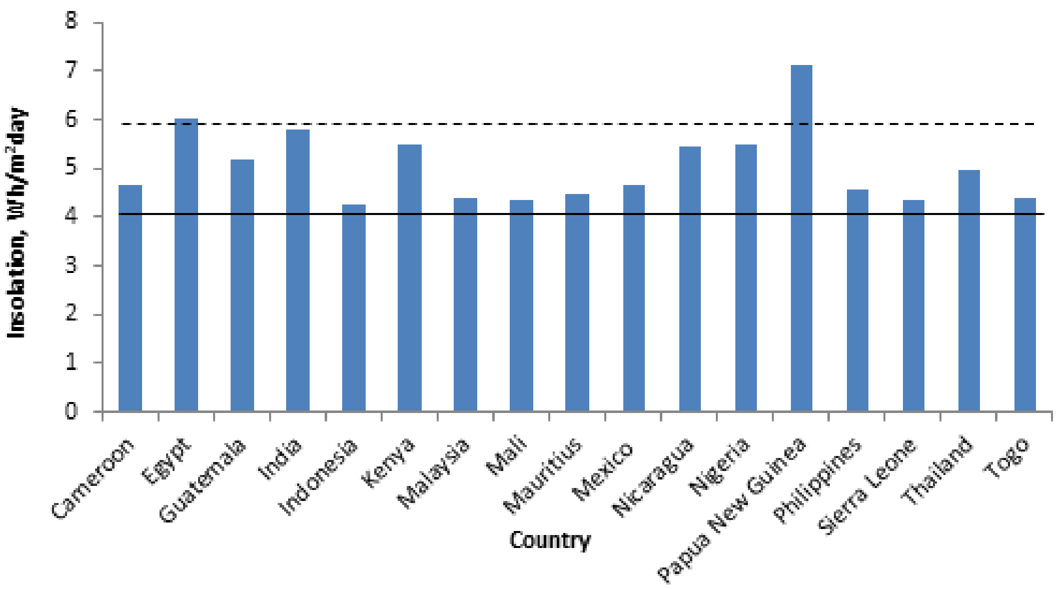

Figure 1.7. Total horizontal solar insolation for some developing countries (Visavale, 2009)

1.8.1. Classification of Solar Dryers

Drying equipment may be classified in several ways. The two most useful classifications are based on (1) the method of transferring heat to the wet solids or (2) the handling characteristics and physical properties of the wet material. The first method of classification reveals differences in dryer design and operation, while the second method is most useful in the selection of a group of dryers for preliminary consideration in a given drying problem. A classification chart of drying equipment on the basis of heat transfer is shown in Figure 1.8 (Ekechukwu,1999; Sharma et al., 2009). This chart classifies dryers as direct or indirect, with subclasses of continuous or batchwise operation. Solar-energy drying systems are classified primarily according to their heating modes and the manner in which the solar heat is utilized (Belessiotis et al., 2011). In broad terms, they can be classified into two major groups, namely:

- passive solar-energy drying systems (conventionally termed natural-circulation solar drying systems) and,

active solar-energy drying systems (most types of which are often termed hybrid solar dryers).

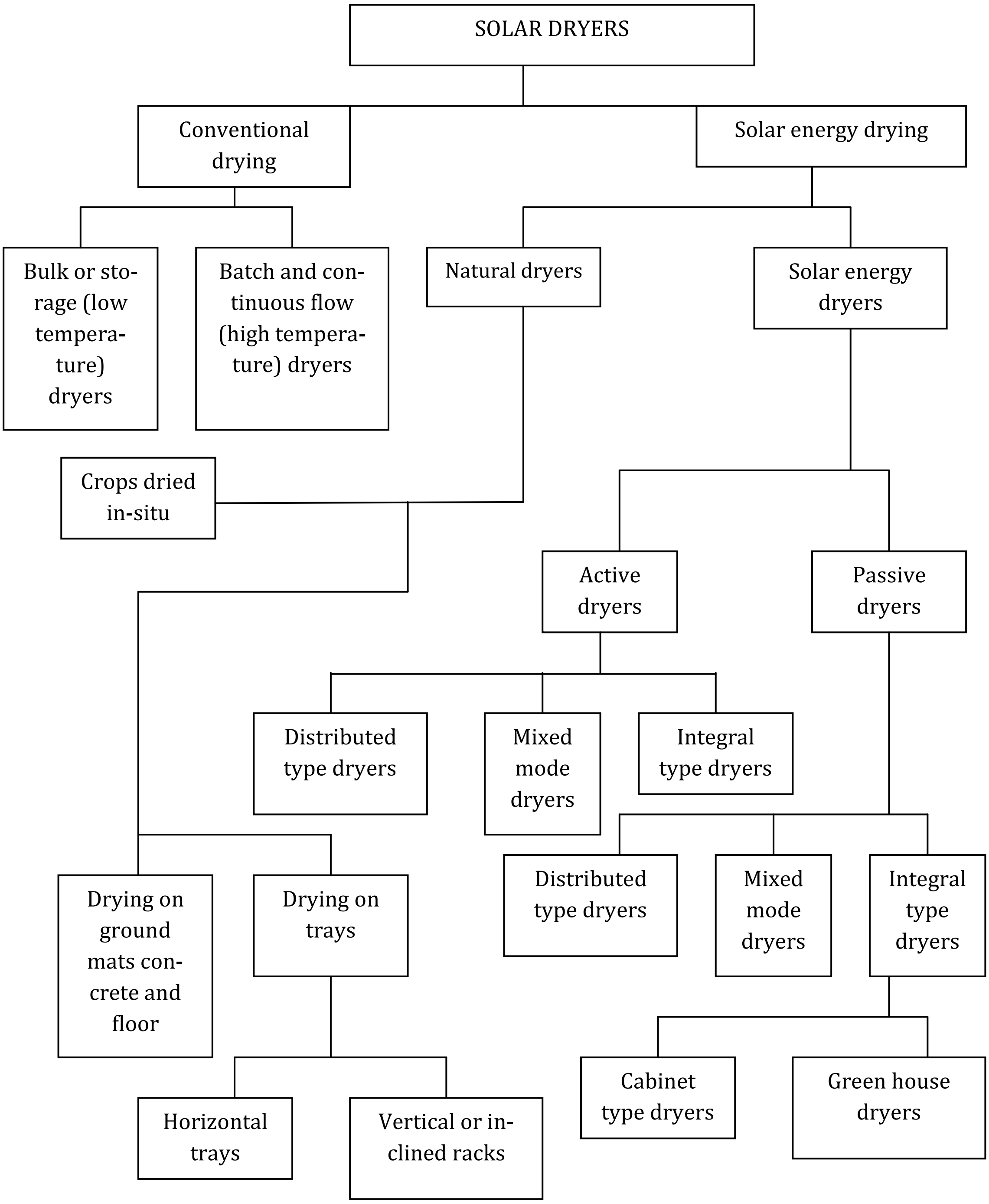

Figure 1.8. Classifications of dryers and drying modes (Ekechukwu,1999)

Three distinct sub-classes of either the active or passive solar drying systems can be identified namely:

- direct-type solar dryers;
- indirect-type solar dryers; and
- hybrid solar dryers.

The main features of typical designs of the various classes of solar-energy dryers are illustrated in Figure 1.9, showing three main groups for solar dryers on the basis of the energy sources used (Leon et al., 2002). The design of solar dryers is adjusted to the quantity, character, and designation of the material to be dried as well as to the energy sources used and accordingly, various types of solar dryers have been developed and are in use to date.

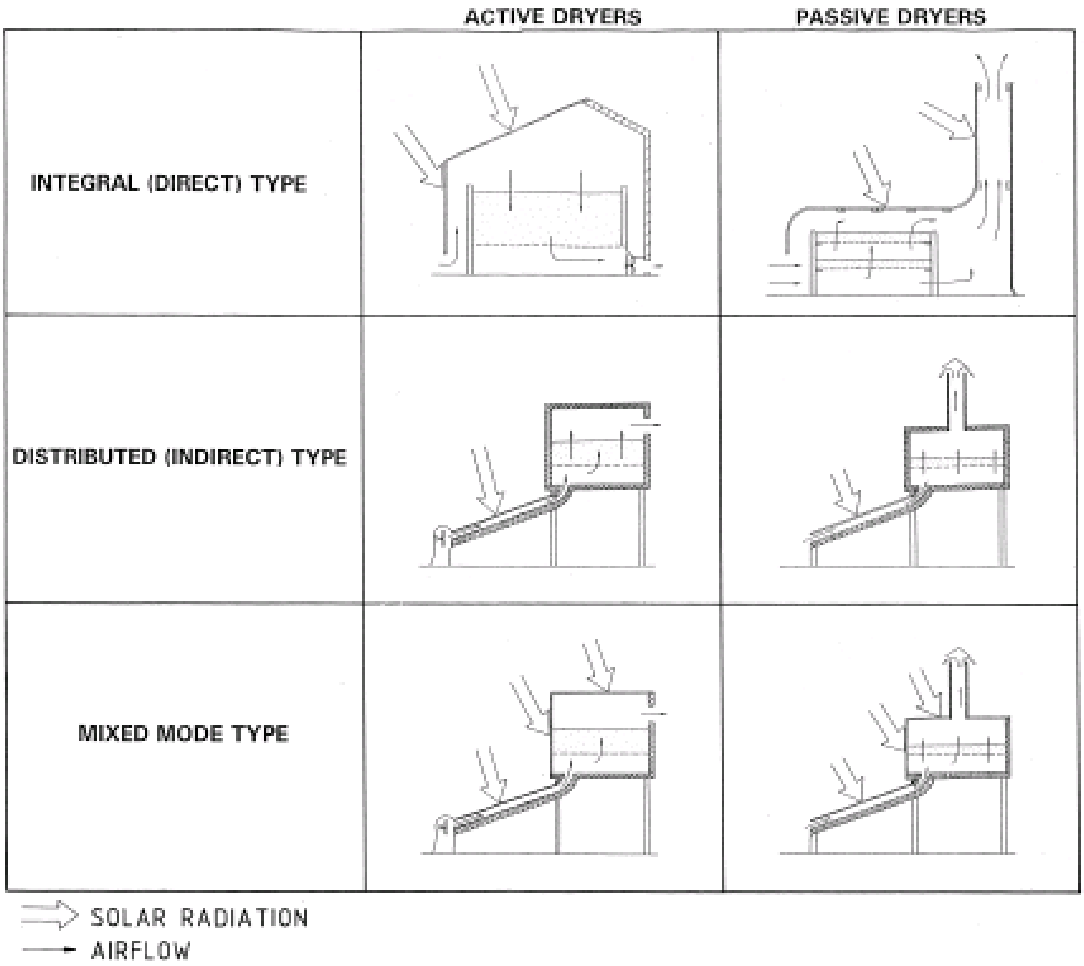

Figure 1.9. Typical solar energy dryer designs(Ekechukwu and Norton, 1999)

1.8.2. Applications of Solar Dryers

1.8.2.1. Solar Drying of Agricultural Products

Solar drying methods as applied to foods have earlier been reviewed by Bolin and Salunkhe (1980, 1982). The former surveyed methods of solar drying having varying levels of technological sophistication and compared the thermodynamics of conventional dehydration with those of solar drying. It has been exhaustively reviewed the drying methods using only solar energy, as well as those using solar plus and auxiliary energy source, besides discussing the quality and economic aspects, suggesting that to produce a high quality product economically it must be dried fast without excessive heat (Singh et al., 2011; Jangam et al., 2011).

Imre (2004) described in detail the construction principles of solar dryers and flat plate collectors along with their economics and performance evaluation. Several authors have studied the usability and performance of various types of solar dryers, energy storage systems (Kalra et al., 1981; Miller, 1985) and pretreatment techniques (Islam et al., 1982; Moyls, 1986; Vaghani, 1986). Cheema and Ribero (1978) studied the comparative performance of three dryers for the drying of cashew, banana and pineapple and found that optimum combination of solar and conventional drying is more suitable. To shorten the drying time Wagner et al. (1979) utilized the principles of parabolic reflector to increase the radiation on the product.

Bolin et al. (1980) discussed the relative merits of five experimental methods for the solar dehydration of fruits, namely: black wooden tray, solar troughs of various materials designed to reflect radiant energy onto bottom of black metal drying trays, cabinet dryers with slanted plate heat collectors with natural convection, utilizing inflated polyethylene (PE) tubes as solar collectors with and without partial air recirculation; and PE semicylinder with a fan blower to be used in inflated hemispheres or as a solar collector, to blow air over the fruit in a cabinet dryer. They reported that utilizing inflated PE tubes method was cheap, 38% faster than sun drying for apricots and could be used as supplementary heat source for conventional dryer.

Kalra and Bhardwaj (1981) described two simple models of solar dehydrator with the functions of direct and indirect dryers for mango products and vegetables which are well suited to rural conditions and small scale industries. Sun drying of grapes requires longer time to dry and also there is a browning, contamination and spoilage of the product when exposed to the open atmosphere (Pangavhane et al.,1999, 2002; El-Sebaii et al., 2002).

A number of investigations are reported (Bolin et al., 1980; Eisen et al., 1985; Lutz et al., 1986; Raouzeous et al., 1986) on the solar dehydration of grapes to reduce drying time and improve quality of raisin which include development of low cost dryer optimized through data obtained from laboratory tests and a solar tunnel dryer with integrated collector and a small radial fan. The effect of various surface dip treatments aimed for removing the waxy layer to increase drying rates and reduce drying times of grapes have been studied. The dips generally found effective include methyl oleate/K_2CO_3, alkaline ethyl oleate emulsion, boiling 0.25 % NaOH or hot (80°C) NaOH-ethyl oleate. Treatment with 4% methyl oleate was also found most effective for prunes (Pangavhane et al., 2002).

Natural convection solar dryers have been the subject of investigation by many workers for studying the drying behavior of several fruits and vegetables. Islam and Flink (1982), conducted experiments on potato at low air velocities as encountered in solar dryers and found that due to extensive external mass transport resistance in deep bed drying, the air flow behavior of the bed was more important than drying behavior of the pieces. Drying time increased less rapidly than increase in bed depth. On the basis of simulated solar drying experiments, Shakya and Flink (1986), concluded that drying rate of potato increased with increased inlet air temperature and/or air flow potential and overall productivity increased with increasing bed depth.

Sharma (1987), described the design details and performance of two types of low cost solar crop dryers, conventional cabinet dryer with direct heating mode and an integrated solar collector-cum-drying system based on the principle of natural convection. Results obtained with several vegetables viz. cauliflower, green peas and potato showed satisfactory overall efficiency and performance of both dryers. Banout et al. (2011) recently had studied the design and performance of a double pass solar dryer for drying of red chilli and Montero et al. (2010) has studied the design and performance for drying of agro-industrial by-products.

Several attempts at developing forced convection solar dryers (both of the cabinet-type and the tunnel-type) have been investigated and experimented on, over the years, and are described in the literature. The forced convection solar crop dryer design include: direct, indirect and mixed-mode solar-dryers. Comparative studies on these three dryer designs suggested that the performance of the mixed-mode forced convection solar dryer is potentially most effective and it appears to be particularly promising in tropical humid regions. The forced convection type solar cabinet dryer, basically a cabinet-type of solar dryer with attached solar air heater and forced airflow, has been considered favorable since such a dryer utilizes solar energy directly, as well as the convective energy of the heated air. Bennamoun (2003), presented the effect of surface of the collector, the air temperature and the product characteristics during solar drying of onion. Nandwani (2007), has discussed the design and development of a multipurpose fruit and vegetable dryer for domestic use.

1.8.2.2. Solar Drying of Marine Products

Marine products i.e. fish being highly perishable are processed by freezing, canning, salting and dehydration (Posomboon, 1998). In most of the developing countries, it has been estimated that about 40% of fish landing is still preserved by either sun-drying or salt curing or drying. Prawns are treated with boiling water prior to drying to reduce the microbial flora to an acceptable level and to improve the flavor of dried prawns. Jain (2006) studied the drying of Bombay duck to determine the heat and mass transfer coefficients by solar drying. Bala and Mondol (2001) described the use of solar tunnel drying as an effective method for drying of silver jew fish (Johnius argentatus) along with salting pretreatment and Reza et al. (2009) have optimized marine fish drying using solar tunnel drying. Jain and Pathare (2007) studied the drying behaviour of prawn and chelwa fish (Indian minor carp), by open sun drying. Sankat and Mujaffar (2004) studied the sun and solar cabinet drying of salted shark fillets. Baird et al. (1981) have extensively reviewed the solar drying of seafood by forced air convection and by direct insolation, as well as hot smoking fish with a solar assisted fish smoker. Kittu et al. (2010) had simulated the thin layer drying model of tilapia fish using a solar tunnel dryer. As a number of solar dryers exist for a large variety of products to be dried, the preference of one over the rests depends on a number of factors like ease of material handling, its drying characteristics, final product quality and sometimes the available resources. **Table 1.1** (section 1.12) presents a general checklist to be considered in the preliminary selection of a solar dryer, and the steps involved in consideration are described (Perry, 2007).

1.9. WORKING PRINCIPLE

Solar energy dryers can broadly be classified into direct, indirect and hybrid solar dryers. The working principle of these dryers mainly depends upon the method of solar-energy collection and its conversion to useful thermal energy for drying.

1.9.1. Open Sun Drying (OSD)

Figure 1.10 shows the working principle of open sun drying by using only the solar energy. The crops are generally spread on the ground, mat, cement floor where they receive short wavelength solar energy during a major part of the day and also natural air circulation. A part of the energy is reflected back and the remaining is absorbed by the surface depending upon the colour of the crops. The absorbed radiation is converted into thermal energy and the temperature of the material starts to increase. However there are losses like the long wavelength radiation loss from the surface of crop to ambient air through moist air and also convective heat loss due to the blowing wind through moist air over the crop surface. The process is independent of any other source of energy except sunlight and hence the cheapest method however has a number of limitations as discussed in section 2.1.1. In general, the open sun drying method does not fulfill the required quality standards and sometimes the products cannot be sold in the international market. With the awareness of inadequacies involved in open sun drying, a more scientific method of solar-energy utilization for crop drying has emerged termed as solar drying.

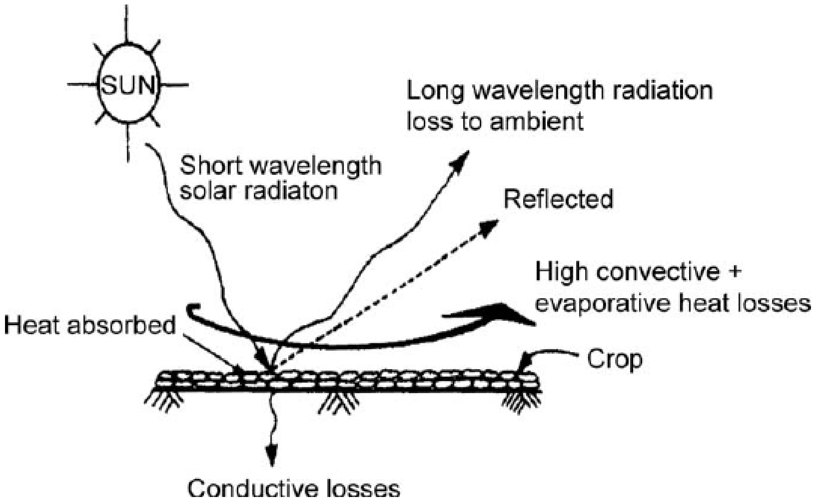

Figure 1.10. Working principle of open sun drying (Sharma et al. 2009)

1.9.2. Direct Solar Drying (DSD)

The working principle of direct solar crop drying is shown in Figure 1.11, also known as a solar cabinet dryer. Here the moisture is taken away by the air entering into the cabinet from below and escaping through at the top exit as shown in Figure. In the cabinet dryer, of the total solar radiation impinging on the glass cover, a part is reflected back to atmosphere and the remaining is transmitted inside the cabinet. A part of the transmitted radiation is then reflected back from the crop surface and the rest is absorbed by the surface of the crop which causes its temperature to increase and thereby emit long wavelength radiations which are not allowed to escape to atmosphere due to the glass cover. The overall phenomena causes the temperature above the crop inside the cabinet to be higher. The glass cover in the cabinet dryer thus serves in reducing direct convective losses to the ambient which plays an important role in increasing the crop and cabinet temperature.

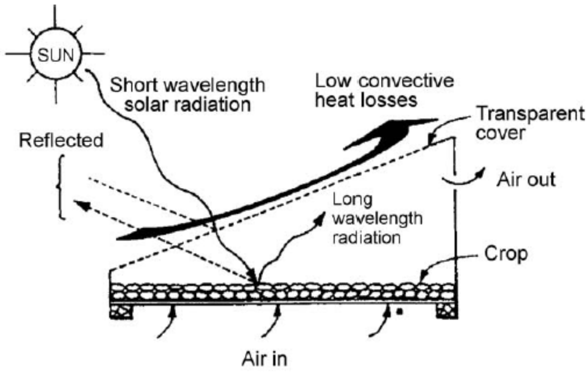

Figure 1.11. Working principle of direct solar drying (Sharma et al. 2009)

The advantages of solar drying over open sun drying are as follows:

a) Simpler and cheaper to construct than the indirect-type for the same loading capacity.
b) Offer protection from rains, dews, debris etc.

A cabinet dryer has the following limitation:

a) Liability to over-heat locally, causing crop damage.
b) Poor vapour removal rates leading to relatively slow overall drying rates
c) Small capacity limits it to small scale applications.
d) Discolouration of crop due to direct exposure to solar radiation.
e) Moisture condensation inside glass covers reduces its transmittivity.
f) Insufficient rise in crop temperature affects moisture removes.
   Limited use of selective coatings on the absorber plate and inside the cabinet dryer.

1.9.3. Indirect Solar Drying (ISD)

These differ from direct dryers with respect to heat transfer and vapor removal. Figure 1.12 describes the working principle of indirect solar drying. The crops in these indirect solar dryers are located in trays or shelves inside an opaque drying cabinet and a separate unit termed as solar collector is used for heating of the entering air into the cabinet. The heated air is allowed to flow through/over the wet crop that provides the heat for moisture evaporation by convective heat transfer between the hot air and the wet crop. Drying takes place due to the difference in moisture concentration between the drying air and the air in the vicinity of crop surface. The advantages of indirect solar drying are:

a) Offers a better control over drying and the product obtained is of better quality than sun drying.
b) Caramelization and localized heat damage do not occur as the crops are protected and opaque to direct radiation.
c) Can be operated at higher temperature, recommended for deep layer drying.
d) Highly recommended for photo-sensitive crops.
e) Have inherent tendency towards greater efficiency than direct solar drying.

They are, however, relatively elaborate structures requiring more capital investment in equipment and incur larger maintenance costs than the direct drying units.

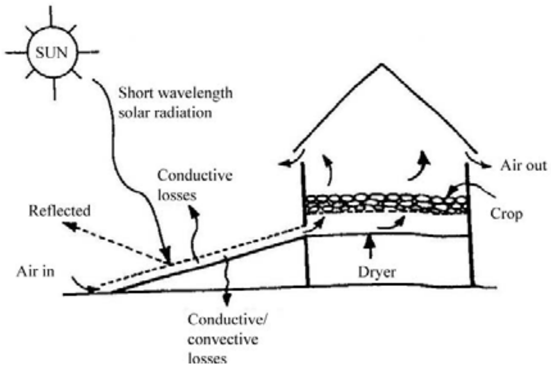

Figure 1.12. Working principle of indirect solar drying system (Sharma et al. 2009)

1.9.4. Hybrid Solar Drying (HBD)

The hybrid solar dryers combine the features of the direct and indirect type solar-energy dryers. Here the combined action of incident direct solar radiation on the product to be dried and air pre-heated in a solar collector heater produces the necessary heat required for the drying process.

1.10. TYPES OF SOLAR DRYER

On the basis of the mode of drying, e.g. direct or indirect, solar dryers may be classified as passive and active ones: (a) Passive dryers, where crops are dried by direct impingement from the sun's radiation with or without natural air circulation, and (b) Active solar dryers, where hot drying air is circulated by means of a ventilator (forced convection).

1.10.1. Passive Solar Drying Systems

In a passive solar dryer, air is heated and circulated naturally by buoyancy force or as a result of wind pressure or in combination of both. Normal and reverse absorber cabinet dryer and greenhouse dryer operates in passive mode. Passive drying of crops is still in common practice in many Mediterranean, tropical and subtropical regions especially in Africa and Asia or in small agricultural communities. These are primitive, inexpensive in construction with locally available materials, easy to install and to operate especially at sites far off from electrical grid. The passive dryers are best suited for drying small batches of fruits and vegetables such as banana, pineapple, mango, potato, carrots etc (Hughes et al., 2011).

1.10.2. Indirect-Type Passive Solar-Energy Dryers

These are indirect-type dryers with natural convection of air for drying. In order to increase the capacity of a dryer i.e. operate with more than one layer of trays with crops within the available area, the trays are generally placed in vertical racks with some space in between consecutive trays. The additional resistance generated for the air movement due to this arrangement of the trays is achieved by the "chimney effect". The chimney effect increases the vertical flow of air as a result of the density difference of the air in the cabinet and atmosphere. A typical indirect passive solar-energy dryer used for crop drying are shown in Figure 1.13. Figure 1.14 shows the design by Ortho Grainger & Twidel (1981) for maize drying. The designs generally comprise of an air-heating solar-energy collector, an insulated ducting, a drying chamber and a chimney.

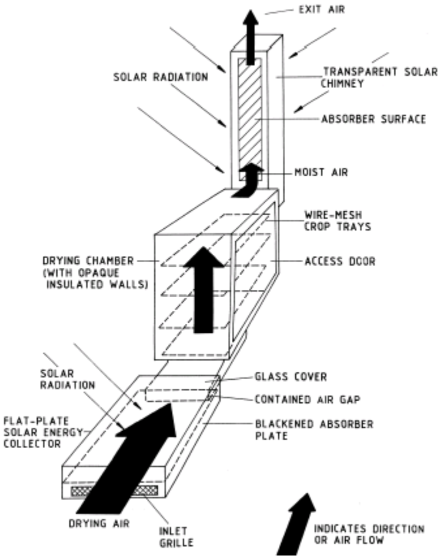

Figure 1.13 Typical distributed-type (indirect) natural-circulation solar-energy (Ekechukwu and Norton, 1999)

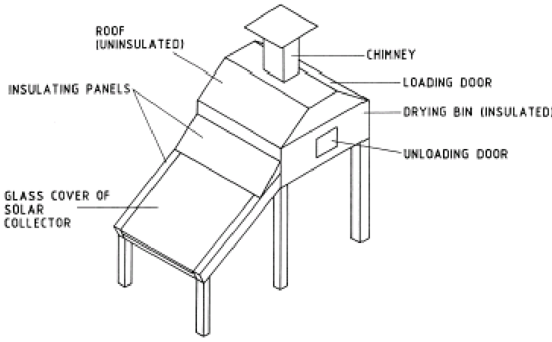

Figure 1.14. A distributed-type natural-circulation solar maize dryer (Ekechukwu and Norton, 1999)

1.10.3. Direct-Type Passive Solar-Energy Dryers

The features of a typical direct-type passive solar dryer are illustrated in Figure 1.15. In these type of solar dryers the direct exposure of the crop to the sunlight enhances the color ripening desired in certain varieties of grapes, dates, coffee and development of full flavour in roasted beans. Two basic types of dryers in this category can be identified as the cabinet and greenhouse dryers.

1.10.3.1. Solar Cabinet Dryers

The passive solar cabinet dryers are generally simple and inexpensive units having high applications for domestic purposes. They are suitable for drying of agricultural products, spices and herbs etc., constructed normally with a drying area of 1-2 m^2 and capacities of 10-20 kg. Figure 1.16 shows a typical passive solar cabinet dryer. The heat for drying is transmitted through the glass cover and is absorbed on the blackened interior and crops as well. The required air circulation is maintained by the warm moist air leaving via the upper vent under the action of buoyancy forces and generating suction of fresh air from the base inlet. Pioneering works on solar cabinet dryers were reported by the Brace Research Institute, (1980).

A number of other designs of passive solar cabinet dryer in configuration to that developed by Brace Research Institute have been built and tested for a variety of crops and locations. Ezekwe (1981) reported a modification of the typical design shown in Figure 1.17 equipped with a wooden plenum guiding the air inlet and a long plywood chimney to enhance natural circulation, accelerating the drying rate by about 5 times over open sun drying. Figure 1.18 shows the design by Henriksson and Gustafsson (1986) with mesh work floor and a chimney with black PVC foil facing the southwards (sunlight).

The passive solar cabinet dryer have an advantage of being cheap and easy in construction from locally available material, however their major drawback is poor moist removal rates and very high temperature (70-100°C) causing overheating of the product.

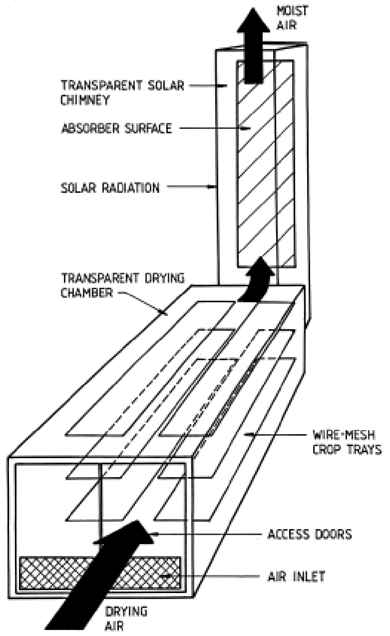

Figure 1.15. Features of a typical integral-type (direct) natural-circulation solar-energy dryer (Ekechukwu and Norton, 1999)

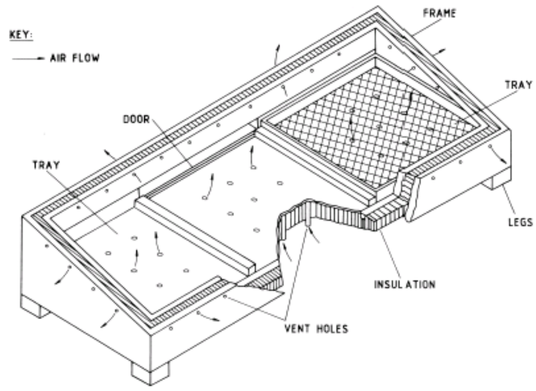

Figure 1.16. A typical natural-circulation solar-energy cabinet dryer (Ekechukwu and Norton, 1999)

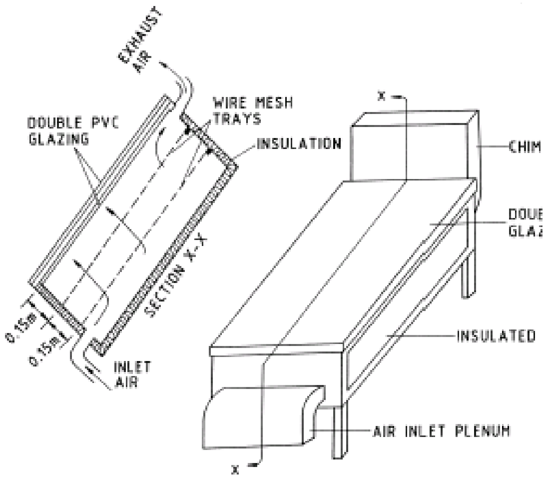

Figure 1.17. A modified natural-circulation solar-energy cabinet dryer (Ekechukwu and Norton, 1999)

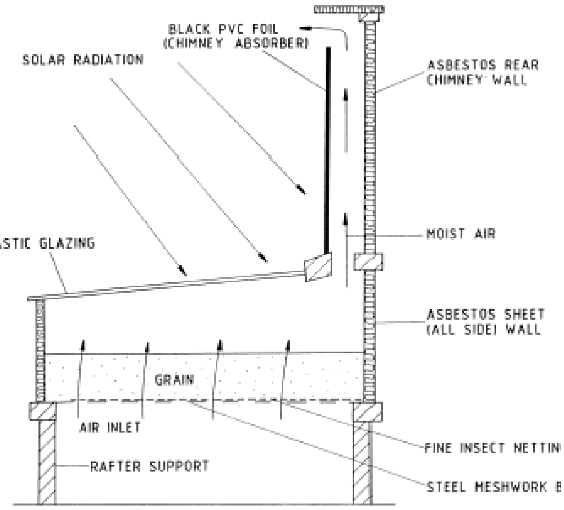

Figure 1.18. A natural-circulation solar-energy cabinet dryer with chimney (Ekechukwu and Norton, 1999)

1.10.3.2. Natural-Circulation Greenhouse Dryers

These are also called as tent dryers and are basically modified greenhouses. They are designed with vents of appropriate size and position to have a controlled air flow. They are characterized by extensive glazing by the transparent cover of polyethylene sheet.

Figure 1.19 shows the earliest form of passive solar greenhouse dryer by the Brace Research Institute, with slanted glass roof, allowing direct solar radiation over the product. The length-wise north-south alignment of the dryer had black coated internals for improved absorption of solar radiation with the ridge-cap over the roof for exit vent. Doe et al. (1977) later designed the widely reported poly-ethylene tent dryer, illustrated in Figure 1.20 consisting of a ridged bamboo framework clad with a clear polythene sheet over it. A black poly-ethylene sheet was also spread on the floor inside the tent to enhance the absorption of solar radiation. The air flow into the tent was controlled by rolling/ unrolling of the cladding at the bottom edge of front side and the vents at the top served as the exit for the moist exhaust air.
Sachithananthan et al. (1983) reported a horticultural greenhouse of clear plastic sheet cladding over a semi-cylindrical metal frame (Figure 1.21). The modification were with a black galvanized iron sheet absorber at floor, inlet vents along the full length of both sides of base and exit with plastic nets at the top to protect from insects and dust.

Fleming et al. (1986) reported a typical greenhouse type solar dryer with a transparent semi-cylindrical chamber with a cylindrical solar chimney posted vertically at one end and a door for air inlet and access to the chamber at other end as shown in Figure 1. 22. Rathore et al. (2010) has conducted various experimental studies on a modified design of hemi-cylindrical solar tunnel dryer for drying of grapes also few researchers (Jaijai et al., 2011) have used a polycarbonate cover for its construction. Afriyie et al. (2011) has reported the study of simulation and optimization of a chimney ventilated solar crop dryer.

