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Solar Dryers for Tropical Food Preservation: Thermophysics of Crops, Systems and Components

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Solar dryers for tropical food preservation: Thermophysics of crops, systems and components

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ABSTRACT

Drying reduces the moisture content of harvested crops thus slowing decay processes to enable longer-term storage. Solar dryers contain the crop being dried, to enhance solar energy collection incurring lower crop losses than are associated with open-sun drying and recurrent costs than are inherent to uses of fossil-fuels for drying. The influences of key environmental, operational and design parameters for solar dryers are discussed including: (i) psychrometry of drying processes and ambient conditions, (ii) how initial crop properties are converted to final desired product attributes, (iii) feasibility of using powered components such as fans and (iv) air-heating solar collector selection.

1. Introduction

Solar crop drying ensues naturally when seeds dry in-situ to render them sufficiently light for air-borne dispersal. Human intervention to dry crops in the open sun to enable their storage for off-season food consumption was probably intrinsic to the inception of farming-based civilizations. The key strategic goal in preserving crops is to reduce the number of undernourished people worldwide (Anon., 2004). Fiber and energy is provided by carbohydrates and protein usually retained after a drying process.

Open sun drying simply exposes harvested crops to solar radiation by placing them on the ground or a mat. It is prone to high crop losses due to (i) uneven moisture removal, (ii) insects and rodents consuming the crop and (iii) failure to achieve safe storage moisture content before the crop has to be collected. As an example, the estimated annual postharvest losses of various commodities together with the associated costs for India is shown in Table 1.

The first modern use of fossil fuels in drying was recorded in France in 1795 for drying of thinly sliced fruits and vegetables (Delong, 1992). Fossil-fuelled dryers are now commonplace as they can operate in any ambient conditions, are readily controlled and their operation and maintenance infrastructures are well established. However, in many remote rural locations supplies of fossil fuels can be (i) insecure (ii) expensive and require combustion equipment and (iii) their use incurs emissions of both local pollution and global greenhouse gases (Imre, 1993). In contrast, solar drying often constitutes a cost-effective and environmentally sustainable use of local solar energy resources and fabrication labour resources.

Solar dryers can be distinguished from open-sun drying by (i) enclosure of the drying crop and (ii) direct or indirect production of a solar heated airflow. When compared with open-air sun drying, solar drying generally is (i) faster, (ii) more efficient (iii) hygienic and (iv) incurs lower crop losses (Arata et al., 1993; Budin and Mihelic-Bogdanic, 1994; Chua and Chou, 2003; Karim and Hawlader, 2004; Mahapatra and Imre, 1990; Muhlbauer, 1986; Zaman and Bala, 1989). There are generally more viable than open sun drying as they provide more control and protection of product quality over a wider range of weather conditions (Alam and Singh, 2004; Sodha and Chandra, 1994; Lorriman and Hollick, 2003; Nair and Bongirwar, 1994; Tiwari, 2003; Esper and Muhlbauer, 1998; Farkas, 2003). In a solar dryer, solar radiation passes through a transparent aperture and retained as heat in a drying chamber, a solar collector, or both. In a passive solar dryer, thermal energy transferred from solar energy collection to the drying chamber is by natural convection whereas in an active system a fan drives heated air through the dryer (Norton, 2013). The interrelationship

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Table 1
Estimates of post-harvest losses for various commodities in India (Alam et al., 1980; Anon, 2004).

		Post-harvest losses	
		% of produce	Value (Rupees in Crore)
Commodity	Grains	10	16,500
	Pulses	15	2000
	Fruits	30	13,600
	Vegetables	30	14,100
	Floriculture	40	400
	Fish	15	2700
	Dairy (milk)	1	900
Total Rs. 50,200 Crore			

between the key factors that determine solar dryer viability (Ekechukwu and Norton, 1999b) are summarised in Fig. 1.

2. Psychometry of air in a solar dryer

The more dry the surrounding air, the greater the rate of evaporation from a crop that lowers the wet bulb temperature. The specific humidity of unsaturated air increases due to water evaporation from a crop as energy transferred from air to water. A thermal equilibrium prevails when the energy transferred from warm air to the crop becomes equal to energy needed for water vaporization. At temperatures below this equilibrium thermodynamic wet bulb temperature or adiabatic saturation temperature, air will rapidly become saturated and if cooled further, will lose water in the form of dew above 0 °C. Water vapour moves from air with a higher humidity ratio (i.e. ratio of water vapour weight to dry air weight) to air with a lower humidity ratio.

As indicated in Fig. 2 for appropriate combination of humidities and temperatures, air taken directly into a drying chamber will be heated sufficiently to enable drying. When the temperature and humidity of directly-introduced ambient air would provide an insufficient drying rate, an air heating solar energy collector produces higher temperature air for introduction to the drying chamber. The indicative conditions for which use of air heating collector is advised are illustratively in Fig. 2; The specific for a particular installation are contingent conditions would depend on crop parameters, collector characteristics and drying chamber specifications (Ekechukwu and Norton, 1999a).

Wet-basis moisture content (defined as the relative weights of moisture present per unit of undried material) is used generally for commercial purposes. For system engineering purposes, the (closely related; see Fig. 3) dry basis moisture content (defined as the weight of moisture present per unit weight of totally dry material) is preferred as on a dry basis the same weight changes are associated with each percentage moisture reduction (Ekechukwu and Norton, 1999a, 1999b; Ekechukwu, 1999). The final moisture contents required for long-term storage of crops, are referred as safe storage moisture content are listed for common crops in Table 2.

National and international standards specify labelling for correct ingredient and nutritional information to ensure that products are safe and fit for consumption. Nutrition colour, flavour and texture of the dried product must also be of acceptable quality to consumers. The term “quality” has three overlapping connotations; (i) degree of excellence, (ii) fitness for purpose, and/or (iii) conformance to specified requirements. The consequences of improper drying can include (i) loss of nutrients, (ii) microbial spoilage, (iii) possibility of food poisoning, (iv) lower market value and (v) excessive shrinkage.

