Chapter 2

Review of Literature
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Development of a solar-biomass integrated drying system with induced draft for drying of spices viz. ginger, turmeric independent of grid power to suit the farmers of North Eastern India is the main objective of this research work. Attempts were therefore, made to review the relevant published literature on these aspects and are presented hereunder.

2.1 A systematic classification of drying systems

All drying systems can be classified primarily according to their operating temperature ranges into two main groups of high temperature dryers and low temperature dryers. However, dryers are more commonly classified broadly according to their heating sources into conventional dryers and solar-energy dryers. All practical designs of high temperature dryers are conventional dryers, while the low temperature dryers are either conventional or solar-energy based systems (Ekechukwu, 1999b).

2.1.1 High temperature dryers

High temperature dryers are necessary when very fast drying is desired. They are usually employed when the products require a short exposure to the drying air. Their operating temperatures are such that, if the drying air remains in contact with the product until equilibrium moisture content is reached, serious over drying will occur. Thus, the products are only dried to the required moisture contents and later cooled (McLean, 1980).

High temperature dryers are usually classified into batch dryers and continuous flow dryers (Hall, 1980; McLean, 1980; Brooker et al., 1974). In batch dryers, the products are dried in a bin and subsequently moved to storage. Thus, they are usually known as batch-in-bin dryers (Brooker et al., 1974). Continuous flow dryers are heated columns through which the product flows under gravity and is exposed to heated air while descending (Hall, 1980). Because of the temperature ranges prevalent in high temperature dryers, most known designs are electricity or fossil-fuel powered. Only a very few designs of high temperature drying systems are solar-energy heated (Ekechukwu, 1987).
2.1.2 Low temperature dryers

In low temperature drying systems, the moisture content of the product is usually brought to equilibrium with the drying air by constant ventilation. Thus, they do tolerate intermittent or variable heat input. Low temperature drying enables crops to be dried in bulk and is most suited also for long term storage systems. Thus, they are usually known as bulk or storage dryers (McLean, 1980). Their ability to accommodate intermittent heat input makes low temperature drying most appropriate for solar-energy applications. Thus, some conventional dryers and most practically-realized designs of solar-energy dryers are of the low temperature type.

2.2 Solar drying

Drying by exposure to sun is one of the oldest methods of using solar energy for food preservation. Solar dryer are more or less simple devices. Indirect solar drying involves some thermal energy collecting devices and dryers of special techniques. In many parts of South East Asia, spice crops and herbs are routinely dried. However, weather conditions often preclude the use of sun drying because of spoilage due to rehydration during unexpected rainy days. Furthermore, any direct exposure to the sun during high temperature days might cause case hardening, where a hard shell develops on the outside of the agricultural products, trapping moisture inside. Therefore, the employment of solar dryer taps on the freely available sun energy while ensuring good product quality via judicious control of the radiation heat (Chua and Chou, 2003).

Solar drying of agricultural products in enclosed structures by natural convection is an attractive way of reducing post harvest losses and low quality of dried products associated with traditional sun-drying (Sacilik et al., 2006; Chen et al., 2005; Chua and Chou, 2003; Bena and Fuller, 2002; Forson et al., 1996).

Active solar dryers 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. The collectors should be positioned at an appropriate angle to optimize solar energy collection. A gear system can be designed to manually adjust the angle of the collectors. Tilting the collectors is more effective than placing them horizontally, for two reasons. Firstly, more solar energy can be collected when the collector surface is nearly
Development of A Solar-Biomass Integrated Drying System for Spice Crops

perpendicular to the sun’s rays. Secondly, by tilting the collectors, the warmer, less dense air rises naturally into the drying chamber. In an active dryer, the solar-heated air flows through the solar drying chamber in such a manner as to contact as much surface area of the food as possible. Thinly sliced foods are placed on drying racks, or trays, made of a screen or other material that allows drying air to flow to all sides of the food. Once inside the drying chamber, the warmed air will flow up through the stacked food trays (Chua and Chou, 2003).

Studies on natural convection solar crop dryers designs of direct, indirect and mixed-mode solar-dryers designs suggested that the performance of the mixed mode natural convection solar crop-dryer (MNCSCD) is potentially most effective and it appears to be particularly promising in tropical humid areas where climatic conditions favour sun drying of agricultural products (Garba et al., 1990; Zaman and Bala, 1989).

The principal types of solar air heaters that can be coupled to the drying chamber of the MNCSCD are: the single pass with front duct (SPFDSAH), single pass with rear duct (SPRDSAH), single pass with double duct (SPDDSAH), and the double pass solar air heater (DPSAH). It has been observed (Mohamad, 1997; Wijeysundera et al., 1982) that the double pass solar air heaters perform better than the conventional single pass systems. However, their application in natural convective flow is limited, since air needs to be forced through the two channels for efficient utilization of the system. Studies on the three types of single pass solar air heaters employing solid absorbers have shown that performance of the SPDDSAH is superior over the other two (Ong, 1982; Macedo and Altemani, 1978; Close, 1963).

It has also been shown that for collectors with tilt angle up to $60^\circ$, the length-to-depth ratio should be between 20 and 200 (Buchberg et al., 1974). Recent modeling work of a SPDDSAH by Hegazy (2000a, 2000b) showed that the channel depth-to-length ratio is an important parameter in determining the useful heat gain. His study suggested that for variable flow conditions, the optimum depth-to-length ratio should be 0.0025 for both natural and forced convection. Thus, the upper limit for the length-to-depth ratio of an air-heater can be assumed to be 400.

A review of the parameters involved in the testing and evaluation of other types of solar dryers can be found in Leon et al. (2002). Exell (1980) presented a basic theory for
the design of natural convection cabinet type crop-dryers and some commercial scale solar dryers have been designed and constructed based on Exell’s semi-explicit approach for dimensioning the MNCSCD (Iloeje et al., 1993).

A mixed-mode natural convection solar crop dryer was designed and used for drying cassava and other crops in an enclosed structure in Kumasi, Ghana. A minimum of 42.4 m² of solar collection area, according to the design, was required for an expected drying efficiency of 12.5%. Under average ambient conditions of 28.2°C and 72.1% relative humidity with solar irradiance of 340.4 W/m², a drying time of 35.5 h was required to achieve a drying efficiency of 12.3% (Forson et al., 2007).

The improvement of the behaviour of solar dryers passes through theoretical studies. Different models for simulation were developed using mass and energy balances in the solid and in the gas phase (Ratti and Mujumdar, 1997). The simulated results were compared with experimental data (Jayarman et al., 1993). It was found that almost two days are necessary to dry the product. The model used to study a solar batch dryer, was based on the equation of heat applied to the product and on the equation of the drying rate (Youcef et al., 2001). In order to represent the moisture transfer, they have used Combes model (Daguenet, 1985), which considers electrical analogies. Variation in the moisture content and the influence of many parameters, such as air velocity, were studied. A solar simulator, with constant receiving energy, was used. It therefore neglects climatic changes, which can have a considerable effect.