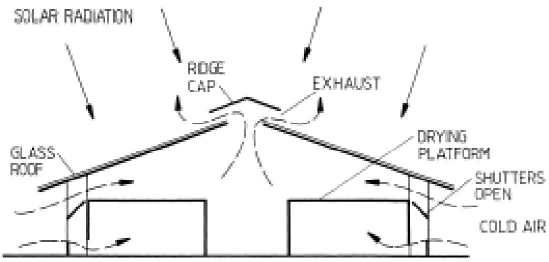

Figure 1.19. Natural-circulation glass-roof solar-energy dryer (Ekechukwu and Norton, 1999)

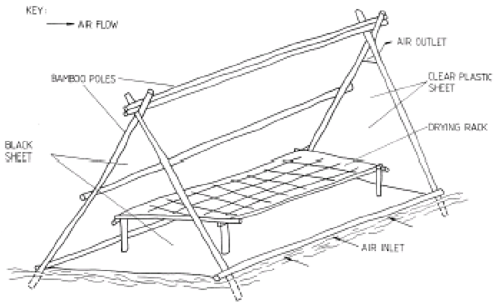

Figure 1.20. Natural-circulation polythene-tent dryer (Ekechukwu and Norton, 1999)

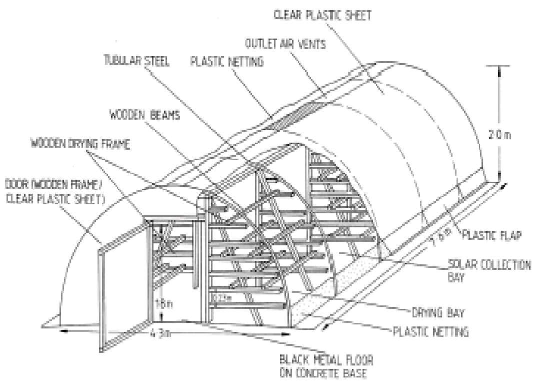

Figure 1.21. Natural-circulation solar dome dryer (Ekechukwu and Norton, 1999)

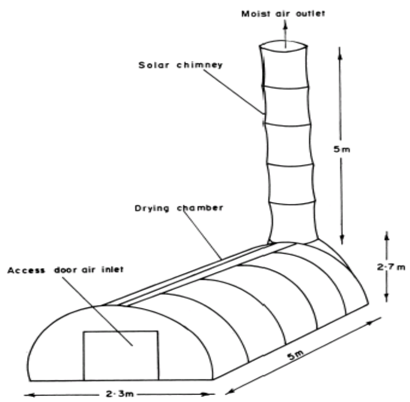

Figure 1. 22 A greenhouse type natural-circulation solar–energy dryer (Ekechukwu and Norton, 1999)

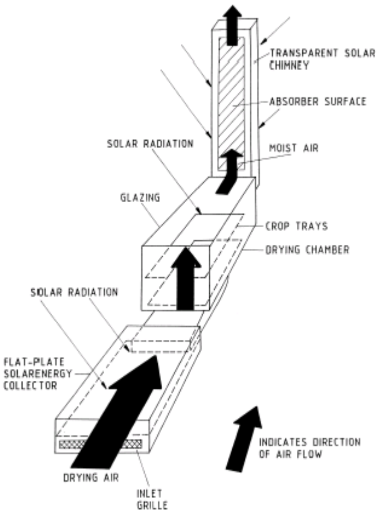

Figure 1.23. Features of a typical mixed-mode natural-circulation solar-energy dryer (Ekechukwu and Norton, 1999)

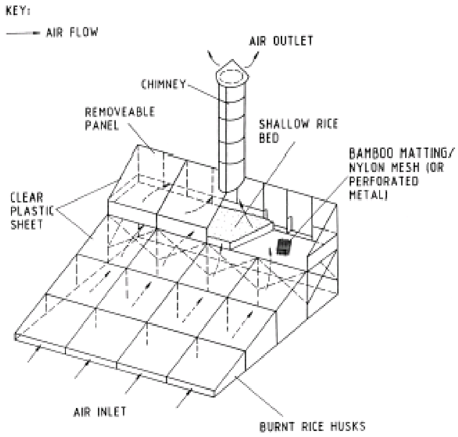

Figure 1.24. A mixed-mode natural-circulation solar rice dryer (Ekechukwu and Norton, 1999)

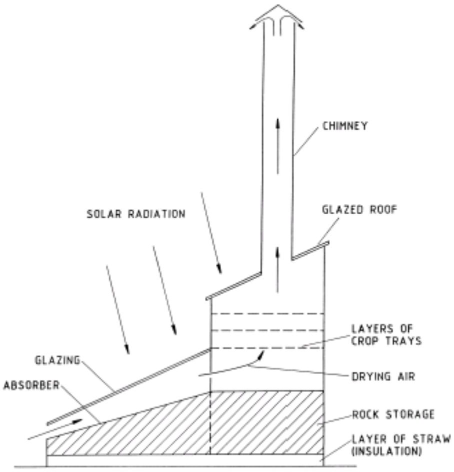

Figure 1.25. A mixed-mode natural-circulation solar-energy dryer with thermal storage (Ekechukwu and Norton, 1999)

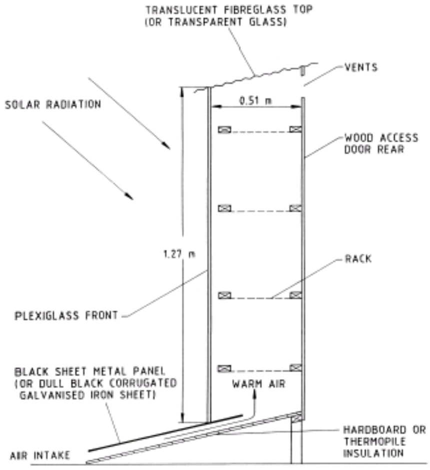

Figure 1.26. A multi-stacked mixed-mode natural circulation solar-energy dryer (Ekechukwu and Norton, 1999)

1.10.4. Hybrid-Type Passive Solar-Energy Dryers

A hybrid type passive solar-energy dryer would have the same typical structural features as the indirect-type and direct-type (i.e. a solar air heater, a separate drying chamber and a chimney), and in addition has glazed walls inside the drying chamber so that the solar radiation impinges directly on the product as in the direct-type dryers as shown in Figure 1.23. Exell et. al. (1980), Sodha et al. (1987), at Asian Institute of Technology developed the widely reported solar rice dryer (Figure 1.24). Ayensu and Asiedu (1986) designed the hybrid dryer consisting of an air heater with a pile of granite functioning as an absorber cum heat storage (Figure 1.25). Sauliner first reported a multi stacked hybrid design different from that of Exell, followed by Lawand at Brace Research Institute also designed and tested by Sharma et al. (1986, 1987), as shown in figure 1.26. The multi-stacked design enables the simultaneous drying of a variety of crops. Several other designs of the hybrid-type passive solar energy have also been reported in (Amer et al., 2010; Hughes et al., 2011).

1.11. ACTIVE SOLAR DRYING SYSTEMS

Active solar drying systems are designed incorporating external means, like fans or pumps, for moving the solar energy in the form of heated air from the collector area to the drying beds. Thus all active solar dryer are, by their application, forced convection dryer. A typical active solar dryer depends on solar-energy only for the heat source, while for air circulation uses motorized fans or ventilator. These dryers find major applications in large-scale commercial drying operations in combination with conventional fossil-fuel to have a better control over drying by consolidating the effect of fluctuations of the solar insolation on the drying air temperature. Active solar dryers are known to be suitable for drying higher moisture content foodstuffs such as papaya, kiwi fruits, brinjal, cabbage and cauliflower slices. A variety of active solar-energy dryers exist which could be classified into either the direct -type, indirect-type or hybrid dryers.

1.11.1. Indirect-Type Active Solar Drying Systems

These active dryers as discussed for indirect dryer in section 2.3 have a separate collector and drying unit. They are generally comprised of four basic components viz., a solar air heater, drying chamber, a fan for air circulation and ductings. Due to the separate air heating unit higher temperatures can easily be obtained with a control on air flow rate. However as the efficiency of collector decreases at higher temperature operation, an optimum temperature and airflow rate has to be determined to have a cost effective design. While most solar collectors are madeup of metal or wood absorbers with appropriate coatings, materials like black polythene are also used as they form an economic substitute. Figure 1.27 shows a typical indirect-type active solar dryer. A few designs also employ the recirculation of drying air, that ensures low exhaust air temperature and thereby efficient use of energy. Figure 1.28 illustrates a system employing partial air-recirculation, in a polyethylene-tube solar collector. The efficiency of the indirect-type active solar dryer also depends on the location of the fan, though not so significantly in small batches. The prime objective of the fan is to maintain a desired flow-rate in the drying cabinet causing uniform evaporation of moisture from the wet material and in the collector is the collection of heat maintaining a negative pressure, reducing the heat losses. Figure 1.29 shows the role of the fan in a typical continuous flow in an active solar dryer, in vertical bin for grain drying. Slama et al. (2011) has recently developed and evaluated a forced convection solar dryer for drying of orange peels.

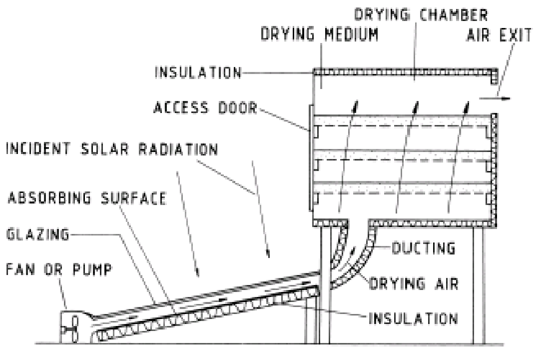

Figure 1.27. Features of a typical distributed-type active solar energy dryer (Ekechukwu and Norton, 1999)

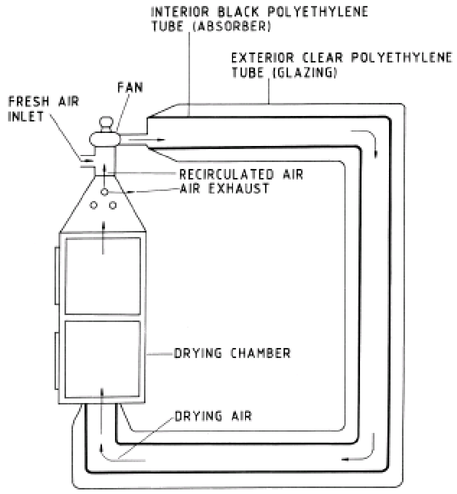

Figure 1.28. A distributed-type active solar dehydrator with partial air re-circulation (Ekechukwu and Norton, 1999)

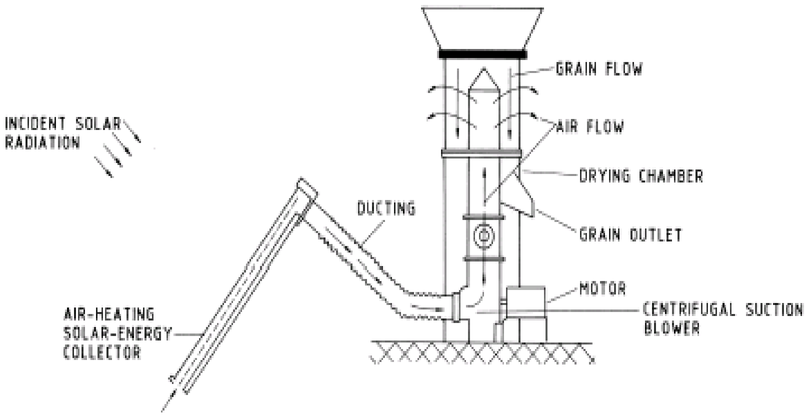

Figure 1.29. A continuous-flow active grain dryer (Ekechukwu and Norton, 1999)

1.11.2. Direct-Type Active Solar-Energy Drying Systems

The direct-type active solar dryers are designed with an integrated solar energy collection unit. Generally, three distinct designs of direct-type active solar dryers can be identified viz., the absorption type, storage type and greenhouse dryers.

1.11.2.1. Absorption Dryers

The direct absorption dryer as the name suggests are designs of the direct-type active dryers wherein the crops absorb the solar radiation directly. Typical practical design for large-scale commercial forced-convection greenhouse dryer, are of the type of solar kilns for timber drying (Figure 1.30), transparent roof solar brans as shown in Figure 1.31 and small scale force-convection dryers equipped with auxiliary heating in Figure 1.32. Typical designs include with the roof or wall of the dryer functioning as a collector of the drying chamber. Figure 1.33 shows the greenhouse dryer designed by Huang et. al (1981) with a semi-cylindrical structure made of a Tedlar coated clear corrugated fibre-glass and an internal dry chamber of rotary or stationary drum with a black-painted outer surface to effect solar absorbtion. Trim and Ko (1982) developed another design with a clear plastic outer cover and a black plastic interior and Akachukwu (1986) described the dryer with a solar kiln design for timber drying with a single glazing of horticultural-grade polythene with an internal internal black-painted corrugated metal absorber over the timber stack.

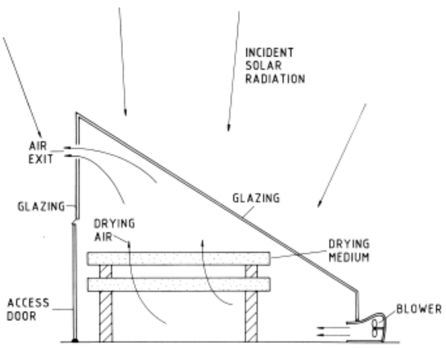

Figure 1.30. A forced-convection greenhouse dryer (Ekechukwu and Norton, 1999)

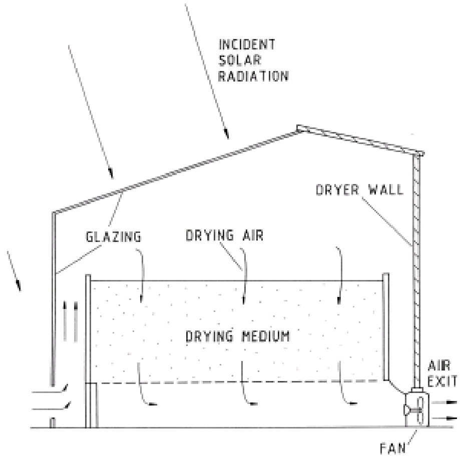

Figure 1.31. A forced-convection transparent-roof solar barn (Ekechukwu and Norton, 1999)

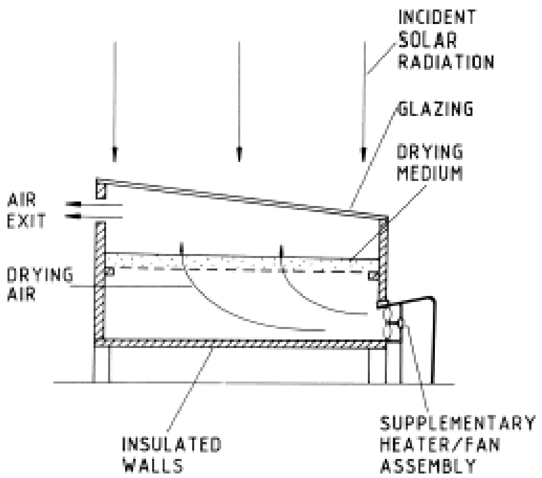

Figure 1.32. Features of a typical active solar-energy cabinet dryer (Ekechukwu and Norton, 1999)

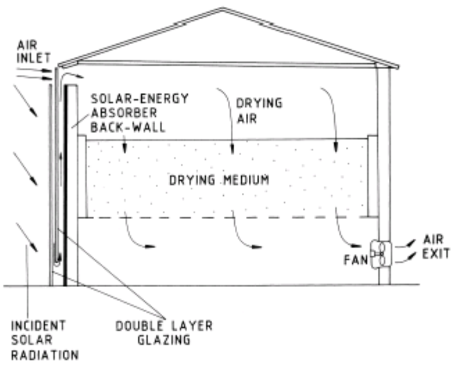

Figure 1.33. Interior-drum-absorber greenhouse active solar dryer (Ekechukwu and Norton, 1999)

1.11.3. Hybrid-Type Active Solar-Energy Dryers

The hybrid solar dryers combine the features of a solar energy with a conventional or some auxiliary source of energy and can be operated either in combination or in single mode with either source of energy. These dryers generally are medium to large installations operating in the range of 50-60%, and compensate the temperature fluctuations induced by the climatic uncertainties. Figure 1.34 shows the features of a typical active-type hybrid solar dryer. Bena and Fuller (2002) described a direct-type natural convection solar dryer combined with a simple biomass burner suitable for drying fruits and vegetables in regions without electricity. Figure 1.34 shows a hybrid solar dryer, a modification of the dryer in Figure 1.35 with auxiliary source of heating. The ambient air flows through a heat exchanger where it is heated to the desired temperature, by combustion gas. Part of the used air is exhausted from the north wall of the dryer and the rest is recycled through the recycling tube and the cooled gas exits through the chimney to the ambient (Condori et al., 2001). Amer et al. (2011) has recently designed and evaluated a hybrid solar dryer for drying of banana, consisting of a heat exchanger and heat storage facility.

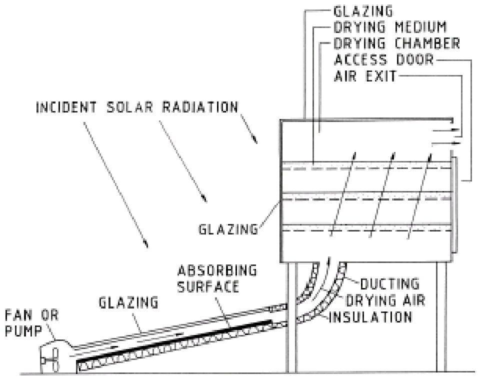

Figure 1.34. Features of a typical mixed-mode active solar-energy dryer (Ekechukwu and Norton, 1999)

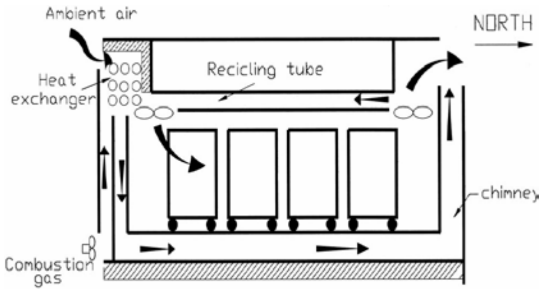

Figure 1.35. Solar tunnel dryer with an additional auxiliary heat source (Ekechukwu and Norton, 1999)

1.12. SELECTION OF SOLAR DRYERS

The diversity of food products has introduced many types and combinations of solar dryers to the food industry. The methods of supplying heat and transporting the moisture and the drying product are the basic variations among different types of solar dryers. Table 1.2 enumerates the typical checklist for evaluation and selection for solar dryers.

Table 1.2. Typical checklist for preliminary evaluation and selection of solar dryers

Sr. no	Parameters	Features
1.	Physical features of dryer	• Type, size and shape • Collector area • Drying capacity/loading density (kg/unit tray area) • Tray area and number of trays • Loading/unloading convenience
2.	Thermal performance	• Solar insolation • Drying time/drying rate • Dryer/drying efficiency • Drying air temperature and relative humidity • Airflow rate
3.	Properties of the material	• Physical characteristics (wet/dry)

	being handled	• Acidity • Corrosiveness • Toxicity • Flammability • Particle size • Abrasiveness
4.	Drying characteristics of the material	• Type of moisture (bound, unbound, or both) • Initial moisture content • Final moisture content (maximum) • Permissible drying temperature • Probable drying time for different dryers
5.	Flow of material to and from the dryer	• Quantity to be handled per hour • Continuous or batch operation • Process prior to drying • Process subsequent to drying
6.	Product qualities	• Shrinkage • Contamination • Uniformity of final moisture content • Decomposition of product • Over-drying • State of subdivision • Appearance • Flavour • Bulk density
7.	Recovery problems	• Dust recovery • Solvent recovery
8.	Facilities available at site of proposed installation	• Space • Temperature, humidity, and cleanliness of air • Available fuels • Available electric power • Permissible noise, vibration, dust, or heat losses • Source of wet feed • Exhaust-gas outlets
9.	Economics	• Cost of dryer • Cost of drying • Payback
10.	Other parameters	• Skilled technician and operator requirements, • Safety and reliability • Maintenance

1. *Initial selection of solar dryers.*

   The initial selection can be of the type of solar dryer that appears best suited for handling the wet material and dry product, that fits well into the continuity of the process as a whole, and that produces the product of desired properties.

2. *Initial comparison of solar dryers.*

   The solar dryers selected in step one should then be evaluated from the available cost and performance data selecting a few. The rests should then be eliminated from further considerations.

3. *Solar Drying tests.*

   Drying tests should then be conducted in small-scale units based on the solar dryers selected in step two. These tests are expected to establish the optimum operating conditions, the ability of the dryer to handle the material physically, product quality and characteristics, and dryer size. Occasionally, simple laboratory experiments can serve to reduce further the number of dryers under consideration, as there is rare scope for changes to be made once the dryer is installed. Based on the results of these drying tests that establish size and operating characteristics formal quotations and guarantees should be obtained from dryer manufacturers. Initial costs, installation costs, operating costs, product quality, dryer operability, and dryer flexibility can then be given proper weight in final evaluation and selection.

4. *Final selection of solar dryer.*

   From the results of the drying tests and quotations, the final selection of the most suitable solar dryer can be made.

The physical nature of the material to be handled is one of the primary features for consideration as these are different for coarse solid, slurry and sheet material. After the preliminary selection of the suitable type of solar dryer, a further analysis for revaluation of its size and cost should be done to select the most economical one. After analysing adequate data on the cost and performance obtained from the equipment manufacturers the factors governing their performance should be due considered. This may involve at times compromising certain steps that precede or follow drying process, like sorting , conveying or packaging and hence must be considered carefully.

1.12.1. Test case of solar drying at ICT Mumbai

Solar cabinet drying of fish

A comparative study was carried out at ICT, Mumbai to compare various aspects of drying kinetics and quality of fish and vegetable dried by open sun, solar cabinet, hot air and freeze drying.

Figure 1.36. Pictorial view of Solar Cabinet Dryer at ICT-Mumbai (Visavale, 2009)

The solar cabinet dryer consisted of an indirect forced convection solar dryer with a solar air collector, a blower for air circulation and a drying cabinet The solar air collector had dimensions of 4 × 5 m. A plain copper sheet painted black was used as an absorber plate for incident solar radiation. It was oriented southward under the collector angle of 31°. The collector and blower system was well insulated to prevent heat losses. The drying cabinet dimensions were length 1.20 m, breadth 0.76 m and height 0.40 m constructed with insulated walls and had 16 shelves. A centrifugal blower (capacity 1000 m^3/h) connected to the drying cabinet provides a maximum air velocity of 1.0 m/s. The circulation fan that supplies fresh air has a power of 1.5 kW. During experiments the air velocity, temperature and relative humidity in the cabinet were in the range 0.9-1.0 m/s, 40-60°C and 50-65%, respectively. The sample data of solar intensity and respective inlet air temperature in the cabinet were recorded during one of the drying experiments and shown graphically in Figure 1.37**.** Geographical location of Mumbai is at 18.96º N and 72.82º E on the sea coast at the average height between 10 to 15 m over the sea level. Summer is hot and humid, while winter is cool and dry. The tray loading density was 4 kg/m^2. To collect the drying data, tray at the centre was selected and weight loss was recorded at predetermined time intervals. The product was uniformly spread on 16 mesh trays which were placed in the drying cabinet. In solar drying processes, the drying air temperature can vary based on the magnitude of the solar radiation. However, the recycle damper was used for controlling the drying air temperature to some extent. The amount of solar radiation was measured with a pyranometer. Temperature and relative humidity were measured by thermocouple and RH-meter, respectively (Jadhav et al., 2010a; Mathew et al., 2010).

Table 1.3. Solar cabinet dryer configuration

Drying Cabinet	
Gross dimensions	1.12 × 0.76 × 0.40 m
Spacing between two trays	0.025 m
Tray material	Al/ SS-316
Tray Dimensions	0.56 x 0.76 x 0.025
Space between two trays	0.025 m
Tray type	mesh tray
Number of trays	16
Tray thickness	0.002 m
Outlet pipe diameter	0.20 m

Mode of air flow	Forced convection
Air flow rate	1000 m^3/h
Air velocity in cabinet	~1m/s
Geographical Location	Mumbai, India. *(18° 53"N & 72°50"E)*
Collector	
Area of absorbing surface	20 m^2
Number of absorbing surface	10
Absorbing material	Black painted copper sheet
Insulation thickness	0.05 m
Insulation material	Plexifoam
Transfer fluid	Air
Collector tilt angle	25°, Facing south
Cover plate material	Glass
Dimensions of each panel	1 m x 2 m
Absorber plate thickness	20 G
Air passage	Rectangular aperture of 0.125 m2
Mode of air flow	Forced convection

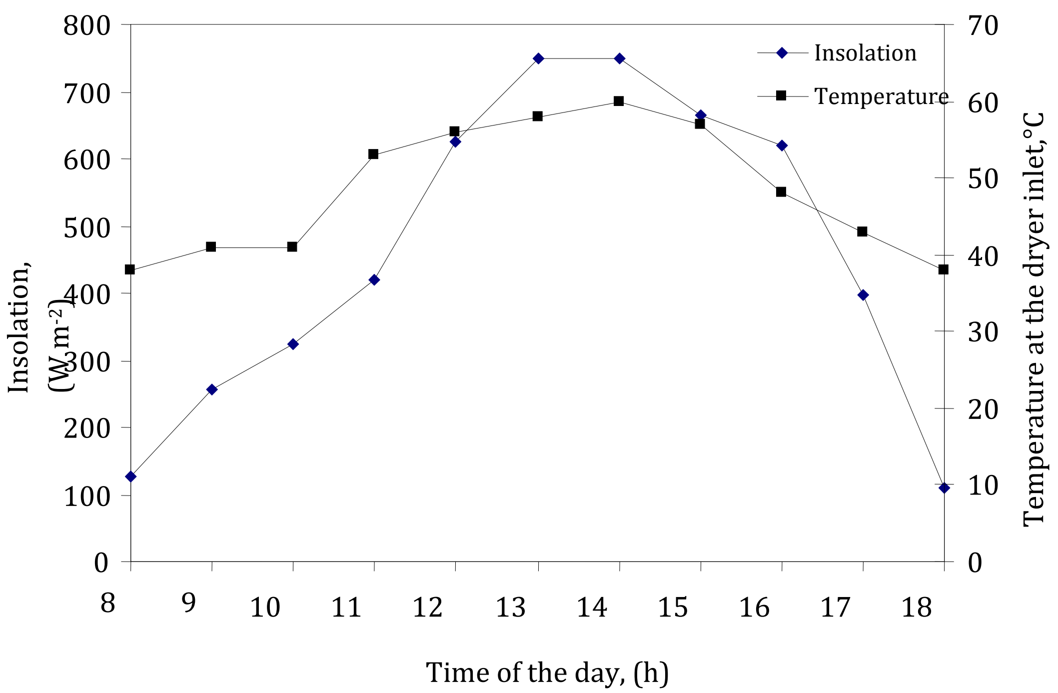

Figure 1.37. Variation of solar radiation throughout the day during day of drying experiment (March 23, 2008) (Visavale, 2009)

The plot for drying rate versus average moisture content for six types of fish using different dryers are shown in Figure 1.38 - 1.43. The specific energy consumption was estimated for the three types of dryers viz., SCD, FD and HAD (Visavale et al., 2011, Visavale, 2009), considering the total energy supplied to dry the fish from initial moisture content of about 74-87% to a moisture content of 5-6 % (approx.). Open sun drying was considered as a non-energy intensive process as only solar radiation was used to dry the samples. The specific energy consumption, H, is expressed as follows (Sharma and Prasad, 2004).

$$H = \frac{\text{Total energy supplied in drying process}}{\text{Amount of water removed during drying}}, \quad \text{kJ/kg water evaporated} \qquad (1.16)$$

Enthalpy of the drying air was estimated from psychometric properties. Specific energy consumption in drying process, H is defined as follows

$$H = \frac{h_1 + h_2 + h_3 + h_4}{\text{Amount of water removed during drying}}, \quad \text{kJ/kg water evaporated} \qquad (1.17)$$

where, h_1 is energy required to heat the air, kJ; h_2 is energy requirement of the air blower, kJ; h_3 is energy requirement of the vacuum pump, kJ; h_4 is energy requirement for freezing the fish sample before freeze drying, kJ. In case of SCD only h_2 was estimated whereas for HAD, both the h_1 and h_2 values were calculated and for FD only h_3 and h_4 were considered.

All drying methods were compared using one way ANOVA at 5% level of significance. The values of critical difference were calculated for all the quality parameters and specific energy consumption and pair wise comparison between drying methods was done to find the significant difference. The best drying method was selected on the basis of selected quality attributes like rehydration ratio, change in color, hardness, sensory quality (overall acceptability) and specific energy consumption.

Specific energy consumption for selected fish (Bombay duck, prawn, pomfret, mandeli, jawala, ribbon fish) dried using four methods is given in Table 1.4 and 1.5**.** There was no significant difference ($p>0.05$) in specific energy consumption during drying of fish by OSD and SCD. It can be observed that, OSD is least energy intensive process as solar radiation is freely available whereas, FD was the most expensive drying process with 21,200 and 13,507 kJ/kg water removal E_{sp} for Bombay duck and Prawn, respectively as high energy is required for prefreezing at (-10°C for 10 h) and to maintain vacuum. After FD, HAD was energy intensive process with 18,950 and 13,507 kJ/kg water removal E_{sp} for Bombay duck and Prawn, respectively. SCD was found to be significantly low energy intensive process saving 88 to 93% (approx.) energy compared to FD and HAD. In SCD only electric energy was used for air recirculation which was quite negligible whereas, free solar radiation was used to heat the drying air.

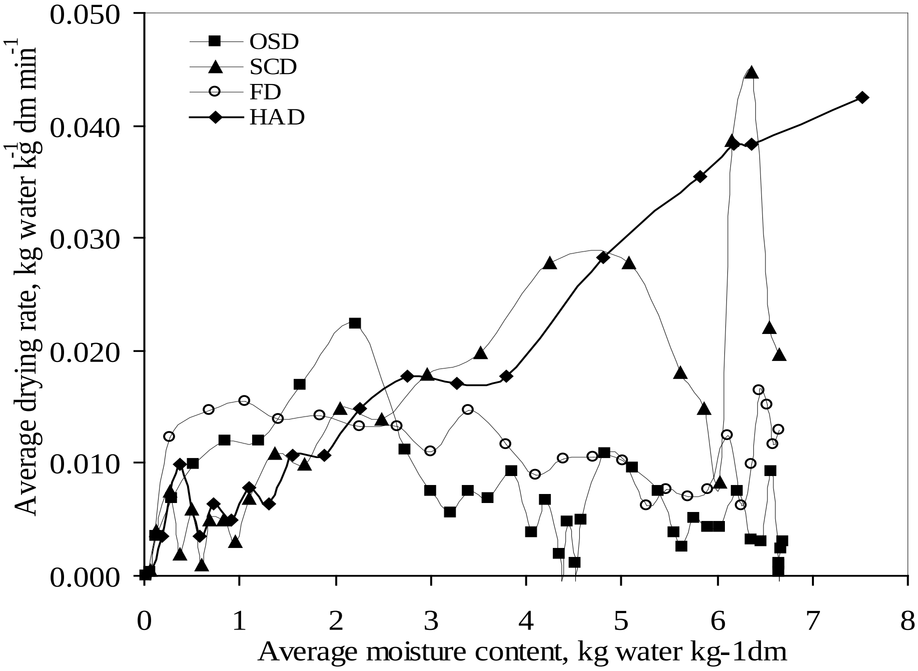

Figure 1.38. Effect of drying method on variation of drying rate with average moisture content for Bombay duck

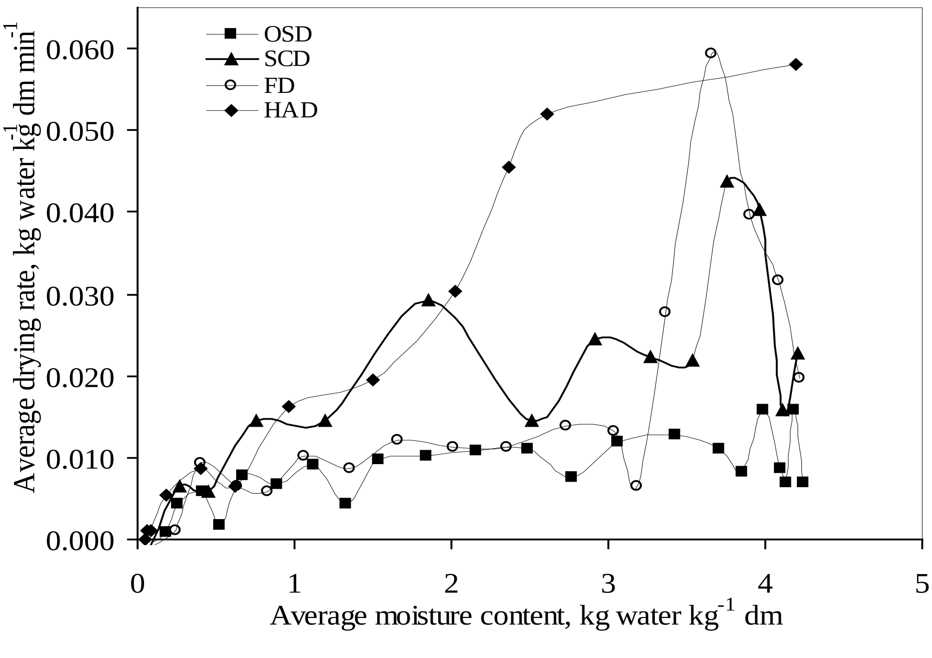

Figure 1.39. Effect of drying method on variation of drying rate with average moisture content for Prawn