Shrinkage during drying alters shape, reduces volume and increase surface hardness. This is a desired outcome for some crops such as some dried fruits. Non-uniform shrinkage leads to imbalanced stresses that crack surfaces. Shrinkage can limits the ability to rehydrate a dried product as moisture-absorbing capillaries are closed; for example when cauliflower is dried. (Jain and Tiwari, 2004b). The stresses causing shrinkage depend on removed water volume, internal crop structure, drying rate, temperature, relative humidity, and velocity of drying air. Being a major factor when controlling the drying rate (Rahman et al., 1996; Zogzas et al., 1994), shrinkage has been the subject of extensively modelling; (Lozano et al., 1983, 1980; Mayor and Sereno, 2004; Mclaughlin and Magee, 1998; Mulet et al., 2000; Ochoa et al., 2002; Park, 1998; Rahman et al., 1996; Ratti, 1994; Simal et al., 1998; Wang and Brennan, 1995). To avoid high drying temperatures can adversely affect the colour and phenolic composition of aromatic, herbal and medicinal plants. pre-treatments have been devised for specific herbs such as thyme (Lahnine et al., 2016). For colour retention in dried cherry tomatoes, osmotic dehydration in a hypertonic solution has been employed for partial water removal before subsequent drying in a solar dryer (Nabneun et al., 2016) to produce high quality dried tomatoes with desired colour in a

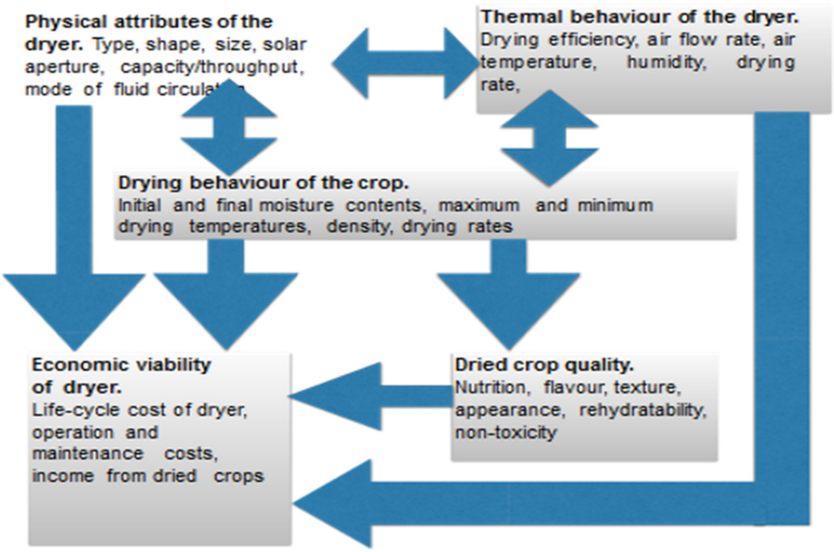

Fig. 1. Interplay between key grouped aspects of solar dryer viability.

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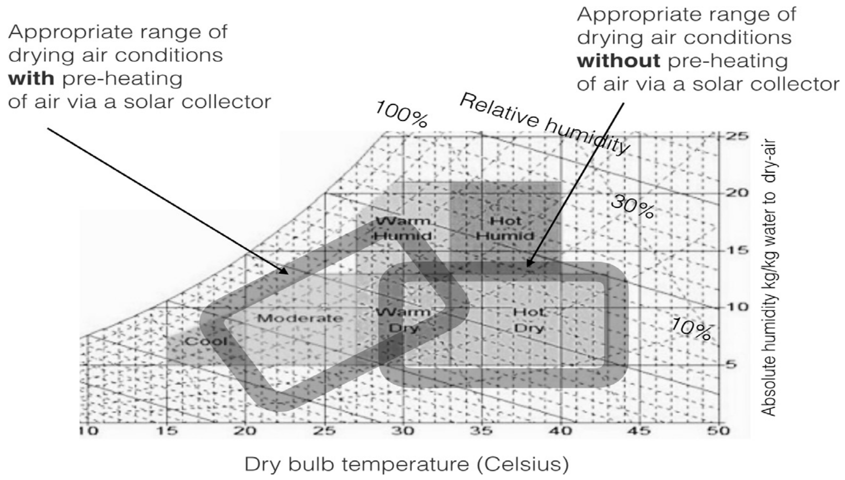

Fig. 2. Indicative psychometry of conditions for the inclusion in a solar dryer of an air heating solar collector.

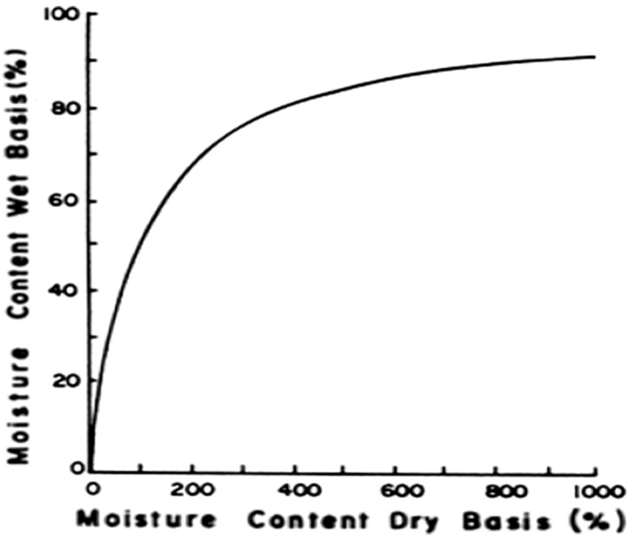

Fig. 3. Difference between moisture contents measured on wet and dry basis.

considerably reduced drying time. The latent heat of vapourisation depends on the crop, its preparation, moisture content, and temperature (Ekechukwu and Norton, 1999a; Ekechukwu, 1999).