In another study (Bennamoun and Belhamri, 2003) using a solar batch dryer with 3 m² collector surface area with an alternative heat source at 50°C, it was reported that the collector surface and the temperature of the heated air essentially affected solar batch drying. Their increase considerably reduces drying time. The influence of the dimension and the total mass of the dried product is less important.

However, natural convection solar crop dryers are normally reported to perform inefficiently (Ekechukwu, 1999b). This is attributed to poor ventilation, which results in excessively high temperatures in the drying chamber. The use of solar dryers with improperly designed airflow mechanism leads to the crops being partially cooked rather than dried. The air circulation is normally poor, particularly in the case of the cabinet-type dryer which has a nearly horizontal roof. Some reports on chimneys have also shown that,
properly designed chimneys can boost the flow of air through an enclosure (Chen et al., 2003; Ong, 2003).

A chimney operates by increasing the buoyancy force to aid the airflow through a structure. This buoyancy force is directly proportional to the difference between the mean air density within the chimney and the density of outside air (McLean, 1980). As the air moves up the chimney, its temperature falls, causing an increase in the average density. At some point when the conditions in the chamber become similar to those outside, the airflow stops or even a reverse flow occurs, unless the wind is strong enough to produce the Bernoulli Effect (Ekechukwu, 1999b).

An experimental investigation into the performance of a solar crop dryer with solar chimney and no air preheating showed that the solar chimney can increase the airflow rate of a direct-mode dryer especially when it is well designed with the appropriate angle of drying-chamber roof. However, the increase in flow rate only increases the drying rate when the relative humidity of the ambient air is below a certain mark (Afriyie et al., 2009). They have also reported that, highest drop in moisture content (MC) of the crop always occurred on the first day of drying. The drying process on this day depended strongly on airflow for removing loosely held moisture (Ekechukwu, 1999a; Okos et al., 1992). Drying at later stages depended more on heat energy required to evaporate the strongly bound moisture from within the crop.

### 2.2.1 Classification of solar-energy drying systems

Solar-energy drying systems are classified primarily according to their heating modes and the manner in which the solar heat is utilized. In broad terms, they can be classified into two major groups (Ekechukwu, 1987), viz. active solar-energy drying systems that are often termed as hybrid solar dryers and passive solar-energy drying systems that are conventionally termed as natural-circulation solar drying systems.

Three distinct sub-classes of either the active or passive solar drying systems can be identified which vary mainly in the design arrangement of system components and the mode of utilization of the solar heat. The main features of typical designs of the various classes of solar-energy dryers are illustrated in Fig. 2.1 (Ekechukwu, 1999b).
Development of A Solar-Biomass Integrated Drying System for Spice Crops

<table>
<thead>
<tr>
<th>TYPE</th>
<th>ACTIVE DRYERS</th>
<th>PASSIVE DRYERS</th>
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<tbody>
<tr>
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<td><img src="image1" alt="Diagram" /></td>
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<tr>
<td>DISTRIBUTED (INDIRECT)</td>
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<tr>
<td>MIXED MODE</td>
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Fig. 2.1 Typical solar energy dryer designs

2.2.1.1 Natural-circulation solar-energy crop dryers

Natural-circulation solar-energy dryers depend for their operation entirely on solar-energy. In such systems, solar-heated air is circulated through the crop by buoyancy forces or as a result of wind pressure, acting either singly or in combination. These dryers are often called passive dryers in order to distinguish them from systems that employ fans to convey the air through the crop. The latter are termed as active solar dryers (Ekechukwu, 1999b).

Natural-circulation solar-energy dryers appear the most attractive option for use in remote rural locations. They are superior operationally and competitive economically to natural open-to-sun drying for reasons viz. they require a smaller area of land in order to
dry similar quantities of crop that would have been dried traditionally over large land areas in the open; they yield a relatively high quantity and quality of dry crops because fungi, insects and rodents are unlikely to infest the crop during drying; the drying period is shortened compared with open air drying, thus attaining higher rates of product throughput; protects crop from sudden rain and their relatively low capital and maintenance costs because of the use of readily available indigenous labour and materials for construction.

Three generic types of natural-circulation solar-energy dryers have evolved retaining many of the advantages of traditional open-to-sun drying viz. integral-type natural-circulation solar-energy dryers; distributed-type natural-circulation solar-energy dryers; and mixed-mode natural-circulation solar-energy dryers.

2.2.1.2 Distributed-type natural-circulation solar-energy dryers

These are often termed indirect passive solar dryers. Here, the crop is located in trays or shelves inside an opaque drying chamber and heated by circulating air, warmed during its flow through a low pressure drop thermo-syphonic solar collector (Norton and Probert, 1984). Because solar radiation is not incident directly on the crop, caramelization and localized heat damage do not occur (Ekechukwu, 1987; Brenndorfer et al., 1985). These dryers are also recommended generally for some perishables and fruits for which their vitamin content are reduced considerably by direct exposure to sunlight and for colour retention in some highly pigmented commodities that are also very adversely affected by direct exposure to the sun (Brenndorfer et al., 1985). Distributed passive solar dryers have higher operating temperatures than direct dryers or sun drying and can produce higher quality products. Thus, they are recommended for relatively deep layer drying (Anonymous, 1980). Their shortcomings, however, are the fluctuations in temperatures of the air leaving the air heaters, thereby making it difficult to maintain constant operating conditions within the drying chamber, and the operational difficulties of loading and unloading the trays and occasional stirring of the product (Anonymous, 1980). Distributed-type dryers, though, have an inherent tendency towards greater efficiency, as the component units can be designed for optimal efficiency of their respective functions (Brenndorfer et al., 1985). They are, however, relatively elaborate structures requiring
more capital investment in equipment and incur larger running costs than the integral units (Ekechukwu, 1987).

A typical distributed natural-circulation solar-energy dryer (Fig. 2.2) would be comprised of the following basic units:

- an air-heating solar-energy collector;
- appropriately insulated ducting;
- a drying chamber; and
- a chimney.

Fig. 2.2 Features of a typical distributed-type natural-circulation solar-energy dryer

Though no detailed side-by-side tests have been reported, it is generally agreed that well designed forced-convection distributed solar dryers are more effective and more controllable than the natural-circulation types (Brooker et al., 1974). Thus, most practically-realized distributed solar dryers are of the forced-convection type. Of the natural-circulation types built, most are of the mixed-mode design which retain most of the
features of distributed dryers. Thus, few practically-realized, typical distributed type-passive solar dryers are reported in the literature (Ekechukwu, 1987).