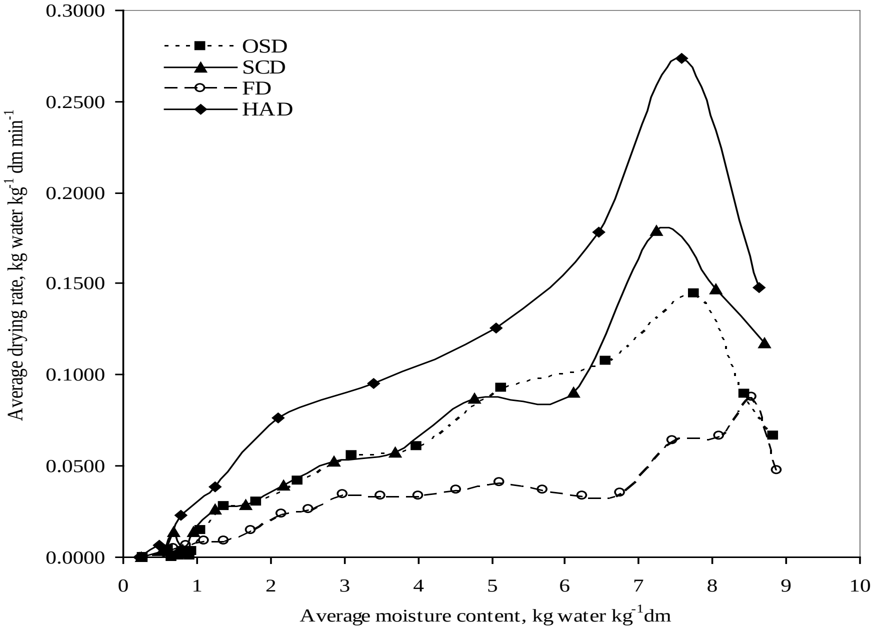

Figure 1.40. Plot for drying rate vs average moisture content for Jawala

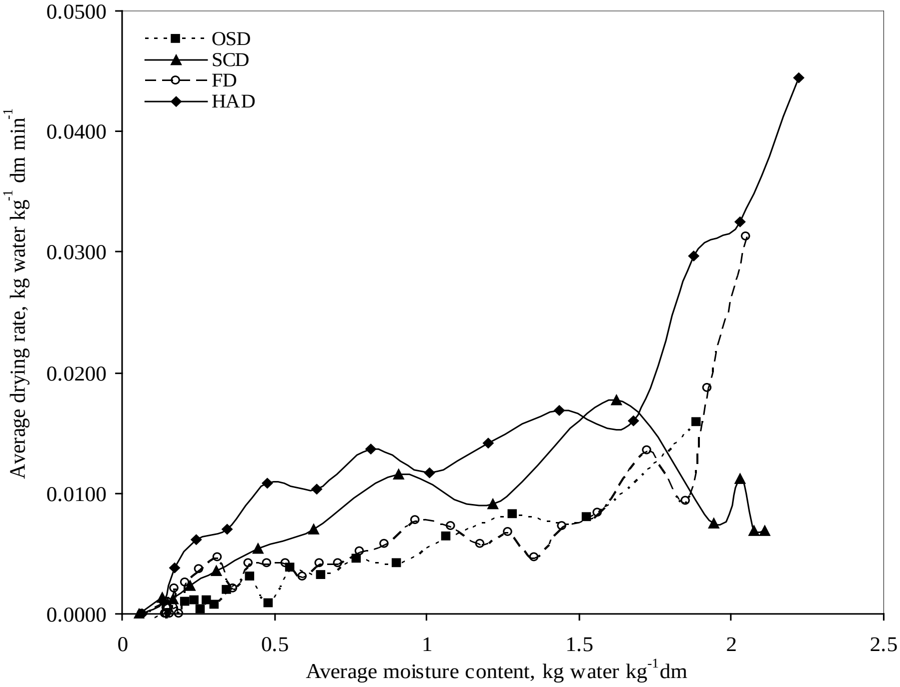

Figure 1.41. Plot for drying rate vs average moisture content for Mandeli

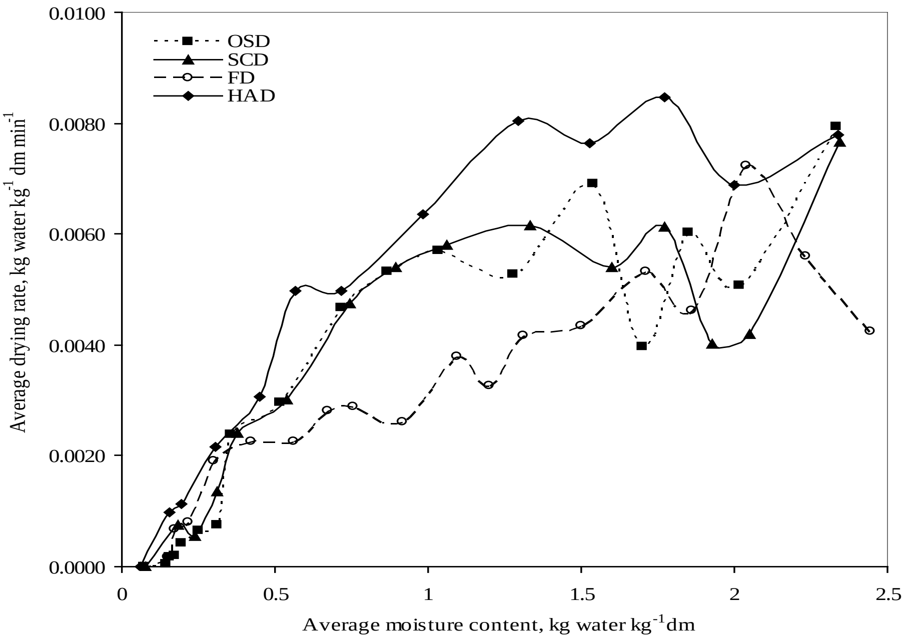

Figure 1.42. Plot for drying rate vs average moisture content for Pomfret

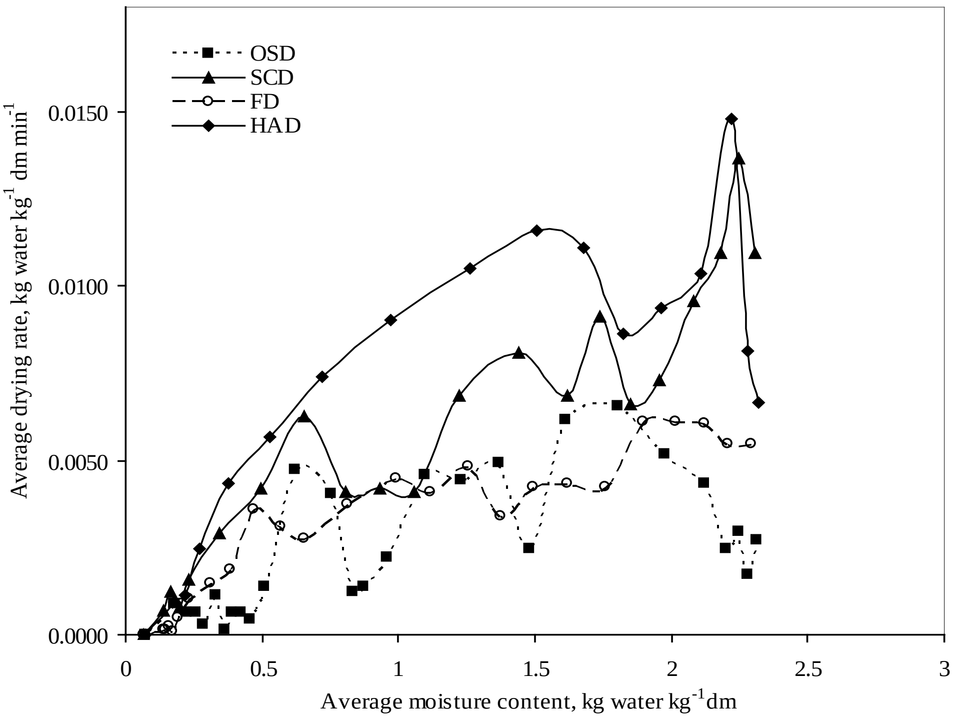

Figure 1.43. Plot for drying rate vs average moisture content for Ribbon fish

Table 1.4. Quality and other drying parameters of Bombay duck, Prawn and Jawala dehydrated using various drying methods (Visavale, 2009)

Dryer	RR		Shrinkage, %	Density, kg m^{-3}		ΔE	Hardness, g	OA	$E_{sp,}$ kJ kg^{-1}	D_{eff} ×10^{9}, m^{2}s^{-1}	DT,h
	25 °C	100 °C		True	Bulk						
Bombay duck: IMC ~85% (w.b)											
OSD	1.75[a]	0.85[a]	68.24[a]	612.18[a]	112.12[a]	33.23[a]	1744.3[a]	5.12[a]	0[a]*	0.31	17.33
SCD	2.55[b]	1.13[b]	56.24[b]	700.12[b]	122.82[b]	21.33[b]	971.68[b]	6.86[b]	2098[a]	1.01	10.00
HAD	2.45[b]	1.12[b]	55.15[b]	760.52[c]	128.18[b]	19.29[b]	1121.52[c]	6.95[b]	18950 [b]	1.51	7.50
FD	2.85[c]	1.15[b]	5.32[c]	400.23[d]	65.23[c]	5.34[c]	892.61[d]	8.87[c]	21200 [c]	0.70	9.83
Prawn: IMC ~78% (w.b)											
OSD	2.56[a,c]	2.25[a]	65.14[a]	410.25[a]	85.21[a]	38.58[a]	1443.33[a]	5.87[a]	0[a]*	0.08	8.50
SCD	3.2[b]	3.01[b]	45.24[b]	422.23[a]	87.81[a]	22.18[b]	1218.22[b]	6.66[a]	959[a]	0.21	4.00
HAD	3.05[a,b]	2.85[b]	43.23[b]	425.41[a]	89.19[a]	20.58[b]	1040.67[c]	6.89[a]	8081[a]	0.31	5.00
FD	3.65[c]	3.35[d]	6.41[d]	315.35[b]	50.12[b]	6.55[d]	516.00[d]	8.72[b]	13507[b]	0.10	6.00
Jawala *(Acetes indicus)*: IMC ~87% (w.b)											
OSD	1.65[a]	0.75[a]	58.14[a]	380.28[a]	91.51[a]	39.15[a]	1245.31[a]	4.28[a]	0[a]*	0.60	6.00
SCD	2.65[b]	1.23[b]	54.18[b]	412.15[b]	98.14[b]	24.43[b]	645.24[b]	6.90[b]	625.14[a]	1.01	3.00
HAD	2.55[b]	1.15[b]	54.11[b]	450.14[c]	104.25[b]	17.19[b]	845.25[c]	6.95[b]	5023.19[b]	2.02	2.00
FD	2.90[c]	1.18[b]	4.12[c]	275.31[d]	45.15[c]	6.15[c]	541.29[d]	8.85[c]	12935.24[c]	0.40	6.00

Table 1.5. Quality and other drying parameters of Silver Pomfret, Mandeli and Ribbon fish dehydrated using various drying methods (Visavale, 2009)

Dryer	RR		Shrinkage, %	Density, kg m^{-3}		ΔE	Hardness, G	OA	$E_{sp,}$ kJ kg^{-1}	D_{eff} ×10^{9}, m^{2}s^{-1}	DT,h
	25 °C	100 °C		True	Bulk						
***Silver pomfret (Pampus argenteus):* IMC ~75% (w.b)**											
OSD	1.07^{a}	0.65^{a}	58.14^{a}	600.15^{a}	102.31^{a}	29.21^{a}	15000.40^{a}	5.05^{a}	0^{a}*	91.23	16.00
SCD	2.01^{b}	1.03^{b}	51.24^{b}	695.21^{b}	135.01^{b}	18.11^{b}	863.51^{b}	6.88^{b}	2367.03^{a}	101.33	11.33
HAD	2.10^{b}	1.11^{b}	52.44^{b}	724.55^{c}	144.51^{b}	18.55^{b}	995.32^{c}	6.91^{b}	21037.13^{b}	101.33	8.33
FD	2.51^{c}	1.21^{b}	4.85^{c}	413.31^{d}	58.32^{c}	5.50^{c}	780.24^{d}	8.50^{c}	30187.29^{c}	81.12	14.00
Mandeli (*Coilia dussumieri*): IMC ~85% (w.b)											
OSD	2.35^{a,c}	2.05^{a}	62.19^{a}	390.28^{a}	75.12^{a}	37.05^{a}	1264.13^{a}	5.80^{a}	0^{a}*	30.39	8.00
SCD	3.5^{b}	3.15^{b}	43.13^{b}	412.58^{a}	79.32^{a}	25.19^{b}	1108.05^{b}	6.50^{a}	1045.15^{a}	61.08	5.00
HAD	3.05^{a,b}	2.78^{b}	42.14^{b}	435.21^{a}	80.72^{a}	21.08^{b}	988.06^{c}	6.65^{a}	7572.23^{a}	4.05	3.00
FD	3.75^{c}	3.45^{d}	5.15^{d}	305.12^{b}	48.14^{b}	5.75^{d}	628.51^{d}	8.88^{b}	16168.97^{b}	2.02	7.50
Ribbon fish *(Lepturacanthus savala):* IMC ~85% (w.b)											
OSD	1.78^{a,c}	2.05^{a}	58.04^{a}	650.11^{a}	350.41^{a}	41.22^{a}	1503.81^{a}	5.55^{a}	0^{a}*	20.27	18.00
SCD	2.25^{b}	2.75^{b}	44.05^{b}	680.24^{a}	412.44^{a}	25.41^{b}	1342.43^{b}	6.65^{a}	1668.40^{a}	40.53	8.00
HAD	2.65^{a,b}	2.78^{b}	43.21^{b}	690.12^{a}	425.43^{a}	23.32^{b}	1303.53^{c}	6.75^{a}	15153.12^{a}	50.60	6.00
FD	3.75^{c}	3.55^{d}	6.01^{d}	495.44^{b}	98.22^{b}	5.78^{d}	686.41^{d}	8.85^{b}	32314.35^{b}	25.27	15.00

**During OSD E_{sp} was assumed 0.00 kJ/kg water removal as natural solar energy was freely available. Similar letters indicate non significant difference (p>0.05)*

It was seen that for all fish, hot air drying exhibited highest moisture diffusivity followed by solar cabinet and freeze drying, whereas, open sun drying showed the lowest diffusivity values. Freeze-drying was the best method of drying for Bombay duck and Prawns resulting in high quality dehydrated product, but it was high energy intensive process. Solar cabinet drying was found to be low energy intensive process compared to freeze and hot air drying resulting in acceptable quality dehydrated fish product.

1.12.1. Economics of Solar Dryers

Solar dryers are generally capital intensive and therefore the financial viability is the key to successfully compete with any of the other dryers. The financial analysis generally includes the cost of dryer (fixed cost), cost of drying (operating expenses) and payback. They can be viable only if the annual cost of extra investment (on the solar dryer) could be balanced against fuel savings, or if the equipment cost could be reduced (Jayaraman, 1995). The user or dryer designer looks for a favourable combination of cost, energy efficiency, quality, and price of the final product (Crapiste and Rotstein, 1997). Payback is the measure of time (number of days/months/years) it takes to recoup the total investment made on a dryer, in the form of operational cash inflow. Payback analysis does not measure the profitability of dryer as it does not take the service life of dryer into consideration. This is discussed in detail by Brenndorfer et al. (1987). Continued use of the dryer rather than seasonal use will decrease the drying cost and payback (Arinze et al., 1996). Economic analysis on a solar dryer should also incorporate the cost benefits due to improved quality, higher yields, less floor area and quicker drying (Sreekumar, 2010).

1.12.2. Dynamic Methods of Economic Evaluation

The economic evaluation of solar dryer ultimately aims at determining the payback time. For the calculation of payback time the dynamic method of calculation takes into account the influence of inflation. The following considerations summarize this method, according to Boer (1978). Payback occurs when the accumulated savings S equals the sum of investment capital (I) plus yearly interest and the accumulated costs (E):

$$S = I + E \tag{1.18}$$

The annual accumulated savings can be calculated from the net income D by reducing the mass and quality losses and thus by increasing the marketing price of the product in case of natural solar dryers.

For passive solar dryers, savings can be calculated from the price of the substituted conventional energy D. Considering the annual interest rate r and the yearly inflation rate (e) for the prices of energy, for n years the annual accumulated savings can be calculated as follows:

$$S = \frac{(1+r)^n - (1+e)^n}{r-e} D \tag{1.19}$$

The sum of first investment cost (C) with interest will be, during n years,

$$I = C(1+r)^n \tag{1.20}$$

Accumulated yearly costs, taking the annual fixed charge rate mC and inflation rate i for equipment into consideration, will be

$$E = \frac{mC(1+r)^n - mC(1+i)^n}{r-i} \tag{1.21}$$

Knowing C and D, diagrams can be made for the determination of payback time n, referring to values of r, m, i and e. From these diagrams the requirements for the expected payback time can be easily seen. Figure 1.44 shows the payback time as a function of D/C for various values of r, m, i, and e, following Boer (1978). One can see from the diagram which D/C values can bring about the desired payback time when the various other parameters are at given values. With parameters differing from the above, the calculation must be made separately following Equation 1.16 through Equation 1.19. A comparison of curves 1 and 2 indicates the influence of interest rate r in cases with no inflation; curves 3 and 6, when compared, lead to the effect of energy prices.

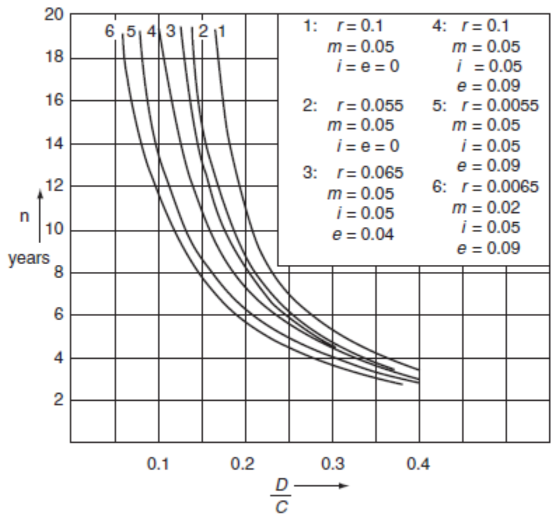

Figure 1.44. Payback time in years as a function of D/C, with different parameters r, m, I, and e. (Boer, 1978)

As can be seen in all the cases examined, the D/C ratio needed for a 10-year payback time falls in the 0.12–0.23 range. Since payback time is a function of D/C, it is obvious that cheaper (smaller C) and less efficient (smaller D) installations are justified insofar as realization of less expense does not mean a significant decrease in the durability (lifetime) of the system. Payback calculations refer to the whole solar energy drying system (Kwon et al., 1980 and Gordon and Rabl., 1982). With appropriate division of the costs, there is of course nothing in the way of making the calculation only for the collector system (Vaishya et al., 1981 and Kovarik, 1978). Construction of the collectors can be planned on the basis of the economic optimum (Vijeysundera at al., 1982 and Chiou aet al., 1965). When the application of a solar dryer results in improved quality of the dried product, the value of D is savings S and has to be increased in relation to the value of the quality enhancement. Table 1.8 shows the economic analysis for Bombay duck fish as a test case using the data given in Table 1.7.

Table 1.6. Data used for economic analysis

Batch size approx.(kg)	40
Total drier cost (US$)	5,400
Depreciation (%)	10
Recovery period (yrs)	3
Product cost price (US$/kg)	0.1

Selling price (US$/kg)	3.4
Annual sale (US$)	4,000
Annual cost (US$)	1,600

Table 1.7. Economic Analysis for Solar Cabinet Drying at ICT Mumbai

Product	Bombay duck *(Harpadon nehereus)*
I.M.C approx. (% w.b)	85
F.M.C approx. (% w.b)	8-10
Drying time (hours)	10
Drying cost (US$/kg)	0.16
Dried product obtained per annum (kg)	1200
Payback period (years)	1.8

Table 1.8. Economic analysis for Bombay duck fish

Economic Analysis of Bombay duck:
Depreciation = (5,400-540)/3 = 1,620 US$/y
Annual profit = 4,000-1,600
= 2,400 US$
Annual earnings =2,400-(5,400-540) × (0.65)/3
= 1,347 US$/yr
Pay-back period = Fixed capital/(Annual earning +Depreciation)
= 5,400/ (1,347 + 1,620)
= **1.8 years**

1.13. CONCLUSIONS

- A comprehensive review of the fundamental principles governing the drying process with classification of the practically realized various designs and selection of solar dryers for drying of agricultural and marine products has been presented.
- The classification clearly illustrates that the solar dryer designs can be grouped systematically according to their operating temperature ranges, heating sources/modes and operational modes.
- It is difficult to have one single criteria for the selection of a solar dryer for a specific region or a product as solar insolation and other parameters change frequently with geographical location, however the general rules of thumb are mentioned to assist in making the final selection.
- The final selection is generally based on the available insolation rate, production throughput, flexibility requirements, cost of fuel to run accessories as well as on the experience and judgment of the fabricator.
- As the solar dryer has a long life of about 20-40 years, the effect of a poor design can have a long-term impact on the economic health of the dryer.

NOMENCLATURE

SCD	solar cabinet dryer
OSD	open sun dryer
FD	freeze dryer
HAD	hot air dryer
E_{sp}	Specific energy consumption, kJ kg^{-1}
DT	drying time, h
a	heat transfer area, m^2
D	diameter, m
X	moisture content, kg/kg dry solid
m_w	mass of water, kg
m_d	mass of dry solid, kg
H_s	saturation humidity, kg/kg dry air
p	partial pressure of water vapor in the air
p_s	vapour pressure of water
P	absolute pressure
H_R	percent relative humidity
C_s	humid heat of moist air, kJ/(kg· K)
T,	temperature, K
h	heat-transfer coefficient by convection, J/(m^2· s· K)
$dw/d\theta$	drying rate, kg water/s
k_g	mass-transfer coefficient, kg/(s· m^2· atm)
d	thickness of bed, m
C, K	constants
c_p	specific heat, J kg^{-1} K^{-1}
c_s	humid heat, J kg^{-1} K^{-1}
n	number of molecules
F	void fraction
t	drying time
Z	height of cylinder, m
D_L	effective diffusivity, m^2 s^{-1}
D_{L0}	effective diffusivity at reference temperature, m^2 s^{-1}
S	savings
I	capital
E	accumulated cost
D	net income
C	investment cost
i	annual interest rate
e	annual inflation rate
n	years/ pay back period

Greek letters

α_w	water activity,
θ	drying time, h
λ	latent heat of evaporation, J/kg
ρ	density, kg/m^3
φ	relative humidity
⍰	normalized drying rate, -
⍰ $_s$	latent heat of vaporization, J kg^{-1}

Subscripts

sp	*specific*
c	constant rate period
f	falling rate period
t	total
mon	monolayer
eq	equilibrium
w	water

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Chapter 2
Solar Drying of Fruits and Vegetables

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Contents

2.1. INTRODUCTION

Apart from the rise of energy costs, legislation on pollution, sustainable and eco-friendly technologies have created greater demand for energy efficient drying processes in the food industry. The food industry can save money by employing energy efficient methods like solar drying. Fruits and vegetables are important sources of essential dietary nutrients such as vitamins, minerals and fiber. Since the moisture content of fresh fruits and vegetables is more than 80%, they are classified as highly perishable commodities (Orsat et al., 2006). Keeping the product fresh is the best way to maintain its nutritional value, but most storage techniques require low temperatures, which are difficult to maintain throughout the distribution chain. On the other hand, drying is a suitable alternative for post harvest management especially in countries like India where exist poorly established low temperature distribution and handling facilities. It is noted that over 20% of the world perishable crops are dried to increase shelf-life and promote food security (Grabowski et al., 2003). Major quality parameters associated with dried fruits and vegetables include color, visual appeal, shape of product, flavor, microbial load, retention of nutrients, porosity-bulk density, texture, rehydration properties, water activity, freedom from pests, insects and other contaminants, preservatives, and freedom from taints and off-odours (Ratti, 2005).

In many countries, the use of solar thermal systems to conserve vegetables, fruits, and other crops has shown to be practical, economical and environmental friendly approach. Solar heating systems to dry food and other crops can improve the quality of the product, while reducing waste produce and traditional fuels, thus improving the quality of life. However the availability of good information is lacking in most countries where solar food processing systems are most needed. Solar-drying technology offers an alternative which can process the vegetables and fruits in clean, hygienic and sanitary conditions, to national and international standards with. It saves energy, time, occupies less area, improves product quality, makes the process more efficient and protects the environment. (Funebo and Ohlsson, 1998; Zhang et al., 2006).

Agricrops include various fruits and vegetables produced on the agricultural land. Being a high moisture commodity most of these get degraded due to microbial spoilage. Fruits & vegetables with their rich contents of minerals, vitamins, dietary fiber and antioxidants are the protective foods and considered as nature gifts for health and well being of humans. Bacterial rotting by microbial respiration as well as physiological breakdown is seen in most of the fruits and vegetables. Sometimes moisture degradation in the quality of fruits & vegetables also starts immediately after the harvest leading to drying & shriveling. Fruits and vegetables absorb environment gasses such as oxygen and produce carbon dioxide and ethylene. They also get infested easily with micro organisms like fungi, bacteria and insects affecting food safety. Drying is the only way to reduce these losses. In Asian countries like India where fruits & vegetables are grown in plenty, facilities for processing are not in existence & lot of them are wasted almost 30% of total fruits and vegetables are reported as post harvest losses in India.

Food problem arises in most developing countries mainly due to the inability to preserve food surpluses rather than due to low production. Agricultural yields are usually more than the immediate consumption needs, resulting in wastage of food surpluses during the short harvest periods and scarcity during post-harvest period (Ekechukwu and Norton, 1997). Hence, a reduction in the post-harvest losses of food products should have considerable effect on the economy of these countries (Sodha et al., 1986). More than 80% of food is being produced by small farmers in developing countries (Murthy, 2009). These farmers dry food products by sun drying, an advantage being that solar energy is available free of cost, but there are several disadvantages which are responsible for degradation and poor quality of the end product. Certain variety of food products are not supposed to be dried by sun drying because they lose certain basic desirable characteristics (Jairaj et al., 2009). Drying and dehydration of fresh fruits and vegetables is one of the most energy intensive processes in the food industry, good understanding of the drying processes plays a vital role in increasing the drying efficiency as well as in maintaining product quality resulting in significant reduction in postharvest losses. Convective hot air drying is still the most popular method applied to reduce the moisture content of fruits and vegetables (Lewicki, 2006). Fruits and vegetables are dried to enhance storage stability, minimize packaging requirement and reduce transport weight. Energy consumption and quality of dried products are critical parameters in the selection of drying process (Al-Juamily et al., 2007). An optimum drying system for the preparation of quality dehydrated products should be cost effective with low drying time and should cause minimum damage to the product. To reduce the energy utilization and operational cost new dimensional solar dryers are good options for drying of fruits and vegetables.

2.2. FRUITS AND VEGETABLES

Fruits and vegetables are the fresh agriproduce having high moisture content and are perishable in nature; fruit normally means the fleshy seed-associated structures of certain plants that are sweet and edible in the raw state, such as apples, oranges, grapes, strawberries, juniper berries and bananas. Vegetable usually means an edible plant or part of a plant other than a sweet fruit or seed. This typically means the leaf, stem, or root of a plant. Some vegetables can be consumed raw, some may be eaten, cooked, some must be cooked in order to be edible and some are dried to increase the shelf life.

Fruit drying has a long tradition. Inhabitants living close to the Mediterranean Sea and in the Near East traded fruits that had been dried in the open sun. Dried fruit is a delicacy, because of the nutritive value (66– 90% carbohydrate) and shelf life. Today, the production of dried fruits is widespread. Nearly half of the dried fruits in the international market are raisins, followed by dates, prunes, figs, apricots, peaches, apples, pears, and other fruits. Significant amounts of sour cherries, cherries, pineapples, and bananas are also dried. The selection of fruit for drying depends on local circumstances. Fruits can be dried whole, in halves, or as slices, or alternatively can be chopped after drying. The residual moisture content varies from small (3–8%) to large (16–18%) amounts, according to the type of fruit (Josef, 2006).

A wide range of dried fruits and vegetables are available in the market in whole, sliced, or ground form. Reduction in moisture during drying of high-moisture materials, like fruits and vegetables, induces changes in shape, density, and porosity. Product quality plays a major role in food drying operation. Upon rehydration, dried vegetables should exhibit desirable sensory and nutritional quality. Numerous processing techniques have been practiced for drying of vegetables. However, it should be noted that water should be removed in such a way that dehydrated products can easily be rehydrated to regain their structure (Jasim, 2011). In fruits and vegetables drying, diffusion transport mechanism has a significant role, especially during the falling rate period, which is controlled by the mechanism of liquid and vapor diffusion. This behavior indicates an internal mass transfer-type drying with moisture diffusion as the controlling step. The water diffusion coefficient reflecting the whole complexity of water transport is referred to as an effective coefficient. Generally, it is difficult to predict the effective mass diffusion coefficient values theoretically; therefore, experimental techniques based on sorption/desorption kinetics, moisture content distribution, or porosity can be used (Bialobrzewski and Markowski, 2004). For vegetables with significantly high moisture content, like celery, it is often assumed that mass diffusion is determined by external conditions of mass transfer. The rate of moisture movement during drying is well described by effective diffusivity (D_{eff}) value (Jasim, 2011).

2.2.1. Fruits

Fruits are mainly fleshy and compound in nature with high moisture content (Table 2.1), All these are as follows,

Table 2.1. Types of Fleshy fruit and Compound fruit

True berry	Pepo	Hesperidium	Aggregate fruit	Multiple fruit	Accessory fruit
Blackcurrant, Redcurrant, Gooseberry, Tomato, Eggplant, Guava, Lucuma, Chili pepper, Pomegranate, Kiwifruit, Grape, Cranberry, Blueberry	Pumpkin, Gourd, Cucumber, Melon	Orange, Lemon, Lime, Grapefruit	Blackberry, Raspberry, Boysenberry	Pineapple, Fig, Mulberry, Hedge apple	Apple, Rose hip, Strawberry

Fleshy fruit, which includes:

Berry – simple fruit and seeds created from a single ovary

Pepo – Berries where the skin is hardened, like cucurbits

Hesperidium – Berries with a rind and a juicy interior, like most citrus fruit

Compound fruit, which includes:

Aggregate fruit – with seeds from different ovaries of a single flower

Multiple fruit – fruits of separate flowers, merged or packed closely together

Accessory fruit – where some or all of the edible part is not generated by the ovary

2.2.2. Vegetables

The green colour of most vegetables is due to chlorophyll, which is the most widely distributed plant pigment. The most common change that occurs in green vegetables during thermal processing and storage is the conversion of chlorophyll to pheophytins, causing a colour change from bright green to olive-brown, which is undesirable to the consumer (Schwartz and von Elbe, 1983; An-Erl King et al., 2001). For green vegetables, pretreatment prior to drying can aid the chlorophyll retention during the drying operation. When vegetables are maturing in the field they are changing from day to day. There is a time when the vegetable will be at peak quality from the stand-point of color, texture and flavor. This peak quality is short and may last only for few days. The vegetables can be stored, in some specific natural conditions, in fresh state that is without significant modifications of their initial organoleptic properties. Fresh vegetable storage can be achieved by short term like freezing or by cold storage and long term by drying. In order to assure preservation for long term storage, it is necessary to process them by drying (Jairaj et al., 2009).

Vegetables are classified according to which part of the plant is consumed. Some of the vegetables may fall into more than one category as more than one part of the same plant is consumed.

2.2.2.1. Types of vegetables

Leafy Vegetables: The plants whose edible parts are the leaves. They are valued because of their mineral and salts content. These includes, broccoli, cauliflower, globe artichokes, kale, collard greens, spinach, arugula, beet greens, bok choy, chard, choi sum, turnip greens, endive, lettuce, mustard greens, watercress, garlic leaves, cabbage, fenugreek, spinach, coriander etc.

Fruit and flower vegetables: The plants whose edible parts are the fruits and the flowers, they are fruits or buds of flowers in reality but are used as vegetables. They are avocado, bitter melon, capsicum, cucumber, eggplant, olive, pumpkin, tomato, snake gourd, winter melon etc.

Root, Tuber and Bulb vegetables: The varieties included in this class are closely related as to food value. Bulbs are usually grown just below the surface of the ground and produce a fleshy, leafy shoot above ground. Bulbs usually consist of layers or clustered segments, Such as onion and garlic. Tubers are vegetables which grow underground on the root of a plant, Such as sweet potatoes, beets, radishes. Roots are a long or round-shaped taproot, Such as asparagus, beet root, carrot, Yam etc.

Podded vegetables: They include all the varieties of beans, peas, and lentils. When these foods are mature and dried, they have the highest food value of all the vegetables. They include, chick pea, drum stick, soyabean, indian bean, okra, moong bean, lentils, peanuts etc.

Seaweed vegetables: Seaweed offers a wealth of essential nutrients found in human blood serum including vitamins, minerals, enzymes, amino acids and fatty acids. They includes Aonori, Carola, Dabberlocks, Dulse, Hijiki, Kombu, Mozuku,Nori, Sea grape etc.

Fungi vegetables: Fungi are commonly known as mushrooms. These includes, cultivated mushroom, honey mushroom, oyster mushroom, shiitake mushroom, straw mushroom etc.

2.2.3 States of Water in Fruits and Vegetables

Water in vegetables is present mainly in two forms, free (or unbound) and bound. Free water behaves as pure water, and bound water, which is physically or chemically bound to food materials, exhibits vapor pressure lower than that of pure water at the same temperature. Free water is the first fraction of moisture adherent to the food surface to be removed. Water remains in the pores and the capillaries. Bound water may exist in different forms: unfreezeable, immobile, monolayer, etc. A fraction of bound water is loosely adsorbed to food materials while higher energy requirement is necessary to remove the trapped water (Jasim, 2011).

Fruit drying involves removing water in different forms (both free and bound) and different amounts. The amount and manner of water removal change the structure of fruit depending on the type of bonding, and also determine the character of the reconstituted dried material. Among the various bonding forms of water, the strongest is the chemical, physicochemical bonding, followed by adsorption, osmotic, micro- and macro-capillary, and, finally, rehydration. During drying, the weakest bound water is removed first; removing moisture by breaking stronger bonds requires energy. Removal of free water does not change the character of the material in either the dried or rehydrated states. Significantly higher energy and special procedures are required to remove bound water, i.e., to decompose the higher bonding energies (Ginzburg, 1968; Ginzburg 1976).

Drying a moist material and decreasing the water activity means evaporation of bound water from inside the solid material into the atmosphere. Breaking water bonds, releasing, and transferring heat connected to phase change require energy. Drying can be done with different types of drying energy: convective (warm air), contact (cooled surface), and radiative (infrared rays), and excitation (microwave) energies. With convective drying, the heated air flow in moisture content meets the wet material and as a result, the moisture moves onto the surface of the material and then into the drying air. Tasks of the warm air are to transfer heat to the material being dried to establish the drying potential and to transfer moisture into the air (Josef, 2006).

Drying technology of fruits and vegetables involves three basic steps

- Preliminary and preparative procedure: cleaning, Washing, slicing and pre-treatments if necessary
- Drying procedure
- Processing after drying, secondary treatments : packaging and storage

2.3. WHY SOLAR DRYING OF FRUITS AND VEGETABLES?

Solar energy a form of sustainable energy has a great potential for wide variety of applications because it is abundant and accessible, especially for countries located in the tropical region. Solar drying of fruits and vegetables overcomes the drawbacks of traditional open sun drying such as, contamination from dust, insects, birds and animals, lack of control over drying conditions, possibility of chemical, enzymic, and microbial spoilage due to long drying times. Solar drying is advantageous over normal convective dryers like hot air dryer, which requires enormous fuel and energy cost.

Due to abundant availability of solar radiation attention has been gradually diverting to utilize this renewable energy for a number of applications. Among these dehydration of food & non-food items is an important sector. This solar drying enables Good Manufacturing Practices (GMP) & yields export worthy processed foods with long shelf life meeting the sanitary & phyto sanitary standards of the importing countries. This novel technology is a very viable & valuable one.

Solar drying of agricultural produce permits

(1) Early harvest;

(2) Planning of the harvest season;

(3) Long-term storage without deterioration;

(4) Taking advantage of a higher price a few months after harvest;

(5) Maintenance of the availability of seeds; and finally

(6) Selling a better quality product

Drying using the sun under the open sky for preserving food and agricultural crops has been practiced since ancient times. However, this process has many disadvantages, spoilt products due to rain, wind, moisture and dust; loss of produce due to birds and animals; deterioration in the harvested crops due to decomposition, insect attacks and fungi, etc. Further, the process is labor intensive, time consuming and requires a large area for spreading the produce out to dry. Artificial mechanical drying, a relatively recent development, is energy intensive and expensive, and ultimately increases the product cost. Solar-drying technology offers an alternative which can process the vegetables and fruits in clean, hygienic and sanitary conditions to national and international standards with zero energy costs. It saves energy, time, occupies less area, improves product quality, makes the process more efficient and protects the environment (Sharma et al., 2009). Difference between the open sun drying and solar drying is as in Table 2.2.

