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Recent Research and Development on Solar Dryer Technologies for Roselle (*Hibiscus sabdariffa* L.) Drying

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Abstract

This paper is an effort to briefly discuss the recent research and development on solar and other types of dryer technologies for roselle (*Hibiscus sabdariffa* L.) drying and to review some important work carried out across the world. After reviewing the available research papers, solar, sun, electric oven, freeze, shade, microwave, cross flow, infrared and other drying technologies are available for drying of roselle leaves and calyces. Efforts also have been made to review the available solar dryer technologies, for drying of other agro-products. It is observed that among the different types of solar dryers, the indirect forced convection solar dryer may be highly suitable or superior for industrial, commercial and large scale applications due to its various important points like speed and quality of drying, easily incorporating back-up unit, easily eliminating the tray reshuffling, scope of integrating with existing drying system, possibility of uniform drying, attached any types of solar air heating unit, reduce drying area needed, reduces labour cost, good controls and automation is possible, reduce the drying time, large capacity drying is possible, stand alone technologies may be designed, on farm operation is possible without grid power. Based on very good concepts available in all research paper, an efficient and engineered indirect forced circulation solar dryer for roselle fruits and leaves drying may be planned to develop. This dryer may be useful for any of the agro-industrial products.

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Keywords

Roselle, Drying technologies, Good concepts, Automation, Indirect forced circulation solar dryer.

Introduction

Roselle and its importance

Roselle (*Hibiscus sabdariffa* L.) is a shrub belonging to the family - Malvaceae. Roselle plant widely grown in tropical regions around the world, such as India (Gujarat, Bihar, Assam, Madras and AP), The Philippines, Malaysia, Caribbean, Central America, Senegal, Africa, Brazil, Australia, Hawaii, Florida, Ethiopia, and Mexico (Domínguez-López *et al.,* 2008 and Gautam, 2004) as a home garden crop. In English-speaking countries, it is called Red Sorrel. Roselle is known as Khati Bhindi, Lal Ambadi by the tribal people of the Gujarat. In Hindi, it is called as Lal Ambary. It is a robust branched shrub-like annual or perennial plant, growing to 1.2 - 2.5 m tall. The leaves are dark green and deeply dissected into three to five narrow lobes, 8-15 cm long. The stems, branches, leaf stalks, and leaf veins are reddish purple.

The flowers are 8 - 10 cm in diameter, white to yellow with a dark red spot at the base of each petal, and have a stout fleshy calyx at the base, fleshy and bright red as the fruit matures.

They take about four to six months to mature. Roselle plant produces about 8 t/ha of fresh fruits or 4 t/ha of fresh calyces. In some of variety, calyx to capsule ratio is high and yield is also more.

Almost every household in Dediapada Taluka region of Narmada district, Gujarat has this plant as vegetable crop. This crop does not require any special care, fertilizer or any major land preparation or more water and more fertile land. In this region at present roselle plants are shown on the bunds of field, nearby house as home garden plant or in forest.

Table.1 Biochemical values of different parts of every 100 g of roselle

Nutrients	Petals	Leaves	Seeds
Protein (g)	1.6	3.5	28.9
Carbohydrates(g)	11.1	8.7	25.5
Fat (g)	0.1	0.3	21.4
Vitamin A (I.E.)	-	1000	-
Thiamine (B1) (mg)	0.05	0.2	0.1
Riboflavin (B2) (mg)	0.07	0.4	0.15
Niacin (B3) (mg)	0.06	1.4	1.5
Vitamin C (mg) (ascorbic acid)	17	2.3	9
Calcium,Ca(mg)	160	240	350
P (mg)	60	--	--
Iron, Fe (mg)	3.8	5	9
Calories	44	--	--
H2O (%)	86.2%	--	--
Fiber (g)	2.5	--	--
Ash (g)	1.0	--	--
Beta carotene equivalent (mg)	285	--	--

Source: Md. Mahbubul Islam (2019) and Sudarmayanti and Yunus, (2011)

Roselle is used as a beneficial plant for centuries. In India, all its parts like the roselle calyces, leaves, stem, flower, seeds, etc. are used for one purpose or the other.

Figure.1 Roselle plants

Some of these uses are: (1) primarily cultivated for the production of bast fibres (from the stem) used for making rosella fibre is strong and is employed in the preparation of gunnies, cordage, rope, burlap, fishing nets and generally for all purposes for which jute is used. Bags made of roselle fibre are extensively employed in Java for packing sugar. (2) The stalks left over after fibre extraction from roselle are used as fuel. (3) Fresh as well as dried calyces and leaves are an essential part and are used in food preparation. (4) In Gujarat and Maharashtra, fruit petals and leaves are used in making juices or drinks, squashes, jellies and pies, to produce a bright red-color, chutney (sweet and sour in taste). (5) The green leaves as a vegetable are used like a spicy version of spinach and are steamed with lentils and cooked with dal as well as salads. (6) The most famous dish by mixing fried leaves with spices in Andhra and Telangana often described as king of all Andhra foods. (7) After monsoon, the leaves are dried and crushed into powder, then stored for cooking during winter in a rice powder stew in some of the region of the India. (8) The dried calyces as well as the dried flower is also used as an essential ingredient in various recipes. The bright red roselle calyces swell are harvested, dried, and sold whole to the herbal tea and beverage industry. The flavor is a combination of sweet and tart (Plotto, 2007). (9) Used for making a face/body scrubs, facial steams, clay masks. (10) Roselle plant can be used for various health benefits purpose like: menstrual pain, anti-inflammatory and antibacterial properties, aids digestion, weight loss, antidepressant properties, antioxidants (Tee *et al.,* 2002; Tsai *et al.,* 2002; Prenesti *et al.,* 2007; Arroyo *et al.,* 2011), anti-cancer properties, anti-aging properties, cough, colds and fever management, wage the blood circulation, blood pressure management, protects liver, maintains healthy teeth and gums, healthy pregnancy.

Drying methods for roselle

Roselle calyx is usually harvested at high moisture content (85%, w.b.). Therefore, drying is an important post-harvest treatment prior to reduce the moisture content and to increase the shelf life. Drying is a process comprising simultaneous heat and mass transfer (Suherman *et al.,* 2012). In order to preserve and extend their life, roselle calyces are sold in dry form.