An indirect solar maize dryer consisting of a single-glazed passive solar air heater with a 1 m² single flat-plate absorber and an air gap of 5 cm from the glazing (Fig. 2.3) was developed (Othieno, 1983; Grainger, 1982; Grainger et al., 1981; Othieno et al., 1981). The air heater was connected to an insulated drying the ventilated greenhouse solar air heaters made of clear plastic covers and black plastic absorbers (Fohr and Figueiredo, 1985). A few other designs are equipped with reflectors or concentrators (Puiggali and Lara, 1982; Puiggali and Varicho, 1982; Alam et al., 1978). One unique design (Shukla, 1984) consisted of a freely-ventilated cylindrical crib (made from chicken wire mesh and local bush stems as the drying chamber) attached to a solar air heater. Moist air exit was via the numerous vents of the mesh work. Performance studies of other practically-realized designs of distributed-type natural-circulation solar dryers have also been reported (Oostuizen, 1986; Iyer, 1985a, 1985b; Preston et al., 1985; Ibrahim and Hansen, 1984; Archuleta et al., 1983; Clark, 1981; Micuta, 1979; Ong, 1979; Wieneke, 1979; Cantania and Wrubleski, 1978).

2.2.1.3 Mixed-mode natural-circulation solar-energy dryers

These dryers combine the features of the integral (direct) type and the distributed (indirect) type natural-circulation solar-energy dryers. Here the combined action of solar radiation incident directly on the product to be dried and pre-heated in a solar air heater furnishes the necessary heat required for the drying process (Fleming et al., 1987; Norton et al., 1987; Fleming et al., 1986).

Typical examples of practically-realized designs of the mixed-mode natural-circulation solar-energy dryers include the widely-reported solar rice dryers developed by Exell (1980) at the Asian Institute of Technology (Sharma and Prasad, 2006; Das and Kumar, 1989; Brenndorfer et al., 1985; Fohr and Figueiredo, 1985; Othieno, 1983; Grainger, 1982; Puiggali and Lara, 1982; Puiggali and Varicho, 1982; Grainger et al., 1981; Othieno et al., 1981; Hall, 1980; Alam et al., 1978; Brooker et al., 1974).
Fig. 2.3 Features of a typical integral-type natural-circulation solar-energy dryer

Fig. 2.4 A mixed-mode natural-circulation solar-energy dryer with thermal storage
Considerable research on the design and application of these dryers has been conducted. A design (Fig. 2.4) consisted of an air heater with a pile of granite to work as absorber cum heat storage, insulated from the base ground by a 5 cm thick layer of straw. A single layer of glass was used as a glazing. The drying chamber, made of plywood sides with a glazed top, held three layers of wire mesh for the products within it. Access to the chamber was via removable panels at the rear. The cylindrical chimney of 30 cm diameter and 1.9 m height above the chamber was made from matt black painted galvanized iron sheets fitted with a metal cap at the top to keep out rain (Ayensu and Asiedu-Bondzie, 1986).

Another distinctively different mixed-mode design is the multi-stacked dryer. This design, first reported by Saulnier (1976), then at the Brace Research Institute, Canada by Lawand (1977), has also been built and tested (Sharma et al., 1987; Sharma et al., 1986). The dryer consists of a bare-plate air-heating solar-energy collector made from a black painted metal panel or corrugated galvanized iron sheet (painted dull black) with either hardboard or thermopile insulation and a multi-stacked drying chamber glazed on the front side and at the top. The air exit is via rear side vents, thus the dryer is not equipped with a chimney. However, the tall column of about 1.27 m (Lawand, 1977) was expected to generate the necessary buoyant head for the natural convective air flow. Loading and unloading of the dryer is accomplished via a wooden access door at the rear. The glazed front is oriented appropriately, depending on the location of the dryer. The multi-stacked design of the dryer enables the simultaneous drying of a variety of materials. The design and construction of several other designs of the mixed-mode natural-circulation solar-energy dryer have been reported (Sharma et al., 1987; Harvey et al., 1985; Roberto, 1984; Archuleta et al., 1983; Martosudirjo and Kurisman, 1979).

A methodology for the determination of temperature dependent drying parameters namely drying constant and lag factor from the experimental drying kinetic curves of cylinders and slices of potatoes using mixed solar dryer had been proposed (Tripathy and Kumar, 2008, 2009a, 2009b). Comparison of experimental dimensionless moisture contents with those calculated with variable (temperature dependent) and constant values of drying parameters demonstrated that the predicted results from variable parameters gave better simulation of the experiments. Major part of these studies related the impact of the
drying parameters and geometry of product on different mode of solar drying. Performance of convective solar dryer was studied by adjustment of the absorber temperature and the air flow rate to find the optimum parameters for dehydration of blanched potato chips (Azam et al., 2011)

A single generalized drying characteristic curve was generated representing 16 drying kinetics and dimensionless parameter called dryer performance index (DPI) characterizing the effectiveness of a potato drying system. The results showed that the methodology proposed, facilitates to generate single generalized characteristic curve (Shobhana and Kumar, 2012).

Dryer size optimization studies of natural and forced convection solar dryer systems based on simulation models have been carried out to achieve minimum cost per unit moisture removal (Chaurey and Kandpal, 2009; Purohit, 2009). To assess the technical feasibility of a solar chimney to dry agricultural products, a prototype was built and tested (Ferreira et al., 2008). The air velocity, temperature and humidity parameters were monitored as a function of the solar incident radiation. Drying tests on foods, based on theoretical and experimental studies assured the technical feasibility of solar chimneys used as solar dryers for agricultural products.

An experimental investigation into the performance of a solar crop dryer with solar chimney without any air preheating arrangement was carried out. Tests were performed on the cabinet dryer, using a normal chimney and repeated with a solar chimney. The results showed that solar chimney increased the air flow rate of a direct mode dryer, if the drying chamber roof is well designed with appropriate angle (Afriyie et al., 2009). Das and Kumar (1989) described the detailed design and performance of a prototype, low cost and simple solar dryer coupled with a vertical flat plate collector chimney. An average rise of air temperature from 21.8 to 68.5°C was reported during the winter months when study was carried out with an average air flow rate of 0.6707 m³/min through the chimney.