Each crop has a characteristic water vapour pressure below or above which moisture will be absorbed or desorbed moisture respectively for particular combinations of temperature and moisture content, At equilibrium moisture content, the corresponding relative humidity of the immediate surrounding air is also in equilibrium with its environment. For particular temperature and relative humidity, a particular crop's equilibrium moisture content depends on the specific crop variety, maturity at harvest, and growth history (Soysal and Öztekin, 2001) Two methods are used to determine equilibrium moisture content (i) in the static method, a crop is exposed to still surrounding air without agitation; however, to reach equilibrium long exposure of the crop, can allow mould to grow before equilibrium is reached and (ii) in the dynamic method, the air temperature in an the crop enclosure is controlled thermostatically and the relative humidity of the surrounding air is regulated with either an acid or a saturated salt solution. Static equilibrium moisture contents determination is preferred for examining stored crops whereas dynamic methods used for crop samples taken from dryers in operation (Bala, 2003). Several theoretical, semi-theoretical and empirical models for the moisture equilibrium isotherms of agricultural crops produces have proposed to determine the relationship between equilibrium moisture content and equilibrium relative humidity (Brunauer et al., 1938; Day and Nelson, 1965; Henderson, 1952; Thomson et al., 1968; Chen and Clayton, 1971; Pfost et al., 1976; Iglesias et al., 1976; Chen and Morey, 1989; Soysal and Öztekin, 2001; Blanco-Cano et al., 2016a). There is no universal equation that represents accurately the moisture equilibrium isotherms of all agricultural crop products. Illustrative representative examples of the relationships between equilibrium moisture content for selected crops are given in Fig. 4.

3. Drying processes

Bound moisture, which exerts an equilibrium vapour pressure less than pure water at the same temperature, is moisture trapped in closed capillaries and/or the water component of juices held within a material by the surface tension. Agricultural crops are generally hygroscopic materials containing both bound and unbound moisture in contrast to non-hygroscopic materials that contain only unbound water. Water vapour pressure increases when a product is heated at constant moisture content, with moisture transfer ensuing from the product to an environment at a lower vapour pressure. In drying, heat transferred to the product surface causes surface moisture evaporation. Water from inside the crop migrates to the crop's surface to replenish surface moisture lost by evaporation. Warm drying air initially rapidly removes surplus surface moisture until there a subsequent, generally slower, steady-state, drying rate prevails that diffusion processes depends on the rate that continue to move moisture to the surface by (Sodha et al., 1985).

For agricultural crops an initial heating period is followed first by an initial constant rate drying period, and then by a subsequent falling rate drying period as shown in Fig. 5. Non-hygroscopic materials, only exhibit a constant drying rate. During a constant drying rate period, the product surface become saturated with moisture at a nearly constant temperature that almost equals to the wet bulb temperature. For a particular moisture content, a constant drying rate changes to a falling drying rate when the rate of moisture transfer through diffusion from within the product to its surface become insufficient to replenish the moisture being evaporated from its surface. During the falling-rate drying period, the moisture the rate of moisture transfer through diffusion from within the product to its surface remains less than the moisture being evaporated from its surface.

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Table 2
Initial and final moisture contents and maximum allowable drying temperatures (Brooker et al., 1974; Brenndorfer et al., 1985; Sharma et al., 1993; Brennan, 1994; Bala, 2003).

			Moisture Content		Maximum Allowable temperature (°C)
			Initial (% wet basis)	Final (% wet basis)safe storage)	
Crop	Grains	Paddy, raw	22–24	11	50
		Paddy,	30–35	13	50
		Parboiled	35	15	60
		Maize	20	16	45
		Wheat	24	14	50
		Corn	24	11	50
		Rice	20–22	9–10	40–60
		Pulses	20–25	7–9	40–60
		Oil seeds	80	5	65
	Vegetables	Green peas	80	6	65
		Cauliflower	70	5	65
		Carrots	70	5	75
		Green beans	80	4	75
		Onion	80	4	55
		Garlic	80	4	55
		Cabbage	75	7	55
		Sweet potato	75	13	75
		Potatoes	80	5	75
		Chilies	80	24	65
	Fruit	Apple	85	18	65
		Apricot	80	15–20	70
		Grapes	80	15	70
		Bananas	80	7	65
		Guavas	80	20	65
		Okra	80	10	65
		Pineapple	96	10	60
		Tomatoes	95	6	60

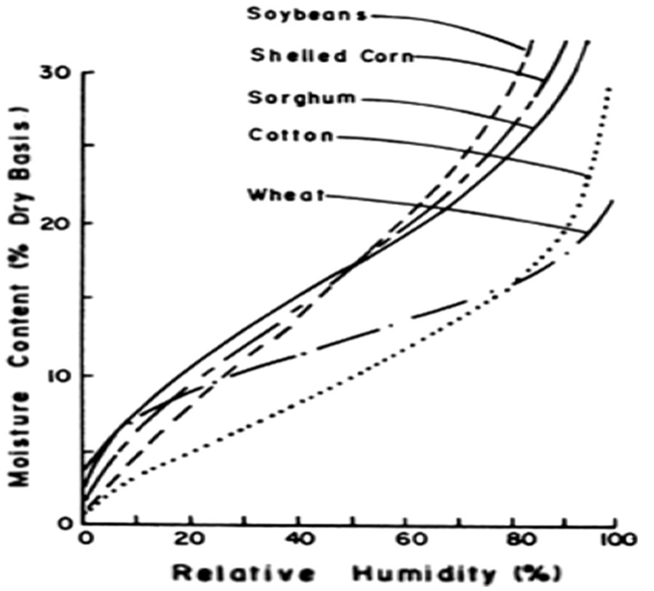

Fig. 4. Variation of equilibrium moisture content with relative humidity for different crops (Henderson, 1952).