A typical solar food dryer improves upon the traditional open-air sun system in five important ways:

- It is faster. Foods can be dried in a shorter period of time. Solar food dryers enhance drying times in two ways. Firstly, the translucent, or transparent, glazing over the collection area traps heat inside the dryer, raising the temperature of the air. Secondly, the flexibility of enlarging the solar collection area allows for greater collection of the sun's energy.
- It is more efficient. Since foodstuffs can be dried more quickly, less will be lost to spoilage immediately after harvest. This is especially true of products that require immediate drying such as freshly harvested grain with high moisture content.

- It is hygienic. Since foodstuffs are dried in a controlled environment, they are less likely to be contaminated by pests, and can be stored with less likelihood of the growth of toxic fungi.
- It is healthier. Drying foods at optimum temperatures and in a shorter amount of time enables them to retain most of their nutritional value such as vitamin C.
- It is cheap. Using freely available solar energy instead of conventional fuels to dry products.

Table 2.2. Difference between open sun drying and solar drying

Open sun drying	Solar drying
Traditional method	More recent invention
Delayed drying	Fast drying
Problems of contamination by birds, insects, etc	No contamination
Less hygienic & less clean	Highly hygienic & very clean
Inferior quality products	Best quality products
May not meet GMP	Meets GMP requirements
Drying possible only on sunny days	Drying possible on all days including cloudy and rainy days with electrical backup
Poor sensory qualities to products - Appearance/Color & Textures	Highly acceptable sensory qualities to products -attractive appearance, color & Texture
Uneven drying	Even/Uniform drying
More nutrient loss	Better nutrient retention
Low profit margins	Best profit margins due to quality products
Space required is higher	Low space required

2.3.1. PRETREATMENTS BEFORE SOLAR DRYING

Fruits, vegetables and their products in the dried form are good sources of energy, minerals and vitamins. However, during the process of dehydration, there are changes in nutritional quality (Sablani, 2006). Product quality is becoming more and more important for dehydrated fruits and vegetables, which must retain quality attributes (color, texture) and nutritional quality after rehydration. Improvement of such qualities can be achieved by pretreatments before drying. Suitable pretreatments can improve the drying process by reducing the drying time, yielding higher-quality products, and energy savings. A more number of vitamins such as A, C and thiamine are heat sensitive and sensitive to oxidative degradation. Sulphuring can destroy thiamine and riboflavin while pre-treatment such as dipping in sulphite solutions reduce the loss of vitamins during drying. As much as 80% decrease in the carotene content of some vegetables may occur if they are dried without enzyme inactivation. However, if the product is adequately blanched then carotene loss can be reduced to 5%. Steam blanching retains higher amounts of vitamin C in spinach compared with hot-water blanching (Ramesh et al., 2001). Blanching in sulphite solution can retain more ascorbic acid in okra (Inyang and Ike, 1998).

Pre-drying treatments such as addition of sugars are needed for vegetable drying in order to avoid damages to tissue structures. Previous work has shown that non-reducing disaccharides such as sucrose and trehalose can protect biological systems from the adverse effects of freezing and drying. Especially trehalose is known to have many advantages. For example, sweetness of a 10% trehalose solution is 45% as that of a 10% sucrose solution. Trehalose is a non-reducing sugar and therefore does not react with amino acids or proteins to cause Maillard browning. Pretreatment with trehalose solution has been claimed to be very effective for producing high quality dried vegetable chips Aktas et al., (2004) found that pretreatment with trehalose solution improved the reconstitutional properties of dried sliced carrot and potato samples compared with the dried products pre-treated with sucrose solution, which is generally used for osmotic dehydration as shown in Figure 2.1. Osmotic treatment is a simultaneous water and solute diffusion process (Rastogi et al., 2004). Many studies showed that sucrose treatment increases the water loss compared with the other osmotic solutions (Reppa et al., 1998; Khiabani et al., 2002).

Various pretreatment methods may be used in conjunction with the drying process to maintain or even improve the quality of a dried product. Among many methods of pretreatment blanching is one of the most common. Blanching is usually performed prior to drying to inactivate enzymes responsible for various undesirable enzymatic reactions. Blanching also helps with color retention and modification of product texture (Mate et al., 1999; Ahmed et al., 2001). Moreover, blanching can help increase the drying rate, hence reducing the drying time (Severini et al., 2005). Dipping or soaking a product (especially vegetable) in organic acids such as citric acid, lactic acid or acetic acid (Karapinar and Gonul, 1992; Yu et al., 2001) is an alternative to blanching as these pretreatment methods can help reduce the number of normal flora and pathogenic organisms. Some organic acids such as acetic acid have been noted to reduce the activity of enzymes responsible for browning (Naphaporn et al., 2010). These are the various pretreatments that can be employed prior to solar drying of fruits and vegetable.

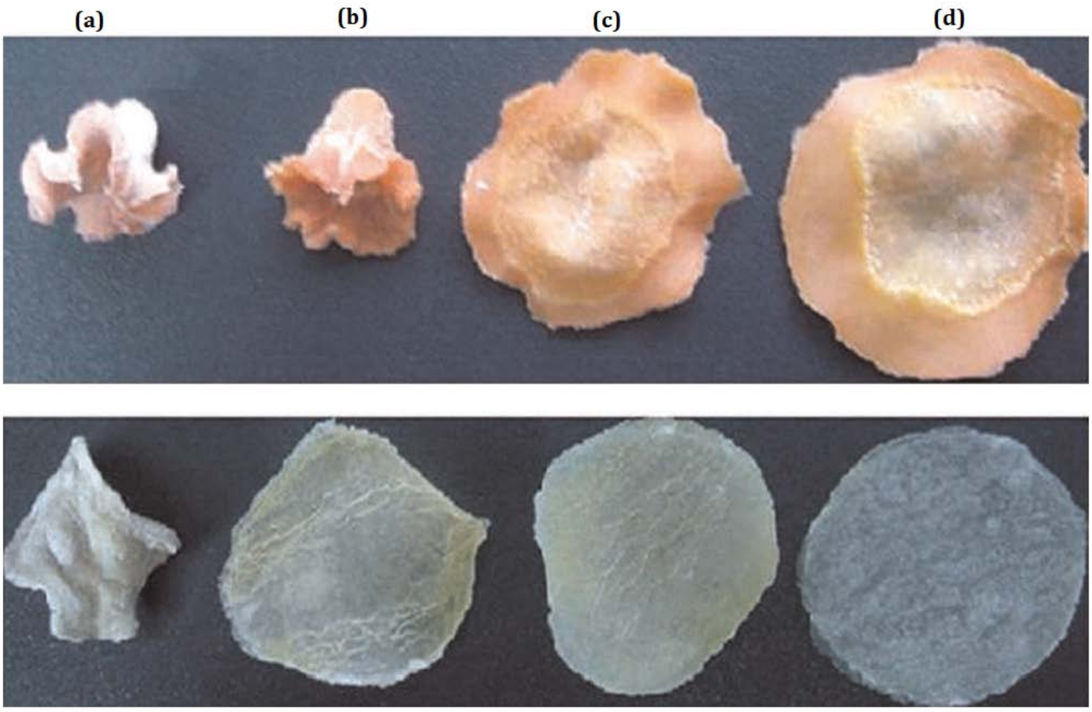

Figure 2.1. Photographs of sliced carrot (upper) and potato (lower) samples after drying at 323 K: (a) non-treated sample, (b) blanched sample; (c) sucrose solution treated sample, (d) trehalose solution treated sample (Aktas et al., 2007).

2.4. A CASE STUDY ON GRAPE

The world production of grapes is presently 65,486 million tonnes (Sharma and Adulse, 2007). Grapes and grape products are among the world's most important horticultural products and consequently are of major commercial interest. They are served as a fresh fruit, dried into raisins, preserved or canned in jellies and jams, and crushed for making juice or wine. Grapes accounted for nearly 13% of total fruits. (Moulton and Possingham, 1998). Drying the grape, either by open sun drying, shade drying or mechanical drying, produces raisins (Fadhel et al., 2005). Raisin is a source of carbohydrates and it contains large amounts of iron, vitamins and minerals (Doymaz, 2006). Raisins are usually included in breakfast, cereals, dairy and bakery as well as confectionery products and more recently in nutritional bars (Ramos et al., 2004). Commercially, grapes are grouped into four major classes and one minor group: (i) table grapes, (ii) raisin grapes, (iii) wine grapes, (iv) sweet juice grapes, and (iv) canning grapes (the minor group). Raisins are the second most important product of the grape vine, wine being the first. Raisins are also classified as currents, golden raisins, monukka raisins, Muscat raisins, dark raisins, and sultanas. Raisins are produced mainly from four varieties, Thompson seedless, Muscat, Sultana, and Black Corinth. Preservation of grapes by drying is a major industry in several parts of the world where grapes are grown.

The grape with an outer waxy cuticle and a pulpy material inside is a complex product for dehydration. The outer waxy cuticle controls the moisture diffusion rates during drying. A chemical or physical treatment is generally applied to decrease skin resistance and hence, improving moisture diffusion through waxy cuticle (Ponting and McBean, 1970). The dipping pretreatment not only reduces drying time but in certain cases also improves the quality of raisins produced. Dipping in hot water and the use of chemicals such as sulfur, caustic, and ethyl oleate (EO) or methyl oleate emulsions are some of the pretreatments widely used in grape drying. These chemicals facilitate the drying process by altering the structure of waxy layer, thus reducing the resistance to water diffusion (Ponting and McBean, 1970; Riva and Peri, 1986). EO acts on grape skin by dissolving the waxy components, which offer high resistance to moisture transfer, yet higher alkali concentrations and longer dipping times can cause adverse changes in dried grapes (Saravacos et al., 1988). Loss of moisture from berries during air-drying is accompanied by changes in fruit structure and texture, such as fruit softening or loss of firmness, which are related to their microstructure. Texture is an important quality criterion of raisin when they are consumed after rehydration in breakfast cereals and dairy and bakery products (Bhat et al., 2006).

This case study is adapted from research work carried out in Advanced Drying Lab, Mumbai, India. A solar cabinet dryer (M/s NRG Technologies, Baroda, India) is used for drying of garlic slices. The solar cabinet dryer has 32 number of perforated aluminum trays. Each tray is having area of 0.46 m^2 with raw material loading density 4 kg/m^2 in the cabinet. The air was heated by non-tracing solar collector panel with 40 m^2 collector area and the heated air was distributed in drying chamber by a blower fitted in a duct located at the left side of cabinet. The air velocity, air temperature and relative humidity in the cabinet were in the range 0.9-1.0 m/s, 53-57°C and 35-45%, respectively. Pilot scale solar cabinet dryer is used for drying of grapes as shown in the Figure 2.2. Figure 2.3. shows various stages during grape drying. Fresh grape consists of 70 to 80% water and many dissolved solids. These soluble solids included numerous organic and inorganic compounds. In grapes, a large portion of the soluble solid is sugars. Glucose and fructose were the main sugars in the grape. The sugar content of the ripe grapes varies between 150 to 250 g/L. In unripe grapes, glucose was the predominant sugar. At the ripening stage, glucose and fructose were usually present in equal amounts (1:1 ratio). In overripe grapes, the concentration of fructose exceeds that of glucose. Various pretreatments used before drying are caustic (NaOH), ethyl oleate, boiled and cold, sulphur fumigation and potassium metabisulphite treatment. Ethyl oleate treatment reduces the drying time to 17 hrs as compared to 12 days time of traditional drying. The solar drying is carried out on trays at 55-58°C. Treatment with ethyl oleate, caustic and boiled and cold requires 17, 22 and 25 hrs respectively. Untreated grapes require 60 hrs of time in the solar dryer. While in the case of traditional drying under the sun or shade drying (Figure 2.4) it takes 10-12 days. Grape drying by solar is as given in the Figure 2.5. Different pretreatment before solar drying produces raisins with different surface appeal and color those are as given in the Figure 2.6. Functions of different pretreatments are as follows,

Caustic/Lye treatment: It is a hot dipping solution of sodium hydroxide (90°C, for 5sec) causes cracking and perforation in the waxy cuticle, increase the drying rate by caustically creating fissures in the product's surfaces

Sulphur Fumigation: This is time consuming process, it requires at least 6 hrs of contact time between grapes and sulphur fumes.

Potassium metabisulfite: This solution is used to prevent darkening of grapes. Prevent browning and helps to maintain light yellow colour. Easy to use and handle than sulphur fumigation because sulphur fumigation is a time consuming process, leads to development of golden brown color than light yellow colour. Potassium metabisulfite used to reduce the darkening due to both enzymic and nonenzymic browning during drying and storage

Ethyl oleate: Ethyl oleate solution in the concentration of 0.5 to 2% in water is used to remove the waxy cuticle layer on the grapes.

Boiled and Cold: Grapes are dipped in the boiled water for 60 sec and immediately dipped in to the cold water this develops cracks on the surface of the grapes and hence eases the drying process

Figure 2.2. Pilot plant of Solar cabinet dryer

Fresh Grapes During Solar drying Dried Raisins

Figure 2.3. Various stages during grape drying

Open sun drying by road side

Shade drying

Unloading of dried raisins

Grading of raisins

Figure 2.4. Traditional way of Grape drying in the Nasik (India) Region

Tray loading on solar

During drying

Figure 2.5. Grapes drying by solar

Ethyl oleate treated

Sulphur treated

Boiled and cold treated

Figure 2.6. Different pretreated raisins

2.5. A CASE STUDY ON GARLIC

Garlic is a bulbulous perennial vegetable spice. The bulb is composed of pungent bulblets commonly known as cloves. Garlic in its dried form is used as an ingredient in precooked foods and instant convenience foods including sauces, gravies, and soups. The increased use of garlic has resulted in the demand of dried garlic. Almost 30% of the fresh produce of garlic gets wasted because of high moisture and improper handling and storage. To reduce these losses solar drying is a good option for the farmers to process their own garlic produce (Aware and Thorat, 2011). A solar cabinet dryer (M/s NRG Technologies, Baroda, India) is used for drying of garlic slices. The solar cabinet dryer has 32 number of perforated aluminium trays. Each tray is having area of 0.46 m^2 with raw material loading density 4 kg/m^2 in the cabinet. The air was heated by non-tracing solar collector panel with 40 m^2 collector area and the heated air was distributed in drying chamber by a blower fitted in a duct located at the left side of cabinet. The air velocity, air temperature and relative humidity in the cabinet were in the range 0.9-1.0 m/s, 53-57°C and 35-45%, respectively. Pilot scale solar cabinet dryer is used for drying of garlic as shown in the Figure 2.2.

Fresh garlic bulbs are opened to remove each separate cloves of garlic. Each clove is peeled using a peeler and peeled garlic cloves are sliced (2mm) using a slicer. These slices are kept on solar trays for drying. . It requires 5 hrs to dry the garlic slices of 2mm. The images of the dried garlic slices and garlic powder are as follows in the Figure 2.7. Dried garlic slices are analyzed for the actives like allicin and also for other properties like color analysis texture analysis etc.

Figure 2.7. Solar Dried Garlic Flakes and Garlic Powder

2.6. A CASE STUDY ON FENUGREEK

This case study is adapted from research work carried out in Advanced Drying Lab, Mumbai, India. A solar cabinet dryer (M/s NRG Technologies, Baroda, India) is used for drying of garlic slices. The solar cabinet dryer has 32 number of perforated aluminium trays. Each tray is having area of 0.46 m^2 with raw material loading density 4 kg/m^2 in the cabinet. The air was heated by non-tracing solar collector panel with 40 m^2 collector area and the heated air was distributed in drying chamber by a blower fitted in a duct located at the left side of cabinet. The air velocity, air temperature and relative humidity in the cabinet were in the range 0.9-1.0 m/s, 53-57°C and 35-45%, respectively. Pilot scale solar cabinet dryer is used for drying of fenugreek leaves as shown in the Figure 2.2. Fenugreeek due to its better color, flavor and nutrients value it can be used throughout off-season. It can be added in various foods like soup, mixed vegetables etc. The dried fenugreek leaves can be stored for six month. During thermal processing the chlorophyll in leaves converted into pheophytins, causing a color change from bright green to olive brown, which is undesirable. Yadav and Sehgal (1997) has indicated that blanching for a short time results in better retention of β-carotene in Fenugreek. Studies on beta-carotene retention in dried vegetables have shown that maximum retention of beta-carotene is obtained by drying vegetables in a solar drier, compared with open-air sun drying because beta-carotene is highly sensitive to direct sunlight (Mulokozi and Svanberg, 2003).

Green leafy vegetables are, in general, good sources of vitamins and minerals. Various species of edible leafy vegetables such as spinach, amaranthus, mint, coriander, bengal gram leaves and cauliflower leaves are rich in iron and β-carotene. These green leafy vegetables are cheap, β-carotene forms 80 percent or more of total carotene in green leafy vegetables while in other vegetables and fruits, β-carotene forms only 15–20 percent of the total carotene (Nageshwara, 1967). These green leafy vegetables are available only for a short period but can be dried for storage. Dehydrated green leafy vegetables are rich sources of β-carotene and iron and can be used in spare seasons.

Fresh fenugreek leaves are separated from other unwanted parts like stem and roots, washed with water, pretreated and solar dried at 50 - 55°C. It takes 3-4 hrs to dry the fenugreek leaves, Fresh fenugreek leaves and solar dried powder is as shown in Figure 2.8. pretreatments given to fenugreek leaves are,

- Sample A - Control sample of methi leaves
- Sample B - Fenugreek leaves treated with steam
- Sample C - Fenugreek leaves treated with 0.1% Sodium bicarbonate
- Sample D - Fenugreek leaves treated with 0.5% Sodium meta bisulfate
- Sample E - Fenugreek leaves treated with 0.5% Citric acid

Fresh fenugreek leaves

Dried powder of fenugreek leaves

Figure 2.8. Solar drying of fenugreek leaves

Figure 2.9. Different pretreated solar dried fenugreek leaves

Various analysis is carried out after dehydration like chlorophyll, carotene and saponins determination, color analysis, drying kinetics etc. During the drying there is a loss of color. The pretreatments help in retention of greenish color of fenugreek leaves. In solar drying of fenugreek sample C is greener than that of other samples. The sample C which is treated with 0.1% Sodium bicarbonate gives better retention of color as shown in Figure 2.9.

2.7. CONCLUDING REMARKS AND FUTURE SCENARIO

From the work carried out to date on solar drying of fruits and vegetables, it is concluded that the solar dryers can be used to a great extent. Farmers should use solar dryers for drying their own agro produce and the use of solar dryers should be promoted by the respective Government authorities in the particular country. If we think of raisins production in India, still the 95% of the raisins are produced by the traditional open sun drying and shed drying, this inferior quality produce can be overtaken by superior quality produce by solar dryers. But to happen so, some steps should be taken to aware the farmers about the use solar dryers for their own fruits and vegetables produce.

One of the most important potential applications of solar energy is the solar drying of agricultural products. It has been established that solar drying of fruits and vegetables is technically feasible and economically viable. Losses of fruits and vegetables during their drying in developing countries are estimated to be 30–40% of production. The postharvest losses of agricultural products in the rural areas of the developing countries can be reduced drastically by using well-designed solar drying systems. Drying time can be further reduced using the same system with heat storage material. Economically sound farmers capable of moderate investments can choose solar dryers according to their individual requirements. In order to encourage small and marginal farmers to use solar dryers, it is necessary to develop a simple, effective and economical natural convection solar dryer. A multipurpose solar dryer capable of drying a variety of agricultural products on a large scale would be a boon to small and marginal farmers. Among the different types of solar dryers, the indirect mode forced convection solar dryer has been demonstrate to be superior in the speed and quality of drying. Incorporation of sensible and/or latent heat storage media within the solar drying systems accelerate the drying process during the night time and low intensity solar radiation periods and exclude the need for using auxiliary heat sources during low solar radiation seasons. Solar drying of agricultural products appears to be financially quite attractive for cash crops (such as tea, cardamom, turmeric, ginger etc.) However, for drying highly perishable products such as fruits and vegetables, it is extremely important to develop low cost solar drying system preferably using local materials and skills. To improve the acceptability of solar dryers among the farmers, it is necessary to develop a large scale solar dryer, which is economically attractive.

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Chapter 3
Solar Drying of Major Commodity Products

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Contents

3.1. INTRODUCTION

3.1.1. Solar Drying

Solar drying is an alternative option to conventional sun drying and hot air drying for several reasons, mainly due to the unlimited and renewable source of solar radiations, which can be harvested by using appropriate solar collector system. This eliminates the use of fossil fuels and reduces environmental impact due to consumption of non-renewables (Green and Schwarz, 2001). The benefits of solar drying with respects to sun and hot air drying have been discussed in many literatures elsewhere (Garg, 1982; Imre and Palaniappan, 1996; Murty, 2009; Abdullah et al., 2001). In general, solar drying shows several benefits as follow (Esper and Mühlbauer, 1998):

- Significant improvement in product quality (colour, texture and taste)
- No contamination by insects, microorganism and mycotoxin
- Reduction in drying time up to 50%
- Reduction of drying and storage losses
- Considerable increase in shelf life of dried products.

3.1.2. Types of Agricultural Commodities

World commodities can be classified into food and non food types (Table 3.1). Most agricultural commodities are traded in dried form for transportation, storage and handling purposes. The preservation of these commodities is limited by its moisture content as indicated in Table 3.2. Considerable losses can occur due to failure to reach the safe moisture level susceptible to quality degradation. Studies reported that spoilage as high as 18% was incurred during drying after threshing of rice (Bassey, 1989).

Table 3.1. Agricultural commodities traded in market

Type	Examples of commodities
Food	Sugarcane, maize, wheat, rice, paddy, cow milk, vegetables, potatoes, cassava, sugar beet, soybeans, tomatoes, barley, meat, watermelons, bananas, onions, cocoa, coffee, palm oil, fruits etc
Non food	Timber, wool, rubber, cotton etc

The moisture contents of the dried products are often specified in standards issued by specific governing bodies. Failure to comply with these requirements would result in penalty imposed to the sellers/exporters. The additional weight due to the higher mois-ture content not only has an implication on cost, but also on health related issue for some commodities i.e. moulds growth or mycotoxin.

Table 3.2. Range of moisture contents of some agricultural commodities

	Moisture content	
Commodity	Initial	Final
Wheat, barley, rye	20 – 25%wb	14 – 16 %wb
Oats, paddy, corn	25 – 45 %wb	12 – 14 %wb
Coffee	50 %db	11 %db
Cocoa	50 %db	7 %db
Pepper	-	5 %db
Onions, garlic	80 %db	4 %db
Wood	Green	10-12 %db
Cotton seed	-	8 %db

3.2. SOLAR DRYING OF SOME SELECTED COMMODITIES

In this chapter focus will be given to agricultural commodities that are conventionally traded in dried form. Discussion will be based on some selected commodities where drying is the major step involved in processing.

3.2.1. Rice/paddy

Rice is one the most consumed cereal crops in the world especially in most Asian countries. The harvested paddy usually contains very high moisture content in between 20 – 25% and it needs to be dried down to 12 – 14% moisture content. Rice drying is an energy intensive process and the range of specific primary energy consumption could range from 1.587 to 6.89 MJ/kg H2Oevaporated (Jittanit et al., 2010).

Application of solar technology in rice drying can be found incorporated into the primary drying or in-store drying systems. Jittanit et al. (2010) investigated a two-stage drying technique whereby fluidized bed drying at 100 – 110°C was used at the first stage and drying with ambient air by a solar dryer was used in the second stage. Several drying strategies were investigated as shown in Figure 3.1. Drying in ambient air was carried out in an indirect type solar dryer with ambient air heated by the solar collector that is installed before the drying chamber. However, after comparing the energy usage with an industrial drying unit, it was found that the best combination was obtained from drying using an industrial dryer (1st stage) and a solar dryer (2nd stage). Specific primary energy consumption was lower in the solar dryer at 2.88 MJ/kg H2O evaporated as compared to the industrial dryer at 4.72 – 6.29 MJ/kg H2Oevaporated. Energy saving between 41.5 and 60.8 Thai Baht/ton paddy was estimated and potential saving of 1.27 – 1.82 million Thai Baht was calculated based on a 30,000 ton paddy processing plant.

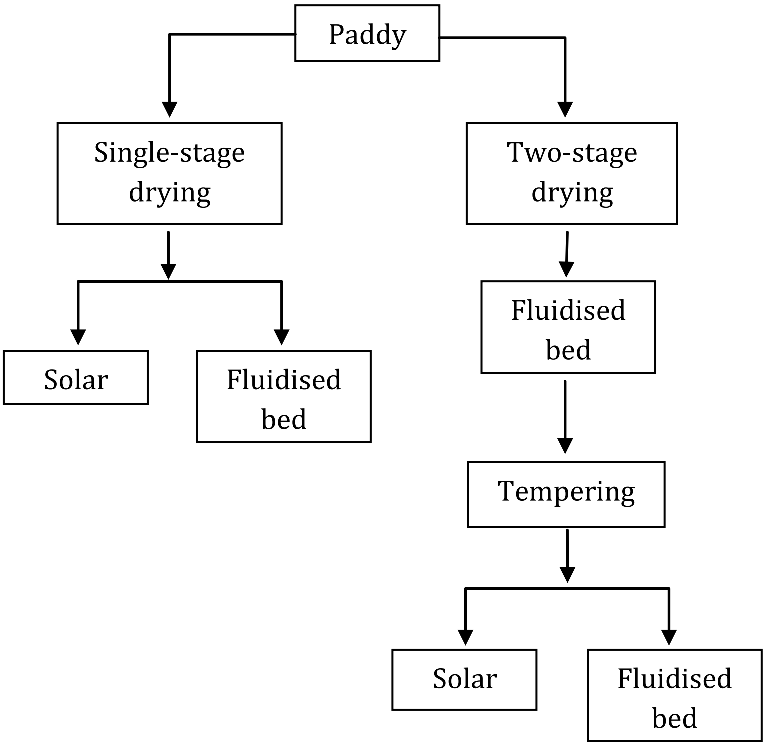

Figure 3.1. Experimental drying strategies for paddy

Kumar et al. (2011) reported experimental studies using an oscillating bed solar dryer for paddy. The dryer consists of a double pass solar collector, blower and a motor powered oscillating bed. The solar collector was constructed using aluminum sheets painted black that acted as an absorber plate. A transparent glass and galvanized sheet were placed above and below the plate. Two reflective mirrors were used to increase the incident radiation on the collector and drying bed. The function of the oscillating bed was to facilitate faster removal of moisture during drying. It was found that temperature increment of 5.7°C – 13.2°C was recorded from the air leaving the collector while additional 3 – 6°C was observed after circulated by the blower. The drying performance of the dryer was the best with bed cover and reflecting mirrors. Maximum pick-up efficiency was recorded at 72.3% while the dryer thermal efficiency was recorded at 35.3% at this combination. Drying can be completed in 1 day for 36 kg of non-parboiled paddy.

Ooi (2006) incorporated solar drying into a box dryer with area 2.4 m x 2.4 m for bed depth of 0.3 m. The corrugated roof was made of galvanized iron or transparent acrylic. When the corrugated iron sheets were used, it worked like a bare plate solar collector with the iron sheets acting as the solar heat absorber (Figure 3.2a). When the transparent acrylic sheets were used, it worked as a glazed solar collector with the iron sheet painted black acting as the solar heat absorber (Figure 3.2b).

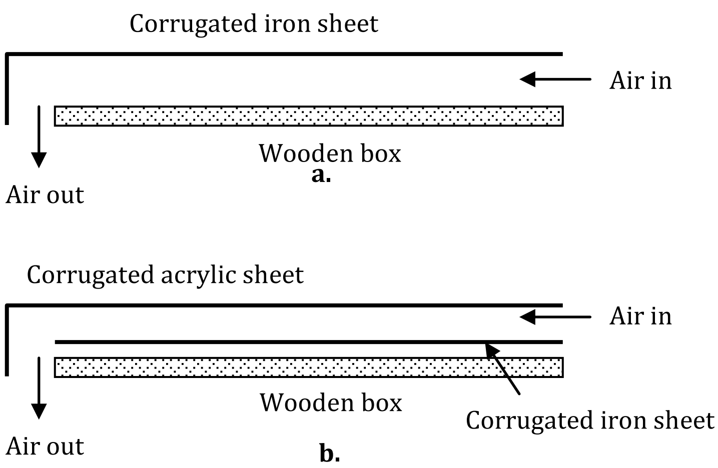

Figure 3.2. The solar collector configuration in a) bare plate b) glazed

Analysis showed that the bare plate collector was capable of operating at 30 – 45% collection efficiency at airflow of 0.1 kg/m^2.s. At an average daily radiation of 4.5 kWh/m^2, the collector is able to raise the drying air temperature by 5 – 10°C with heat output of 0.15 – 0.2 kW/m^2 of collector area. On the other hand, the glazed collector was able to achieve a higher efficiency at 50 – 60% and raised the drying air temperature up to 10 – 20°C with heat output between 0.2 – 0.25 kW/m^2 of collector area.

3.2.2. Corn/Maize

Li et al. (2011) investigated solar assisted heat pump in-store drying for corn. This solar drying system consists of a set of solar collectors, a heat pump and a mechanical grain stirrer (Figure 3.3). Heat was generated from the joint solar collector and heat pump sys-tem. The purpose of installing the heat pump was to solve the problem of the intermit-tent availability of the solar radiation. Four working modes can be selected de-pending on the weather conditions, namely the solar energy heating mode, the heat pump heating mode, the solar assisted heat pump heating mode and the heat pump de-humidification mode, which are summarized in Table 3.3.

Table 3.3. Working mode of the solar assisted heat pump in-store drying system

Mode	Condition
Solar energy heating mode	when solar radiation is sufficient in day time
Heat pump heating mode	when solar radiation is unavailable
Solar assisted heat pump heating mode	when solar radiation is insufficient in day time
Heat pump dehumidification mode	when ambient humidity is high

The components installed in this drying system are as shown in Table 3.4. An air duct connected the solar assisted heat pump system to the bottom part of the granary. During trials, it was observed that the average temperature difference between ambient air and granary inlet air was about 8.9°C while average relative humidity varied from 13.6% to 37.7% lower than the ambient air. It took about 240 hr to reduce the moisture content of the corn from 16.6% to 14.5% (w.b). Power consumption per grain ton to reduce the moisture content by 1 % was 1.24 kWh and the value was much lower than the official standard (2.0 kWh).

Table 3.4. Details of the components installed

Component	Specification
Solar air collector	4 m x 6 m enclosing a total area of 96 m^2
Air source heat pump	Compressor 22 kW
Grain stirrer	2.2 kW and 4 m length auger
Granary	37.2 m x 22.9 m x 7.8 m and capacity 3.7 ton

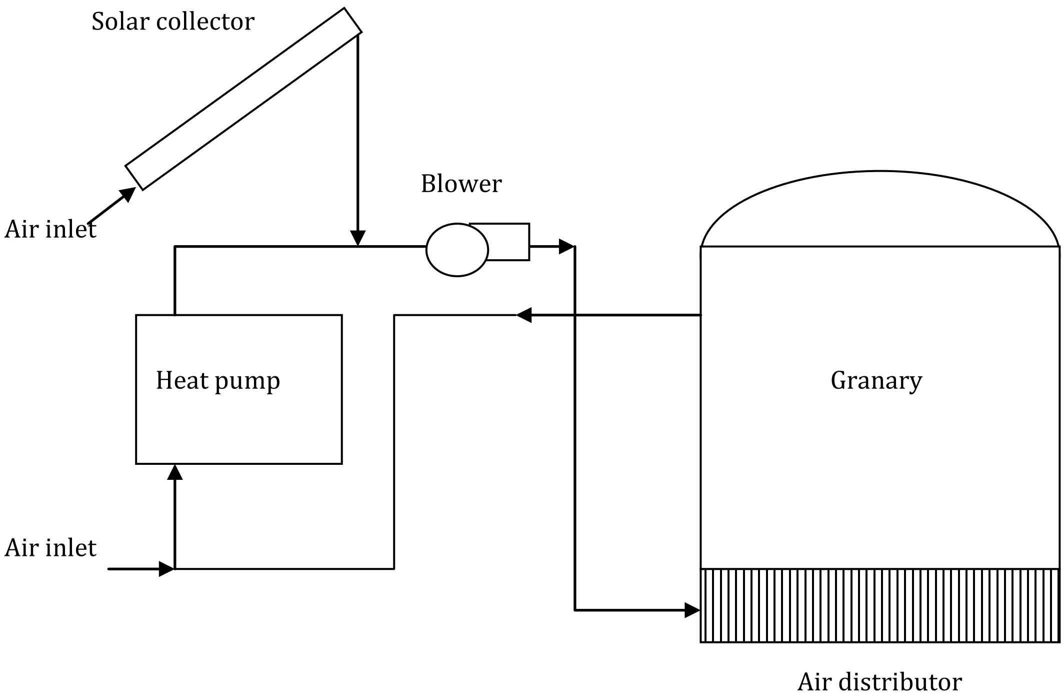

Figure 3.3. The schematic layout of the solar assisted heat pump granary

Santos et al. (2005) developed an in-bin corn drying system that was connected to an energy storage solar collector system (1.8 m^2 of collector area). The bin volume was 1.77 m^3 and able to load with 1.3 ton of corn (bulk density 721 kg/m^3). Pebble bed was used as the energy storage system. Airflow used for drying was supplied at a rate of 2.1 m^3/min. Saving of 30% in fuel consumption can be achieved by drying under these specifications at corn loading of 1.28 ton at 50°C with air flow rate of 1526.8 m^3/day.

A simple solar drying system that consists of three parts namely the collector, drying chamber and air blower was developed and investigated by Abdullah et al. (2011). The solar collector had a V-corrugated absorption plat of two air passes and covered with single glass. Total collector area measured 2.04 m^2. The dimension of the drying chamber measured 1.06 m x 0.66 m x 0.56 m and can be loaded with 38 kg of corn. Moisture content reduction from 21% to 13% can be achieved in 4 hours. The range of drying air temperature obtained was from 30°C to 45°C at ambient condition of 8.5°C to 20°C. The solar collector efficiency can be raised by 3.25% and 11.11% by increasing the volumetric air flow rate from 0.025 m^3/s to 0.03 m^3/s and 0.03 m^3/s to 0.035 m^3/s, respectively.

3.2.3. Cocoa

The solar dryers developed for cocoa drying falls under various categories of design i.e. direct, indirect, tunnel and green house effect solar drying systems. Minka (1986) re-ported no increase in drying rates as compared to sun drying. The solar dryers tested were the marquee dryer, which consisted of a drying platform covered by transparent structure and the solar cabinet dryer. Bonarparte et al. (1998) developed and tested direct solar cabinet (13.5 kg/m^2 loading) and indirect solar dryers (40.4 kg/m^2 loading) and observed temperature increment up to 20°C and 15°C above ambient recorded in these dryers, respectively. Hii et al. (2006) reported no significant finding in product quality between solar and sun dried cocoa beans as quality changes occurred in a rather similar rate in both drying systems (20 kg per batch drying load). The solar dryer developed measured 153 cm x 91.5 cm in area with perforation measured at 1 cm diameter holes arranged in 2 cm square pitch.