Their main form of consumption is after leaching them with water (Daniel *et al.,* 2012). Dried roselle calyces can be obtained in two ways: (1) to harvest the fruits fresh, decor them and then dry the calyces; (2) To leave the fruits to dry on the plants to some extent, harvest the dried fruits, dry them further if necessary, and then separate the calyces from the capsules.

Open sun drying method

In developing countries, Traditional open sun drying of roselle calyces can cause loosing/reducing antioxidant capacity, and it is also take too much time (Daniel *et al.,* 2012 and Meza-Jiménez *et al.,* 2009). Based on information got from farmers in tribal region of the Gujarat, the Rosella petals takes 5 days to dry with traditional drying.

The drying process under the sun is also not hygienic due to contamination by insects, birds and dusts, rodent problem or bird dropping, viruses or bacteria, fungal growth, it must be taken and stored as soon as the weather change (Sengar *et al.,* 2022; Kumar *et al.,* 2008). Due to rewetting of the roselle during drying by rain and too slow drying rate in the rainy season, antioxidant and toxic substances such as an alphatoxil produced by molds is often found in the dried products. This is one of the main problems obstructing the growth of exports of herbs and spices to national as well as international markets. (Janjai and Tung, 2005)

Various drying method

Janjai and Tung (2005) developed and tested a solar dryer (Fig. 2 and 3) for drying 200 kg of roselle flowers and lemon-grasses using hot air from roof-integrated solar collectors within 4 and 3 days respectively. The dryer (1.0m × 2.0m × 0.7m) is a bin type with a rectangular perforated floor. Hot air is supplied to the dryer from fibre glass-covered 16 solar collectors, each of which has an area of 1.0 × 4.5 m² (total area 72m²), which also function as the roof of a farmhouse. The bottom side of the dryer is made of a rectangular perforated plastic plate and the top side is open for loading and unloading the products to be dried and for allowing moist air to leave the dryer. To reduce the heat losses, walls of the dryer were insulated with of high-density foam sandwiched between two aluminium sheets.

Hot air from the collectors is sucked by a 2 hp axial fan into the box and then blown through products in the dryer to obtain a uniform air flow distribution. The dried products were completely protected from rains and insects and of high quality.

The solar air heater had an average daily efficiency of 35% and it performs well both as a solar collector and a roof of a farmhouse. Based on the economic situation in Thailand, the investment rate of return and the Pay-back period of the developed dryer were calculated to be 70.3% and 3.9 years, respectively.

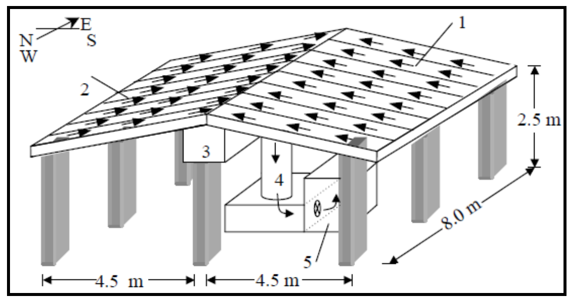


Figure.2 Schematic diagram of the solar dryer using hot air from a roof-integrated solar collectors (1) south-facing solar collectors, (2) north-facing solar collectors, (3) horizontal air duct, (4) vertical air duct, (5) dryer

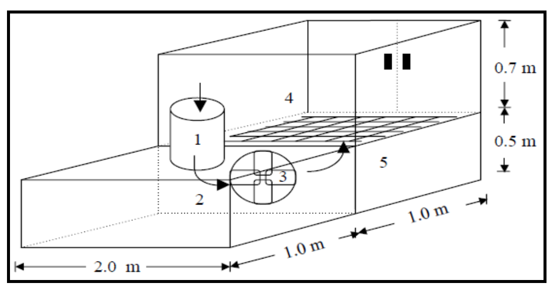


Figure.3 Schematic diagram of the dryer: (1) air duct from the collectors, (2) air distribution box, (3) fan, (4) product container, (5) space underneath the product container.

Saeed *et al.,* (2008) studied the effects of drying conditions on the drying behaviour of roselle. The experiments were conducted in five constant temperatures (from 35°C to 65°C) and five RH (30 to 50%) inside the laboratory drying chamber (Fig.4). Drying air temperature was found to be the important factor affecting the drying kinetics of roselle; raising the drying temperature from 35°C to 65°C dramatically reduced the drying times. The effect of the RH was lower than that of temperature; increasing the RH resulted on longer drying times.

Higher equilibrium moisture contents were obtained with high RH and low temperatures. The drying process of fresh whole calyces of roselle took place in the falling-rate period, starting from 91.1 IMC to 15.5%wb FMC.

The time required for drying roselle was considerably decreased with the increment in the drying air temperature. There was an acceleration of the drying process due to the decrease of the air humidity from 50% to 30%. Furthermore, drying was observed only in the falling-rate period.

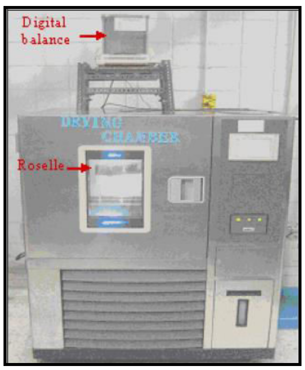
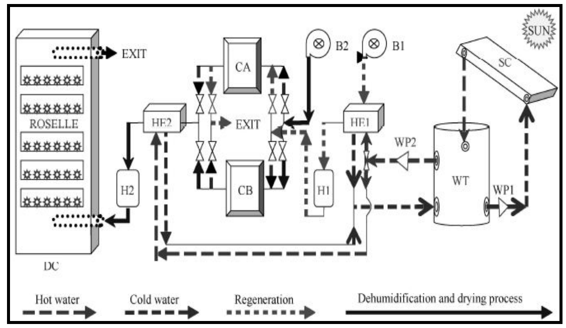


Figure.4 Laboratory drying chamber

Saeed (2010) conducted thin-layer drying experiments in a solar assisted dehumidification drying system (Fig.5) for roselle calyces. A 9.86 m² flat-plate solar collector, auxiliary electric heaters and a cabinet-type drying chamber (100 cm L × 100 cm W × 240 cm H) were used.

The configuration of the system's components is shown in Figure 1. The investigations were carried out at five different air temperatures (from 35°C to 65°C) and two different air velocities (1.5 and 3.0 m/s).