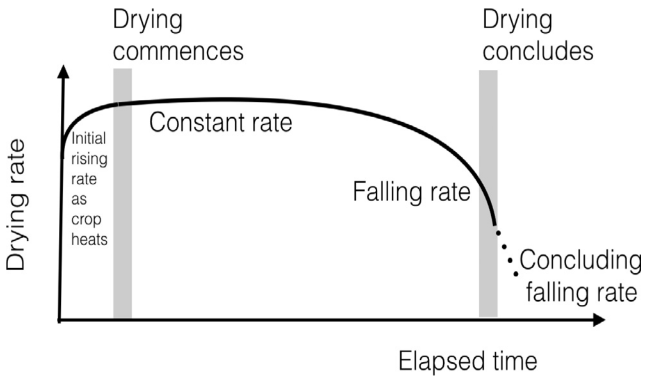

Fig. 5. Drying progression.

For grains, their initial moisture content is lower than the critical moisture content, so drying takes place wholly under at a falling drying rate. The drying of fruits, most vegetables and most tropical tuber crops proceeds through both constant and falling drying rates. For thin layer drying, the large air to crop volume ratio exposes a crop to almost constant drying air conditions in which the drying rate depends mainly on crop type and size, for a given moisture content and drying air temperature (Diamante and Munro, 1991, 1993; Gunhan et al., 2005; Midilli and Kucuk, 2003; Togrul and Pehlivan, 2002; Yaldız and Ertekin, 2001; Doymaz, 2007). Even though air contains only between 0.4 and 1.5% by-weight, water vapour, effective control of the moisture content of incoming air is essential for optimal heat and mass transfer in a solar dryer.

Models of moisture diffusion for porous capillary products (Luikov, 1996) have found limited application due to the lack of measured phenomenological coefficients coupling the joint effects of moisture, temperature and total pressure gradients on moisture, total mass and energy transfers in crops (Karathanos, 1999).

In deep layer drying, moisture movement takes place at a drying zone initially at the base of bed which extends up through the crop bed in the direction of the drying air as drying proceeds. This zone maintains a moisture equilibrium between the total crop mass and the drying air. Above the established drying zone, as drying has yet to commence, the crop is still at the initial moisture content, with surrounding air still in equilibrium with the initial crop moisture content. Condensation at the upper layers of the crop mass at this initial stage of drying is usually negligible. As soon as the drying front reaches the top of the bed, the falling drying rate period commences (Ekechukwu, 1999; Hall, 1980). For shallow crop bed drying at high air flow rates, to avoid overdrying the lowest layers, the drying zone can be extend up to the

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bed with the desired final average moisture content reached before equilibrium between bottom layer and the drying air is reached. The desired moisture content of the crop can be obtained by maintaining optimal air temperatures and flow rates. Guidelines for product management in small-scale solar drying are available (Flores, 2007).

Through a small portion of vitamin C may be lost by preparatory blanching, without blanching still active food enzymes can still active, reduce product quality. Blanching is essential for almost all kind of vegetables except onions, peppers, okra, herbs, and some types of corn that become sweeter as they mature. Syrup blanching before dehydration, helps to retain some vitamin content, fixes the colour, and relaxes surface tissues to aid both dehydration and rehydration. In syrup blanching, a prepared crop is submerged in a boiled syrup for about ten minutes then rinsed in cool water. Syrup blanching is use for sweeter dessert fruits like, plums, peaches, berries, nectarines, apples, pears, peaches, and apricots (Flores, 2007). Fruits such as cherries, seedless grapes, melons, prunes, plums and grapes do not require pre-treatment before drying. Light-coloured fruits such as apples, apricots, peaches, pears and nectarines become darker with loss of flavour and vitamins A and C during drying and storage due to oxidation (Kamiloglu et al., 2016). Direct solar exposure during drying produces dried mushrooms with a high vitamin D content (Nolle et al., in press).

4. Solar air heaters

4.1. Attributes of solar air heaters

A solar air heater can be of a wide range of types and configurations as shown in Fig. 6 (Selcuk, 1977; Ekechukwu and Norton, 1999b; Norton, 2013; Duffie and Beckman, 2013).

Absorber plates can be made of copper, aluminium and steel in decreasing order of cost and thermal conductance. Glazing is usually plastic films or glass sheets (Tiwari, 2003). To improve collection efficiency, a spectrally selective absorber coating can be used if cost effective and heat transfer between the absorber plate and the flowing air can be improved by introducing turbulence, but this also introduces additional pressure drop. In a non-porous air heater, airflow can be above and/or behind the absorber plate (Sodha et al., 1982) but most commonly air passes below the absorber in a plenum between the absorber and the insulation. Porous absorbers include slit (Li et al., 2014) and expanded-metal plates, overlapped glass plate absorbers, wire mesh and porous beds. In solar air heater with a porous absorber, solar radiation penetrates to a greater depth, radiative losses are lower and the pressure drop is usually lower than a non-porous absorber but increases with increasing dimensionless porous layer thickness (Bovand et al., 2016). However, improper selection of matrix porosity and thickness may give reduced efficiency as outside its optimum thickness a matrix may not be heated sufficiently to transfer the heat to an air stream. In non-porous solar air heaters, the air to be heated can flow above and/or below, the absorber. When both the front and rear are exposed to reflected solar energy then a double exposure air heater is formed in which the air stream receives heat from both sides of the absorber plate. In two-pass solar air heaters, air flows between either (i) two aperture or (ii) between inner cover and the absorber plate and then through the passage behind the plate (Satcunanathan and Deonarine, 1973; Caouris et al., 1978; Wijeysundera et al., 1982; a two pass mode increases collector efficiency by about 10–15% (Pirasteh et al., 2014).