A hybrid solar dryer that uses rocks (painted in black) as solar collectors was developed in East New Britain (Hollywood et al., 1996) for 200 – 250 kg bean loading. The drying system consists of two sections namely the solar collector (filled with 3.5 m3 rocks) and the drying chamber (Figure 3.4).

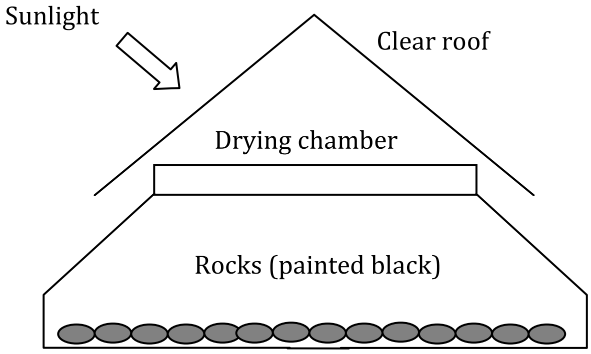

Figure 3.4. The hybrid solar dryer developed in East New Britain

Drying period was recorded within 4 days and extended drying was recorded at night due to the heat released from the rocks. Temperature increment was recorded at 10°C above ambient at night time. Despite overcast days, bed temperature still remained 5-7°C above ambient temperature. The dryer was tested at East New Britain area with average annual rainfall of 2500 mm. It was not recommended to use this dryer at region that has 3569 mm annual rainfall in order to have optimum drying condition. The cost of the dryer was about USD 1140.

A different design was developed and tested by Fagunwa et al. (2009) that was based on a solar collector and a thermal heat storage chamber (Figure 3.5). The chamber

(1 m x 0.875 m x 0.5 m) was completely filled with gravels to absorb heat during day time and the collector was also loaded with 5 mm layer of black painted gravels. The dryer (50 kg wet loading) was designed to dry cocoa beans within 3 days for an average of 8 hours period of insolation. Temperature increment of 6-24°C above ambient was recorded throughout the whole drying cycle which indicated a positive gain from the thermal storage system. The dried beans showed good quality attributes and comparable to the traditional sun dried cocoa beans.

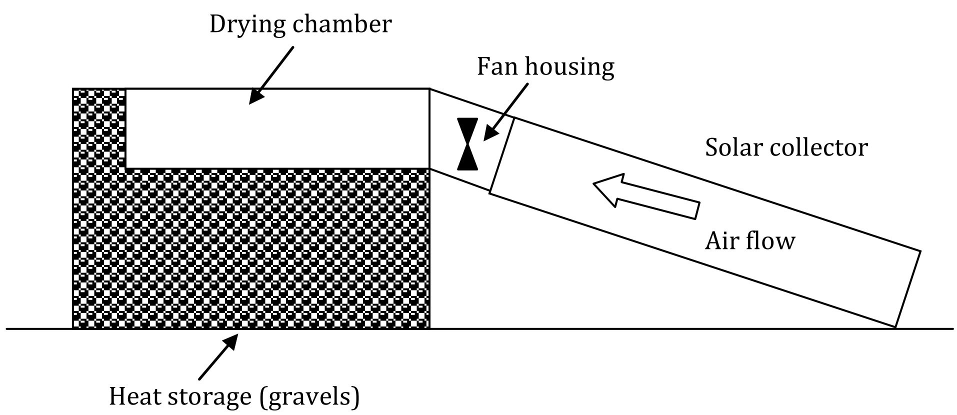

Figure 3.5. Schematic view of a solar dryer with thermal heat storage

A solar tunnel dryer constructed with an auxiliary fan was tested in Indonesia (Mulato et al., 1999) for drying capacity of 25 kg/m^2. The dryer consists of two sections namely the solar collector and the drying chamber with total length of 20 m. These two sections were connected in series arrangement and a fan was installed in front of the solar collector system. Heated air of about 55°C was recorded with relative humidity as low as 30%. Reduction in drying time of about 30-40% was observed as compared to sun drying.

Most of the solar dryers designed and tested as mentioned previously are mostly meant for low capacity operation. In order to meet a higher drying throughput, a solar processing center with solar air heaters incorporated into the roof was developed in Indonesia (Mulato et al., 1999). This drying system can serve 100 farmers and able to produce 85 ton of dried cocoa beans per year. Thermal efficiency was recorded at 45-50% at insolation of 5kWh/m^2. At these conditions, drying air temperature of 45-50°C at relative humidity of 15-20% can be obtained. The drying process was carried out on a flatbed dryer equipped with air blower. Average drying time was found shortened by one third as compared to sun drying. Another example of high capacity solar dryer tested for cocoa beans is the GHE solar dryer developed by Abdullah et al. (2001). An auxiliary heating unit was installed at the back of the dryer to back up drying at night and during bad weather. Table 3.5 shows the drying efficiency between the GHE and conventional sun drying techniques.

Table 3.5. Drying efficiencies between the GHE and conventional drying techniques

Dryer	Drying temperature (°C)	Drying time (hr)	Load (kg)	Efficiency (%)	Specific energy (MJ/kg H_2O)

GHE	50	40	228	18.4	12.9
	49.2	32	400	55.0	5.2
	45.8	43	190	18.0	14.4
Conventional	38	108	5000	10-20	n.a.

3.2.4. Coffee

Chapman et al. (2006) reported that poor coffee quality in Southern Thailand which was contaminated with Ochratoxin A (OTA), was due to extended and poor drying conditions. The survey carried out in the study reported 73% of the coffee samples collected were contaminated with OTA and that 14% of those with levels at or above 5 ppb. Studies were therefore carried out to improve the drying technique through the use of solar drying as shown in Table 3.6.

Table 3.6. Experimental trials of coffee drying

No.	Drying method	Open air	Polyethylene tunnel
1	Parchment dried on bamboo table	Yes	Yes
2	Cherry dried on bamboo table	Yes	Yes
3	Enclosed Solar drying	-	-
4	Parchment dried on cement patio	Yes	Yes
5	Cherry on cement patio	Yes	Yes

The polyethylene tunnel measured 7 m x 4 m x 2m in dimension and constructed from 30 mm diameter PVC pipes and enclosed with a 200 micron UV resistant clear polyethylene (Figure 3.6).

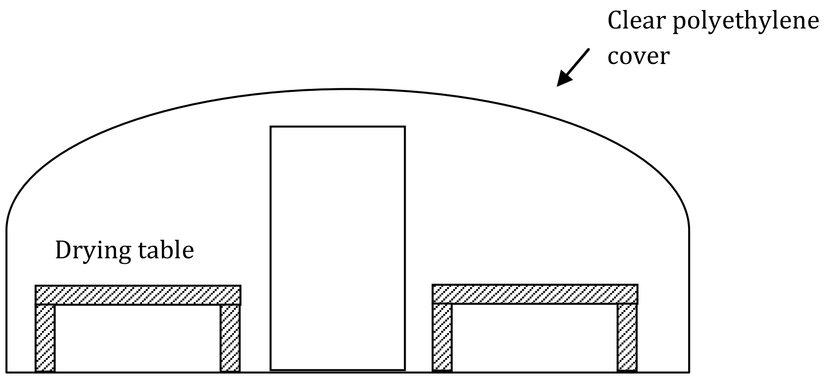

Figure 3.6. Schematic view of the polyethylene solar tunnel

In the solar dryer, a drying chamber measured 3 m x 1 m was constructed and loaded with 90 kg of coffee. The dryer was fitted to an air solar collector with hot air distributed to the dryer via a centrifugal blower with power usage at 500 W and able to distribute air flowrate of 2.5 m^3/min at 16,000 rpm. The cost of construction was about USD 190 and the cost to operate the electrical blower was less than 1 USD for 12 hours daily. Trials showed that parchment dried coffee using the solar dryer showed an increase in efficiency of 20-40% and about 3.4 times higher than coffee cherry. Drying time in parchment coffee inside the solar dryer were 1.5 times faster than the open air drying or in the tunnel on bamboo or cement floor. The solar dryer was able to in-crease the air temperature by 4 to 5 °C.

Application of a solar tunnel dryer for coffee drying was reported by Amir et al. (1991) that consist of a centrifugal blower, solar air heater and a tunnel drying chamber. The tunnel (width 2 m) and solar collector (width 1 m) were attached side by side and measured 20 m in length. The air was initially heated in the collector and the flow was channeled back into the tunnel through a U-shaped duct at the end of the drying unit. Drying temperatures of 40 – 60°C can be achieved by adjusting the air flowrate from 400 – 900 m3/hr. Fermented coffee beans of 500 – 600 kg were loaded into the dryer and it took 50 hours to reach the final moisture content below 125 while sun drying required 75 hours. Consumption of electrical energy was 41.7 Wh/kg dry material or 5.0 kWh/drying batch.

Abdullah et al. (2001) develop prototype of a greenhouse effect (GHE) solar dryer and tested it performances for various crops including coffee (Figure 3.6). The GHE unit consisted of several important components such as the radiation absorber, heat ex-changer (two units with 100 W blower attached), the auxiliary heating using hot water, air blowers (0.5 HP) and chimneys. To enhance thermal performance, a blackened steel plate was installed inside the structure either on the upper section or at both sides of the wall. Studies on coffee drying were carried out using UV stabilized plastic sheet (1.5 mm thick, 70% transmissivity) to form the GHE enclosure. The floor size was 6 m x 2.2 m with height 2.8 m. A wooden bin (3 m x 2 m x 1 m) was placed at the middle of the dry-ing floor and loaded with 1.1 ton of wet coffee berries at 0.3 m depth. Results were ob-tained for the drying of Robusta coffee in this dryer. Drying efficiency was recorded at 57.4% as compared to conventional drying at 21.1% while specific energy was recorded at 5.5 and 11.6 MJ/kg water, respectively, in each method. Dying time was recorded at 58 hours in the GHE unit as compared to 70 hours in conventional drying.

3.2.5. Chilli

Leon and Kumar (2008) investigated a solar assisted biomass drying system with thermal storage in drying chilli. This drying system was adopted as solar energy based air heaters/dryers often suffered from fluctuation in temperature, relative humid-ity and air flow rate. The system aimed to deliver air at 55 – 60°C at 70 – 100 m3/hr con-tinuously day and night. The solar dryer consists of the following major components:

- An unglazed transpired solar collector for day time use
- A biomass gasifier to supply hot air to the rock bed
- A heat exchanger to transfer heat from the stove flue gas to the air
- A rock bed thermal storage system that was connected to a stove/heat ex-changer unit
- A mixing chamber to obtain delivery air at both day and night time

Schematic of the solar biomass heating system is as shown in Figure 3.7. The solar drying system operated differently in day time and night time conditions. In day time, the solar collector supplied the complete hot air when there was sufficient solar radia-tion. In the event of insufficient solar radiation, part of the rock bed will supply the defi-cient energy. During day time, the stove was also operated to charge the rock bed with heat but was shut down in the evening. During night time, ambient air and hot air extracted from the rock bed entered the mixing chamber to obtain the desirable drying temperature of 55 – 60°C. The temperature was regulated by adjusting the ratio of ambient air mixing with air from the rock bed.

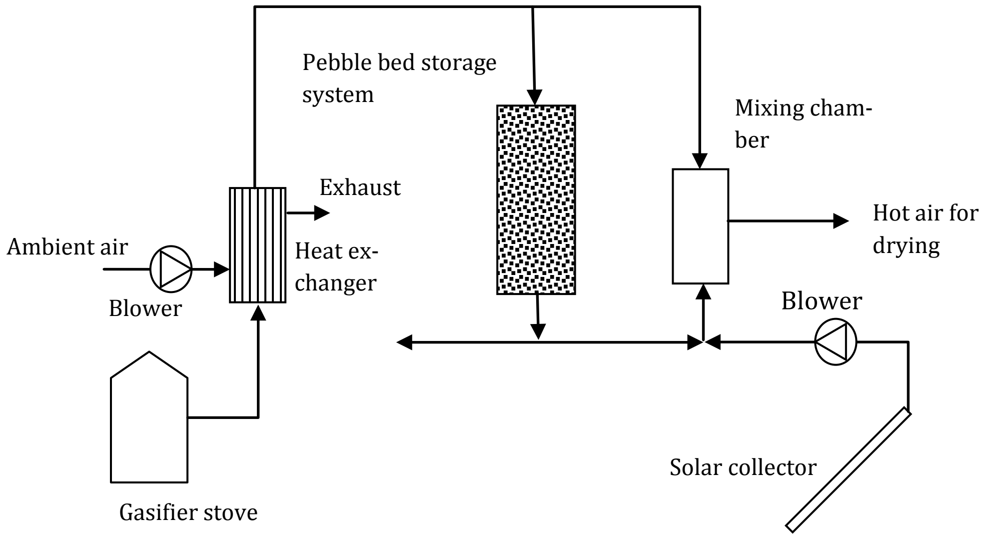

Figure 3.7. Schematic layout of the solar biomass heating system

In the test carried out for chilli drying a solar drying chamber (1.2 m x 1 m x 1.2 m) fitted with a rotary wind ventilator, 22 kg of chillies was spread onto four wire mesh trays of 0.96 m x 1.13 m each. Drying air of 60°C was chosen as the optimum temperature for product quality requirement. Eucalyptus wood chips (< 3 cm long) were used as fuel for the biomass stove. It was found that the drying time can be reduced by 66% as com-pared to sun drying with superior product quality. Average temperature rise during the full duration of drying was recorded at 26°C. Overall drying efficiency of the system was estimated at 10.08% as compared to solar cabinet drying at 7.4% and sun drying at 4.3%, respectively. The cost of construction of the solar drying system was estimated at USD 2600.

A mixed mode type solar tunnel dryer was developed and tested for drying chillies under tropical condition (Hossain and Bala, 2007). The dryer consisted of a flat plate solar collector covered with plastic sheet, a drying tunnel, two electrical fans and a 40 W photo-voltaic module that was installed at the inlet of the collector to serve as power source for the fan. The whole drying unit measured 20 m long and 1.80 m wide. The collector and drying chamber were made of plain metal sheets and wooden frames and glass wool was used between the two metal sheets at the bottom of the dryer as to prevent heat loss. The drying tunnel was made the same length as the solar collector. Transparent UV stabilized plastic sheet (0.2 mm) was used in the design. Trials were carried out using blanched red and green chillies at loading of 80 kg. Air temperature at the outlet of the collector was recorded ranging from 40°C to 60°C while the ambient temperatures fluctuated between 20 – 35°C. This was found equivalent to an average temperature increment of 21.62°C at the outlet of the collector. Reduction in drying time was observed where solar tunnel drying was able to complete the drying process 13 hours earlier than sun drying.

Mohanraj and Chandrasekar (2009) developed a solar dryer that consists of a flat plate solar air heater of area 2 x 1 m2 and connected to a drying chamber (insulated with 10 mm glass wool) measured 1 m x 1 m x 1.5 m in dimension. The drying chamber can be filled with 50 kg of chili per batch. A blower was installed at the inlet of the solar collector to deliver the air into the drying chamber while the humid air exited at the top of the drying chamber. Based on this setup, the average drying temperature recorded at the inlet of the dryer was 50.4°C with maximum and minimum temperatures recorded at 68°C and 43°C, respectively. Relative humidity of the chamber outlet air was recorded at 78% and 36% at the initial and end of drying, respectively. The specific moisture extraction rate was estimated at 0.87 kg/kWh while the average dryer thermal efficiency was calculated at 21%.

3.2.6. Nuts

Shelled and unshelled pistachio nuts were dried inside a solar assisted dryer that consists of a drying cupboard, air collector, an auxiliary heater and a circulation fan (0.73 kW). The drying cupboard was constructed with 16 shelves made of wire-mesh bottomed trays (Midilli, 2001). Fresh air was heated to 40-60°C upon passing through the solar collector. Drying of both shelled and unshelled pistachio was completed in 6 hours while those dried under the sun failed to complete drying within the same drying period. Maximum temperatures were measured between 60°C and 55°C inside the drying cupboard while the maximum ambient temperature recorded was 30°C. The relative humidity measured inside the solar dryer was between 37% and 62% while those re-corded for the ambient was between 60% and 75%.

Ghazanfari et al. (2003) developed and studied a solar dryer for pistachio nuts in Iran as shown in Figure 3.8. The chamber has a North-South length of 170 cm and an East-West depth of 65 cm. Four perforated sliding trays (80 cm x 70 cm x 10 cm) were fitted in the chamber that was made from plywood without any insulation. The transparent cover was made from 4 mm thick glass. A fan (0.4 m3/m2.s) was installed at the top back of the chamber to assist air flow. The dryer has drying capacity of 25 kg/m^2 with initial moisture content at 40% w.b. Maximum temperature was recorded at 56°C inside the chamber when the ambient air was at 36°C. Maximum product temperature was at 34°C and 42°C at two consecutive days of drying. At such conditions the dryer was able to dry the pistachio nuts down to 6.0% w.b. in 36 hours.

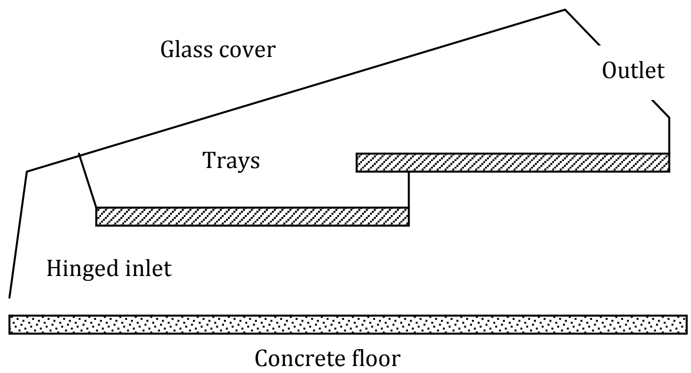

Figure 3.8. Schematic layout of the solar dryer

Solar drying of ground nuts was carried out in Thailand that consists of a solar collector system (2.75 m long x 1.75 m width), absorbers, single pass cover, black plate and insulation (Tarigan and Tekasakul, 2005). Absorber was made of blacked painted zinc plate (0.05 cm thick) and covered with glass (0.5 cm thick). A biomass burner was used as a backup heating system that used bricks as heat storage and installed just beneath the drying chamber (Figure 3.9). Drying tests were carried out at 35 kg and 64 kg fresh un-shelled ground nuts. In the 35 kg test, the biomass burner was only used at night time by burning 40 kg of woods. In average it took about 16 hrs to dry from moisture content of 135% to 13% d.b. Drying at day time was relatively shorter than the night time at less than 10 hours drying duration. However, it took about 3 days to dry 64 kg of groundnuts when the burner was not used at all during night time. The system efficiency was found to be 21.3% and 23%. The back-up heater was found to have overall efficiency of 40% with caloric value of wood at 13.1 MJ/kg.

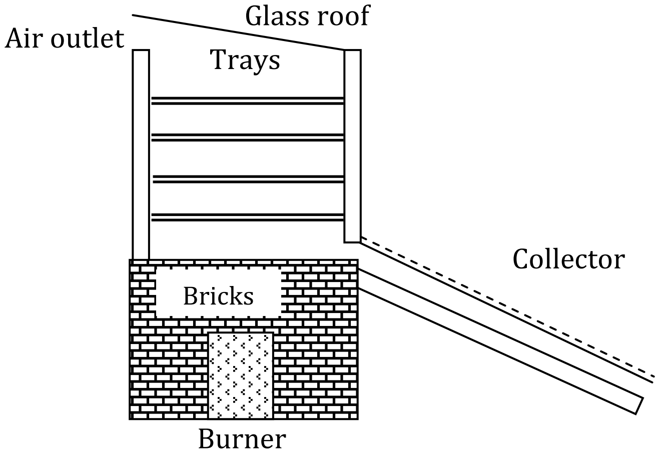

Figure 3.9. Side view of the solar dryer with biomass burner

Cashew nut dried using a solar cabinet dryer was reported by Mursalim et al. (2002) in Indonesia. Results showed that the dryer was able to heat up the ambient air from 27.2°C to 78.7°C. Average drying efficiency was 64% as compared to sun drying at 39.7%. Product quality was rated at first class as according to the Cashew Nut in Shells in Indonesia.

3.2.7. Tobacco

Drying of tobacco leaf is considered one of the most energy and labour intensive processes among all commodities. Drying is part of the curing process such that the desirable chemical and colour changes can occur in the leaf. About 50% of the moisture in the leaf needs to be removed and this can be carried out by natural convection, forced air curing and bulk curing (Huang and Bowers, 1986). It was estimated that average heat energy usage was 37060 kJ/kg, 40775 kJ/kg and 29540 kJ/kg, in each of the respective curing technique.

Two types of greenhouse solar dryers, namely the loading supporting wall design and the shell design, were constructed and investigated by Huang and Bowes (1986) as shown in Figure 3.10. In the load supporting wall design, the tobacco bulk racks were supported by exterior and interior walls. Solar radiation was transmitted through the clear corrugated fibre-glass and absorbed by the black plastic heat absorber inside the structure. Forced air was supplied to transfer the heat inside the curing compartment. The stagnant air space between the transparent exterior and the heat absorber acted as an insulation layer. The concrete slab and block foundation served as an additional heat storage system.

In the shell design, the greenhouse structure was covered with clear corrugated fi-bre-glass to form a large solar collector with an integrated gravel energy storage system for night time usage. An auxiliary fan to circulate the air over the absorbers and portable frames were used to support the tobacco racks. The gravel energy system was designed to store excess solar energy. Air was heated by the black surfaces of the absorber panels and gravel bed and it was then forced through the gravel and bottom air ducts by the fan. Soil drainage pipes were installed at the base to distribute the airflow uniformly through the gravel base.

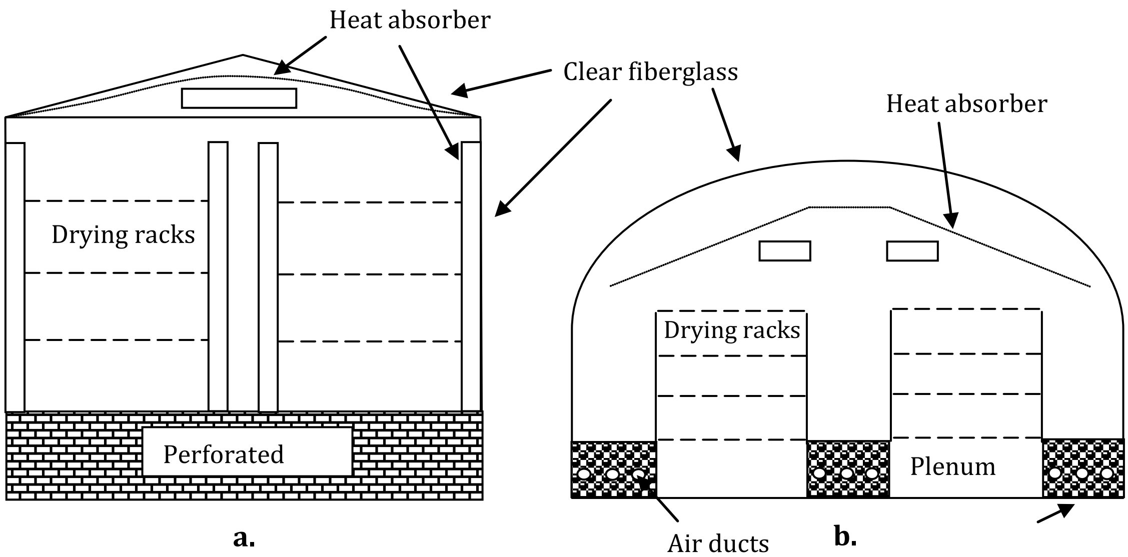

Figure 3.10. Green house solar dryer type a) load supporting wall design and b) shell design (not to scale)

Results showed that the load supporting wall design was able to save 15-25% fuel as compared to the conventional bulk curing barn. Average unit fuel consumption was es-timated at 1.30 lit LPG/ kg cured barn based on 856.8 kg of cured weight. In contrast, the shell design showed better saving at 33% – 51% as compared to the commercial unit. The savings in both designs can be largely attributed to the total utilization of the solar energy, immediate plus storage, the thermal enclosure design, insulation and proper energy management.

Soponronnarit (1995) cited a study that investigated a solar assisted curing barn of 1 ton fresh leaves capacity and measured 3.6 m x 3.6 m x 4.8 m in dimension. An array of 38.5 m2 flat plate solar heaters and a 6 m2 rock bed unit were also installed. Forced air was supplied by two units of blower at 1.5 kW and 0.75 kW each. LPG was used as an auxiliary fuel source in this system. It was found that average fuel saving of 28% was possible and average thermal efficiency was estimated at 40.5%. LPG consumption of

0.48 kg or 22.2 MJ per kg of cured leaves was achieved during drying. The payback period for the dryer was reported at 7 years.

3.2.8. Timber and Wood

Timber drying is a highly energy intensive process and this operation consumes about 70% of the total energy used in the production of most wood products (Taylor et al., 1996). Solar drying research on timber was first initiated in 1961 in India as cited by Satar (1994). The following are some aspects that determine the technical feasibility and economic viability of solar timber drying (Satar, 1994):

- Temperature and humidity: proper regulation of temperature and humidity to prevent damaging effects to the timber
- Drying time: increased in drying rate justified for the use of solar dryer
- Drying quality: as above, the better product quality justified the application of solar drying
- Thermal energy: this relates to the efficiency of the dryer, which is largely attributed to insulation of the kiln

Satar (1994) investigated the drying of several species of hardwood planks and the findings of the studies are shown in Table 3.7. Solar drying can dry timber to a much lower moisture content which cannot be achieved by air drying.

Table 3.7. Results from drying of several species of hardwood planks

Drying period	Drying time (days) from green to 12% moisture content		
	Solar	Air	Kiln
Winter period (Nov. – March)	10 - 26	22 - 68	6 - 12
Post winter period (April – May)	12 - 30	32 - 79	6 – 14
Monsoon period* (June – August)	18 - 40	58 - 123	6 – 14
Post monsoon period (Sept. – Oct.)	12 - 32	36 - 84	6 – 14

*18 – 20% mc

Studies using solar dryer, electric resistance dryer and dehumidifier were carried out on sawn timber planks by Ong (1999). The solar dryer measured 3 m long x 1.22 m wide with sides and bottom constructed from 50 mm thick polyurethane slabs laminated with iron sheets. The capacity of the dryer was 3.1 m3 and covered with 4 mm glass window inclined at 7°. Side vents allowed air to ventilate and two swing doors at the front of the dryer were used for loading purpose. A black painted corrugated galvanized iron sheet was placed below the glass roof to act as solar collector while a 40 mm diameter axial fan was used to distribute 3000 m3/hr of drying air. Comparison shows that electric drying was fastest with constant energy input throughout the day (Table 3.8). Maximum temperature was recorded inside the solar dryer at mid-day at 50°C. The following results were obtained from the studies. Ong (1999) reported that solar drying achieved a faster drying rate compared to natural drying but the difference was marginal.

Table 3.8. Comparison of drying durations from different drying methods

	Electric dryer	Solar dryer	Dehumidifier
No of days	8	12	12
Moisture content	44% to 15%	42% to 15%	84% to 15%

Luna et al. (2009) analyzed the evolution of solar timber kilns and recommended the various components of design for future adaptation. The analysis was carried out based on organic approach and the degree of development was later analyzed using the laws of technological system evolution derived from the TRIZ theory. Based on the analyses, three arrangements of solar kiln can be classified in the existing design:

- Arrangement 1: solar kiln with integrated collector in which all units are constructed into one
- Arrangement 2: solar kiln with lateral semi-integrated collector where the units are linked only by the interaction components, the air ducts and the fan.
- Arrangement 3: Solar kiln with thermal energy storage

By applying the TRIZ theory and taking into consideration the degree of evolution that has been taking place in existing kiln design, a new design was proposed that consist of the following:

- Type 2 arrangement (Figure 3.11)
- Use of storage with independent heating
- Integration of an heater in the storage system
- Management of different drying cycles according to product quality

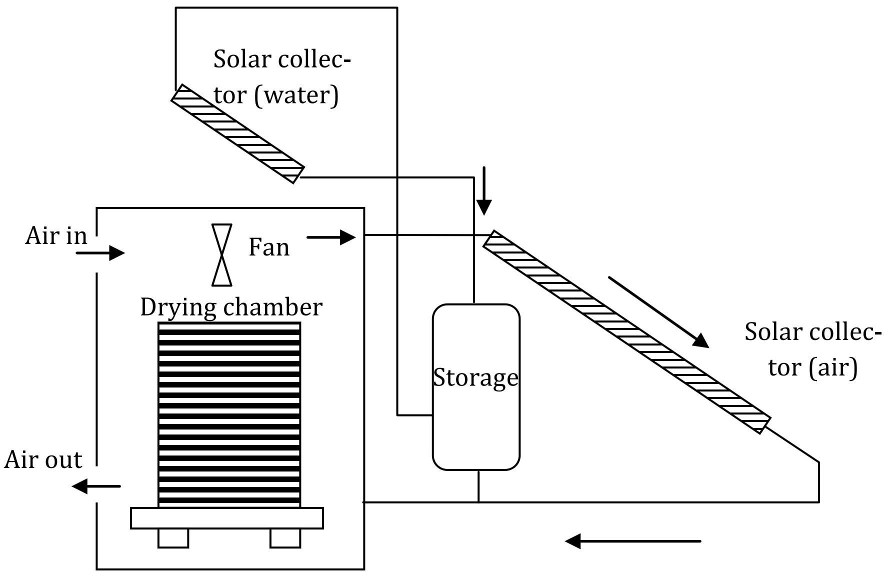

Figure 3.11. The proposed solar dryer with energy storage

Based on this design, drying model and simulation was carried out with and without energy storage (Luna et al., 2010). The energy storage enables drying to be continued at nighttimes. The storage unit used water as the storage fluid in a reservoir and air as the heat extraction fluid. Air was heated through dimpled vertical tubes in a water reservoir and the whole unit was connected to a solar water collector. Considerable reduction in drying time, as much as 30%, can be achieved based on the simulated results with energy storage. The proposed drying configuration also enables the control over the quality of the finished product without increasing the drying time.

3.3. PRODUCT QUALITY CONSIDERATION

The quality aspect of dried product is important in any drying system especially in solar and sun drying. This is mainly due to the possible extended drying duration as the source of solar radiation depends on the weather condition. The prolonged drying duration, coupled with unfavorable drying condition could contribute to product spoilage i.e. mould growth. Typically, the product quality of any dried products can be classified into the physical, chemical, biological and nutritional parameters (Perera, 2005; Sablani, 2006); whichever is applicable to both edible and non-edible products.

Not all commodities can be benefited from the use of solar drying in terms of quality improvement i.e. no significant effect on quality, especially when compared against sun drying. However, certain products are better when dried under mild drying condition as compared to hot air drying. Cocoa is one such commodity where fast drying using hot air will give a detrimental effect to the flavour of the dried product (Bravo and Mc Gaw, 1974). Certain products need to be cured for reasons related to physical and chemical changes, and this cannot be accelerated via high temperature drying. This is especially true for product that undergoes flavour development process. A specific chapter has been included in this e-book which further explains the product quality aspects during solar and sun drying.

3.4. REASONS FOR LIMITED USE OF SOLAR DRYING TECHNOLOGY

The adaptation of solar drying technology is relatively scarce especially in developing countries. Most of these countries are producing some of the major commodities for export worldwide i.e. chilli, herbs, spices, timber, cotton. Technology transfer activities involved highly intensive extension activities and services in order to disseminate the correct information and advice to the farmers especially those at the remote areas. Government and non-governmental organization have to educate the right target groups and promote the use of solar drying technology. In this regard, the level of adaptation is still low due to several reasons which can be summarized as follow:

- High capital cost of installation i.e. solar panels, insulation, building.
- Lack of government incentive to encourage the use of new technology.
- No premium price is given for better quality product dried using solar drying.
- Farmers are reluctant to learn new technique and replace the conventional one that has been used for decades.
- Difficulties in getting spare parts and lack of skilled personnel for periodic maintenance job.
- Limited funding to carry out continuous and follow up extension work to promote the use of solar dryers.

In addition to that, Soponronnarit (1995) and Mercer (2008) pointed out the following which might have contributed to the low uptake of solar drying technology:

- Lack of durability in the design
- Misuse i.e. parts used for other purposes
- Lack on dependability/reliability during wet season
- Low educational level of potential user
- Lack of electricity to power the auxiliary heater/fan
- Allocation of dryer to each household, may make it prohibitive

It was cited by Soponronnarit (1995) that the following factors should be considered before the implementation of any solar drying project:

- Large capacity dryers are more promising than the small scale ones
- The dryer should yield maximum utilization factor i.e. multi-product/use
- An auxiliary heat source need to be provided to ensure reliability
- Forced convection indirect dryers are preferred due to better control
- Retrofit systems should be examined

Nevertheless, there has been some successful examples of commercial installation of solar drying such as the large scale (1 tonne capacity) solar greenhouse dryer for fruits and vegetables built in Lao People's Democratic Republic (Janjai et al., 2011), the solar cocoa processing center with annual production of 85 tonnes built in Indonesia (Mulato et al., 1999) and also from compilation of works carried out in various countries as reported by Weiss and Buchinger (http://www.aee-intec.at/0uploads/dateien553.pdf).

3.5. CLOSING REMARKS

Solar drying has proved to be viable in drying various agricultural commodities provided the surrounding conditions (weather, insolation, location, etc) are conducive for the implementation of this type of drying technique. However, there are still many issues that must be overcome especially in the transfer of technology and the commercialization of this drying technology to the potential users. Training, guidance and management of the whole processing steps, which includes solar drying, should be emphasized to ensure quality control of the dried product.

3.5. NOMENCLATURES

GHE	Green house effect
wb	Wet basis (%)
db	Dry basis (%)
OTA	Ochratoxin A
UV	Ultraviolet

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Chapter 4
Solar Drying of Fishery Products

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Contents

4.1. INTRODUCTION

Fish is the major source of animal protein and important food item in many Asian countries. In poor households fish intake is 13 and 83 g raw whole fish per person per day; the frequency of intake of small fish is high, and made up to 50-80% of all fishes eaten during the fish production season in rural Bangladesh and Cambodia (Roos et al., 2007). Dried fish is also popular because of its special taste and flavor. Dried and seasoned squid products, dried fish such as Bombay duck and pomfret, dried shrimp and dried shark fin are some of the most popular items consumed in Asian countries.

Drying is the oldest preservation technique of agricultural products and the traditional method of sun drying is widely practiced to preserve fish and shrimp in many parts of the world. In developing countries, including Bangladesh, traditional fish-drying is practiced on the ground, raised bamboo platforms and bamboo made structures (Figure 4.1). The drying process in the sun takes usually about 1 week depending on the climatic conditions. The longer duration of drying causes considerable spoilage, blowfly infestation, broken pieces and contamination with filth and soil particles. Some reports indicate that losses from insects, animals and weather may be up to 30 to 40% (Hollick, 1999; Wall et al., 2001). To avoid insect infestation, insecticides are applied in Bangladesh and that creates the risk of health hazards. Besides, considerable postharvest could occur during processing, storage and during different stages of marketing channel. The physical and organoleptic qualities of most of the traditional sun-dried products available in the market are also not satisfactory for human consumption.