The best alternative to overcome the disadvantages of traditional open sun drying and the use of fossil fuels is the development of solar dryers. In addition to mitigation of fossil fuel use, the quality of the dried crops is also higher and the loss of dried products is considerably reduced (Vijayavenkataraman et al., 2012).
2.3 Biomass fired dryers

Experimental method for designing a biomass bed dryer was studied. The bed drying of wooden biomass particles has been studied with a particular focus on the so-called drying zone, where the actual drying takes place. Drying experiments and continuous bed temperature measurements were performed in a small experimental batch dryer. The experiments indicate that the drying zone velocity increases with increasing drying temperature and air velocity but is not influenced by its height position. Further, the width of the drying zone increases with increasing air velocity and height position, but is not influenced by temperature. Cross-sectional variations of the front velocity as well as the drying zone width were observed. An evaluation method based on the measurements was developed and presented as a first step towards designing continuous biomass bed dryer (Lermana and Wennberg, 2011).

The calorific value of fuel is affected by percentage of moisture present in it. Moisture content in the fuel depends upon the atmospheric relative humidity as all the biomasses are hygroscopic in nature. During monsoon season, fuel will have very high moisture content which affects the combustion. By utilizing the waste heat, effort was done to reduce moisture content of biomass using warm bed of (PCM) phase change mater (Gowtham et al., 2012).

Vortex-type furnaces are classified under the direct combustion processes. The vortex principle creates two-vortex spirals: cold air travels downward along the inside wall of the combustion chamber and the flame and hot products of combustion travel upward in the inner spiral at the center of the combustion chamber, and it causes thorough mixing of the air with the volatile gases and the entrapment of unburned particulate matter in the flame spiral to increase the combustion rate and completeness of fuel combustion. In addition, the vortex sustains the temperature of the combustion chamber, creates turbulence in the movement of fuel particles, and allows enough time for the complete burning of the fuel and larger particulate matter. These are the elements which control the combustion rate of solid fuels. Aconcentric-vortex type biomass-fuelled furnace was developed and evaluated. It consisted of an agricultural residue fired furnace which can be used for heating the air to a grain dryer. Measurements were made of furnace combustion efficiency at various fuels feed rates and air flow rates. The highest furnace efficiency
Development of A Solar-Biomass Integrated Drying System for Spice Crops

obtained was 85% at a feed rate of 82 kg/h and a mass flow rate of 1810 kg/h. The temperature of the flue gas varied from 420 to 870 °C at various feed rates and air flow rates. The maximum heat release occurred when the furnace was supplied with 310% excess air over that needed for complete combustion (Claar et al., 1987). A husk fired furnace was developed and tested by Singh et al., (1980). The paper describes the development and testing of a cyclone type husk fired furnace which can be used for heating of the drying air. Measurements were made of furnace efficiency at various husk feed rates and air flow rates. The highest furnace efficiency obtained was 80% at a husk feed rate of 20 kg/h and volume flow rate of 168 m³/h. The temperature of the flue gas varied from 150° to 1000°C at various husk feed rates and air flow rates. The flue gas analysis indicated that maximum heat release occurred when the furnace was supplied with 110% excess air over that needed for complete combustion. Kajewski et al. (1977) conducted a study at Iowa State University on the use of direct combustion system for converting agricultural crop residue to thermal energy. An incinerator-type furnace was built for burning cornstalks to provide heat for drying high-moisture grain. Dahlberg (1977) reported about a direct-fired combustion chamber-type incinerator furnace that burned corn cobs for drying whole ear seed corn. Several problems were found during the operation of the incinerator type furnace viz. slag formation on the grate, corrosion occurring on the metallic parts of the dryer and particulate material being deposited on the corn located in the drying floor. On a gasifier combustion process for converting corn cobs into thermal energy, it was reported that the quality of the exhaust appeared sufficiently clean for grain drying application. Corn cobs up to 46% moisture content were successfully used and the thermal efficiency of the gasifier was 70-80% (Payne et al., 1980).

Another low operating cost convective dryer, using agricultural waste as fuel and working on the principle of natural convection of hot air currents, was developed. The dryer was made in two parts. The bottom portion was a mild steel angle frame covered with asbestos sheet on the sides and wire mesh on the top. A drum-type, combustion heat-exchange unit with fins for effective heat transfer was located at the centre of this chamber. A chimney with a regulator valve was provided at the other end to allow the smoke to escape. Drying chamber was made of softwood and plywood to hold 20 food trays. The bottom of the drying chamber was open and the top portion was provided with an air vent.
Development of A Solar-Biomass Integrated Drying System for Spice Crops

with an adjustable opening. Fuel was burnt in the burning chamber at the rate of 3 kg/h. The capacity of the dryer was 100 kg of wet material. The average temperature in the dryer, at this rate of combustion, was reported to be 49°C at no load, and 46°C while drying. The trays were interchanged and the materials were mixed and stirred at an interval of one hour. The drying time required for soy split to reduce moisture content from 60 to 10% was 15 h and the same to dry flakes from 30 to 10% was 6h (Patil and Sukla, 1988).

2.4 Hybrid dryers

Specialized dryers are normally designed with a specific product in mind and may include hybrid systems where other forms of energy are also used (Whitfield, 2000; Mumba, 1995; Foster and Mackenzie, 1980). The energy collected by a flat plate solar collector depends on the solar insolation at the site as well as the positioning of the solar collector with respect to the sun. Maximum energy can be collected only if the sunrays strike collector perpendicularly at all-time throughout the day. The best way to collect the maximum solar energy is by using solar tracking systems to follow the sun as it moves each day, and thus to maximize the collected beam radiation. This of course can be very expensive since it requires a continuous tracking system. It is possible to collect 40% more solar energy by using a two-axis tracking system (Markvart, 1994).

An alternative to continuous tracking is to periodically adjust the position of the collector so that sunlight rays are as close as possible to the perpendicular position. Where manual tracking is necessary due to the high cost of tracking devices, as is the case in many developing countries, one has to balance between maximizing net energy absorbed and reducing labour costs (Chua and Chou, 2003). Nevertheless, it is necessary to calculate the optimum tilt angle which maximizes the amount of collected energy. A small solar dryer with limited sun tracking capabilities was designed and tested by Gikuru and Stephen, (2006). The dryer had a mild steel absorber plate and a polyvinyl chloride transparent cover and could be adjusted to track the sun in increments of 15°. The performance was tested by adjusting the angle of the dryer made with the horizontal either once, three, five or nine times a day when loaded with coffee beans and under no load conditions. The dryer setting which had the highest number of tracking adjustments developed the highest temperature at all times.
Another solar dryer design is the semi-cylindrical parabolic solar concentrator. A semi-cylindrical parabolic solar concentrator is based upon the direct conversion of solar energy to thermal energy by heating, reaching temperatures above 300°C, depending on the efficiency of the concentrator. It is for this reason that parabolic solar concentrators are suitable for use in a wide variety of industrial processes which use thermal energy, such as dairy, processed waste etc., replacing in this way the use of fossil fuels (Romero et al., 2011). The main basis of the prototype solar concentrator is a parabolic reflective surface, which takes advantage of every ray of light coming from the infinite is concentrated at the focus. At focus, a metal tube is placed which serves to transform solar energy to thermal energy (Romero et al., 2011). These collectors are mounted with their surfaces facing towards the equator and the tilt angle is set approximately equal to latitude (Jamil and Tiwari, 2009). In general, solar concentrating systems comprise a reflective surface in the shape of paraboloid of revolution intended to concentrate solar energy on an absorbing surface, which makes it possible to reach a high temperature. A more sophisticated parabolic collector trough was designed, that avoided the need to track the sun altogether, by combining two parabolas together (Fig. 2.5) to form the ‘Compound Parabolic Trough Solar Collector’ (Anonymous, 2009). A properly designed compound parabolic trough solar collector can focus solar energy from multiple directions to a common focal line (Fig. 2.6) that is the focal line for both parabolas. Such a compound parabola solar collector (CPC), need not to track the sun (Anonymous, 2014).