Solar air heating collectors with staggered fins attached to the rear side of the absorber plate have collector efficiencies higher than solar air heaters without fins (Fudholi et al., 2015; Mahapatra and Imre, 1990). A vee-corrugated absorber provides a large surface area for heat transfer to the air stream, through the acceptance angle for the Vee-groove must be either optimised to avoid a large amount of radiation being lost due to multiple reflections (Hollands, 1963, and/or mitigated by the use of a spectrally selective absorber coating. With this type of absorber, airflow can be either on one or both sides of the absorber (Parker, 1981). Vee-grooves can be in the form of triangular ducts made of a conductive material (e.g. aluminium) so that heat conduction gives warm walls through which air flows. Carbon steel, stainless steel, bronze and aluminium metal wood have been used to fabricate low cost porous absorber collectors (Rashidi et al., 2017). Carbon steel, is however susceptible to rust. Metal wools generally can filter and clog with dust. Overlapped glass plate air heaters consist of a set of glass plates above one another with a portion of a glass plate, beneath the preceding one being blackened with the rest transparent. Absorbed solar radiation heats the black portions of glass plate, passing heat to the air flowing parallel to these plates there by combining low-pressure drop and high efficiency at moderate operating temperatures (Löf, 1962). However, the large glass area required can lead to a high initial cost. A model has developed for optimising inflatable solar collectors to provide heated air to solar dryers (Nunes del Oliveira et al., in press). In an unglazed

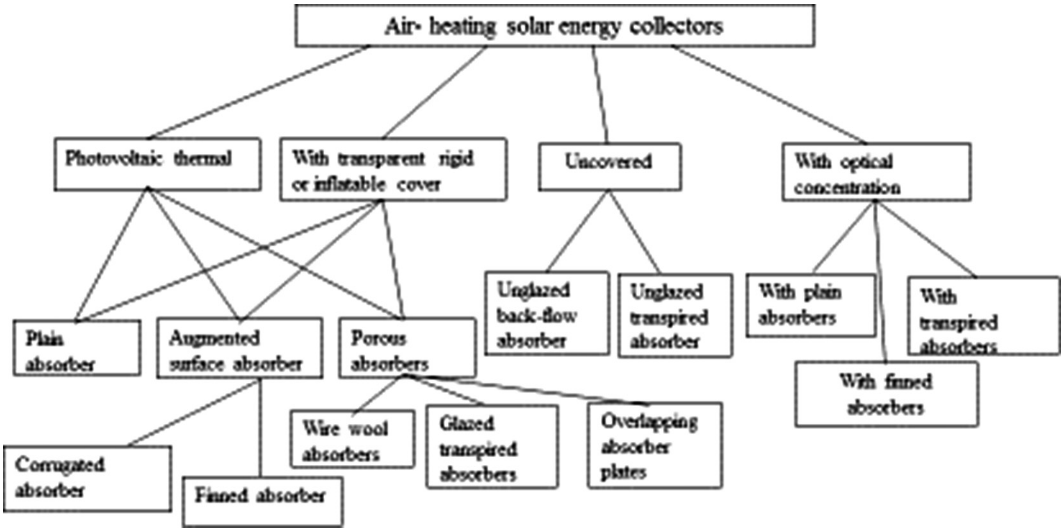

Fig. 6. Taxonomy of air heating solar energy collectors used for solar drying.

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transpired air collector a fan entrains ambient air through a perforated steel or aluminium perforated absorber surface integrated on a building façade (Shukla et al., 2012; Hollick, 1994, 1998; Lorriman and Hollick, 2003). An air channel plenum is formed between the perforated absorber and an existing wall. Generally, 100–300 mm diameter perforations cover 0.5–2% of the collector aperture area. 62% of heat gain is typically from the warm boundary layer on the front side, 28% entrained via perforations and 10% from the back surface of collector. Porosity, plenum dimensions, plenum air velocity, wind, velocity and collector absorptance determine the performance of transpired solar collectors.

By producing both electrical and thermal energy use of either (i) co-located separate solar thermal collectors and PV panels or (ii) a hybrid photovoltaic-thermal (PV/T) system eliminates the dependency on grid/or battery storage to operate air circulating fans. photovoltaic/thermal air (PV/T air) collectors have included both single and double pass air heaters (Bhargava et al., 1991; Hegazy, 2000; Sopian et al., 2000; Sandnes and Rekstad, 2002). Hegazy (2000) in an investigation of four different type of photovoltaic (PV)/thermal solar air collector configurations found that the overall electrical and thermal efficiency can increase by 55% at 0.04 kg/m^2 s mass flow rate of air when flow through between the top glass cover and a solar cell. Zakharchenko et al. (2004) analysed silicon cells integrated onto a black plastic solar heat absorber in an (unglazed PV/T system. The integration of a reflector in a PV/T system can enhance both electrical and thermal output (Tripanagnostopoulos et al., 2002; Coventry, 2005). For a double pass PV/T solar collector with a compound parabolic concentrator, installation of fins on the rear side increased heat transfer between photovoltaic panel and air (Othman et al., 2005, 2007). Various dryer designs have used solar thermal collectors have been equipped with reflectors to concentrate solar energy (Akyurt and Selcuk, 1973; Chew et al., 1989; Hodali and Bougard, 2001; Madhlopa and Ngwalo, 2007; Tiwari et al., 1994; Shams et al., 2016).

5. Solar dryer configurations

5.1. Solar drying taxonomy

The taxonomy of drying using solar energy is given in Fig. 7.

To fully model a solar drying process requires detailed examination of solar radiative heat transfer, dehydration of porous foodstuffs, fluid dynamics and modelling the chemical changes in dietary properties. It has been noted that multi-objective process optimization requires, as a minimum, the development of more complete multiphysics models (Defraeye, 2014).

5.2. Open sun drying

In open sun drying as shown in Fig. 8 the portion of solar energy absorbed at the crop surface increases the crop temperature resulting in

(i) emission of long wavelength thermal radiation
(ii) convective heat loss
(iii) mass transfer of moisture from the surface of the crop to ambient air of drying which depends upon the rate of this diffusion process by which moisture moves to the surface depending upon product type (Sodha et al., 1985, 1987).