Figure 4.1. Drying of fish in bamboo made structures

Solar drying can be considered as an elaboration of sun drying and it is an efficient system of utilizing solar energy (Bala, 1997a & 1998; Zaman and Bala, 1989; Mühlbauer, 1986). The tropics and subtropics have abundant solar radiation. Hence, the obvious option for drying would be natural convection solar driers. Many studies on natural convection solar drying of agricultural products have been reported (Excell and Kornsakoo, 1978; Excell, 1980; Oosthuizen, 1995; Bala and Woods, 1994 & 1995; Sharma et al., 1995). Considerable studies on simulation and optimization have also been reported (Bala and Woods, 1994 & 1995; Simate, 2003). The success achieved by indirect natural convection solar driers has been limited, the drying rates achieved to date are still not very satisfactory (Oosthuizen, 1996). These prompted researchers to develop forced convection solar driers such as (i) solar tunnel drier (Esper and Mühlbauer, 1993), (ii) indirect forced convection solar drier (Oosthuizen, 1996), (iii) greenhouse type solar drier (Janjai et al., 2008a), (iv) roof integrated solar drier (Janjai et al., 2008b) and (v) solar assisted drier (Smitabhindu et al., 2008). Numerous tests in the different regions of the tropics and subtropics have shown that fruits, vegetables, cereals, grain, legumes, oil seeds, spices, fish and even meat can be dried properly in the solar tunnel drier (Esper and Mühlbauer, 1993; Mühlbauer et al., 1993; El-Shiatry et al., 1991; Schirmer et al., 1996; Esper and Mühlbauer, 1994 & 1996; Bala, 1997b; Bala et al., 1997 & 1999; Bala et al., 2002; Bala et al., 2003; Bala and Mondol, 2001).

The purpose of this chapter is to present the developments and potentials of solar drying technologies for drying fishery products

4.2. SOLAR DRYING SYSTEMS

The major two categories of solar driers are natural and forced convection solar driers. In the natural convection solar driers the airflow is established by buoyancy induced airflow while in forced convection solar driers the airflow is provided by using fan either operated by electricity/solar module or fossil fuel.

Natural convection solar drying has advantages over forced convection solar drying as it requires lower investment though it is difficult to control the drying temperature and drying rate. Due to low cost and simple operation and maintenance, natural convection solar drier appears to be the obvious option and popular choice for drying of agricultural products. Natural convection solar drier can be classified as (i) indirect natural convection solar drier, (ii) direct natural convection solar drier and (iii) mixed mode natural convection solar drier.

The limitations of natural convection solar driers prompted researchers to develop forced convection solar driers. Mühlbauer and his associates at the Institute of Agricultural Engineering in Tropics and Subtropics, University of Hohenheim, Germany developed the solar tunnel drier. Solar tunnel drier consists of a flat plate air heating collector and a tunnel drying unit with a small fan to provide the required airflow over the product to be dried. Solar tunnel drier can be operated by a 40 Watt photovoltaic module independent of electrical grid. The collector and drying chamber can be made of plain metal sheets and wooden frames in a number of small sections and joined together in series. These sections can be dismantled easily for transportation from one place to another. Glass wool is used between the two metal sheets at the bottom of the drier as an insulation material to reduce the heat loss from the bottom. Collector size of the drier is 10 m x 2 m. The photovoltaic system has the advantage that temperature of the drying air could be automatically controlled by the solar radiation.

Numerous tests in the different regions of the tropics and subtropics have shown that fruits, vegetables, cereals, legumes, oil seeds, spices, fish and even meat can be properly dried in the solar tunnel drier. Bala (2000) has widely demonstrated the potentiality of the solar tunnel drier in Bangladesh for small scale industrial production of high quality dried fish which has a wide acceptance in the supermarkets in Bangladesh.

Figure 4.2 shows solar tunnel drier in operation for drying of fish at Cox's Bazar, Bangladesh.

Figure 4.2. Drying of fish in solar tunnel drier

4.3. EQUILIBRIUM MOISTURE CONTENT

Equilibrium moisture content of a product is defined as the moisture content of the product after it has been exposed to a particular environment for an infinitely long period of time (Bala, 1997a). The equilibrium moisture content is dependent upon the relative humidity and temperature conditions of the environment as well as species, variety and maturity of the product. This can be classified as static equilibrium moisture content and dynamic equilibrium moisture content. Dynamic equilibrium moisture content is obtained by fitting of a thin layer drying equation to the experimental data, whereas the static equilibrium moisture content is obtained after long term exposure of the product to a constant atmosphere. Static equilibrium moisture content and dynamic equilibrium moisture content should be used for storage design and drier design respectively.

Figure 4.3 shows the sorption isotherms for shrimp (Tirawanichakul et al., 2008). When equilibrium is approached starting from dry material (MC<EMC), water from the surrounding air will be adsorbed in the material and moisture content will rise. When equilibrium is approached starting from moist material (MC>EMC), water will be evaporated from the material and moisture content will decrease. However, equilibrium moisture content after desorption remains on a higher level than equilibrium moisture content after adsorption. Adsorption isotherms are relevant for the storage process, e.g. to prevent remoistening of dried material by keeping relative humidity in the storage room at a suitable level. For drying, the desorption isotherms are relevant. Sorption isotherms have a lower course at higher temperatures. Consequently, the difference between actual moisture content and equilibrium moisture content as a driving force for drying will be increased at higher temperatures and drying rate will be accelerated.

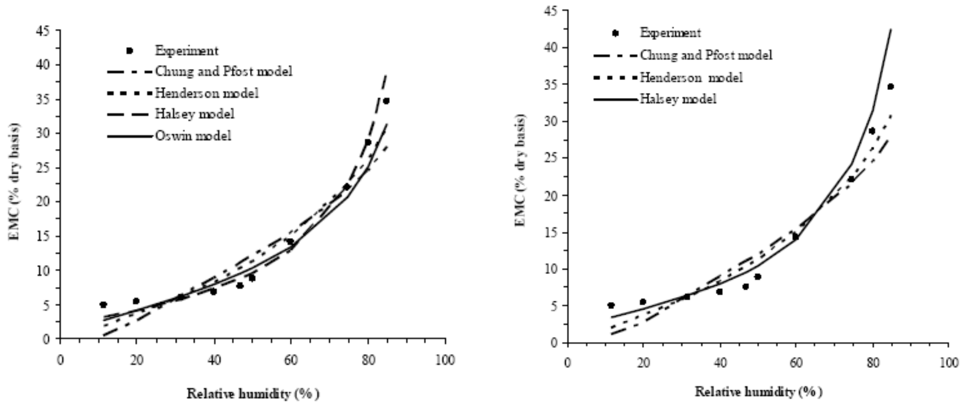

Figure 4.3. Sorption isotherms of shrimp: small shrimp (left) and large shrimp (right) (Tirawanichakul et al. 2008)

Many studies have been reported to suggest numerous isotherm models for food materials (Van den Berg, 1984; Lomauro et. al., 1985; Sun and Woods, 1994; Lahsasni et al., 2004a; Kaymak-Ertekin and Gedik, 2004; Janjai et al., 2006; Janjai et al., 2007a; Janjai et al., 2007b). However, limited studies have been reported on isotherm models for fishery products (Andriazafimahazo et al., 2010; Tirawanichakul et al. 2008).

Figure 4.3 shows predicted and experimental EMC data of shrimp. From Figure 4.3, the experimental results showed that EMC exponentially increased with increasing relative humidity. The predicted data of Oswin and Halsey's equation for small and large size shrimp was the best fitting model for all drying experiments, respectively. Andriazafimahazo et al. (2010) found good fit of adsorption isotherm of shrimp using Henderson equation as shown in Figure 4.4.

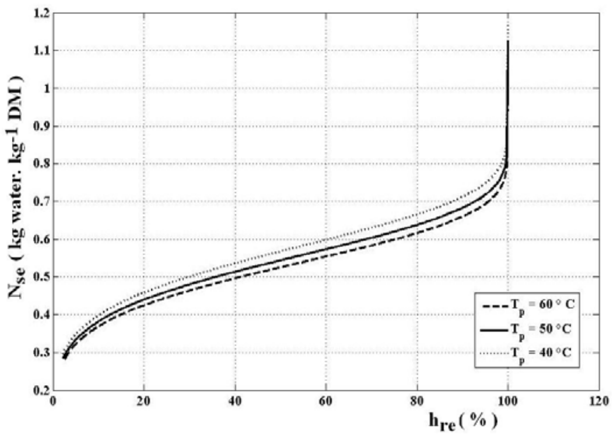

Figure 4.4. Shrimp isotherm curves at different temperatures predicted from Henderson model (N_{se} = equilibrium moisture content and h_{re} = equilibrium relative humidity) (Andriazafimahazo et al., 2010)

4.4. QUALITY ANALYSIS

4.4.1. Color Change

Color of a dried product can be measured by a colorimeter in CIE (Commission Internationale d'Eclairage) Lab chromaticity coordinates. L^*, a^* and b^* represent black to white, green to red and blue to yellow colors, respectively. Out of five available color systems, the $L^*a^*b^*$ and $L^*C^*h^o$ systems are usually selected because these are the most used systems for evaluation of the color of dried food materials (Zhang et al., 2003).

Hue angle indicating color combination is defined as:

$$\text{Hue angle} = \tan^{-1}\left(\frac{b^*}{a^*}\right) \quad \text{(when } a^*>0) \qquad (1)$$

$$\text{Hue angle} = 180° + \tan^{-1}\left(\frac{b^*}{a^*}\right) \quad \text{(when } a^*<0) \qquad (2)$$

and Chroma indicating color saturation is defined as:

$$\text{Chroma} = \left(a^{*2} + b^{*2}\right)^{\frac{1}{2}} \qquad (3)$$

Figure 4.5 shows the measured results of color for dried shrimp. Results showed that higher drying temperatures tend to decrease the total color difference of samples (ΔE), but the redness value (Hunter *a-value*) of the shrimp and the brightness value (Hunter *L-value*) of dried shrimp do not change significantly up to 70°C.

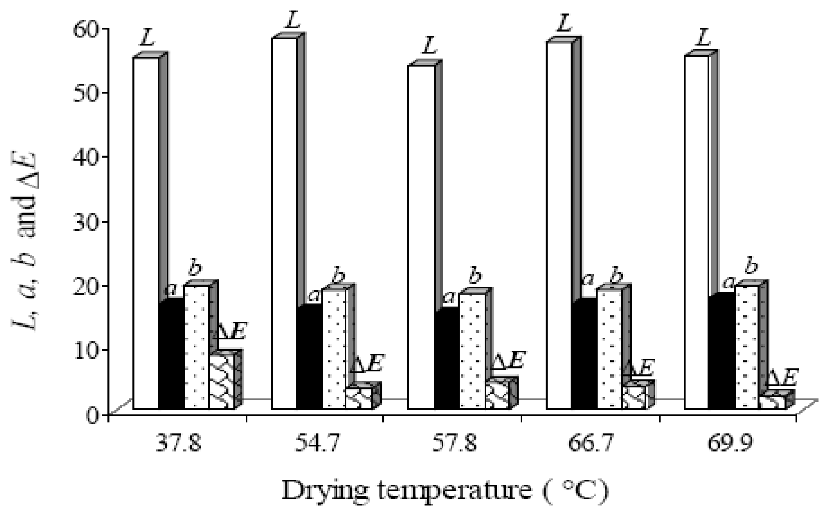

Figure 4.5. Color of small size shrimp dried at various drying air temperatures

4.4.2. Organoleptic Characteristics

The analysis of the properties of products and materials—mainly foodstuffs by means of the sense or organs is called organoleptic test. Organoleptic testing is to a certain extent subjective, since perceptions among different persons vary, depending on the state of the body. It is used where foodstuffs are directly liked or disliked by human. Reza et al. (2009) conducted organoleptic tests of different type of sea fish available in Bangladesh. The organoleptic characteristics of dried fish were determined to find the suitable drying temperature. The quality of the dried fish products was assessed on the basis of color, odor, texture, insect infestation, presence of broken pieces and overall quality. The color of solar tunnel dried silver Jew fish, Bombay duck, big-eye tuna and ribbon fish were from whitish to light brown color, whereas the Chinese pomfret was light-intense orange. Odor was very much natural in all samples. No insect infestation or broken pieces were found around the products. All these results were not significantly different ($P < 0.05$) for two different temperature ranges for production of dried fish. The overall quality of the products produced in the drier was of excellent to good quality for all five marine fish species. It was observed that the flavor and color are important factors influencing the overall consumer acceptance.

4.5. SOLAR DRYING PERFORMANCES OF SELECTED FISHERY PRODUCTS

Large scale field studies were conducted at Bangladesh Agricultural University, Mymensingh, Bangladesh and Silpakorn University at Nakhon Pathom, Thailand to demonstrate the potentiality of the solar driers for production of high quality dried fruits, vegetables, spices, medicinal plants and fish. Packages of technology for solar drying of fish have also been developed at Bangladesh Agricultural University, Mymensingh, Bangladesh.

The drying air temperature can be set easily in the solar tunnel drier while the temperature profile is regulated by solar radiation. Of course, the design should be such that the drying air temperature must not exceed the maximum permissible drying air temperature for a long period so that the cooking of the fish is avoided.

Figure 4.6 shows the variations of the ambient air temperature and relative humidity of a typical drying run during solar drying of Bombay duck at Cox's Bazar in Bangladesh. The ambient relative humidity decreases with the increase in the ambient temperature. The second day of the experiment was bright in the morning and cloudy in the afternoon which resulted in the sharp fall and rise in the relative humidity.

The patterns of temperature changes of the drying air at the collector outlet and airflow rate of a typical drying run are shown in Figure 4.7. The variation of the airflow rate helped to regulate the drying temperature. During high insolation period more energy was received by the collector which was intended to increase the drying air temperature, but it was compensated by the increase of the air flow rate. While during low solar insolation period less energy was received by the collector and airflow rate was low. Hence the decrease in temperature due to low solar insolation was compensated by the increase in temperature due to low airflow rate. This resulted in minimum variation of the drying air temperature throughout the drying period and saved the product from overheating/partial cooking of fish due to excess temperature.

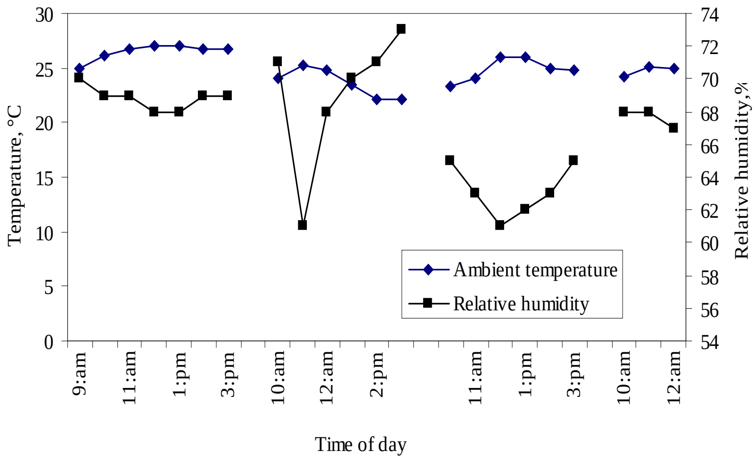

Figure 4.6. Ambient temperature and RH profiles during drying of Bombay duck

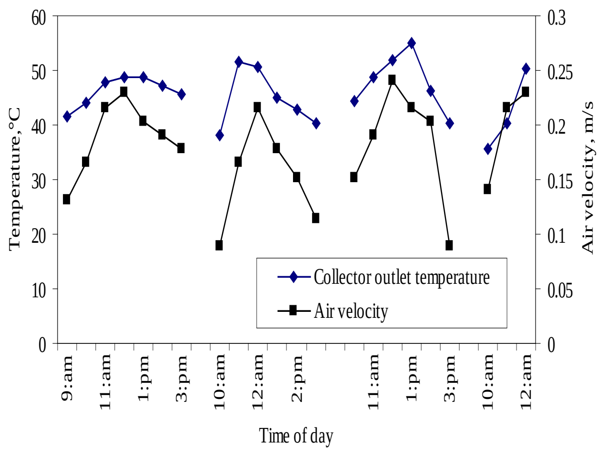

Figure 4.7. Collector outlet temperature and air flow rate profiles during drying of Bombay duck

Figure 4.8 shows the variations of collector outlet temperatures with solar radiation. The equation relating collector outlet temperature (°C) and solar radiation (W/m^2) is given below:

$$\text{Collector outlet temperature}\,(°C) = 0.0282 \times \text{solar radiation} + 35.523 \quad (R^2=0.30) \qquad [4]$$

The coefficient of determination R^2=0.30 is highly significant at 1% level. Here the intercept is significant but the slope is insignificant and hence the collector outlet temperature changes within a close range. Thus, the drying air temperature can be controlled by solar radiation.

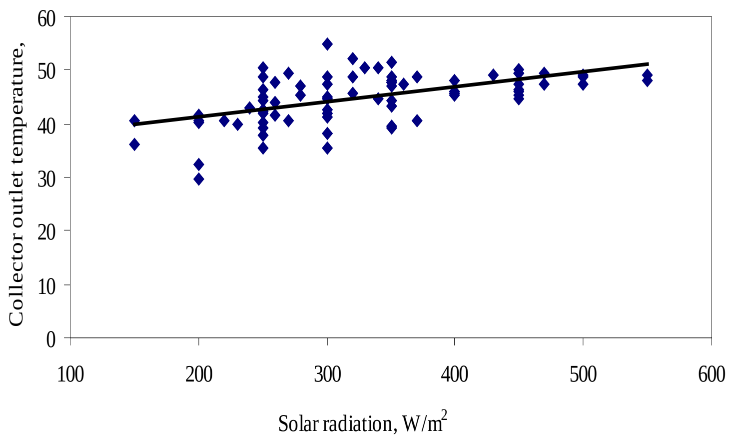

Figure 4.8. Air temperature at the outlet of the collector as a function of solar radiation

Solar tunnel driers have been widely tested in the fields in Bangladesh for drying of fish. The typical drying curves of three different types of fish in solar drier and those dried in the sun are shown in Figure 4.9 to Figure 4.11. Figure 4.9 shows that drying in the solar tunnel drier required 3 days to dry silver Jew fish from 74.45% (wb) to 14.29% (wb) as compared to 74.4% (wb) to 20.29% (wb) in 3 days in traditional sun drying.

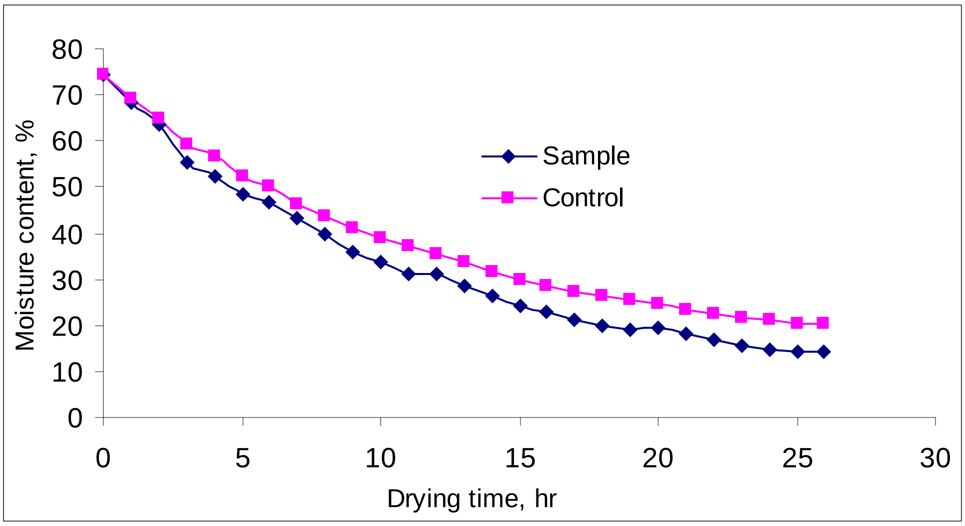

Figure 4.9. Moisture content profile during solar drying of silver Jew fish

Figure 4.10 shows that drying in the solar tunnel drier required 3.75 days to dry ribbon fish from 73.03% (wb) to 14.19% (wb) as compared to 73.03% (wb) to 23.46% (wb) in 3.75 days in traditional sun drying while Figure 4.11 shows that drying in the solar tunnel drier required 1.5 days to dry Bombay duck from 90.32% (wb) to 13.73% (wb) as compared to 90.32% (wb) to 26.04% (wb) in 1.5 days in traditional sun drying.

There was considerable reduction in drying time of fish in solar tunnel drier and there was no difference in drying rate at different positions of solar tunnel drier. The solar dried fish was better in terms of color, texture, taste and flavor.

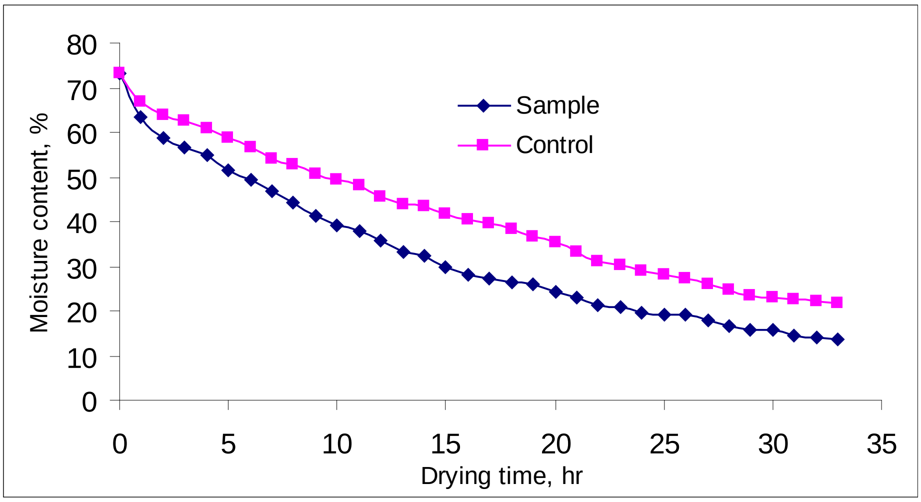

Figure 4.10. Moisture content profile during solar drying of ribbon fish

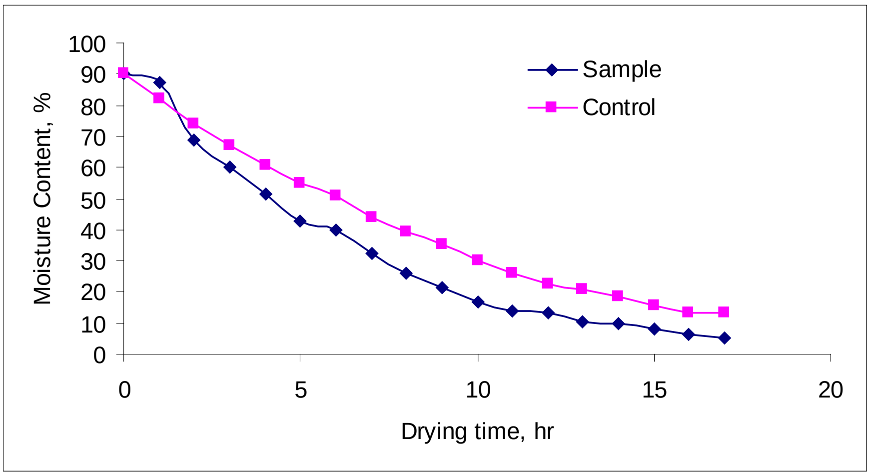

Figure 4.11. Moisture content profile during solar drying of Bombay duck

Figure 4.12 shows the comparison of solar drying of silver Jew fish, ribbon fish and Bombay duck using solar tunnel drier. The initial moisture content of silver Jew fish and ribbon fish is almost same (73–74%) while the initial moisture content of Bombay duck is 90%. The trends in moisture changes of silver Jew fish and ribbon fish are same while Bombay duck dries at a much higher rate. This might be due to the fact that the skin of the Bombay duck is comparatively much thinner and the cells of muscles are damaged during the solar drying resulting much higher drying rate. Although the drying patterns of silver Jew fish and ribbon fish are similar and the resulting difference is mainly due to the differences in skin permeability to the diffusion of moisture from the inside of the fish into outside of the skin of the fish. The changing pattern of moisture content of silver Jew fish, ribbon fish and Bombay duck reduced during the falling rate period, due to acceleration of water migration inside the fish. It was observed that during air drying, at first, moisture is being removed from the surface of the fish and then water moves from the deeper layers to the surface. Once all the surface moisture has been carried away, falling rate period starts and this depends on the rate at which moisture can be brought to the surface of the fish. As the concentration of moisture in the fish falls, the rate of movement of moisture to the surface is reduced and the drying rate becomes slower, approaching zero at equilibrium between the product and the surrounding drying conditions.

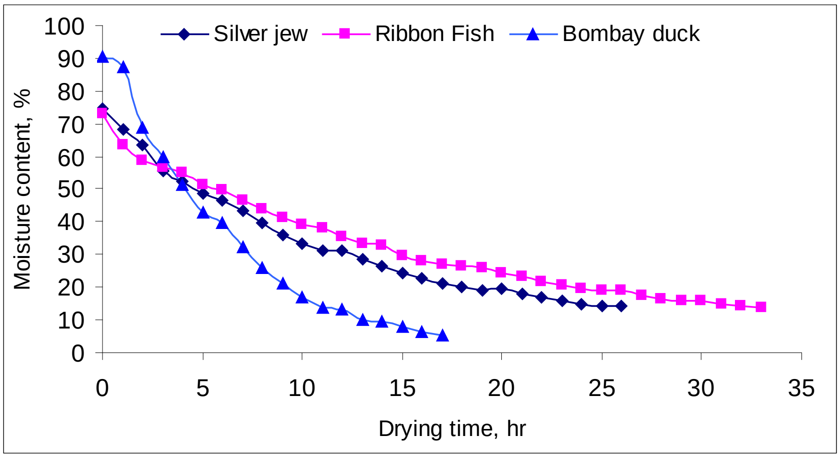

Figure 4.12. Comparison of moisture content change of three tropical marine fish during solar drying using solar tunnel drier

Variation of solar radiation over the different period of day resulted in higher/lower insolation. Interestingly, during high insolation period, the increased air velocity driven by the solar-powered DC fans compensated the temperature inside the drier, and reversely during lower insolation period compensated by lower air velocity. The effect of variation of air temperature inside the drier was thereby minimized, resulting in the uniform drying of the fish products.

Sengar et al. (2009) reported solar drying of prawns (Kolambi) in India. Salted prawns were found to be most liked for its color and texture than unsalted solar dried sample in sensory evaluation. Unsalted prawns sample dried in solar drier was overall accepted, while traditionally open sun dried sample was least liked for its color and texture. Local fisherman can recover solar drier cost within the period of 0.19 years by adopting solar drying technology

4.6. POTENTIALS AND LIMITATIONS

The following are some observations made based on series of field trials:

i. Studies have demonstrated the potentialities of solar tunnel drier for drying of fish and the drying air temperature must not exceed the maximum permissible drying air temperature. In case of a solar tunnel drier the drying air temperature can be achieved by simply adjusting collector length (in solar tunnel drier) or air flow rate by changing the number of fans in operation.
ii. Solar driers with UV stabilized plastic cover require frequent replacement of the plastic cover. However, this problem can be overcome if solar drier with polycarbonate cover is used.
iii. The photovoltaic system has the advantage that the temperature of the drying air is automatically controlled by the solar radiation.

iv. In cloudy days the PV ventilated solar driers can be used for drying since it operates on diffuse solar radiation but the drying rate is significantly reduced.
v. One major disadvantage of this drier is that it does not have any back up heating system. But in rainy days the PV ventilated solar drier can be used if it is integrated with either a biomass furnace or oil or gas burner.
vi. The year round operation of the PV ventilated solar driers for production of different solar dried products would further reduce payback period and would justify the financial viability of the PV ventilated solar driers as attractive and reliable alternative to the sun drying in the tropics and subtropics.
vii. Solar tunnel driers are now in operation in different regions of the tropics and subtropics.
viii. Since the drier is PV operated it can be used in the areas where there is no electric grid connection.
ix. The photovoltaic driven solar drier must be optimized for efficient operation.

4.7. CONCLUDING REMARKS

The use of solar drier leads to considerable reduction of drying time in comparison to sun drying and the quality of the solar dried fishery product is comparable or better than sun dried products. Field level tests demonstrate that PV ventilated solar tunnel drier is appropriate for production of quality dried fish in the tropics and subtropics. The solar drier can be operated by a photovoltaic module independent of electrical grid. The photovoltaic driven solar driers must be optimized for efficient operation. Finally, solar driers are environmentally sound as compared to hot air driers that use fossil fuels.

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Chapter 5
Quality Characteristics of Solar Dried Products

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Contents

5.1. INTRODUCTION

Product quality is the only attribute that assesses the acceptance of a product for safe consumption or use by human beings apart from marketable opportunities. This attribute is equally important in fresh, semi-dried and fully dried products in both edible and non-edible categories. Traditionally, most agriculture products are dried under direct sunlight to achieve the required degree of dryness. This has been done ever since humankind realizes the importance of drying. With the introduction of advanced drying technique, many agriculture products are dried by using mechanical dryers. Nevertheless, in many parts of the world sun drying is still a usual practice especially in developing countries (Esper and Mühlbauer, 1998; Garg, 2001; Benali, 2004; Mercer, 2008; Murthy, 2009).

Comparisons of product quality between sun and hot air drying have been discussed in many published literatures. However, when comparing these drying techniques against solar drying, it depends on several factors such as types and designs of solar dryers, the nature of the products when expose to sunlight (UV radiation) and the drying rate. Hot air drying has been associated with several quality damaging issues such as case hardening, colour deterioration, high degree of shrinkage, degradation of nutrients, flavour loss etc. (Duncan, 1991; Ratti, 1994; Perera, 2005; Kyi et al., 2005; Sablani, 2006; Santos and Silva, 2008; Hii et al., 2011).

On the other hand, sun drying has its inherent disadvantages owing to the unpredictable weather conditions, which often lead to quality deterioration (Garg, 2001; Murthy, 2009). Therefore, solar drying in some extent helps to solve these problems. However, this is only possible when care is taken during the design, construction and testing of the solar dryer for the target agriculture product.

5.2. PRODUCT QUALITY ATTRIBUTES

In general, the quality attributes of dried products can be classified into physical, chemical, biological and nutritional depending on the type of product (food or non-food) as shown in Table 5.1. Some established grading systems are available for some dried products such as for cocoa, coffee, spices, timber and etc. It is recommended to search for these standards from relevant authorities before the dried product is produced and packed for shipment.

For food product, it is particularly important not to have microbiological contamination for food safety reason. As a rule of thumb, the water activity of dried food products should not exceed the critical value of 0.85 and 0.62 to prevent the activity of bacteria and yeasts/moulds, respectively (Table 5.2). However, in most countries that still utilize sun drying especially to dry food products; it is hard to govern the food safety in this particular aspect as the product is easily contaminated with airborne contaminants. Therefore, solar drying is recommended as the drying product is enclosed or contained inside the drying chamber and not exposed to the surrounding. Further elaboration of some of these quality attributes can be found from various published literatures

(Lewicki, 1998; Abbott, 1999; Szczesniak, 2002; Benali, 2004; Perera, 2005; Rahman, 2005).

Table 5.1. Selected dried product quality attributes

Attribute	Parameters
Physical	colour, texture, shrinkage, porosity, rehydration, breakage, split
Chemical	flavour, odour, water activity, shelf life
Nutritional	calorie, vitamins, minerals, fibres, lipids, proteins, carbohydrates, antioxidants
Biological	mould, yeast, E. coli, Salmonella, mycotoxins, aflatoxins
Sensory	appearance, odour, flavour, mouthfeel and texture

Table 5.2. Critical water activity (a_w) to inhibit microorganisms

Microorganisms	a_w
Bacteria	< 0.85 – 0.86
Yeasts and moulds	< 0.62

5.3. QUALITY OF SOLAR DRIED PRODUCTS FROM SELECTED STUDIES

The following tables (Table 5.3 – Table 5.7) show the research findings summarized from various solar drying studies for food and non-food type products. The summary covers as much as possible those products that are commonly dried using sun light especially for food products. Further details of the studies can be obtained from the cited papers as indicated in the tables.