The drying rate of Roselle was highly influenced by the drying air temperature. Higher temperatures resulted in higher drying rate. Air velocity had minor effect on the drying rate compared to that of the air temperature. Drying air temperature was the main factor affecting the drying behaviour of roselle since raising the temperature dramatically reduced the drying time. At 45°C, increasing the drying-air velocity resulted in shorter drying time.



B = air blower, CA = column A; CB = column B; DC = drying chamber; H = heater; HE = heat exchanger; SC = solar collector; WP = water pump; WT = water tank

Figure.5 Regeneration (column A) and dehumidification (column B)

Hahn *et al.,* (2011) constructed a polyethylene plastic covered tunnel (Fig.6) for drying roselle calyxes to analyze three different systems: (1) used controlled fans for heating the air inside the tunnel to its maximum capacity; (2) re-circulated air and passed it through a silica gel desiccant filter for drying the air and (3) used hot air from a hybrid solar-biogas combination system.

These three drying techniques were evaluated and compared to search for optimum drying conditions. Drying time, product quality and ambient parameters were monitored and compared for each system. Calyx colour images, water loss and calyx crispness of dried products were evaluated along the tunnel. Roselle drying using fan control took 27h, optimizing energy consumption and increasing air temperature within the tunnel.

An air recirculation system using silica gel for removing air moisture decreased the drying time to 8h and obtained crisper calyxes. Moisture retained by the silica gel desiccant material was automatically removed by heat regeneration. Calyxes were dried in 4.5h at 70°C with a hybrid solar biogas system. One kg of biogas was burned per kg of dried product.

Figure.6 Chamber used for roselle drying

Tjukup Marnoto *et al.,* (2014) designed and developed an indirect type natural circulation solar cabinet dryer (Fig.7) (120 cm (L) × 80 cm (W) × 75 cm (H) rear and 65 cm (H) front) for drying of roselle flowers. This dryer consists of collector solar rays, transparent double glass covered collector, drying chamber, dryer rack, rear door and air vents. The traditional open sun drying method takes five days and less healthy. Solar dryer technology can speed up the drying process and protect materials from dust contamination. Roselle petals of 2.3kg with 90.84% IMC dried until the 7.63% water content, takes only 2 days, although the weather (27-28 September 2013) was cloudy. It was much faster than using open drying system. The temperature in the drying chamber was not more than 50°C, so it was good for drying groceries, not damaging chemical substances on the product. The relative humidity in the space dryer was about 40% and it was still relative low.

Drying performance was affected by. Drying rate and drying performance was expressed by the efficiency and specific moisture evaporation rate (SMER) was influenced by moisture amount of the product to be dried or by moisture amount that can be hydrated and external factor such as weather. The daily efficiency on first and second day were 14.93% and 5.78%, while daily SMER on first and second day were 0.222 and 0.0256 (kg/kWh).

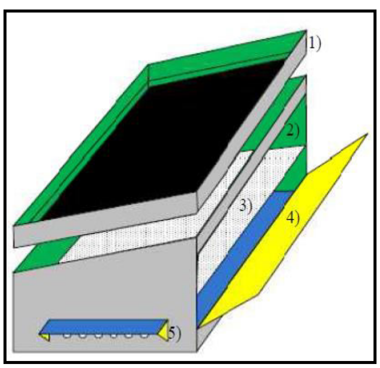


Figure.7 Sketch of solar dryer with double glass cover collector

Tham *et al.,* (2018) studied the drying kinetics and the quality attribution of roselle. The experiments were conducted using four different drying methods including solar drying (SD), solar with intermittent heat pump drying (SIHP), low temperature heat pump assisted dryer (HP) and hot air drying (HA). SD for roselle was conducted in a solar greenhouse dryer (SGD) (Fig.8) having natural convection mode with no active air provided. A hemisphere SGD was built with steel structure and covered with transparent thin sheet made from polyethylene. On the other hand, a heat pump was introduced in SGD to improve the drying time and efficiency. The layout of the SGD and drying shelves was illustrated in Fig. 1. Basically, the even span SGD facial facing 266° west and 13 units of drying shelves are arranged in series and parallel inside the SGD.

Temperature for each experiment was maintained below 45 °C to define the low temperature drying. Relative humidity of dryers was recorded below 40% during the experiment. Among the four drying methods, HP achieved the highest drying rate, while SD had the lowest drying rate. Greater amount of flavonoids compounds was found in SD and SIHP dried finished product as compared to other drying methods.

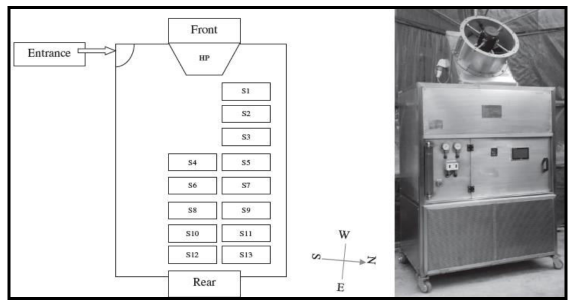


Figure.8 The layout of SGD (from top view), location of drying shelves and heat pump

Hanem *et al.,* (2022) studied the effect of each of the different drying methods viz. drying in the shade, direct sunlight, electric ovens and solar dryer, and the different storage periods (0, 2, 4 and 6 months) on the quality of roselle The results showed that the method of drying in the shade gave the best results for most of the characterizes studied and the results for the different storage times did not differ significantly between them. (Fig.9)

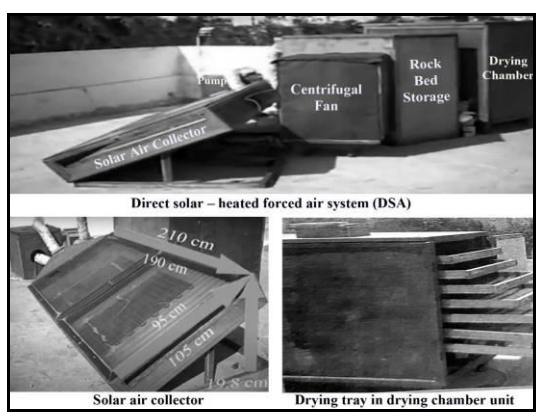


Figure.9 Direct solar- heated forced air system

Other than solar drying system, pilot-scale spray drying for roselle extract (Maskat *et al.,* 2014) was developed to determine the effects of inlet air temperature (150, 160 and 170°C) and feed rate (280, 350 and 420 ml/h) on powder properties. Sandopu *et al.,* (2015) studied the comparison between six different drying methods (As shown in Table 1) for roselle leaf. The result shows that the room and freeze dried samples were found to have best quality in terms of colour, total flavonoid content, total phenolic content, chlorophyll content and ascorbic acid content compared with those subjected to infrared, cross-flow, microwave, oven or sun drying. Samples treated by room and freeze drying retained maximum antioxidant potential.