The main disadvantages of open sun drying is crop loss due to (i) consumption by rodents, birds, insects, and micro-organisms, (ii) unexpected rain or storms, (iii) excessive or insufficient drying, (iv) contamination due to dust, dirt, insects, and micro-organisms, (v) colour loss due to UV exposure, (vi) large area required, (vii) re-adsorption of moisture during off sunshine hours, and (viii) it often produces products of insufficient quality to be marketable in domestic and international markets (Esper and Muhlbauer, 1998; Koyuncu, 2006; Lutz et al., 1987; Mustayen et al., 2014; Oztekin et al., 1999; Sodha et al., 1985; Sodha and Chandra, 1994). Open sun drying of agricultural and other products may have commenced as an artificial continuation of an in-situ drying. A large portion of the world's supply of dried fruits and vegetables continues to be sun dried in the open without technical aids (Szulmayer, 1971).

5.3. Direct passive solar dryers

When solar energy collection forms a integral part of the roof/wall of the drying chamber forms a direct dryer as shown in Fig. 9.

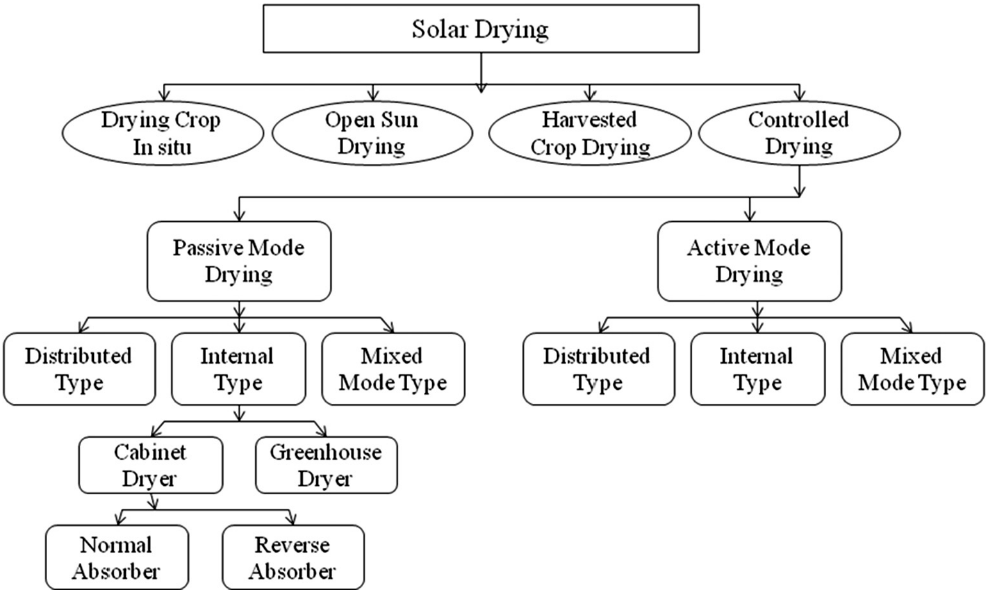

Fig. 7. Solar drying taxonomy.

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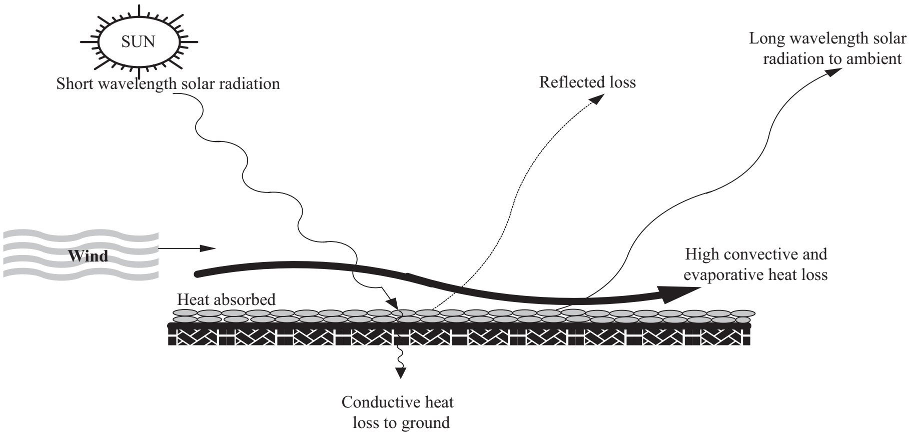

Fig. 8. Open sun drying.

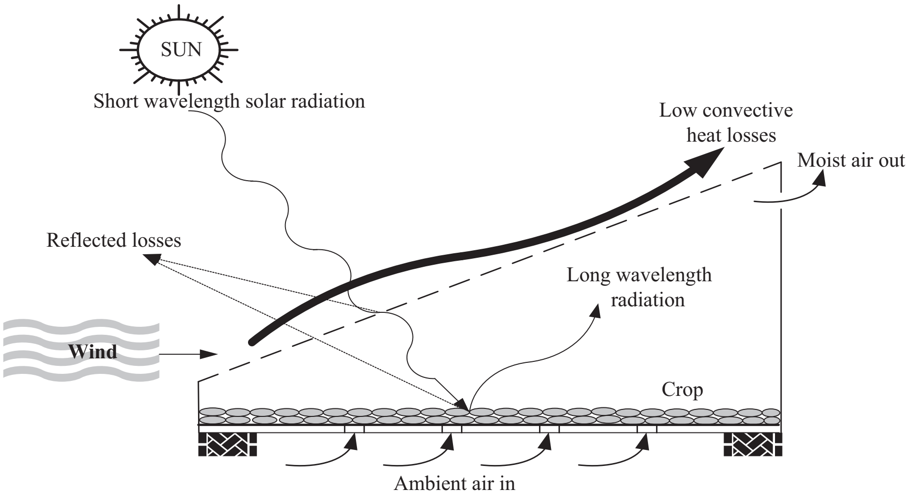

Fig. 9. Schematic diagram of direct solar drying.

In a direct passive solar dryer, solar radiation is directly incident on a crop placed in a transparent wall-drying chamber. The relative humidity of the resident air decreases to carry moisture. Natural air circulation removes the moisture removed by natural air circulation (Ekechukwu and Norton, 1999a, 1999b; Onyegegbu et al., 1994).