Table 5.3. Solar dried vegetable products

Product type	Type of solar dryer	Major findings	References
Carrots	Solar cabinet dryer	- High β-carotene loss was found in solar cabinet dried carrots due to longer drying time and exposure to light leading to oxidation. - Low rehydration ratio was observed due to greater shrinkage in solar dried samples.	Prakash et al. (2004)
Sweet potato	Green house solar dryer	- Solar dried sample showed no significant losses in total carotenoids as compared to sun and hot air dried samples. - Sun drying showed the lowest retention value.	Bechoff et al. (2009)
Green leaves	Indirect solar	- Higher losses of β-carotene and ascorbic acid were observed in solar	Negi and Roy (2001)

	lar dryer	drying as compared to hot air cabinet drying upon storage. - Chlorophyll loss was also higher in solar dried sample. - Retention of the quality parameters of leafy green vegetables was better at faster drying conditions.	
Spinach, cowpeas, sweet potato and cassava leaves	Enclosed solar dryer	- Maximum retention of ascorbic acid and total carotene was observed in enclosed solar dryer with shade as compared to sun drying. - Sun drying showed minimum retention of these nutrients.	Maeda and Salunkhe (1981)
Okra	Solar tent dryer	- Degradation of vitamin C destruction during solar drying of okra was not influenced significantly by sample thickness. - Vitamin C remained fairly constant after 48 h of drying. - Slice thickness showed no significant effect on the changes in whiteness of the solar dried okra with drying time.	Adom et al. (1997)

Table 5.4. Solar dried fruit products

Product type	Type of solar dryer	Major findings	References
Lemon slices	Solar dryer associated with the PV module	- Dried lemon samples with bright colour were observed under complementary solar drying using gradual temperature increment (range 36 – 52°C). - Lesser browning was observed as compared to hot air drying at 60°C.	Chen et al. (2005)
Grapes & figs	Indirect and direct solar dryers	- Vitamin C content of dried fruits was low due oxidation during solar drying especially when the samples were either scalded or sulfurized. - The colour of grapes dried using indirect solar dryer showed high acceptance as compared to the natural dried sample (medium acceptance). - The texture and colour of figs dried using mixed solar dryers showed better acceptance than the natural dried samples.	Gallali et al. (2000)

Plums	Greenhouse dryer	- Both solar and open sun drying of plums pre-treated by combination of 1% potassium hydroxide and 60°C dipping temperature or by combination of 1% sodium hydroxide and 60°C dipping temperature resulted in relatively higher values of redness and yellowness as compared to artificial drying. - The combined effect of solar radiation and these pre-treatment combinations reduced the darkish colour of plums during solar drying and open sun drying.	Tarhan (2007)
Indian gooseberry	Forced convective solar dryer	- Flaking treated sample retained maximum ascorbic acid (76.6%). - The greater retention of ascorbic acid in flaking treated sample might be due to reduced exposure of the sample in the drying air. - Loss of taste and flavour were found lower in flaking and pricking treatments.	Verma and Gupta (2004)
Papaya latex	Rock bed indirect solar dryer	- Solar dried latex had a slightly higher preteolytic activity than the fresh sample because of the effect of ultraviolet radiation on the histidine residue which is essential for proteolytic activity. - This was attributed to the use of the indirect dryer since the latex was not exposed to any direct radiation.	Narinesingh and Mohammed-Maraj (1989)

Table 5.5. Solar dried grains/seeds/beans

Product type	Type of solar dryer	Major findings	References
Cocoa beans	Direct solar dryer	- Overall quality evaluation (flavour, acidity, fermentation index, appearance and odour) indicated that loading of 20 kg cocoa beans is recommended. - At this quantity, duration of drying was shorter and this reduces the risk of putrefactive development in the beans due to unfavourable weather condition.	Hii et al. (2006)
Cocoa beans	Indirect and direct type	- Dried sample from indirect dryer showed the highest cut test score while the direct dryer showed the lowest.	Bonaparte et al. (1998)

	solar dryers	- The dried beans from the direct dryer were more brittle and higher in acidity than the open air and indirect dryers. - Dried beans from the indirect dryer showed the highest quality in overall.	
Coffee	Solar tunnel dryer	- Visual and organoleptical tests showed no significant difference between the solar dried and sun dried coffee beans. - This could be due to the rather similar drying rates between solar and sun drying.	Amir et al. (1991)
Coffee	Solar dryer with black transpired air solar collector	- Coffee beans dried faster in the solar dryer but still produced an acceptable cup with no serious defects. - No OTA forming fungi was found in solar dried samples.	Chapman et al. (2006)
Rice	Mixed mode passive solar dryer	- Solar dried rice resulted in higher degree of whiteness than sun dried rice. - Samples dried in solar dryer are similar in flavour than those dried under the sun.	Mehdizadeh and Zomorodian (2009)
Corn	Drying bin installed will bin-wall solar collector	- The quality of solar dried corn was superior to that dried using one-pass high-temperature treatment. - The improvement was in physical characteristics of the kernels i.e. stress cracking, bulk density and breakage susceptibility.	Otten and brown (1982)
Pistachio nuts	Direct solar dryer	- Both solar and sun dried samples showed excellent taste as compared to hot air dried samples. - No aflatoxin was found in both sun and solar dried pistachio nuts.	Ghazanfari et al. (2003)

Table 5.6. Solar dried medicinal plant, herb and spice products

Product type	Type of solar dryer	Major findings	References
Thyme	Solar dryer using wire basket	- The essential oils extracted from the oven dried and solar dried samples were 0.5% and 0.6% (per 100 g dry wt), respectively. - The oleoresin and ash content were 27% for both drying methods and 1.6%, 2.03% and 2.25% for the fresh, oven dried and solar dried samples, re-	Balladin and Headley (1999)

		spectively.	
Turmeric	Solar bio-mass dryer	- Dried turmeric rhizomes obtained from solar drying by two different treatments namely water boiling and slicing were similar in terms of physical appearance. - Sample dried in open sun was found having lesser volatile oil.	Prasad et al. (2006)
Wild coriander	Direct cabinet solar dryer and indirect cabinet	- Some leaves from upper trays of the direct solar dryer were completely brown in colour which could be due to the effect of direct solar radiation in combination with high temperatures. - The highest preservation of natural colour and absence of browning were observed from samples using indirect solar dryer. - Essential oil from samples dried in the indirect solar dryer was closer in its composition to those obtained from oven or the fresh one.	Banout et al. (2010)
Pegaga leaf	Solar assisted dehumidification dryer	- The colour of solar dried pegaga leaf did not become darker due to the lower air temperature used (T< 56°C) and the lower RH used (RH < 36%). - Pegaga leaf dried at 65°C using warm air became darker.	Yahya et al. (2004)
Olives leaf	Indirect forced convection solar dryer	- The values of *L** parameter of the solar dried olive leaves increase compared to the fresh one. - The luminance of the leaves was improved by solar drying but the greenness of the leaves reduced. - Dried olive leaves dried at 60°C (at 3.3 m^3/min) showed total phenols close to the fresh leaves. - The olive leaves dried at 40°C (1.62 m^3/min) exhibited the lowest DPPH radical scavenging activities.	Bahloul et al. (2009)
Henna, rosemary, marjoram and moghat	Unglazed transpired solar dryer	- The amounts of oil obtained from medicinal plants dried in the solar dryer were higher compared to the traditional drying methods. - Higher test scores for sensation were obtained for the solar dried plants (rosemary, marjoram, and moghat) in terms of colour, odour, and taste.	Hassanain (2010)

Table 5.7. Solar dried wood/timber products

Product type	Type of solar dryer	Major findings	References
Hard wood	Various solar dryers	- No objectionable drying defect is noticed but check, split and some distortions are observed in many air and steam kiln dried timbers. - This is attributed to that in solar drying, timber receives a mild reconditioning treatment at night due to rehumidification.	Sattar, (1994)
Timber boards	Semi greenhouse type	- The reduction of drying air temperature at night makes drying rate almost constant and this helps the timber boards to release the formed stresses accumulated at day time.	Helwa et al. (2004)
Logs of *Gmelina arborea*	Solar kiln	- Moisture content differences between the inner and surface of the board is small. - High stresses within the wood fibres are prevented in solar dried samples. - For air dried samples, defect was observed during drying such as warp and stain on the air dried wood. This could be due to too high ambient relative humidity.	Ogunsanwo and Amao-Onidundu (2011)

5.4. CONCLUDING REMARKS

Solar drying are broadly applied in various agriculture products such as fruits, vegetables, grains, seeds, beans, herbs, spices, rubber, tobacco, timbers and woods. Generally, the main processing variables that determine the final quality of the solar dried products are the drying time as well as the exposure period to sunlight. Prolonged drying period and contact with ultraviolet light (UV) could degrade some valuable phytochemicals and vitamins in dried products such as chlorophyll, essential oil, β-carotene and ascorbic acid. Nevertheless, the usage of indirect solar dryer and pre-treatment on raw materials could overcome these problems. The drying rate of product is important as it influences the physical and chemical changes, and therefore affects both the quality attributes and level of acceptance of the product by consumers. Appropriate methods should be used to monitor and evaluate these quality attributes.

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Chapter 6
Recent advancements in solar drying

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Contents

6.1. INTRODUCTION

Drying is one of the most energy intensive unit operations that easily account for up to 15% of all industrial energy utilizations (Chua et al., 2001). From 1980s, apart from the rise in energy prices, legislation on pollution, working conditions and safety requirements have become more stringent. To meet these requirements and optimize energy consumption, new technologies in drying method and dryer design have been in demand (Hawlader et al., 1998). Solar-drying technology offers an alternative which can process the vegetables and fruits in clean, hygienic and sanitary conditions to national and international standards. It saves energy, time, occupies less area, improves product quality, makes the process more efficient and protects the environment (Sharma et al., 2009). Solar drying refers to a technique that utilizes incident solar radiation to convert it into thermal energy required for drying purpose (Simate, 2001). Imre (1986) reported that, solar drying is not simply an energy consuming process, carried out by the use of solar energy, but a process for producing products of required quality; and the quality of the dried product do has an effect to the economy. Moreover, solar-energy drying, where feasible, often provides the most cost-effective drying technique (Ratti & Mujumdar, 1997). One of the objectives of the solar dryer is to supply the product with more heat than is available under ambient conditions. Thus, sufficiently increasing the vapor pressure of the moisture held within the product to enhance moisture migration from within the product. Therefore, significantly decreases the relative humidity of the drying air to increase its moisture carrying capability and to ensure sufficiently low equilibrium moisture content (Dincer & Cengel, 2001; Dincer & Sahin, 2004). Hodali & Bougard (2001) reported that, solar dryers represent an alternative technique to traditional sun drying of agricultural products. Most of the works on solar drying applications have been directed to low temperature drying systems. In order to maintain the quality characteristics, for many biological products, a maximum permissible temperature should not be exceeded.

Kiebling (1996) has listed 66 different solar dryers, their configurations, capacity, products dried and cost. Fuller (1995) and Ekechukwa and Norton (1999) have reviewed many solar dryers, and compared their performance and applicability in rural areas. Sharma (2009) has presented a comprehensive review of various designs, details of construction and operational principles of a wide variety of practically realized designs of solar drying systems along with a systematic approach for the classification of solar dryers. A review of new technologies, models and experimental investigations of solar driers has been presented by Ramana (2009). Popular types of driers in Asia-Pacific region, and new types of driers with improved technologies have been discussed. A comprehensive procedure for performance evaluation of solar food dryers has been presented by Augustus et al., (2002), a detailed review of parameters generally used in testing and evaluation of different types of solar food dryers has been presented. In this chapter a review on a performance of solar drying system of selected agriculture products is presented. A review on the development and performance of the recent advancements in solar drying systems for agriculture products are presented.

6.2. REVIEW OF SOLAR DRYING OF SELECTED AGRICULTURE PRODUCTS

Most solar dryers developed are designed for specific products or class of products, for example vegetables such as chili, cassava, onion, radish, ginger, peas, corn, mushroom, tamarind and coconut, and fruits such as mango, apple, pineapple, banana and grapes (FAO, 1980). Selection of solar dryer for a particular agriculture product is determined by quality requirements, product characteristics and economic factors. A review of these types of solar dryers with aspect to the product being dried, technical and economical aspects has been discussed by Fudholi et al. (2010). Table 6.1 shows the review of solar drying of selected agriculture products:

Table 6.1. The review of solar drying of selected agriculture products

Product dried	Observations	Reference
Apples	Solar tunnel dryer, The moisture content was reduced from 82 to 11% in 32 h for the open sun drying, whereas the solar tunnel dryer took only 28 h.	Elicin and Sacilik et al., 2005
Chillies	Multi-purpose solar tunnel dryer, Reduction in drying time in comparison to that of conventional sun drying, Average air temperature rise in drier was about 22 °C above the ambient temperature and it was almost constant in the drier.	Hossain and Bala, 2007
Bananas	Multi-purpose solar tunnel dryer, Bananas could be dried within 3–5 days, compared to the 5–7 days needed for open drying.	Schimer et al., 1996
Cassava	Mixed-mode natural convection solar dryer, Experiments revealed that 49.1, 65.9 and 162 kg of cassava could be dehydrated in 30–36 h with an expected average solar irradiance of 400 W/m^2, ambient conditions of 25 °C and 77.8% relative humidity.	Forson et al., 2007
Cauliflower	Forced convection solar dryer using V-groove solar collector	Kadam and Samuel, 2006
Copra	Forced convection solar drier, Reduced the moisture content from about 52% to 8% and 10% in 82 h for trays at the bottom and top, respectively. The maximum drying air temperature recorded during peak sunshine hours was 63 °C.	Mohanraj and Chandrasekar, 2008
Cocoa	Direct solar dryer, Overall quality assessment showed that the 20 kg treatment was able to produce reasonably good-quality beans as compared to other loadings and therefore is recommended for direct solar dryer.	Hii et al., 2006

Grape	Multipurpose natural convection solar dryer, The drying time of the grapes reduced by 43% compared to the open sun drying.	Pangavhane et al., 2002
Green peas	Indirect type natural convection solar dryer, 1 kg of green peas dried at 45.5–50.5 °C for 8–10 h to a final moisture content of 5% .	El-Sebaii et al., 2002
Mangoes	Indirect type natural convection solar dryer Sliced fresh mangoes having an initial moisture content of 85% dried at 31.7–40.1 °C for 20 h to a final moisture content of 13%.	Madhlopa et al., 2002
	Natural convection solar dryer, Mango having an initial moisture content of 84 dried with maximum temperature allowable at 40 °C for 15 h to final moisture content of 27.6%	Toure and Kibangu-Nkembo, 2004
Onion slices	Hybrid solar drier, Onion slices dried from initial moisture content of about 86% (w.b.) to final moisture content of about 7% (w.b.), The maximum savings in total energy up to 70.7% can be achieved with recycling of the hot exhaust air.	Sarsavadia, 2007
Tobacco leaves	Hybrid solar dryer, The loading capacity of the dryer was 1000 kg. The results indicated that solar energy accounted for 25–30% of the total energy consumed.	Soponronnarit, 1995
Turmeric rhizomes	Hybrid solar drier Open sun drying had taken 11 days to dry the rhizomes while solar biomass drier hybrid took only 1.5 days.	Prasad et al., 2006
Pineapple	Hybrid solar drier, The dryer reduced the moisture content of pineapple slices from about 66% to 11% (d.b.) and yielded a nutritious dried product. The average values of the final-day moisture pickup efficiency were 15%, 11% and 13% in the solar, biomass and solar–biomass modes of operation, respectively.	Madhlopa and Ngwalo, 2007
Tea	Hybrid solar drier, The total energy required to maintain a drying chamber temperature of 50 °C is 60.2 kWh. The auxiliary energy contribution is 17.6 kWh. Hence, solar energy contributes 42.6 kWh during the process and contributes approximately 70.2% of the overall energy requirement.	Ruslan et al., 2003
	Solar dryer with the VGroove type solar collectors, The fresh tea leaves are dried from an initial moisture content of 87% (wet basis) to 54%	Sopian et al., 2000

	(wet basis) at a drying temperature of 50 °C and flow rate of 15.1 m^3/min	
Strawberry	Indirect solar dryer, The performance of the solar collector to heat the drying air is assumed satisfactory; it could raise the ambient temperature to around 47 °C at peak conditions which is considered adequate for strawberry drying.	El-Beltagi et al., (2007)

6.3. RECENT ADVANCED IN SOLAR DRYING FOR AGRICULTURE PRODUCE

Over the past three decades there has been nearly exponential growth in drying R&D on a global scale. Improving the drying operation to save energy, improve product quality as well as reduce environmental impact remained the main objectives of any development of drying system (Fadhel et al., 2011). The technical development of solar drying systems can possibly proceed in two directions. Firstly simple, low power, short life, and comparatively low efficiency-drying system. Secondly, the development of high efficiency, high power, long life expensive solar drying system (Othman et al., 2006).

6.3.1. Double pass solar drier system

The principal types of solar air heaters that can be coupled in solar drying system are: the single pass with front duct, single pass with real duct, single pass with double duct, and double pass solar air heater (Fudholi et al., 2010). It has been observed that the double pass solar air heaters perform better than conventional single pass system (Wijeysundera et al., 1982; Mohamad, 1997; Sopian et al., 2007). Wijeysundera et al. (1982) concluded that two-pass designs perform better than the single-pass air heaters and reported an increase of 10–15% in collector thermal efficiency. However, the use of a double-pass resulted in an increase in the pressure drop across the collector. Mohamad (1997) conducted theoretical study of a double pass solar collector with porous media in the second channel. Sopian et al. (2007) performed the experimental studies on the performance of a double-pass solar collector with porous media in the second or lower channel (Figure 6.1). The second or lower channel of the solar collector is filled up with porous media which acts as heat storage system. This increased the outlet temperature and the performance of the system.

Banout et al. (2011) have designed the double pass solar drier system. Figure 6.2 shows the details description of the Double pass solar drier (DPSD).

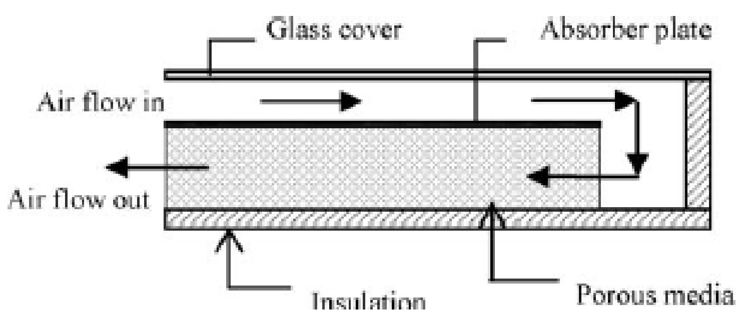

Figure 6.1. The schematic of a double-pass solar collector with porous media in the second channel (Sopian et al., 2007)

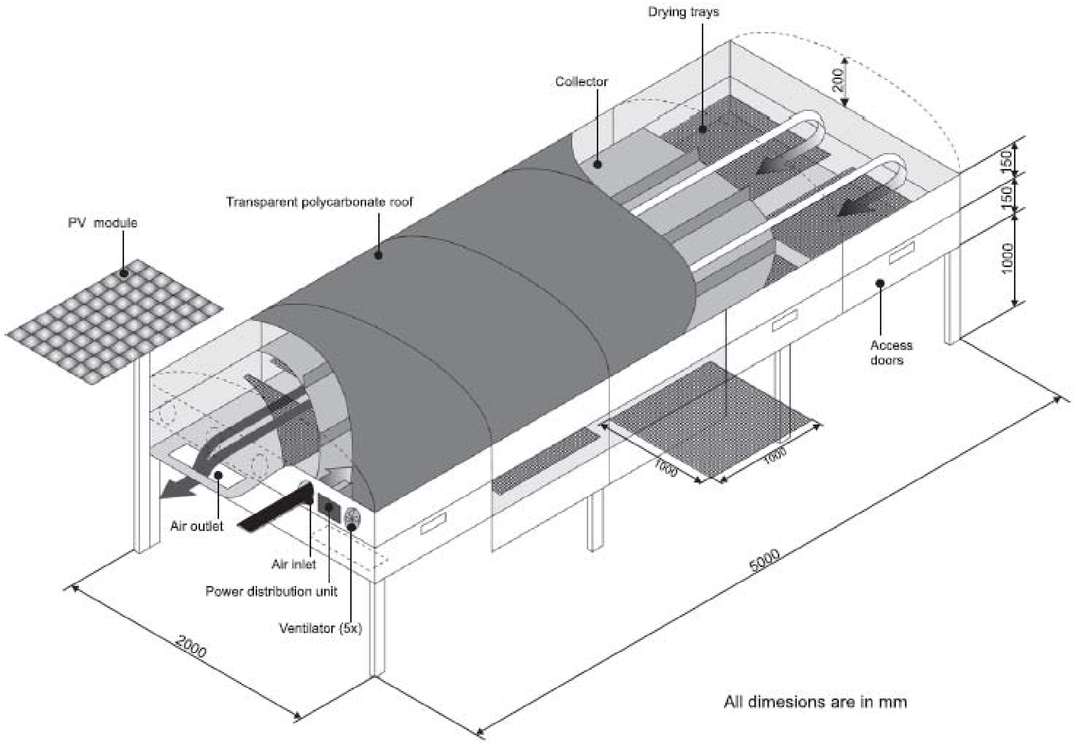

Figure 6.2. Description of the Double pass solar drier (DPSD) (Banout et al., 2011)

The dimensions of the drier are as follows: length 5 m, width 2 m and height 0.30 m as shown in Figure 6.1. The drier consists of five equal modules that are connected together. The supporting structure of each module is made from square steel rods. The sides are equipped with doors enabling access on each side into the drying chamber. The casing is done from a custom-made sandwich material consisting of four layers. Moving from inside out these are: aluminum sheet metal (corrosion resistance and odor absorbing free), 2 mm layer of cork (insulation barrier from high heat that could harm the insulation), 20 mm styrofoam (insulation) and galvanized metal sheet (protection from outside influences). The absorber is made by galvanized metal sheet painted black matt to ensure good absorption of solar radiation. The absorber plate here is fixed between the cover material and the backing layer of insulation. The air to be heated flows on either side of the absorber plate, thus increasing the heat transfer surface area. The absorber plate is, thus, at a lower temperature and, consequently, reradiates less heat. The absorber is supplied by axial metal fins that increase the absorber surface. Polycarbonate panel sheet represent the glazing of the collector part of the drier. It is a UV light stable material with good shatter resistance and transmissivity. At the beginning of the drier there are five DC fans which provide the necessary air-flow through the absorber and drying chamber. The fans are connected directly to a photovoltaic panel by a parallel connection. No regulatory systems are required as the system regulates the air-flow itself due to the position of the sun during the day. The drying chamber is fitted with ten trays 1 x 1 m, made from a steel frame and a High Density Polyethylene (HDPE). This form of plastic is temperature resistant and does not represent intoxication danger for the product (Banout et al., 2011).

The performances of a new designed DPSD have been compared with those of a typical cabinet drier (CD) and a traditional open-air sun drying for drying of red chilli in central Vietnam. The DPSD resulted in the shortest drying time to meet desired moisture content of chilli (10% w.b.), which corresponds to the highest drying rate comparing to other methods. The DPSD showed higher performance compared to CD, which the overall drying efficiency was more than two times higher in case of DPSD compared to CD. All measured and calculated parameters for performance evaluation of DPSD compared to typical CD and traditional open-air sun drying are summarized in Table 6.2, (Banout et al., 2011).

Table 6.2. Performance evaluation of DPSD compared to CD and traditional open-air sun drying

(Banout et al. 2011)

Product	Red chilli (*Capsicum annum* L.)		
Initial moisture content (% w.b.)	90.21		
	Day 1	Day 2	Day 3
Global radiation on the plane of solar collector (MJ/m^2)	22.20	22.30	23.81
Average ambient temperature (°C)	34.65	33.18	34.17
Average ambient relative humidity (%)	51.89	59.33	57.76
Parameter	DPSD	CD	Open-air sun drying
Quantity loaded (full load) (kg)	38.40	3.30	7.20
Loading density (kg/m^2)	3.66	3.67	3.67
Collector area (m^2)	10	0.9	ND
Collector tilt (°)	0	0	0
Solar aperture (m^2)	10	0.9	1.96
Tray surface area (m^2)	9.4	0.9	1.96
Air-flow rate (m^3/h)	648.65	64.52	ND
Drying time including nights, up to 10% (w.b.) m.c. (h)	32	73	Not reached
Overall drying efficiency, up to 10% (w.b.) m.c. (%)	24.04	11.52	8.03
First day drying efficiency (%)	15.22	9.32	7.09
Heat collection efficiency (%)	61.62	45.63	ND
Pick-up efficiency, up to 10% (w.b.) m.c. (%)	22.04	18.94	ND
Average temperature of exit air (°C)			
Day 1	52.58	44.45	34.65
Day 2	54.14	45.48	33.18
Day 3	54.52	49.38	34.17
Average relative humidity of exit air (%)			
Day 1	23.65	39.89	51.89
Day 2	24.00	36.70	59.33
Day 3	23.56	31.00	57.76
Maximum drying temp. at no-load (°C)	70.50	60.10	38.80
Maximum drying temp. with load (°C)	64.30	56	38.80
Duration of drying air temp. 10 °C above ambient temp. (h)	25	18	0

w.b., wet basis; m.c., moisture content; ND, not determined.
DPSD – Double-pass solar drier; CD – cabinet drier.

6.3.2 Indirect active hybrid solar – Electrical dryer system

Boughali et al. (2009) studied the indirect active hybrid solar –Electrical dryer in the eastern Algerian Septentrional Sahara. The indirect active hybrid solar–electrical dryer constructed and installed at LENREZA laboratory (laboratory of new and renewable energy in arid zones), university of Ouargla, Algeria. It consists mainly of a flat plate solar collector, drying chamber, electrical fan, resistance heater (3.75 kW: accuracy ± 2%) and a temperature controller. The solar air collector has an area of 2.45 m^2, and was inclined at an angle of 31^0 (latitude of Ouargla city) with the horizontal facing south all the time and used a painted matte black metal galvanized of 0.002 m thickness to absorb most of the incident solar radiation. The top losses were minimized by placing a glass cover of 0.005m thickness over the top of the metal galvanized sheet, and an insulation layer of polystyrene sandwiched between two parallel galvanized metal sheets was used as sides and back insulator. The air was drawn under the glass sheet, between the glass and the absorber. The solar collector was connected directly to the drying chamber without any air ducts. The drying cabinet fabricated with a galvanized iron box with insulated polystyrene walls of dimensions 1.65 x 0.60 x 1.00 m (height, width and depth) contains six product trays each tray has an area of 0.4 m^2 with possibilities to extend to eight product trays. The drying trays were made of a wooden frame on all four sides and a wire mesh on the bottom to uphold the samples and/or to change the position of the trays. The mass sample used in this experiment was 2 kg in each tray with airflow 0.0314, 0.0470 and 0.0628 m^3/s. There was a distance of 0.12 m between trays in order to obtain uniform air circulation. The door of the dryer was properly sealed to prevent air leakage. In solar drying process, the auxiliary heater was used to adjust the drying air temperature. The preliminary heated drying air by solar radiation, arrived at the inlet of cabinet dryer was heated by electrical resistance if its temperature was less than consign temperature; which is controlled thermostatically and then aspired by an exhaust fan through the product to the environment. The exhaust fan of 20 cm diameter (model KFA30, power input 40 W, running at 1400 rpm and volumetric flow at 0.325 m^3/s) was manually controlled by a valve, allowing the choice of the desired air mass flow. The fan was fixed below product trays at the bottom of the dryer to ensure an even distribution of air and evacuate the humidity of the product to the surrounding. The design and photo for the hybrid solar dryer are presented, respectively, in Figure 6.3 and Figure 6.4 (Boughali et al., 2009).

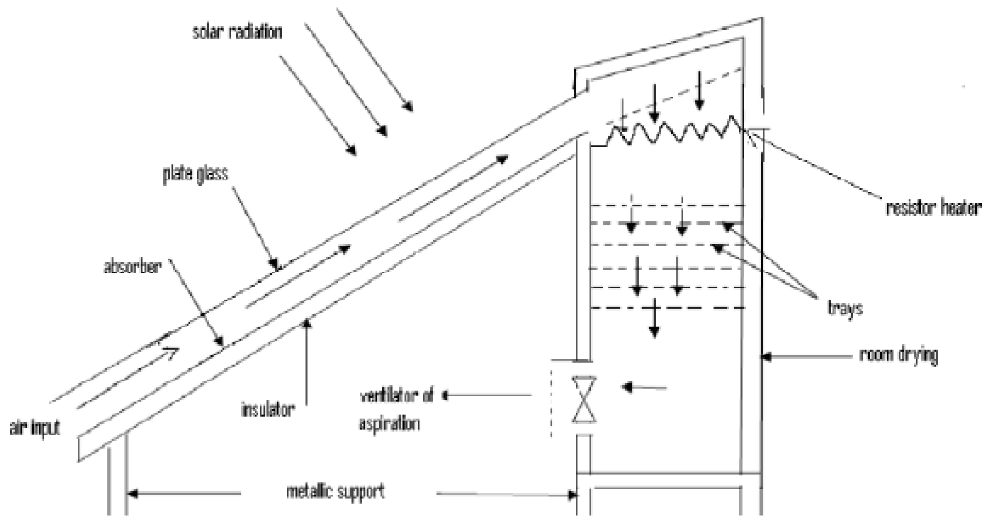

Figure 6.3. Schematic diagram of an indirect active hybrid solar–electrical dryer (Boughali et al., 2009)

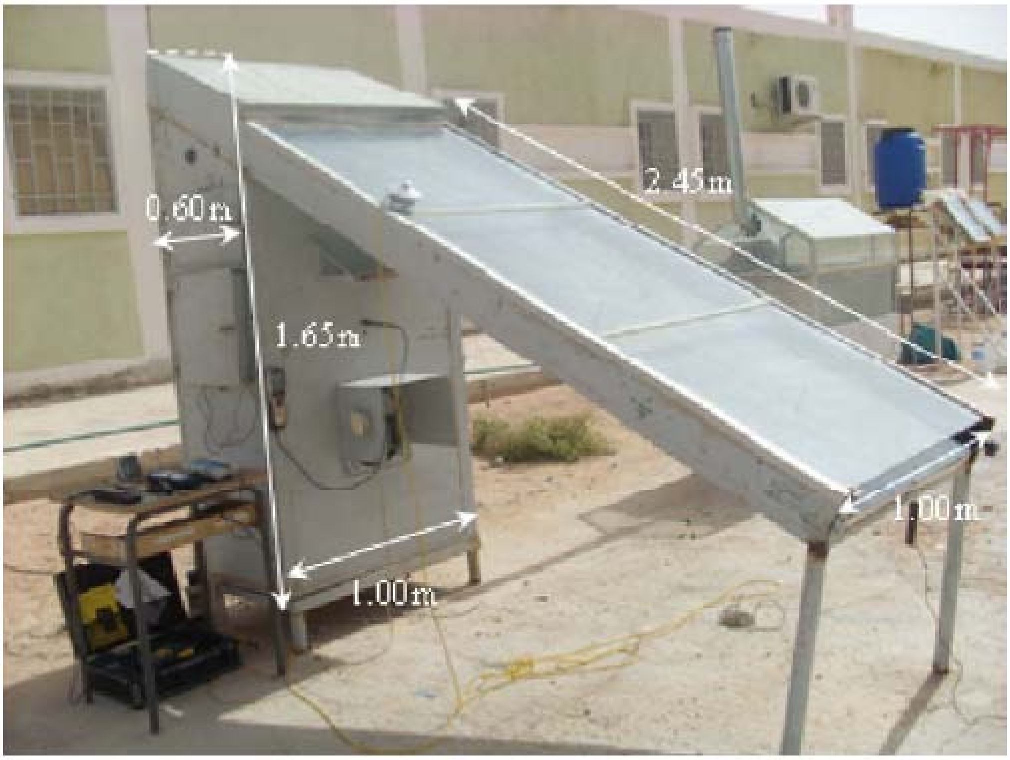

Figure 6.4. Photo of an indirect active hybrid solar–electrical dryer(Boughali et al., 2009).

An experimental tests with and without load were performed in winter season in order to study the thermal behavior of the dryer and the effect of high air mass flow on the collector and system drying efficiency. The fraction of electrical and solar energy contribution versus air mass flow rate was investigated. Slice tomato was studied with different temperatures and velocities of drying air in order to study the influence of these parameters on the removal moisture content from the product and on the kinetics drying and also to determine their suitable values. Many different thin layer mathematical drying models were compared. Table 6.3 displays the fraction of electrical and solar energy used in dryer process. It was noticed that when airflow rates of the drying air increased from 0.0405 kg/m^2 s (1 m s^{-1}) to 0.0810 kg/m^2 s (2ms^{-1}) the percent energy contribution by the solar air heater decreased from 25.074% to 13.22% while that of auxiliary heater increased from 74.92% to 86.78%. This increase in contribution of the auxiliary heater is due in fact to the collector outlet temperature of the air drying which will be decreased significantly in high airflow rates and hence the air drying will be required to be heated by the auxiliary heater by larger temperature difference. From the energy point of view it is preferable in drying operation to use low airflow rate which has a fraction of solar energy used greater than other air flow(Boughali et al., 2009).

Table 6.3. Energy contribution of solar collector, electrical heater and blower for the hybrid dryer (Boughali et al., 2009)

$T = 65$ °C Velocity (m s^{-1})	Solar air heater (kWh)	Fraction of solar energy used (%)	Electrical (Heater + blower) (kWh)	Fraction of electrical energy used (%)	Total energy (kWh)
1	7.56	25.07	22.59	74.92	30.15
1.5	6.83	20.54	26.42	79.45	33.25
2	4.61	13.22	30.24	86.78	34.85

6.3.3 Solar dryer system with swirling flow

Gülsah and Cengiz (2009) designed a new solar dryer system with swirling flow for drying seeded grape. The schematic diagram of the system is shown in Figure 6.5.

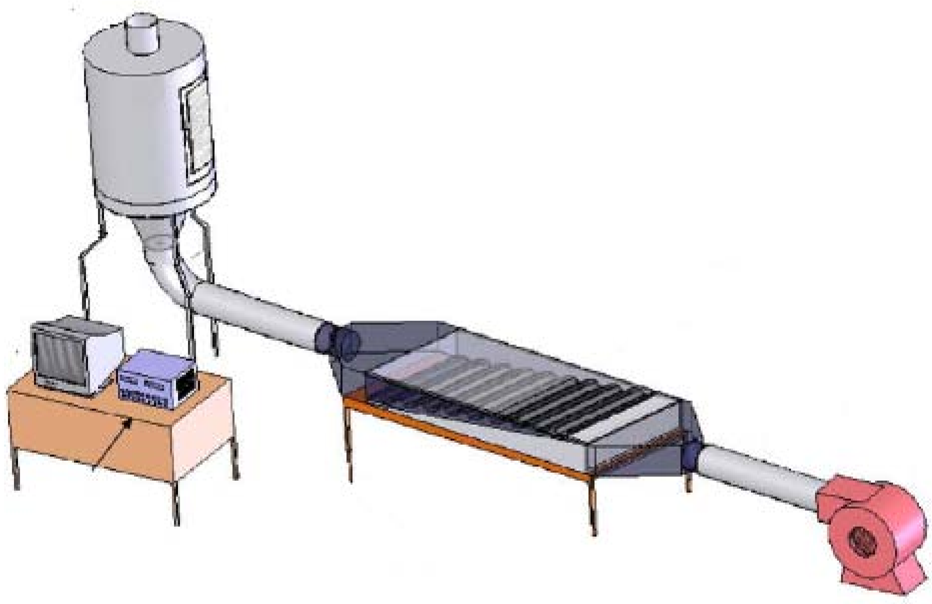

Figure 6.5. Schematical view of designed experiment set (Gülsah and Cengiz, 2009)

A swirl element was installed in the entrance of the chamber to give rotation effect to the air (Figure 6.6). Also 32 pieces of bended sheet strips with dimensions 21 x 5 x 3 mm were installed inside the chamber so as to direct the air flow (Figure 6.7).

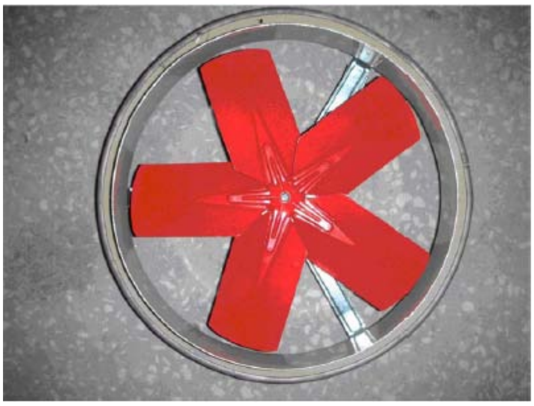

Figure 6.6. The swirl element with triangle arranged and 60° angle (Gülsah and Cengiz, 2009)

Figure 6.7. Air directing elements installed inside drying chamber (Gülsah and Cengiz, 2009)

A new type of air solar collector, having dimensions 940 x 1850 x 200 mm^3 was manufactured for supplying hot air necessary for drying. In order to increase collector's efficiency absorbing surface was manufactured in steps. Also holes of 15mm diameter were drilled 6 pieces on each step for increasing turbulence effect on the developed expanded surface collector. In the developed system various drying air velocities were examined in terms of drying periods. Drying periods of dried grapes in the drying chamber with air solar collector and over cement ground were compared. Also drying experiments were made with air directing elements installed inside the dryer and a swirl element to the entrance of drying chamber was then compared with drying in open air under natural conditions in terms of drying period. Accordingly 200 h of drying period under natural conditions decreased to 80 h with the developed dryer having swirl element with an air velocity of 1.5 m/s. With the increased in the difference of dryer's entrance and exit temperatures drying period gets shorter (Gülsah and Cengiz,2009).