Amoasah *et al.,* (2018 and 2019) studied the effect of different drying methods like oven, sun and solar (Fig.10) on proximate composition (in the year 2018) and mineral content (in the year 2019) of roselle calyces. The experiment was set up in a 3 × 3 factorial arrangement in a Completely Randomized Design (CRD) with three replications. The study concluded that oven drying was more efficient than solar and sun in reducing the moisture, maintaining fat, ash and carbohydrate contents of roselle calyces. Solar drying resulted in higher protein content while sun dried calyces produced higher fiber content in all the three accessions. With respect to methods of drying, sun recorded significantly highest calcium, iron, magnesium, sodium, and zinc content. On the other hand, Oven drying resulted in the highest potassium and phosphorus content.

Figure.10 Solar dryer

Minh (2020) evaluated the spray drying for roselle extract into dried powder. It was concluded that the optimal spray drying variables for roselle powder should be 8% isomalt, 12% whey protein concentrate, inlet/ outlet air temperature 140°C/85°C, feed rate 12 ml/min. Based on these optimal conditions, the highest physicochemical attributes of the dried roselle calyx powder would be obtained.

Denise *et al.,* (2020) evaluated the drying of roselle by spray dryer with different diameter nozzles and carrier agents. Results showed that both carrier agents and the diameter of the sprinkler nozzle influenced the yield and the chemical and antioxidant properties of roselle. It was also found out that controlling the drying parameters is necessary to evaluate how the process affects the content of antioxidant compounds.

Lema (2022) studied to examine the effects of sun, oven and freeze drying on the physico-chemical and nutritional properties of roselle calyx for its anthocyanin.

The antioxidant (%RSA), total anthocyanin content (TAC) and their HPLC identification, physico-chemical as well as proximate composition were determined.

The results showed that freeze drying increased the drying rate significantly and retained the antioxidant activity (32 mg/100 g QE) then fresh calyx, sun and oven drying, freeze-dried calyx also have higher TAC (176.9 mg/l) than sun and oven dried calyx. The findings demonstrated that freeze drying the roselle calyces preserve their quality characteristics.

Roselle drying through solar, sun, electric oven, freeze, shade, microwave, cross flow, infrared and other technologies are available in the reviewed research papers. The different drying methods employed for calyces and leaves of roselle are given in Table 2.

Drying methods for other agro-products

In this section, various types of latest solar drying technologies developed for other agro-products were studied for their special feature. Classification of solar dryers (Fig.11) can be divided by the solar ray contact materials dried and also based media flow dryers. (Sharma *et al.,* 2009; Jairaj *et al.,* 2009; Lalit *et al.,* 2011; Chavda and Rathore, 2017).

Forced or natural circulation or mixed mode can be provided to both direct and indirect dryers, thus making six types of solar dryers (Chavda and Kumar, 2008) as shown in Fig.11.

Table.2 Different drying methods employed for calyces and leaves of roselle

Reference	Produce and capacity	Method of drying	Drying parameters	Moisture reduction		Best method	Reasons
				IMC % (wb)	FMC % (wb)		
Lema *et al.*, 2022	Fresh roselle calyces(2 kg)	Sun	Avg.34.9°C for 120 h	78	14	Freeze drying	Higher drying rate and preserve their quality
		E.Oven	60°C for 48 h		16		
		Freeze	-20°C for 31 h		12		
Hanem *et al.*, 2022	Fresh roselle calyces(2 kg)	Shade	----	86	12 - 14	Freeze drying	Higher dry weight, drying rate and preserve their quality
		Sun	6 and 10 days		13 - 16		
		E.Oven	60°C for 36 h		10		
		Solar direct type forced air system	6 and 8 days		12-14		
Amoasah *et al.*, 2018	Fresh roselle calyces (100g)	E.Oven	60°C for 24 h	86	6 - 8	E.Oven drying method	Reducing the moisture, increasing fat, ash and carbohydrate
		Solar (cabinet type)	56.5°C for from 9 am to 4 pm for 7 days		10 - 13		Higher protein content
		Sun	Avg.34.9°C from 9 am to 4 pm for 7 days		7 - 9		Higher fibre content
Amoasah *et al.*, 2019	Fresh roselle calyces (100g)	E.Oven	60°C for 24 h	86	6 - 8	---	Highest potassium & phosphorus content
		Solar	56.5°C for 48 h		10 - 13	---	---
		Sun	Avg.34.9°C for 72 h		7 - 9	---	Highest calcium, iron, magnesium, sodium and zinc content
Sandopu *et al.*, 2015	Fresh roselle leaves (500g)	Shade (Room)	27±2°C for 4 days	86	5 – 6	Room and freeze drying	Retention of chlorophyll, ascorbic acid and antioxidant compounds
		Sun	35±3°C midday for 1 day		2 – 3		
		E.Oven	65°C for 5 h		8 – 9		
		Microwave	850 W for 5 min		7 – 8		
		Cross flow	50±5°C for 16 h		4 – 5		
		Infrared	1.1 - 1.3µm wavelength radiation at 50±5°C for 5h		5 – 6		
		Freeze	Vacuum tray at 0.012 mbar and −110°C		5 – 6		
Janjai and Tung, 2005	Roselle flowers (200kg)	Solar using roof-integrated solar collectors & bin type dryer	4 days	90	16	---	Products protected from rains and insects; high quality; collector efficiency = 35%; IRR = 70.3%; PBP = 3.9 yrs
	Lemon-grasses (200kg)		3 days	70	6	---	