Work was also carried out to study the physical behaviours and quality evolution of sliced potato treated by a convective indirect solar drier. The process of drying was through a hybrid solar drier with forced convection via photovoltaic and electric network. Impact of the drying process on the quality of sliced potatoes was studied by determining the colour evolution (Chouicha et al., 2013). A direct type natural convection solar drier integrated with a simple biomass burner was fabricated (Fig.2.7) and evaluated under winter season of Delhi in India for drying of turmeric rhizomes. Drying was done in the developed system with hot air temperature between 55 and 60°C. Dried turmeric rhizomes obtained by two different treatments viz. water boiling and slicing were found similar in quality with respect to physical appearance like colour, texture etc. but with significant variation in volatile oil. The quantitative analysis showed that the traditional drying i.e.,
Development of A Solar-Biomass Integrated Drying System for Spice Crops

open sun drying had taken 11 days to dry the rhizomes while solar biomass drier took only 1.5 days and produced better quality produce. The efficiency of the whole unit obtained was 28.57% (Prasad et al., 2006).

![Fig. 2.5 Compound Parabolic Concentrator (Ong, 1979)](image)

Fig. 2.5 Compound Parabolic Concentrator (Ong, 1979)

![Fig. 2.6 Different incident rays reflect on focus of CPC.](image)

Fig. 2.6 Different incident rays reflect on focus of CPC.
2.5 Energy consumption

Any drying system should be energy efficient due to obvious reasons. In addition to solar dryers, studies on advanced dryer designs viz. micro-wave, infrared, vacuum etc., with and without convective hot air drying have been made to compute energy consumption for drying of various agricultural commodities viz. mulberry, garlic cloves, pomegranate arils etc. (Motevali et al., 2011; Akbulut and Durmus, 2010; Tippayawong et al., 2008; Sharma and Prasad, 2006). The specific energy requirements for individual and combinations of different drying methods namely micro-wave, infrared, vacuum and conventional hot air for drying of mushroom slices were determined and reported that minimum energy was consumed in the micro-wave and maximum energy was in vacuum dryer that were 0.13 and 6.22 kWh, respectively (Motevali et al., 2011). Investigations on effects of drying variables namely; particles size, bed depth and drying air temperature on energy utilization, energy utilization ratio, energy loss for fluidized bed drying of carrot cube showed that small particles, deep beds and high inlet air temperatures increased these values due to high heat and mass transfer (Nazghelichi et al., 2010). Energy consumption during drying varies owing to different shapes of food product. Cylinders and slices of potato samples, using mixed-mode solar dryer under outdoor conditions were dried (Tripathy and Kumar, 2009b). It was found that the cylindrical samples in comparison to slices resulted in faster moisture removal and hence lower specific energy consumption.
The drying efficiency determination based on energy ratio in terms of drying time is the traditional method commonly used in performance evaluation of any dryer system. This approach does not provide any information of system performance in terms of its environmental behavior with respect to a given fossil fuel being replaced. A mathematical framework was developed to estimate several dryer performance indicators namely: drying efficiency, specific energy consumption (SEC), CO$_2$ emissions mitigation, carbon credits earned and amount of different fossil fuels saved due to use of solar drying. The variables investigated were absorbed thermal energy, air flow rate, food product loading density and sample thickness. The results of investigation indicated that for all drying test conditions, the given dryer was capable to mitigate the maximum CO$_2$ emissions with the replacement of coal by solar energy. Larger values of absorbed energy and load density was found to cause increased SEC and CO$_2$ mitigation potential whereas reverse trend was observed for sample thickness (Singh and Kumar, 2013).

Thermodynamic analysis, particularly exergy analysis is an essential tool for system design, analysis and optimization of thermal system (Dincer and Sahin, 2004). Exergy is defined as the maximum amount of work which can be produced by a stream of matter, heat or work as it comes to equilibrium with a reference environment (Dincer, 2002). In the drying process, the aim is to use a minimum amount of energy for maximum moisture removal for the desired final conditions of the product. Akbulut and Durmus (2010) carried out energy and exergy analyses of thin layer drying of mulberry in a forced solar dryer using the first law of thermodynamics. Energy analysis was carried out to estimate the ratios of energy utilization and the amounts of energy gain from the solar air collector. However, the second law of thermodynamics was used to determine exergy losses during the drying process. The drying experiments were conducted at different five drying mass flow rate varied between 0.014 kg/s and 0.036 kg/s. The effects of inlet air velocity and drying time on both energy and exergy were studied. The main values of energy utilization ratio were recorded for the five different drying mass flow rates. It was concluded that both energy utilization ratio and exergy loss decreased with increasing drying mass flow rate while the exergetic efficiency increased.
2.6 Drying Kinetics

In the drying of ginger, the water is evaporated from the freshly harvested ginger rhizome to moisture content close to that of its storage environment. According to Rao and Rizvi (1986), if the drying sample is a flat plate of thickness L, drying on both sides and under the given boundary conditions, moisture content can be expressed in the following form:

\[ MR = \frac{M(t) - M_{eq}}{M_0 - M_{eq}} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp \left[ -\frac{(2n-1)^2 \pi^2 D t}{L^2} \right] \]  \hspace{1cm} (2.1)

Where, MR is moisture ratio of free water still to be removed at time t to the total free water initially available, and n = 1/4, 1, 2, 3, . . . the number of terms taken into consideration. For a long-term drying, where equilibrium moisture is attained, the higher order terms are neglected by setting n = 1/4, 1. Hence, the above equation could be further simplified to a linear form:

\[ \ln(MR) = \ln\left(\frac{M(t) - M_{eq}}{M_0 - M_{eq}}\right) = \ln\left(\frac{8}{\pi^2}\right) - \left(D \frac{\pi^2 t}{L^2}\right) \]  \hspace{1cm} (2.2)

Therefore, a plot of \( \ln(MR) \) against \( \pi^2 t / L^2 \) gives a straight line with slope \( -D \), which represents the rate of moisture loss. D is known as the effective diffusivity, which is a lump value that does not consider things separately but it is important to indicate the drying characteristics.