Solar cabinet dryers, probably the first types of solar dryer to be studied scientifically (Lawand, 1965, 1966, 1977; Kapoor and Agrawal, 1973), have been used in many climates to dry a wide variety of crops (Datta et al., 1988; Sharma et al., 1990; Thanvi and Pande, 1987). Intended for domestic use a solar cabinet dryer consists of a box insulated at both its base and sides, with a single or double-glazed roof. Holes at its base and at upper parts of the sides allow buoyancy driven moisture removal (Tiwari and Ghosal, 2005; Chua and Chou, 2003). That can be enhanced by the addition of a chimney (Ghaffari and Mehdipour, 2015). Adequate moisture removal is essential both for the drying process and to prevent insolation transmission being reduced by moisture condensating inside the glass cover.

A cabinet type dryer can dry a crop more rapidly than to open-sun drying (Esper and Muhlbauer, 1998; Sodha et al., 1985) Cabinet dryers are perfectly suitable for drying small batches of fruits and vegetables such as banana, pineapple, mango, potato, carrots, and French beans (Jayaraman et al., 2000). In a cabinet dryer solar energy ultraviolet exposure can discolour a crop, use of photo selective acrylic operture materials can reduce both loss of colour and anti oxidant content. This has been demonstrated for the drying of apricots (Milczarek et al., 2016). Insolation transmission can be reduced due moisture condensation inside glass cover. In a reverse absorber cabinet dryer, the absorber plate is downward facing with reflected solar radiation incident on it from below (Goel et al., 1987; Goyal and Tiwari, 1997, 1999; Jain, 2007; Tiwari, 1986). In this dryer, the crop is not exposed directly to solar radiation to which lessens discolouration and surface cracking of the crop. Convective heat loss from the absorber is suppressed due to it being downward-facing.

Vents sized and placed to adjust the airflow gives control over the drying process in large scale, properly designed greenhouse dryers when compared to cabinet dryers (Anon., 1980). Greenhouse dryers are recommended for drying many different agricultural products (Bala and Hossain, 1998; Charters et al., 1989; Dajokoto et al., 1989; Ekechukwu and Norton, 1997; Fuller et al., 1994; Hossain and Bala, 2007; Hossain et al., 2005; Jain and Tiwari, 2004a, 2004b, 2003; Lutz et al., 1987; Lutz and Muhlbauer, 1986; Muthuveerappan et al., 1978, 1985; Shaw, 1981; Sodydov and Khairiddinov, 1982; Brenndorfer et al., 1985; El-Sebaii et al., 2002; Sallam et al., 2015; Sodha et al., 1987; Brenndorfer et al., 1985; Cura and Trim, 1982; Doe and Ahmed,

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1977; Doe, 1977, 1979). A greenhouse solar dryers can also employ a chimney that maybe augmented with a blackened internal absorber to achieve faster moisture removal (Ekechukwu and Norton, 1997, 1998, 1999a, 1999b).

5.4. Indirect passive solar dryers

When a solar collector is separated from drying chamber it forms an indirect solar dryer as shown in Fig. 10. Mixed –mode type dryers combine features of direct and indirect dryers (Ekechukwu and Norton, 1999a; Mustayen et al., 2014; Tiwari and Ghosal, 2005).

In an indirect solar dryer, an opaque drying chamber contains a crop placed on trays. The drying chamber is heated by circulating air warmed by a low pressure-drop air-heating solar collector.

Since solar radiation does not directly incident on the crop, caramelisation and localized heat damage do not usually occur. These dryers are suitable for retaining (i) vitamins in preserved fruits, and (ii) colour in highly pigmented commodities. The separate air heater and drying chambers (Jain and Tiwari, 2015; Jain, 2007; Pangavhane et al., 2002; Pangavhane and Sawhney, 2002) are usually connected by a flexible insulated conduct. A door provides loading access to north side of the drying chamber. The air collector can be inclined to receive maximum solar radiation for the particular time of year when dried crop is harvested. A wide variety of phase change and sensible thermal energy storage has been employed with solar dryers (Kant et al., 2016; El Khadraoui et al., 2017b) with a particular emphasis on the use of rock beds (Jain and Jain, 2004; Sharma et al., 1991; Tiwari et al., 1994; Madhlopa and Ngwalo, 2007, and water. Many autonomous solar dryers have no auxiliary heating as thermal mass provides short-term heat storage to enable drying to continue in intermittently, cloudy or inclement weather (Condori et al., 2017 Ayua et al., in press). Crops that dry rapidly are suited to such dryers as thermal mass is rarely sufficient to sustain drying nocturnally (Sekyere et al., 2016).

A typical mixed-mode natural circulation solar-energy dryers is similar to indirect mode dryer but incorporates glazed surfaces to the drying chamber (Archuleta et al., 1983; Ayensu and Asiedu-Bondzie, 1986; El-Sebaii et al., 2002; Exell et al., 1979; Mustayen et al., 2014; Ong, 1979; Roberto, 1984; Sharma et al., 1986; Simate, 2003; Eissen and Miihlbauer, 1983; Ayensu and Asiedu-Bondzie, 1986).