Tjukup Marnoto *et al.*, 2014	Roselle flowers (2.3kg)	Indirect type natural circulation solar cabinet dryer	50°C for 2 days	90.8	7.6	---	Speed up the drying process; protect materials from dust contamination; daily efficiency on first and second day = 14.93% & 5.78%; specific moisture evaporation rate on first and second day = 0.222 and 0.0256 (kg/kWh)
		Sun	5 days	90.8	9.7	---	Less healthy
Saeed *et al.*, 2008	Fresh roselle calyces (60 g)	Laboratory drying chamber with constant temp. and humidity	Temp.35, 45, 55, 60 & 65°C RH = 30 to 50%	91.1	15.5	---	EMC and times reduced with increasing the drying-air temp.; EMC increased with increasing RH
Saeed *et al.*, 2010	Fresh roselle calyces (10 kg)	Solar-assisted dehumidification cabinet type drying system	Temp.35, 45, 55, 60 & 65°C Air velocity = 1.5 & 3.0 m/s	90.8	16.0	---	EMC and times reduced with increasing the drying-air temp.; EMC increased with increasing RH
Babalola *et al.*, 2001	Fresh roselle calyces (10 kg)	Forced air oven g	60°C	85-88	10	----	Good source of nutrients; consumption should be encourages among the disadvantaged groups in developing countries.
Hahn *et al.*, 2011	Fresh roselle calyces (10 kg)	Tunnel dryer	70 °C for 4.5 h	86	10	----	Very quick drying; the product is very crispy and breakable.
Suherman *et al.*, 2012	Fresh roselle calyces (250g)	Thin layer (Tray Dryer)	Temp. 40, 50 and 60°C for 100, 110 & 180 min.; Air Vel. = 1.5 to 1.6 m/s	85	8	----	The Newton model was the best one to describe drying process.
Ashaye, 2013	Fresh roselle calyces	Sun	3 days	86	15-17	Oven drying	Better nutrient quality
		Oven	24 h at 50°C	86	6-8		
Langova *et al.*, 2013	Fresh roselle calyces	Hot air	60°C	86	13-15	----	----
Ismail and Mohammed, 2014	Fresh roselle calyces (100g)	Oven	105°C for 45 – 60 min.	85	10-13	----	----

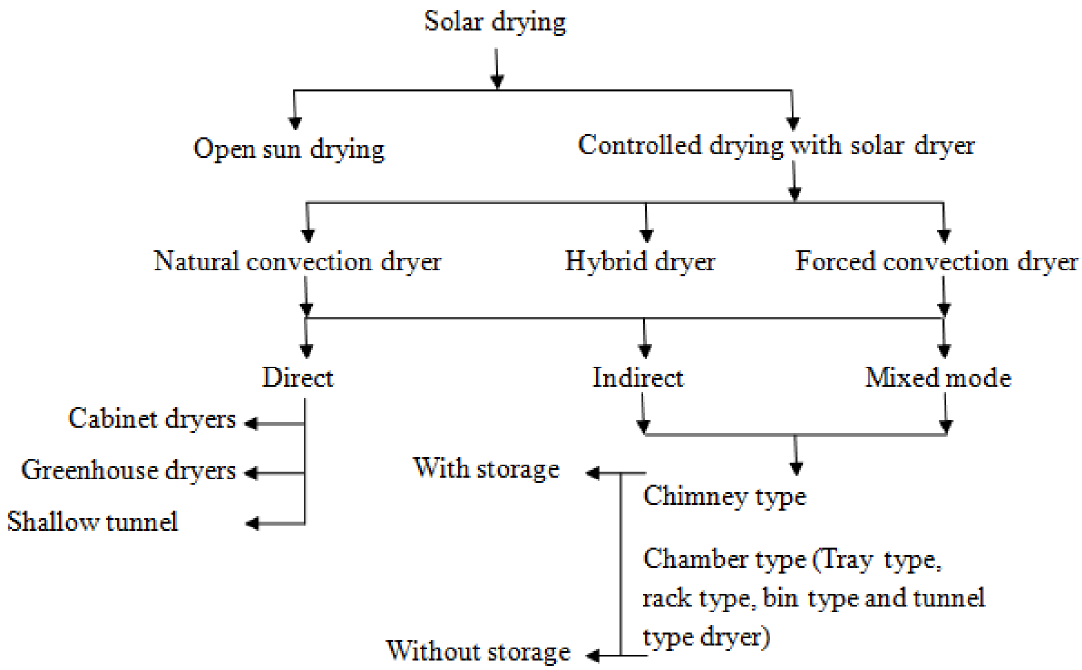


Figure.11 Classification of solar dryer

Yahya *et al.,* (2016) investigated the performance of a solar dryer (SD) and a solar-assisted heat pump dryer (SAHPD) (Fig.12) for drying of cassava Chips. The SD and SAHPD decreased the mass of cassava from 30.8 kg to 17.4 kg within 13 and 9 h at average temperatures of 40°C and 45°C, respectively. The moisture content of cassava decreased from 61% (w.b.) to 10.5%, with a mass flow rate of 0.124 kg/s.

The average thermal efficiencies were 25.6% and 30.9% for SD and SAHPD respectively. The average drying rate and specific moisture extraction rate were 1.33 kg/h and 0.38 kg/kW h, respectively, for SD as well as 1.93 kg/h and 0.47 kg/kW h, respectively, for SAHPD.

The pick-up efficiencies varied from 3.9% to 65.8% and 15.9% to 70.4% for SD and SAHPD, with average values of 39.3% and 43.6%, respectively. The average solar fractions were 66.7% for SD and 44.6% for SAHPD. The coefficient of performance of the heat pump ranged from 3.23 to 3.47, with an average of 3.38.

Vlachos *et al.,* (2002) designed and tested a novel low cost tray dryer equipped with a solar air collector, a heat storage cabinet and a solar chimney. The developed dryer is easy to fabricate and operate and can be put into operation at low cost. (Fig.13) Measurements of total solar radiation on a horizontal plane, ambient temperature and ambient humidity, air speed, temperature and RH inside the dryer as well as moisture loss-in-weight data were measured to study the performance of the dryer.

Figure.12 Solar-assisted heat pump dryer (SAHPD)

No load and full load experiments were carried out without and with drying material on the trays respectively. Drying was also tested during night operation and under adverse weather conditions.

For all the employed conditions, the material gets completely dehydrated at a satisfactory rate and with an encouraging system's efficiency. Fairly promising results were obtained regarding the solar dryer's efficiency.