Study was carried out to understand the drying behavior of ginger with high levels of moisture content. Ginger slices were dried in a series of drying experiments in thin layers in an oven at 50, 55, 60, 65, 70 and 75°C. Equations were developed between drying constant and temperature; between shape factor and temperature both analytically and graphically. A mathematical relationship was established between moisture ratio and drying time (Borah and Saikia, 2005). A mathematical model was developed to predict the crop temperature, rate of moisture removal and air temperature for a steady state condition by Jain and Tiwari (2003). The rate of moisture transfer for potato slices and cauliflower was found to be significantly higher than that of other crops.
Development of A Solar-Biomass Integrated Drying System for Spice Crops

It was reported that using a mechanical dryer it took 8 h to dry chillies from 200.87% to 9.13% moisture content (db) at 50°C air temperature (Chandy et al., 1992) and 26 h from 300% to 8–9% moisture content (db) at 45°C air temperature (Mangaraj et al., 2001). The effective moisture diffusivity $D_{\text{eff}}$ of chillies increased from 13.635 to 19.949 mm² h⁻¹ as the drying air temperature of a rotary dryer increased from 50°C to 65°C. The activation energy of diffusion $E_a$ was calculated as 24.476 MJ kg mol⁻¹ (Kaleemullah and Kailappan, 2005).

An indirect type natural convection solar dryer consisting of a flat plate solar air heater connected to a drying chamber was investigated experimentally and theoretically with drying of some fruits and vegetables. Linear correlations between drying constant $k$ and product temperature $T_{dp}$ were found to satisfactorily describe the drying curves of the materials dried. The product constants $c$ and $n$ of Henderson’s equation were determined for the crops under study using the experimentally measured relative humidity of the drying air and simple mathematical model was derived for the drying chamber based on energy and mass balance equations and using the proposed correlation for $k$ as well as values of constants $c$ and $n$ (El-Sabaii et al., 2002). Predictions of crop temperature, air temperature and moisture evaporation rate were computed using Matlab software on the basis of solar intensity and ambient temperature and the models were experimentally validated (Jain and Tiwari, 2004). A method based on energy balance was proposed for determination of convective heat transfer coefficient $h_c$, considering the effects of heat capacity of the product, radiative heat transfer from the product to the drying chamber and solar radiation absorbed in the product dried by Tripathy and Kumar (2009b). Experiments with potato cylinders and slices indicated that the cylindrical samples exhibit higher values of $h_c$ and faster drying rate compared to those of slices.

An investigation on diffusive drying kinetics in wheat while drying, application of simplified analytical solution to experimental data was tried. The experimental curves of moisture ratio versus time, grouped by initial moisture level, showed the expected strong speeding-up effect of temperature on drying rate. When these curves were grouped by temperature, the dimensionless drying curves tended to depart from each other as drying proceeded, falling faster when starting from higher initial moisture contents. This was an
Development of A Solar-Biomass Integrated Drying System for Spice Crops

evidence of the dependency of the effective diffusion coefficient of water in wheat with moisture content (Giner and Mascheroni, 2002).

Diffusivity reflects the capability of moisture evaporation rate of any material to be dried while keeping other drying conditions under control. Jayashree and Visvanathan (2013) found moisture diffusivity for sun drying of ginger as $1.91 \times 10^{-7}$ m$^2$s$^{-1}$. Using air temperature range of 50 to 80°C and at constant air velocity of 1.5 m$^{-1}$, Falade et al. (2007) found variation in effective moisture diffusivity from $9.92 \times 10^{-8}$ to $1.02 \times 10^{-7}$ m$^2$s$^{-1}$ while drying Dioscorea alata and 0.829 $\times$ 10$^{-6}$ m$^2$s$^{-1}$ to 1.298$\times$10$^{-5}$ m$^2$s$^{-1}$ while drying Dioscorea rotundata. The values were also reported to be same while drying yam.

Knowledge of the dehydration characteristics of biological materials is essential to the design, optimization and control of the dehydration processes. Some work has been done on the dehydration characteristics of garlic. It was reported that, drying at 60°C for 4 h in a fluidized dryer gave good quality product with moisture content below 3% (Sharma and Prasad, 2004; Baysal et al., 2003; Condori et al., 2001; Dawn et al., 1998; Pezzutti and Crapiste, 1997; Madamba et al., 1996; Pinaga et al., 1984). Study was undertaken to investigate the dehydration characteristics of the Kastamonu garlic (Allium sativum L.) in a convective hot-air dryer by Sacilik and Unal (2005). The dehydration characteristics of garlic slices were examined at air temperatures of 400, 500 and 600°C and sample thicknesses of 3 to 5 mm. The effective diffusivity varied from 195 to 335 mm$^2$s$^{-1}$ in the air temperature range of 40 to 60°C. The activation energy was found to be 23.48 kJ mol$^{-1}$

Research on the kinetics of convection drying of vegetables has shown that the first period of drying exists, and non-linear changes in water content of the vegetables occur. The non-linear changes in the water content resulted from shrinkage of the drying materials (Pabis and Jaros, 2002). Chua et al. (2003) reported about intermittent drying processes which employ time-varying heat input tailored to match the drying kinetics of the material being dried. Unlike the conventional practice of supplying energy for batch drying processes at a constant rate, the required energy may be supplied by combining different modes of heat transfer (e.g. convection coupled with conduction or radiation or dielectric heating simultaneously or in a pre-selected sequence) in a time-varying fashion so as to provide optimal drying kinetics while maintaining quality of the dried product. This is most important while drying of heat-sensitive materials like spices. Almost all
biological materials primarily dry under falling rate period of drying where internal diffusion of heat and moisture controls the overall drying rate and intermittent heat supply is beneficial in such conditions.