6.3.4 Solar assisted heat pump dryer system

Heat pump dryers have been known to be energy efficient when used in conjunction with drying operations. The principal advantages of heat pump dryer is the ability to recover energy from the exhaust gas as well as their ability to control the drying gas temperature and humidity. Heat pumps have been extensively used in industry for many years, although their application to process drying and, in particular, to drying textile products is relatively lower. The solar assisted heat pump drying system has been operated successfully. The heat pump recirculation mode and solar mode can be used to produce the same quality of drying, this allows the drying process to be continues and to save energy by not burning fossil fuels (Best et al., 1994).

Best et al. (1994) designed and operated a solar assisted heat pump drying prototype system. The prototype had a drying chamber 3.78 m. Long divided in six sections, two of them with four drying trays and the other four sections with three each for a total of 20 trays. The heat pump consisted of modified 7 kW packaged air conditioning system. The compressor and the condenser were mounted in the frontal part of the equipment and the evaporator at the end of the drying chamber. The solar collector was fixed on top and consisted of a horizontal single glazed flat plate collector with air flowing on both sides of the black painted absorber. The advantage of the low temperature and better control in the drier showed that the heat pump assisted solar drying system is an excellent alternative to traditional drying systems.

A solar assisted heat pump drying system with an energy storage tank has been studied by Xie et al. (2006). The drying system is designed such a way that some of the components can be isolated depending on the weather conditions and usage pattern. The performance of the whole system has been modeled and investigated under a typical summer day of the city Baoding, China. Results show that the coefficient of performance (COP) of the SAHP drying system is 5.369, while it is 3.411 without solar energy inputs. With an energy storage tank, the SAHP drying system performs more stable and modulates the mismatch between solar radiation and the energy needed in the night.

Hawlader and Jahangeer (2006) built a fully equipped experimental solar assisted heat pump drying system set-up for drying of green beans. This system illustrated in Figure 6.8 schematically. The experimental set-up comprised of two separate paths which used for air and refrigerant. Solar air collector, air-cooled condenser, auxiliary heater, blower, dryer unit, evaporator, and temperature and flow control devices were in the air path. The refrigerant path consists of a vapour-compression heat-pump unit, with collector evaporator, an open-type reciprocating compressor, evaporator pressure regulators, expansion valves, condenser tank, and a fan-coil unit. The two evaporators are connected in parallel with individual expansion valves. Evaporator 1 acts as a dehumidifier and Evaporator 2 performs as an evaporator collector. A bare flat plate solar collector was used as the evaporator and R134a as the refrigerant. The values of COP, obtained from the simulation and experiment are 7.0, and 5.0, respectively, whereas the solar fraction (SF) values of 0.65 and 0.61 are obtained from simulation and experiment, respectively.

Hawlader et al. (2008) compared the performance of an evaporator–collector and an air collector used in an integrated solar system. It was found that the evaporator–collector performed better than the air collector in a solar assisted heat pump drying system. The air collector efficiency was raised because of higher mass flow rates of air and using of dehumidifier in system. The range of efficiency of the air collector, with and without dehumidifier, was found to be about 0.72–0.76 and 0.42–0.48, respectively. It was also revealed that the efficiency of the evaporator–collector was higher than that of the air collector and it increased with increment of refrigerant mass flow rate. A maximum evaporator–collector efficiency of 0.87 against a maximum air collector efficiency of 0.76 was obtained.

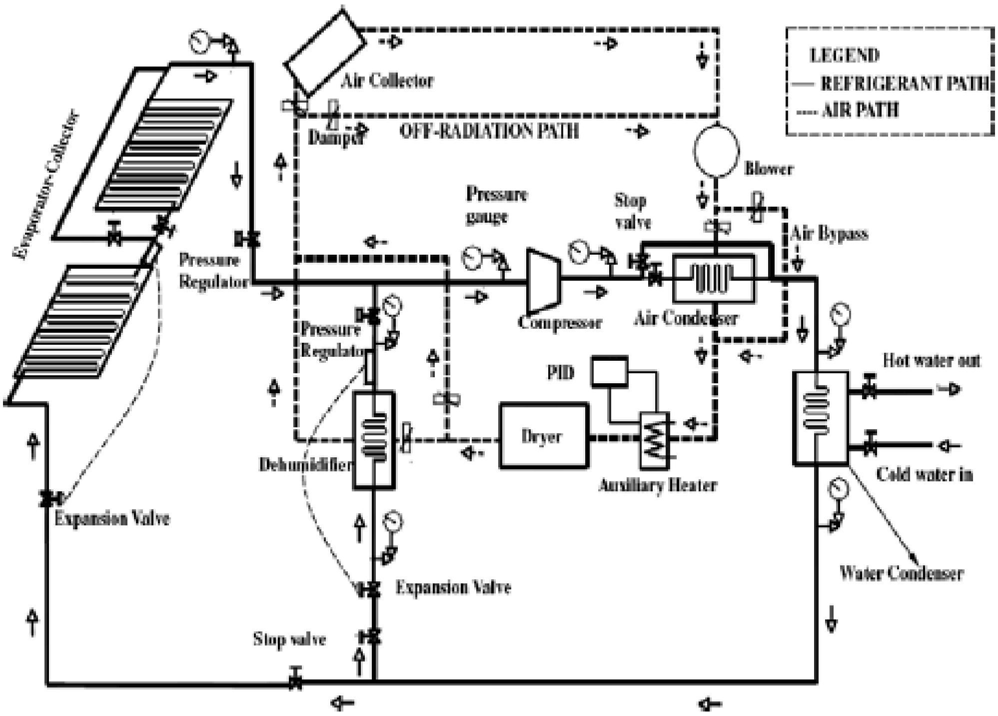

Figure 6.8. Schematic of a solar assisted heat-pump drying system and water heater (Hawlader and Jahangeer, 2006)

A heat pump dryer using multifunctional solar thermal collector designed and studied at the National University of Malaysia (Universiti Kebangsaan Malaysia) (Daghigh et al., 2009). This system consists of five main components: vapor compression heat pump system, multifunctional solar thermal collector, drying chamber, air duct and solar collector hot air channel (Figure 6.9). The multifunctional solar thermal collector attached to the system used to maintain the power in the drying chamber and also to increase the system efficiency and consists of aluminum rods and fins to transfer heat to and from the air passing through it. The collector is covered by the transparent plastic sheet on the top, and insulated by rubber foam on the bottom. The multifunctional collector is designed to operate as heat collector during sunshine hours and as evaporator during night hours or when solar radiation is insufficient. Therefore, it will increase the overall efficiency of the system and also extended the operation time (Abdul Majid et al., 2007).

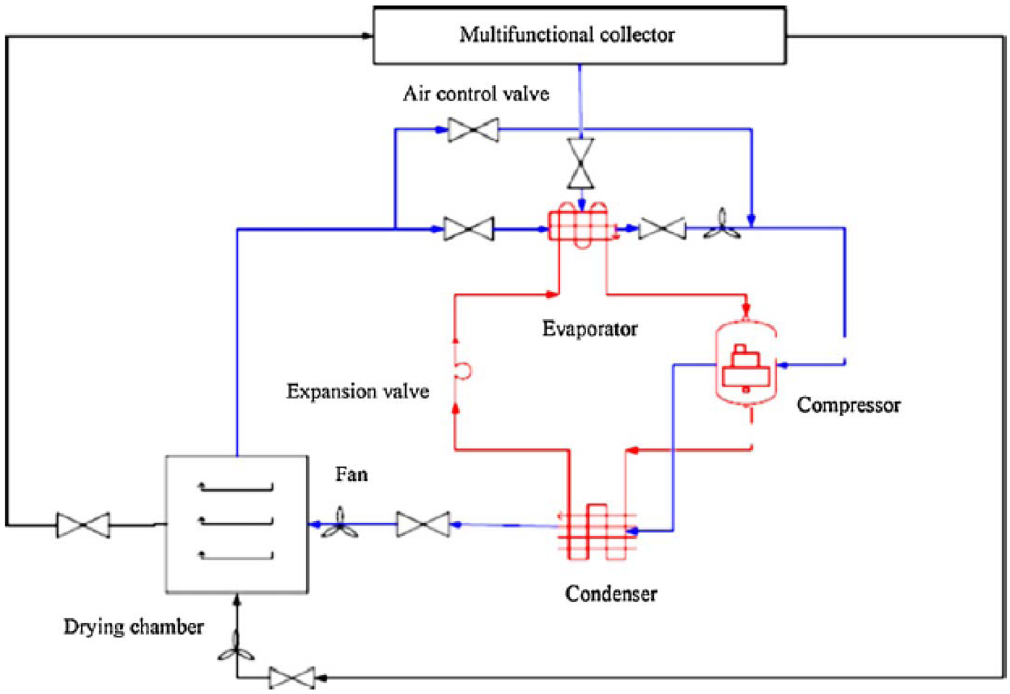

Figure 6.9. Solar assisted heat pump drying using multifunctional solar collector-schematic diagram (Abdul Majid et al., 2007).

6.3.5 Solar assisted chemical heat pump drying system

A chemical heat pump (CHP) is proposed as one of the potentially significant technologies for effective energy utilization in drying. Ogura and Mujumdar (2000) studied the CHP and proposed a chemical heat pump dryer (CHPD) system for ecologically friendly effective utilization of thermal energy in drying (Figure 6.10). CHPs are those systems that utilize the reversible chemical reaction to change the temperature level of the thermal energy which stored by chemical substances (Kawasaki et al., 1999). These chemical substances play an important role in absorbing and releasing heat (Kato et al., 1996). The advantages of thermochemical energy storage, such as high storage capacity, long term storage of both reactants and products, lower of heat loss, suggests that CHP could be an option for energy upgrading of low temperature heat as well as storage (Ranade et al., 1990).

Solar drying system with solid–gas chemical heat pump (SACHPD) has been proposed by Ibrahim et al., (2009a). Figure 6.11 shows the schematics of a solar-assisted solid–gas chemical heat pump dryer. The system consists of four main components solar collector (evacuated tubes type), storage tank, chemical heat pump unit and dryer chamber. The reaction used in this study was:

$$CaCl_2 \cdot 2NH_3 + 6NH_3 \rightarrow CaCl_2 \cdot 8NH_3 + 6\Delta H_r \qquad 8.1$$

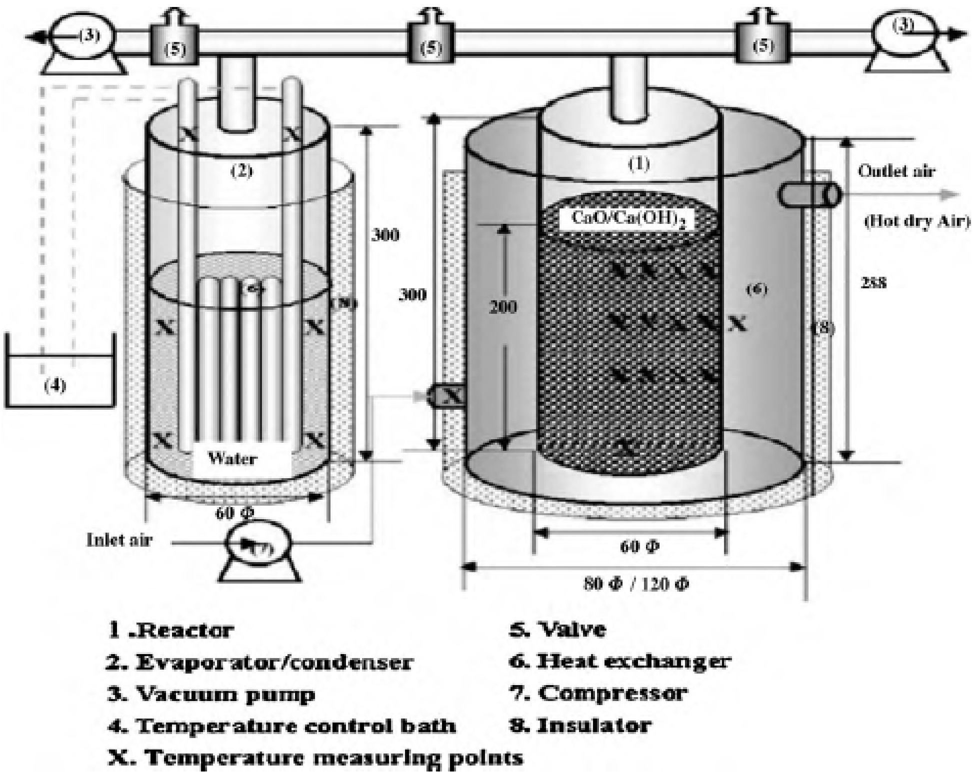

Figure 6.10. Standard-type CHP unit (Ogura and Mujumdar, 2000)

The drying chamber contains multiple trays to hold the drying material and expose it to the air flow. The general working of chemical heat pump in this study occurs in two stages: adsorption and desorption. The adsorption stage is the cold production stage, and this is followed by the regeneration stage, where decomposition takes place. During the production phase, the liquid–gas transformation of ammonia produces cold at low temperature in the evaporator. At the same time, chemical reaction between the gaseous ammonia and solid would release heat of reaction at higher temperature. The incoming air is heated by condensing refrigerant (ammonia) and enters the dryer inlet at the drying condition and performs drying. After the drying process, part of the moist air stream leaving the drying chamber is diverted through the evaporator, where it is cooled, and dehumidification takes place as heat is given up to the refrigerant (ammonia). The air is then passing through the condenser where it is reheated by the condensing refrigerant and then to the drying chamber (Fadhel et al., 2011). In this study the material dried is lemongrass.

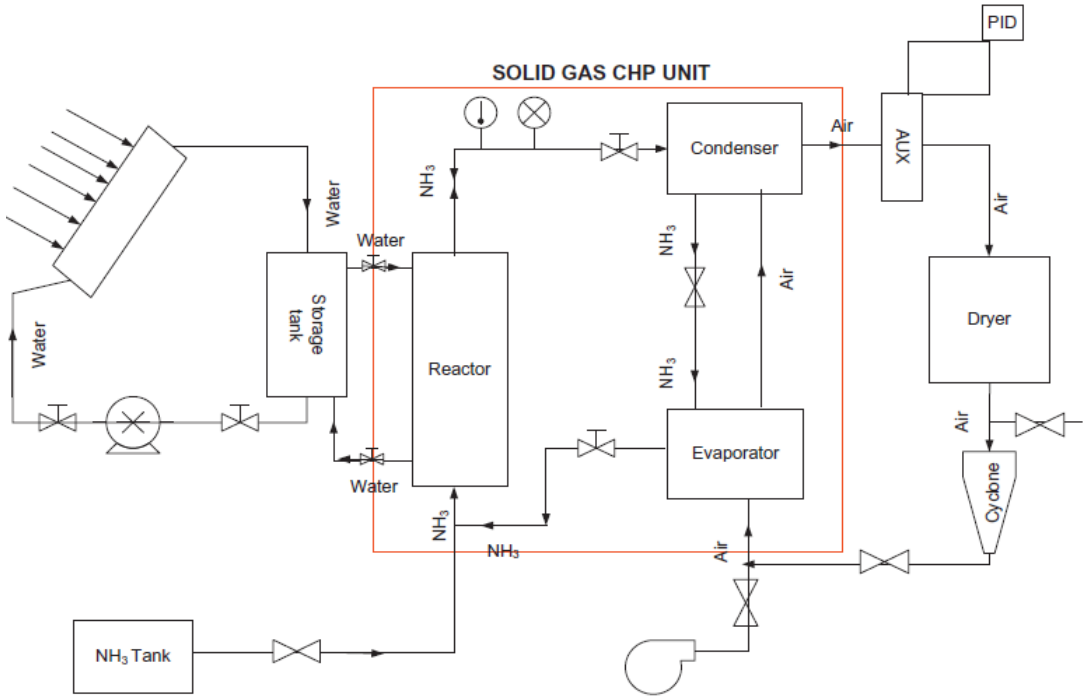

Figure 6.11. Schematic diagram of solar-assisted chemical heat-pump dryer (Ibrahim et al., 2009a)

A series of experiments has been performed on the (SACHPD) system to evaluate the performance. The performance of the system has been investigated experimentally for different environment climate conditions. Two representative days for clear and cloudy conditions were presented (Ibrahim et al., 2009b). The maximum values of the solar fraction (SF) and the coefficient of performance of chemical heat pump (COP^h) of the system are 0.713 and 2 on a clear day, against the maximum values of 0.322 and 1.42 on a cloudy day. The total system energy output of 51 kWh and 25 kWh were obtained for clear and cloudy days, over 9 hours drying time. Figure 6.12 show the system solar fraction while Figure 6.13 shows the coefficient of performance of chemical heat pump.

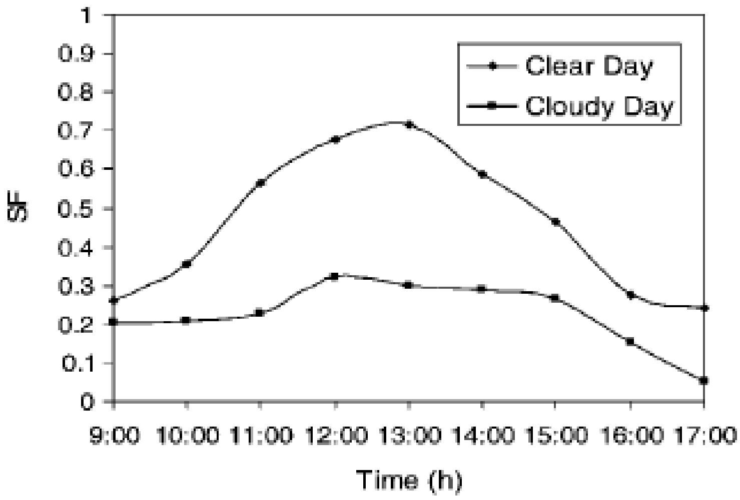

Figure 6.12. System solar fraction (Ibrahim et al., 2009b)

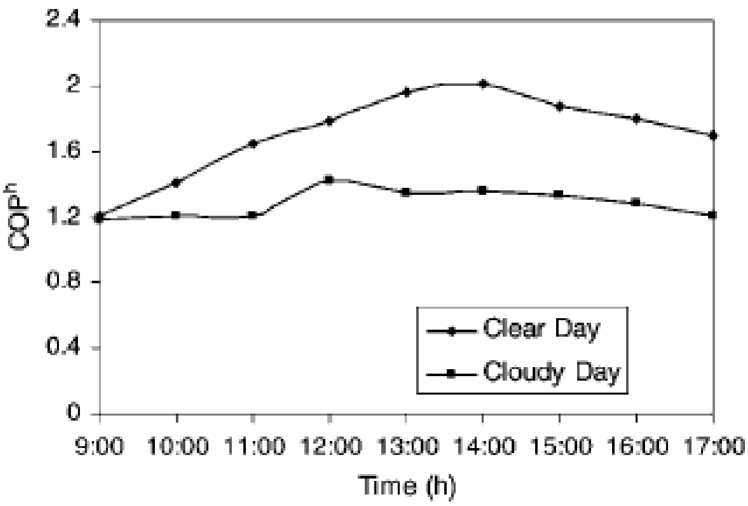

Figure 6.13. Coefficient of performance of CHP (Ibrahim et al., 2009b)

6.3.6 Solar-assisted dehumidification system

The temperature of air in drying process affects the quality, evaporation capacity as well as drying period. In addition, short time period is required for higher temperature drying. At higher temperature, pure water vapor pressure becomes higher; therefore, the difference between water vapor partial pressure and pure water vapor pressure becomes higher. This pressure difference is the driving force for water evaporation in to the air. However, drying at high temperature is not suitable for the materials which are sensitive to heat because it can cause cracks, browning which further reduce the taste of final product as well as the evaporation of the active ingredients such as in medicinal herbs (Sopian et al., 2009).

Yahyaa et al. (2008) have designed and tested a solar dehumidification system for medicinal herbs. A schematic diagram of the solar assisted dehumidification drying system is shown in Figure 6.14. The system consisted of a solar collector, an energy storage tank, auxiliary heater, and adsorbent, water to air heat exchanger, a water circulating pump, drying chamber, and other equipment. It is made up of essentially three processes, namely regeneration, dehumidification, and batch drying. During regeneration process, the air outside the dryer is heated with the heat exchanger and is supplied to the adsorbent. The adsorbent is heated with this hot air and water content rate is reduced, removing the water content. The water content is evaporated by the hot air and leaves the dryer. During dehumidification (adsorption) process, the air inside the dryer passes through the heat exchanger by use of the blower. However, since no hot water is circulated in the heat exchanger, the air reaches the adsorbent. The air was dehumidified with the adsorbent and is supplied to the drying chamber as the dry air. The relative humidity and temperature of the drying chamber were 40% and 35 $^{\circ}$C respectively (Sopian et al., 2009). The performance indices considered to calculate the performance of the drying system are: Pick up efficiency (η_p), Solar Fraction (SF) and Coefficient of Performance (COP). The results indicated that the maximum values of the pickup efficiency (η_p), solar fraction (SF) and coefficient of performance (COP) was found 70%, 97% and 0.3, respectively with initial and final wet basis moisture content of *Centella Asiatica L* type,88% and 15%, respectively at an air velocity of 3.25 m/s. Good agreement was found between predicted results and measured results.

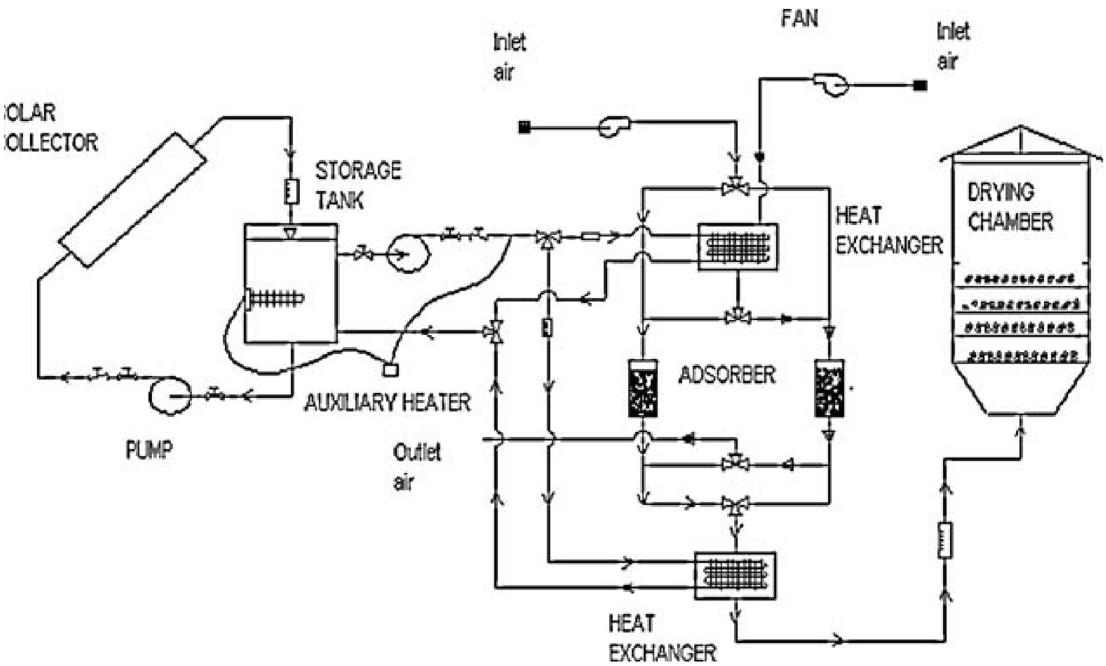

Figure 6.14. Schematic diagram of the solar assisted dehumidification system (Yahyaa et al., 2008)

6.3.7 PV-ventilated solar greenhouse dryer system

The greenhouse drier is a system that uses the regular structure of a greenhouse to work as solar drier during the warmer months of the year, when the greenhouse is not used. This double function, greenhouse and drier, improves the return rate of the initial investment (Condori and Saravia, 1998). A number of studies have been reported on solar greenhouse drying (Condori and Saravia, 1998; Garg and Kumar, 2000; Condori et al., 2001; Jain and Tiwari, 2004; Farhat et al., 2004).

Janjai et al. (2007) have reported the experimental performance of a PV-ventilated solar greenhouse dryer for drying of chillies. The greenhouse dryer has a concrete floor with the area of 5.5 × 8.0 m². It is covered with transparent polycarbonate plates *and it was designed in the parabolic shape of facilitate the construction. Three fans powered by a solar cell module of 53 W were used to ventilate the dryer.* The structure of the greenhouse is shown in Figure 6.15. *To investigate its performance, the dryer was used to dry 4 batches of chilies during December, 2003 to March, 2004. The air temperature inside the dryer was 60-65°C at the noon of a clear day. High drying air temperature with reasonably low relative humidity inside the dryer during almost whole period of the day demonstrated the potentiality of solar drying inside the greenhouse dryer. The temperatures at three locations (top, middle and bottom) inside the dryer follow the similar pattern. Heat stored in the concrete floor helped to reduce variation of drying air temperature due to the fluctuation of solar radiation. The use of solar cell module helps to regulate indirectly the drying air temperature. The results from the experiments demonstrate that the drying time for drying of 100-150 kg of chilies in the dryer was significantly less than that required for natural sun drying but the drying efficiency increases with loading capacity.*

Janjai et al. (2009) in their another study presented the experimental and simulated performance of a PV-ventilated solar greenhouse dryer for drying of peeled longan and banana. To investigate the experimental performances of the solar greenhouse dryer for drying of peeled longan and banana, 10 full scale experimental runs were conducted. Of which five experimental runs were conducted for drying of peeled longan and another five experimental runs were conducted for drying of banana. The drying air temperature varied from 31°C to 58 °C during drying of peeled longan while it varied from 30 °C to 60 °C during drying of banana. The drying time of peeled longan in the solar greenhouse dryer was 3 days, whereas 5–6 days are required for natural sun drying under similar conditions. The drying time of banana in the solar greenhouse dryer was 4 days, while it took 5–6 days for natural sun drying under similar conditions. The quality of solar dried products in terms of color and taste was high-quality dried products. A system of partial differential equations describing heat and moisture transfer during drying of peeled longan and banana in the solar greenhouse dryer was developed and this system of non-linear partial differential equations was solved numerically using the finite difference method. The numerical solution was programmed in Compaq Visual FORTRAN version 6.5. The simulated results reasonably agreed with the experimental data for solar drying of peeled longan and banana. This model can be used to provide the design data and is also essential for optimal design of the dryer Janjai et al. (2009).

Figure 6.15. The greenhouse solar dryer. (Janjai et al. 2007)

6.3.8 Photovoltaic/Thermal solar collector (PV/T) drying system

One of the ingenious methods of solar energy conversion systems is the photovoltaic thermal air collector or hybrid solar collector, which converts solar radiation to both thermal and electrical energies for use in drying systems. The integrated arrangement for utilizing thermal energy, as well as electrical energy, with a PV module is referred to as hybrid PV/T system (Chantana et al. 2009). The hybrid PV/T system can be used for air heating and water heating.

Chantana et al. (2009) presented the conceptual design of the Hybrid PV/T assisted desiccant integrated hot air combined with an IR drying system (HPIRD) (Figure 6.16).

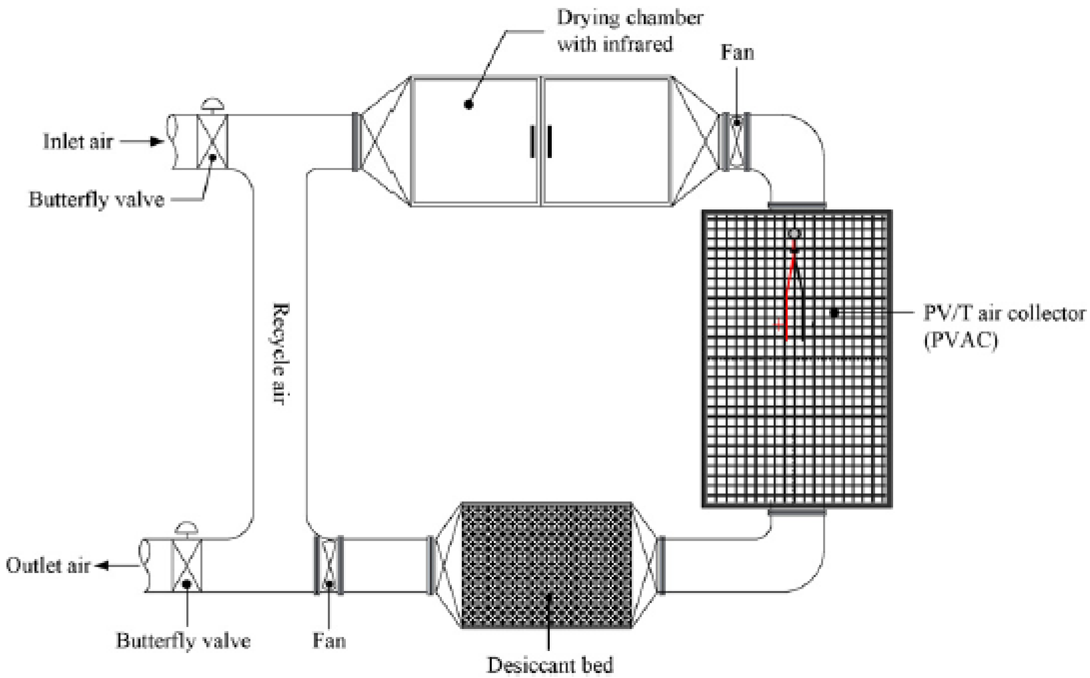

Figure 6.16. Schematic of hybrid PV/T-desiccant integrated infrared drying system (HPIRD) system (Chantana et al. 2009)

The hybrid PV/T-desiccant integrated infrared drying system (HPIRD) consists of three main functions: (i) a PV air collector (PVAC), (ii) a desiccant silica gel bed (DB), and (iii) an infrared drying system, fabricated as a single unit (lab scale). The PVAC performs two functions: to generate electricity, which operates the fan in the drying chamber, and to preheat air under a PV panel by means of a solar air collector. The DB system employed silica gel to dehumidify air before use in the drying chamber; the system has three beds of silica gel in a DB case. A HA-IR drying system was designed to dry agricultural products by using infrared combine with hot air. The chamber is made from a stainless steel sheet 0.5-mm thick, and 0.8m×0.35m×0.4 m. The infrared heat source in the drying system was a black ceramic IR heater with 800Wfitting on top side and an electrical heater used to heat up drying air. The chamber walls were insulated (syntatic insulator, 25-mm thick) to prevent heat loss. The chamber temperature was regulated by using a temperature controller with two trays fitted inside it (Chantana et al., 2009). The performance evaluation studies indicated that the HPIRD drying test at 60 ^{0}C and velocity of 0.6 m/s reduced the drying time by 44% with less energy consumption (63%) compared to hot air drying. HPIRD drying also gave better results over hot air-infrared drying. Finally, drying time, drying rate and energy consumption were reduced considerably with the hybrid drying system. The dryer can be used for drying various agricultural products, especially herbs, of which quality is easily lost due to a long drying time. Therefore, the HPIRD is a suitable model and is recommended because it reduces drying time, energy consumption and improves the quality of dried products.

A hybrid photovoltaic-thermal (PV/T) greenhouse dryer of 100 kg capacity has been designed and constructed at Solar Energy Park, Indian Institute of Technology, New Delhi), India. The developed dryer has been used to dry the Thompson seedless grapes (Mutant: Sonaka) (Barnwal and Tiwari, 2008). The hybrid photovoltaic-thermal (PV/T) integrated greenhouse (roof type even span) dryer has been developed having floor area of 2.50 m x 2.60 m, 1.80 m central height and 1.05 m side walls height from ground and 30 ^{0} roof slope. The greenhouse dryer has been integrated with two PV modules (glass to glass; dimensions: 1.20 m x 0.55 m x 0.01 m; 75 Wp each) on south roof of the dryer. The PV module produces DC electrical power to operate a DC fan (inner diameter = 0.080 m, outer diameter = 0.150 m) for forced mode operation and also provides thermal heating of greenhouse environment. To provide air movement in the greenhouse dryer, 0.15 m height is open at bottom side and further 0.10 m is provided with wire mesh. The air moves from bottom to top through three-tier system of perforated wire mesh trays as the air at bottom becomes hot. The UV stabilized polyethylene sheet has been fitted over the structural frame of the dryer which helps in trapping of infrared radiation. It also prevents unnecessary circulation of ambient air and thus maintains the desire temperature inside the greenhouse. The developed hybrid photovoltaic-thermal (PV/T) integrated greenhouse dryer is shown in Figure 6.17.

Figure 6.17. Hybrid photovoltaic-thermal (PV/T) integrated greenhouse dryer (Barnwal and Tiwari 2008)

The grapes were manually sorted in two grades namely GR-I and GR-II, due to difficulty in handling of 100 kg grapes during experimentation. The spoiled grape berries were discarded for prevention from infection to the intact grapes by fungi or bacteria. The GR-I grapes were of greenish color and seems to be premature while GR-II grapes were of yellowish color and fully mature. The grapes were washed with fresh ground water to remove undesired materials, e.g. dust and foreign materials. The surface water from grapes was removed by using cotton cloths. Experiments were conducted for drying of grapes in the month of April, 2007. Various hourly experimental data namely moisture evaporated, grape surface temperatures, ambient air temperature and humidity, greenhouse air temperature and humidity, etc. were recorded to evaluate heat and mass transfer for the proposed system. It has been found that the value of the convective heat transfer coefficient for grapes (GR-I) lies between 0.26 and 0.31 W/m^2 K for greenhouse and 0.34–0.40 W/m^2 K for open conditions, respectively and that for grapes (GR-

II) lies between 0.45–1.21 W/m^2 K for greenhouse and 0.46–0.97 W/m^2 K for open conditions, respectively (Barnwal and Tiwari 2008).

6.4. CONCLUSION

Numerous types of solar drying systems have been designed and developed in various parts of the world. Improving of the drying operation to save energy, improve product quality as well as reduce environmental effect remained as the main objectives of any development of solar drying system. Solar dryers have been proposed to utilize free, renewable, and non-polluting energy source provided by the sun.

In this chapter the development, technical and performance of several advancements of solar drying system with aspect to the agriculture product being dried were presented. The use of solar drying systems in the agricultural area to conserve vegetables, fruits and crops has shown to be practical, economical and the responsible approach environmentally.

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Solar Drying: Fundamentals, Applications and Innovations

Drying is a highly energy-intensive unit operation and is of great importance in almost all industrial sectors. Drying is an essential step in food preservation to improve shelf life by reducing potential of microbial attack. There has been remarkable development in the innovative drying techniques for food products. Drying using solar radiation, i.e. drying under direct sunlight, is one of the oldest techniques used by mankind to preserve agriculture based food and non-food products. This form of energy is free, renewable and abundant in any part of the world especially in tropical countries. An improved drying method using solar radiation -know as solar drying- is becoming a popular option to replace mechanical thermal dryers owing to the high cost of fossil fuels which is growing in demand but dwindling in supply. This e-book is an exploratory preliminary effort to make relevant knowledge on solar drying freely available for readers all over the world. We have tried to cover fundamentals, specific applications and recent developments in solar drying. This book is also useful for self-study by engineers and scientists trained in any discipline and so as for the readers who have some technical background.

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