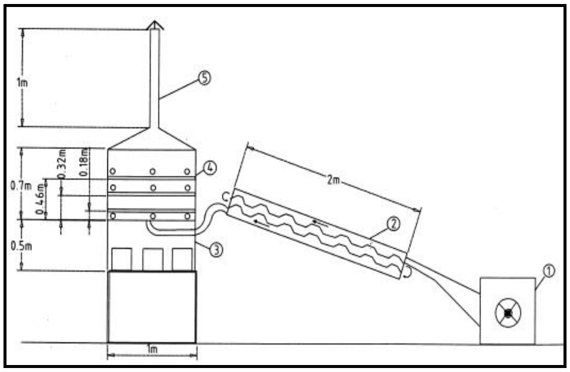


Figure.13 An outlay of the solar dryer (1. Centrifugal fan, 2. Solar collector, 3. Storage cabinet, 4. Drying chamber, 5. Solar chimney) The two corrugated sheets in the solar collector with the characteristic "reverse Z" air flow path as well as the relative position of the three drawers in the drying chamber

Singh *et al.,* (2004) developed a multi-shelf design with intermediate heating, passive, integral, direct/indirect and portable solar dryer at farm itself. (Fig.14) Intermediate heating of air in-between trays results in uniform drying in all the trays.

A novel feature of this dryer is that the product can be dried under shade or otherwise as per requirement. The maximum stagnation temperature was 75°C in November at Ludhiana (31°N). During experiments on drying of fenugreek leaves the moisture evaporation on first, second and third drying day was 1.4, 0.9 and 0.4 kg/m² of aperture area.

To overcome the problem of reduction in efficiency on second and third drying day, a semi-continuous mode of loading has been investigated, in which the efficiency remains almost the same on all drying days. The shelf life of the dried product is more than one year.

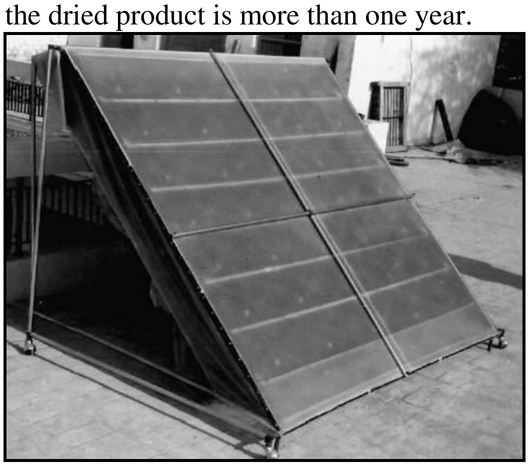


Figure.14 PAU Portable farm solar dryer

Mohanraj and Chandrasekar (2009) developed an indirect forced convection solar drier (Fig.15) integrated with different sensible heat storage material and tested its performance for drying chilli under the metrological conditions of Pollachi, India. The system consists of a flat plate solar air heater (2×1) m² with heat storage unit, a drying chamber with width, depth and height of (1×1×1.5) respectively and a centrifugal blower. Drying experiments had been performed at an air flow rate of 0.25 kg/s. Drying of 50 kg of chillies in a forced convection solar drier reduced the moisture content from around 72.8% (w.b.) to 9.1% in 24h. Average drier efficiency was estimated to be about 21%. The specific moisture extraction rate was estimated to be about 0.87 kg/kWh.

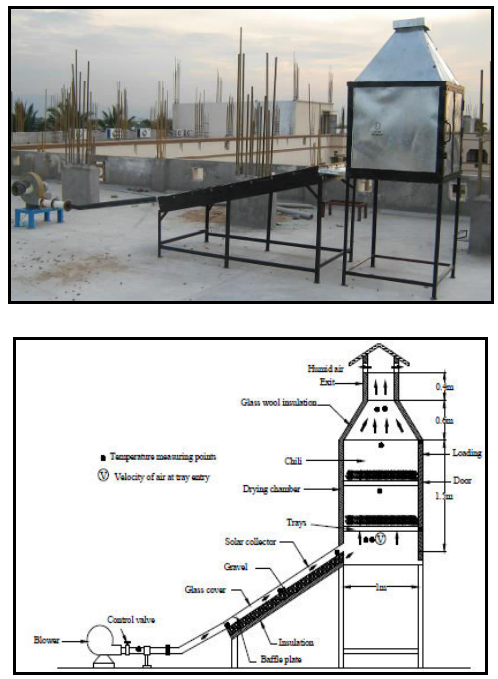


Figure.15 Indirect forced convection solar drier

Fudholi *et al.,* (2011) designed and tested forced convection solar drying system for drying kinetics of seaweed at Malaysia. The main components of the system (Fig.16) are double-pass solar collector array with finned absorber (1.2m × 4.8m), the blower, the auxiliary heater and the drying chamber (4.8 m L, 1 m W and 0.6 m H) having a capacity of 150 to 200 kg.

The double-pass finned collector efficiency is about of 38-78%. The initial and final moisture content were 94.6% (w.b.) and 10% (w.b.) respectively. The drying time is about of 7 hours at average solar radiation of about 600 W/m² and air flow rate 0.0613kg/s.

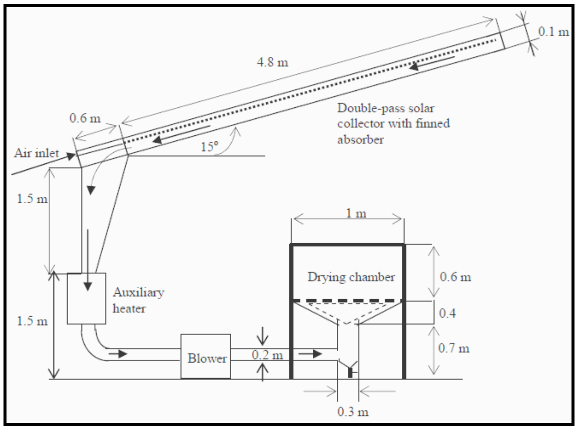


Figure.16 Forced convection solar drying system

Chavda and Kumar (2008) wrote an article on solar drying of agro products. In the article, they have covered the various solar drying systems for amla, ayurvedic churnas, tomato, mushroom, which was designed and developed at Sardar Patel Renewable Energy Research Institute (SPRERI). The institute concentrated its work on forced circulation solar drying system and developed its first system in its campus in 1994. This system consists of solar air heaters, drying chamber, blower, ducting, controls and thermal back up (optional). Solar air heaters are flat plate collectors or packed bed collectors or unglazed collectors that can be installed on the ground, roof etc.

An electrical blower of adequate capacity is used to circulate air in the solar air heater. The blower is usually connected between collector and dryer so that the collector works under slight negative pressure to minimize the effect of any minor leaks. Different types of dryers can be connected to solar air heaters. Tray dryer, continuous dryer, tunnel dryer, etc. are some of the types to which solar air heater can be integrated. Air duct designed to match the different components of the solar drying system and maintain desired flow rate is another critical component. Line diagram of a typical forced circulation solar drying system is shown in Fig.17.