5.5. Active forced-circulation solar energy dryers

Active solar energy dryers use fans to circulate heated air from the solar collector to the drying chamber. For higher moisture content crops such as papaya, kiwi fruits, brinjal, cabbage and cauliflower slices, active solar dryers have often found to be more suitable than passive solar dryers (Taylor and Weir, 1985; Chua and Chou, 2003). Forced-convective greenhouse dryers are used for large-scale commercial applications (Huang and Bowers, 1977; Huang and Toksoy, 1981, 1983; Huang, 1980; Ozisik et al., 1980; Müller et al., 1989; Taylor and Weir, 1985). There is a large diversity of forms from large-scale transparent roof "solar barns" (Shove et al., 1981) to small-scale forced-convection dryers (Bailey and Williamson, 1965; Bassey, 1985; Umarav and Ikramov, 1978). For a active indirect solar dryer the components, are a drying chamber, air heating solar collector, fan and connecting ducts (Garg et al., 1994; Ong, 1982, 1999; Roa and Macedo, 1976; Sharma et al., 1993; Tiris et al., 1994; Eissen and Miihlbauer, 1983; Fohr and Arnaud, 1992; Akachukwu, 1986; Plumptre, 1979; Calderwood, 1981; Pattanayak et al., 1978; Reddy et al., 1979; Smith, 1977; Trim and Ko, 1982; Bolin et al., 1978; Calderwood, 1981; Miller, 1985; Tiris et al., 1995; Tschernitz and Simpson, 1979). By controlling air-flow rates, active indirect solar dryers can achieve efficient drying with good final product quality particularly where real-time monitoring of crop moisture content is used for process control. In small-scale indirect solar dryers, the effect of airflow rate on the maximum evaporation rate depends on the ratio of the total drying area to the cross-sectional area of the drying chamber (Blanco-Cano et al., 2016b). To achieve acceptable evaporation notes for typical units and operating conditions, this ratio is recommended in between 200 and 300.

5.6. Mixed mode active solar dryers

Inactive mixed mode solar dryers (Akyurt and Selcuk, 1973; El Khadraoui et al., 2017a; Selçuk et al., 1974; Simate, 2003; Lutz et al., 1987; Mabrouk and Belghith, 1994; Mastekbayeva et al., 1998). Forced circulation of heated air from an air-heating solar collector to the glazed drying chamber is accomplished by fans operated either by AC electricity obtained fromas grid or DC electricity produced by photovoltaic (PV) modules (Jain and Tiwari, 2004a, 2004b; Mumba, 1995a, 1995b, 1996; Tsamparlis, 1990;

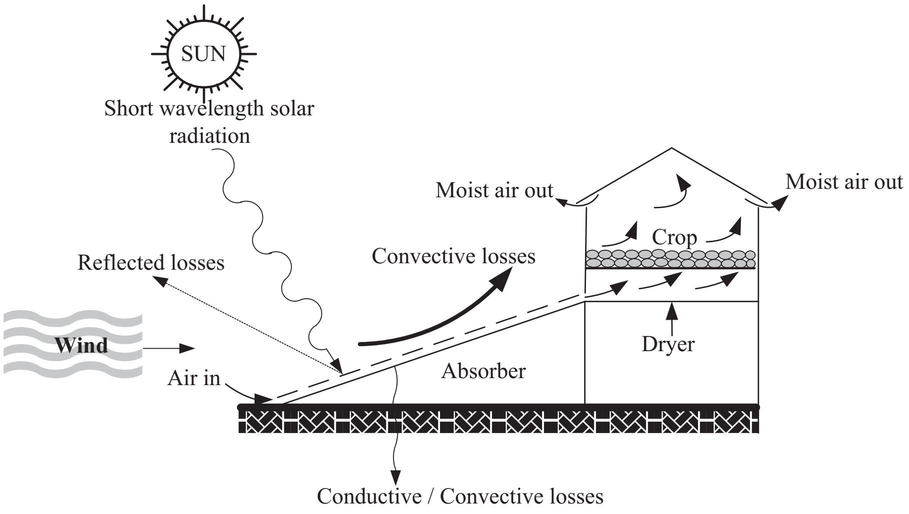

Fig. 10. Indirect solar drying.

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Farkas et al., 1999; Huang et al., 2001; Saleh and Sarkar, 2002). PV powered fans have been integrated into tunnel type and greenhouse type hybrid mixed mode dryers (Bala et al., 2003; Hossain and Bala, 2007; Hossain et al., 2005; Barnwal and Tiwari, 2008).

A solar collector can form the roof and/or wall of a drying chamber (Ong, 1979; Bowrey et al., 1980; Kocher et al., 1981; Muthuveerappan et al., 1985; Bala and Janjai, 2007) or an agricultural building for which a batch dryer located inside the building (Chua and Chou, 2003; Imre and Palaniappan, 1996; Imre, 1995). Such active solar dryers have been used for drying of higher moisture content foodstuffs such as papaya, kiwi fruits, brinjal, cabbage and cauliflower slices. In solar collector-wall dryer (Kocher et al., 1981), a black-painted and glazed concrete wall forms the solar collector whilst also serving as thermal storage (Ivanova and Andonov, 2001; Ivanova et al., 2003).

Hybrid solar dryers have used biomass for auxiliary heating to prolong drying continually into the night. Such dryers have used for nuts such as cashews (Dhanushkodi et al., in press). Biomass fuels have also been dried in solar tunnel dryers (Subhana and Natarajan, 2016). A mathematical model has been developed for drying mushrooms that includes shrinkage (Rahman et al., 2016). A solar-assisted heat pump dryer has been used to dry cassava (Yahya et al., 2016) and when combined with heat recovering and thermal storage, was found to be particularly suitable for mushroom drying (Qui et al., 2016). Too rapid drying of nuts can lead to core hardening with poor interior drying recirculation of the solar drying air is thus employed to give a drying rate that provides acceptable product quality whilst making efficient use of the heated air. This technique has been applied successfully to the drying of pistachio kernals (Mokhtarian et al., 2016).

6. Conclusion

For many crops, particular combinations of crop pre-preparation, solar drying equipment and process management are now in use successfully to dry crops in applicable seasonal weather conditions. In other instances, promising research has not been applied to-date to significantly reduce crop-processing losses. More research is required to determine how solar drying could be readily incorporated into existing part-harvest processing chains thereby reducing barriers to appropriate adoption. As has been shown, solar crop drying brings together the complexities of internal crop structures, human nutrition, food aesthetics and process of crop decay with those of solar dryer design and process control under varying solar radiation intensities. It is probably unnecessary to have a theoretical framework that deals in all details of such a complex system in all circumstances. However research that draws together generic crop, dryer and climate combinations would enable more systematic future development of solar drying. The lack of clear benchmarks for performance inter-comparison impedes the ability of new research to build constructively on previous work.

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