2.7 Quality attributes

Drying air temperature is particularly important for heat sensitive materials. Nevertheless, not only thermal degradation viz. loss in quality, colour, shape, texture, nutrient content, etc. should be considered during the drying of food products like grains, sugar, fruits, vegetable, etc. but their sensitivity to mechanical stress and long drying times as well (Lewicky and Lenart, 1993; Grabowski and Mujumdar, 1992; Talburt and Smith, 1987). Studies were made to examine the loss of curcumin, capsaicin and piperine, the active principles of turmeric (Curcuma longa), red pepper (Capsicum annuum) and black pepper (Piper nigrum), respectively as a result of subjecting the spices to domestic cooking processes by Suresh et al. (2007). Significant loss of spice active principles was observed when the spices were subjected to heat processing. Curcumin loss from heat processing of turmeric was 27–53%, with maximum loss in pressure cooking for 10 min. Capsaicin losses from red pepper ranged from 18% to 36%, with maximum loss observed in pressure cooking. Piperine losses from black pepper ranged from 16% to 34%, with maximum loss observed in pressure cooking. Singh et al. (2010), reported that alpha-turmerone, a major component in fresh rhizomes is only minor one in dry rhizomes. Also, the content of beta-turmerone in dry rhizomes is less than a half amount found in fresh rhizomes. The essential oil and ethanol oleoresin of fresh rhizomes have higher antioxidant properties as compared dry ones. In a study by Kiran et al. (2013) on influence of cultivar and maturity at harvest on essential oil of ginger, reported that oleoresin content gets decreased with maturity and oleoresin percent of raw ginger ranged between 11.43 and 9.42%. Volatile oil of Australian ginger has been reported to increase from about 1.8 to 4.4% (dry weight basis) through the harvesting season (Parthasarathy et al., 2008).

The turmeric volatile oils were isolated from fresh, dried and cured rhizomes by conventional Clevenger’s hydro distillation. Yield of volatile oil obtained for fresh, dried and cured rhizomes was 3.52±0.23, 3.05±0.15 and 4.45±0.37%, respectively on a dry weight basis. However, the yield of volatile oil obtained from cured rhizome was higher
Development of A Solar-Biomass Integrated Drying System for Spice Crops

than that of fresh (26%) and dried (46%) samples (Gounder and Lingamallu, 2012). The method of drying usually has a significant effect on the quality and quantity of the volatile oils (Asekun et al., 2007).

Drying resulted not only in the disappearance of some volatile components but also in the appearance of others which were absent in fresh ginger pulp. Aldehydes and alkenes play the most important role in ginger aroma. The effect of drying also resulted in the loss of cyclocompounds, alcohols, aldehydes and ketones. When fresh ginger was dehydrated relative contents of benzene decreased as compared to those in fresh ginger (Ding et al., 2012). The optimum temperatures for artificial drying were reported to be 45.5 – 81°C. However, it was recommended that ginger for spice market should be dried at under 57°C but, for extraction purposes 81°C should be satisfactory (Richardson, 1966).

It is well known that the quality is strongly affected by drying methods and drying process (Krokida, et al., 2000). Nejad et al. (2003) investigated the effect of drying methods on quality of pistachio nuts. Many technologies have been developed to achieve best products at the lowest cost, such as hot air drying, vacuum drying, freeze drying, heat pump drying. In a heat pump drying, substituting normal air with an inert gas, the dried product qualities were also improved (Hawlader et al., 2004; Perera, 2001; O’Neill et al., 1998). Reineccius (2004) thought that the spray drying is the best method for retaining flavour. For dried fruit and vegetables, the main quality factor is the general appearance of the dried material, whereas for commodities such as spices, the amount of volatile extractable constituents is the main aspect of quality (Brenndorfer et al., 1987). Pungency is an important quality characteristic of ginger. Purseglove (1972) noted that the main pungent principles of ginger rhizome are gingerol homologues and their dehydrated products - shogaol homologues, which may result from thermal process or long-term storage. The quantities of the main pungent principles (gingerol and shogaol) extracted from fresh, nonsteam-distilled solar-dried and steam-distilled solar dried ginger rhizomes increased but the oleoresin quality decreased because some gingerols dehydrated and produced shogaols (Balladin et al., 1998; Ballandin et al., 1996). In a modified atmosphere heat pump drying study, by using inert gases such as N₂ and CO₂ as the drying media, the effective diffusivity was increased resulting in better retention of flavor. For N₂ and CO₂
the incremental of 6-gingerol were 43.5% and 45.4%, respectively compared with normal air drying (Hawlader et al., 2006).

Quality attributes of paprika spice is its strong colour and very little pungency. Selection of proper drying conditions is necessary for minimizing thermal stress, overdrying and retention of carotenoids, vitamin C, tocopherols and capsaicin compounds responsible for quality maintenance. Loss of red colour is caused by oxidation of carotenoids. The stability in quality of paprika during storage is dependent on its drying conditions and degradation rate of quality is directly proportional to increase of drying air temperature (Ramesh et al., 2001). Organoleptic evaluation of dried chilli samples indicated that mechanically dried samples were the best, followed by green house-type solar drying, solar cabinet drying and was very poor in case of open sun drying (Mangaraj et al., 2001).

For shelf life extension of fresh ginger gamma-irradiation was found to extend the shelf life of farm fresh ginger. A 5 kGy radiation dose and $10^0 \text{C}$ storage temperatures were found to keep peeled ginger samples microbe free and acceptable until 70 days of storage, whereas non-irradiated (control) peeled ginger spoiled within 40 days under similar storage conditions. The decrease in 6-gingerol, the compound responsible for the pungency of ginger, was found to be insignificant after irradiation (Mishra et al., 2004).

During performance evaluation of a hybrid drier for turmeric, the volatile oil was studied and was found between 2.89% and 3.35% but in open sun drying it was only 1.75%. The quality of product with respect to physical appearance like colour, texture remained maintained in the drier whereas in open sun drying it was deteriorated. It was reported that, water boiling (pretreatment) of turmeric reduced the volatile oil. Study concluded that without boiling treatment drying was a better option for preserving quality of the dried product and slicing improves drying rates (Prasad et al., 2006). Effects of curing and drying methods on curcumin content of three turmeric cultivars were studied by Lokhande et al. (2013). Shade-net drying of turmeric resulted higher retention of curcumin content than the mechanical and sun drying. But the colour of shade net dried samples was dull in appearance due to lower rate of moisture loss. Harvesting time is also an important factor when accumulation of yellow pigment is concerned. The value of a particular turmeric cultivar is determined on the basis of its curcumin content. Studies revealed that
Development of A Solar-Biomass Integrated Drying System for Spice Crops

C. domastica varieties which are of short duration, contains lower amount of curcumin than C. longa which are of longer duration varieties (Govindrajan, 1980).