Philip and Chavda (2003) designed and developed a solar hot air dryer (Fig.18) for drying of 100 kg fresh onion flakes (moisture content decreased from 80% to 8% w.b.) in approximately four hours. The system consisting of solar air heaters (36 nos. × 2 m² = 72 m²), an electric blower, drying chamber, ducting, controls and thermal back-up of 9 kW heater was developed. Dampers provided enabled mixing of cold air with hot air to obtain desired temperature. During no-load test, solar radiation from 600 to 950 W/m² and air heater outlet temperatures varied from 70°C to 90°C during the experiment. Dryer inlet and outlet temperatures varied from 64°C to 87°C and 60°C to 83°C, respectively.

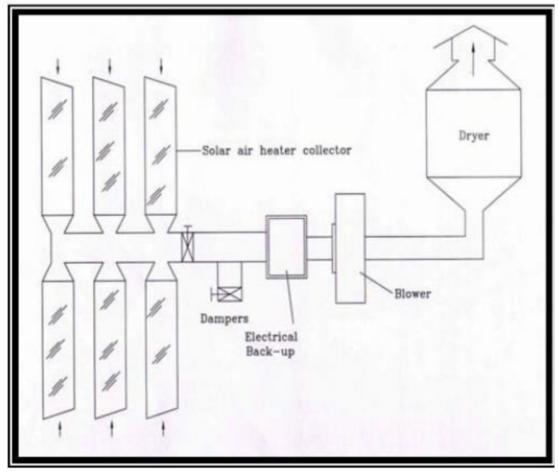


Figure.17 Line diagram of indirect type FCSD system

During full-load test, maximum solar radiation and maximum ambient temperature were 900 W/m² and 41°C, respectively at about 1 p.m. Average air heater outlet temperature was around 85°C. Dryer inlet and outlet temperatures were about 75° and 45°C, respectively. The system dried two batches of onion on a good sunny day. During the experiments, the electrical back-up was not used for air heating. Dryer outlet temperature increased as the product gradually got dried. After conducting extensive testing on onion drying, the system was used to dry a number of other agro products like potato chips, ginger, mango, mushroom, chilly, dates, curry leaves, mint leaves, spinach, sapota, etc. This system is suitable for drying of various agro products and chemicals at temperature varying between of 55°C to 75°C in all regions having bright sunshine for about 250 days in a year. Cost economics is highly in favour of solar drying if it replaces electricity, LDO and similar fuels.

Figure.18 Indirect forced circulation solar drying system for 100 kg onion

Chavda and Kumar (2008) A solar hot air dryer (Fig.19) to dry 60 kg of fresh sliced amla in about 7h duration was designed and installed at SPRERI. The system consisted of 32 m² of glazed air heaters, a two horsepower electric blower, tray dryer with 24 trays, electrical heater as backup and ducts and controls. Blower capacity identification depends on the product to be dried, air heating collector connection, temperature required to dry the product, type of air heating unit and pressure drop. In this case, a higher capacity blower was installed so as to meet the requirement of future up-gradation of the drying system by increasing the no. of air heating unit. Figure 7 is the photograph of the system. The outlet air temperature of the solar air heater varied from 55 to 70°C and the dryer inside temperature varied from 50 to 65°C depending on the solar radiation and state of drying. The system could dry a batch of 60 kg fresh sliced amla in a day. The electrical backup was used only when the product was not fully dried by the evening. This system was used to dry many other products also.

Figure.19 Solar air heating unit for drying system

Chavda and Kumar (2009) designed and developed an indirect, forced convection solar cabinet dryer (Fig.20) with LPG back up for tomato drying by SPRERI. A 60 m² packed bed solar collector was used to capture the solar radiation for heating the drying ari during the daytime, while a LPG burner was used to supply heat when enough solar energy was not available to get the desired drying temperature.

Figure.20 Packed bed solar air heaters and drying chamber of indirect forced convection solar cabinet dryer with LPG back up for tomato drying

The heat generated from the LPG burner was supplied to the incoming air through a heat exchanger. The temperature inside the drying chamber could be maintained around 80°C for 9 h. This dryer is by no means limited to drying of the tomato. Currently, seven dryers of similar design have been used by farmer and industrial groups in Gujarat and Maharashtra states for drying ayurvedic medicines, mushroom, handmade paperm wooden planks, aonla and other products.

Chavda and Kumar (2009) SPRERI designed roof integrated glazed and unglazed solar dryer (Fig.21), for a government entrepreneur, who was engaged in processing and manufacturing of the ayurvedic medicinal powder and herbs. The system consisting of 18m² of glazed flat plate and 40 m² unglazed solar air heaters, a two horsepower blower and a tray dryer capable of loading 100 kg of ayurvedic product per batch. A batch could be dried in about six to eight hour in a day. Figure 5 and 6 show the solar dryer for ayurvedic product to which an electrical based thermal backup was integrated. Its efficiency and pricing comes in the middle of above two models of the systems. The payback period for the system is around three years.

Figure.21 Roof integrated glazed and unglazed solar dryer for ayurvedic medicinal powder and herbs oyster mushroom

Chavda and Kumar (2009) Roof integrated unglazed solar air heater based solar dryer (Fig.22) has been installed at the industry in village: Itola in Vadodara district.

This firm, M/s Mashika Agritech Pvt. Ltd. grows Oyster Mushrooms on a commercial basis. The system consists of 80 m² roof integrated unglazed solar air heater, electrical back up, drying chamber (75 kg), ducting and other controls and safety devices.

This type of dryer is suitable for low temperature drying products like mushroom and leafy vegetables. Though the efficiency is lower but the cost of fabrication and installation is also lower and payback period is also less than 2 years. Total temperature gain of 10 to 15°C could be achieved.