Air-drying of agricultural products is responsible for reduction of the water activity values through moisture removal. However, other processes, promoted by high temperatures, can occur simultaneously with moisture removal during drying, resulting in undesirable alterations of certain characteristics of the material, such as shrinkage and colour changes (enzymatic and non-enzymatic browning) (Maskan, 2001a). In addition, there is a partial destruction of tissue structure, which results in water permeability, consequently rehydration ability can also decrease, and changes in the texture (case hardening) (Lewicki and Jakubczyk, 2004; Krokida, Karathanos, et al., 2000). Most of the dried food materials must be rehydrated by immersion in water until use.

Three main processes take place simultaneously during rehydration: the imbibitions of water into the dried material and the swelling and the leaching of soluble (Lewicki, 1998a; McMinn and Magee, 1997). Rehydration characteristics are employed as a parameter to determine quality because they are indicative of the degree of alterations occurring during processing (pre-treatments, drying, and rehydration) (Funebo and Ohlsson, 1998; Lewicki, 1998b). In this context, texture is an important characteristic in order to obtain the optimal processing of the food material (Bourne, 2002). Textural characteristics depend on temperature and time of pre-drying and rehydration processes (Marabi et al., 2006; Krokida and Philippopoulos, 2005; Peleg, 1997).

Colour characteristics are also important quality attributes as rehydrated samples should closely resemble the colour characteristics of fresh food material to increase acceptability. The determination of rehydration conditions in order to minimize colour changes during dehydration or rehydration process has great importance from economic viewpoint (Moreira et al., 2008).

Air-drying and rehydration characteristics of date palm (Phoenix dactylifera L.) fruits were studied by Falade and Abbo (2007). They reported that, activation energies for air-drying of date were lower than for rehydration for the date palm fruits. This could be attributed to the difficulty of restoring the dried date to their fresh state due to cell disruption which took place during drying. Irreversible rupture and dislocation which occurred during moisture removal may have resulted in loss of integrity and hence a dense
Development of A Solar-Biomass Integrated Drying System for Spice Crops

structure of collapsed, greatly shrunken capillaries with reduced hydrophilic properties as reflected by the inability to rehydrate fully (Lewicki, 1998b).

Drying characteristics of water chestnut were evaluated in a commercially available cabinet oven at different air temperatures to compare the drying rate and to analyse the effect of different drying air temperature on rehydration properties. Rehydration characteristics were significantly affected by the drying air temperature and found to decrease with increase in drying air temperature (Singh et al., 2008).

2.8 Critiques on Review

Work done by different researchers was reviewed in a systematic manner. Operating temperature primarily dictates the classification of dryer into high or low temperatures dryers. High temperature dryers are necessary when very fast drying is desired. Low temperature drying enables crops to be dried in bulk and is most suited also for long term storage systems. Some conventional dryers and most designs of solar-energy dryers are low temperature type dryers. Studies on natural convection solar crop dryer designs of direct, indirect and mixed-mode solar-dryer designs suggested that the performance of the mixed mode natural convection solar crop-dryer is potentially most effective in tropical humid areas where climatic conditions favour sun drying of agricultural products. However, natural convection solar crop dryers are normally reported to perform inefficiently. The air circulation is normally poor, particularly in the case of the cabinet-type dryer which has a nearly horizontal roof. Some reports on chimneys have shown that, properly designed chimneys can boost the flow of air through an enclosure. A solar chimney can increase the airflow rate of a direct-mode dryer especially when it is well designed with the appropriate angle of drying-chamber roof.

Using agricultural waste as fuel and working on the principle of natural convection of hot air currents, works were carried out to develop biomass fired dryers. In such dryers, drying trays were interchanged and the materials were mixed and stirred at a regular interval. Specialized dryers are normally designed with a specific product in mind and may include hybrid systems where other forms of energy are also used. A direct type natural convection solar drier integrated with a simple biomass burner was tested for drying of turmeric rhizomes.
Quality of the product dried finally reflects the acceptability of a drying system. Work was carried out to study the impact of the drying process on the quality of sliced potatoes by determining the colour evolution. Dried turmeric rhizomes obtained from the solar drier integrated with a simple biomass burner mentioned earlier were studied for physical appearance like colour, texture as well as variation in volatile oil.

Any drying system should be energy efficient due to obvious reasons. Energy consumption during drying varies owing to different shapes of food product. It was found that the cylindrical samples in comparison to slices result in faster moisture removal and hence lower specific energy consumption. The drying efficiency determination based on energy ratio in terms of drying time is the traditional method commonly used in performance evaluation of any dryer system. Work was carried out on energy and exergy analyses of thin layer drying of mulberry in a forced solar dryer. The effects of inlet air velocity and drying time on both energy and exergy were studied in the work. It was concluded that both energy utilization ratio and exergy loss decreased with increasing drying mass flow rate while the exergetic efficiency increased.

Drying kinetics study was done to understand the drying kinetics of thin layer drying of ginger that were sliced and oven dried in a series of drying experiments at 50, 55, 60, 65, 70 and 75°C. Outcome of the work was a mathematical relationship established between moisture ratios and drying time. An indirect type natural convection solar dryer consisting of a flat plate solar air heater connected to a drying chamber was investigated experimentally and theoretically with drying of some fruits and vegetables. Linear correlations between drying constant and product temperature were established. An investigation on diffusive drying kinetics in wheat while drying, the experimental curves of moisture ratio against time, grouped by initial moisture level, showed direct correlation between temperature and drying rate. In a study of dehydration characteristics of garlic slices, it was found that the effective diffusivity varied from 195 to 335 mm² s⁻¹ in the air temperature range of 40 – 60°C.

Quality attributes of heat sensitive materials are of much importance under hot air drying. Apart from thermal degradation viz. loss in quality, colour, shape, texture, nutrient content, etc. during the drying of food products, their sensitivity to mechanical stress and long drying time should be given due considerations. In a study to understand the effect of
Development of A Solar-Biomass Integrated Drying System for Spice Crops

heat processing of spices on the concentrations of their bioactive principle, significant loss of spice active principles was observed. Drying resulted not only in the disappearance of some volatile components but also in the appearance of others which were absent in fresh ginger pulp. It was reported that, when fresh ginger was dehydrated, relative contents of benzene decreased as compared to those in fresh ginger. In a study of comparison of the retention of 6-gingerol in drying of ginger under modified atmosphere heat pump drying and other drying methods, inert gases such as N₂ and CO₂ was used as the drying media which resulted in increase of effective diffusivity. Study on performance evaluation of a hybrid drier for turmeric drying it was reported that retention of volatile oil was near double when compared to open sun drying. Drying carried out using heated air also results in undesirable alterations of certain characteristics of the material, such as shrinkage and colour changes. In addition, there is a partial destruction of tissue structure, which results in water permeability, consequently rehydration ability and changes in the texture. The determination of rehydration conditions in order to minimize colour changes during dehydration / rehydration process is an important quality attribute.