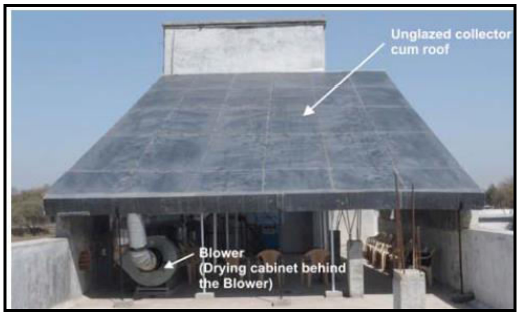


Figure.22 Roof integrated unglazed solar dryer for oyster mushroom

Chavda and Tilak (2013) wrote an article on solar tunnel dryer for amla. SPRERI designed and installed a modular, semi-continuous, indirect type, solar forced circulation tunnel dryer (Fig.23) for amla for a newly established agro industry.

It consists of air heating area, diversion unit and drying tunnel. In the system, the drying chamber was placed just below the air heating unit, facilitated with track for rolling the trays one by one.

The improved quality of finished products due to colour retention and low temperature drying can result in higher selling price of the product.

In order to dry amla candy and salted amla having about 80% moisture to 10% (w.b.), the developed system consisting of 20 m² of solar air heaters, tunnel type drying chamber of 100 kg capacity and exhaust fan was designed and developed. This system can be used for drying of different agro-industrial products except powder materials.

Figure.23 Indirect type solar forced circulation tunnel dryer for amla

Kumar *et al.,* (2008) designed, fabricated and tested a truncated pyramid-type solar cooker cum dryer so as to meet the requirements of local farming households (Fig.24). The truncated pyramid geometry concentrates the incident light radiations towards the bottom and the glazing glass surface on the top facilitates the trapping of energy inside the cooker.

One of the salient features of the proposed design is to completely eradicate the need for tracking the sun during cooking, as tracking of sun does not yield better performance. Cooking tests were carried out as per requirements of the BIS. During testing, the highest plate stagnation temperature, under no-load condition, approached 140°C and under full-load condition, water temperature inside the cooker reached 98.6°C in 70 min.

Two figures of merit, F_1 and F_2, were calculated and their values were 0.117°C.m²/W and 0.467°1, respectively, meeting the standards prescribed by the Bureau of Indian Standards for solar box-type cookers. Minor modifications in design are recommended to achieve higher temperatures and reduce cooking times. The design also allows trays to be retained for use as a household dryer. It was also found that tracking of the sun did not give better performances.

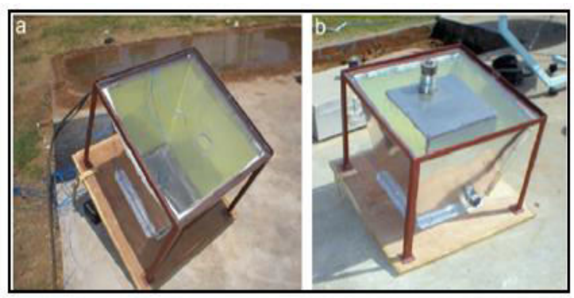


Figure.24 Just functional conceptual truncated pyramid dryer cum cooker realized by SPRERI:
(a) Truncated pyramid type solar cooker and
(b) truncated pyramid type solar dryer

Chavda *et al.,* (2017) designed and developed a shallow solar tunnel dryer of 21 m² at SPRERI. The system consisted of two parts, one for air heating and the other for loading agro-industrial products means drying unit.

The system had been designed in a modular fashion for easy scaling up. An intermediate zone called diversion unit was built between the heating and drying zones and this could be used to introduce a thermal backup for the dryer if it becomes necessary for a specific application. The system was designed to operate at a temperature of 50 to 60^{o}C. The payback period was less than two years. This system can be used in remote areas, far away from the main electricity or areas without reliable energy supplies or in farmers field itself due to grid independent operation of the system. The temperature rise inside the dryer was up to 67.4°C at noon. The thermal efficiency of the collector was 26.0%. A 26 kg of green chillies was dried in 15 h drying time (1.73 kg/h drying rate) from moisture content 87% to 10% w.b. In the other words, the samples were dried in the two days indicating drying rate of about half a kg of water per sq. m. area per day.

Figure.25 Shallow Solar tunnel dryer with Six DC fans and solar photovoltaic modules

Serm Janjai (2012) developed a greenhouse type solar dryer for small-scale dried food industries. The dryer consists of a parabolic roof structure covered with polycarbonate sheets on a concrete floor. The system is 8m W × 20m L and 3.5m H, with a loading capacity about 1,000kg of fruits or vegetables. A 100kW-LPG gas burner was used to supply hot air during cloudy or rainy days to ensure continuous drying operation. A 9 DC fans (15W) powered by 3 PV modules (50W) were used to ventilate the dryer. To investigate its performance, the dryer was used to dry 3 batches of tomato. Results showed that drying air temperatures varied from 35°C to 65°C. The drying time was 2-3 days shorter than the natural sun drying and good quality dried products were obtained.

Figure.26 Large-scale solar greenhouse dryer with LPG burner

Alonge and Jackson (2014) designed and preliminary tested an indirect forced convection solar dryer (Fig.27) to dry cassava (*Manihot spp*) chips and to study the effect of the enhanced airflow on the drying rate of the product. The system was constructed at a total cost of Rs.40,550. The calculated collector area is 0.32 m², fan ratings is 20 CFM; 24 VDC; 1.4 A. Photovoltaic Panel rating is 15 W, while battery rating is 24 VDC. At no load, maximum temperatures of 60°C and 48°C were obtained in the collector unit and drying cabinet respectively, when the ambient temperature was 35°C. Under load condition maximum temperatures of 57.5°C and 50°C were obtained in the collector unit and drying cabinet respectively, when the ambient temperature was 36.4°C. The dryer efficiency was calculated as 53.2%, the dryer capacity was 116.3g/hr and drying time was 10 h, as opposed to 2-3 days in natural convection solar dryers as reviewed in this work.

Figure.27 Indirect forced convection solar dryer to dry cassava chips

Padmanaban *et al.,* (2016) designed and developed a laboratory scale forced convection based solar dryer for drying Amla at Coimbatore. The solar dryer consists of a box type absorber and a drying chamber fitted with one blower. The north face of the dryer was kept insulated, and having door to load and unload material in trays. The experimental results show that reduction of drying time of amla was nearly 79% in comparison to open sun drying. The average time required to dry 1 kg amla from moisture content of 80% to 10.06% on wet basis was found to be 36 h whereas in open sun drying it takes 7 days to achieve the same drying rate.

Figure.28 Laboratory scale forced convection solar dryer for drying Amla

Hussein *et al.,* (2017) designed and tested a hybrid photovoltaic solar dryer (Fig.29) at Nigeria. The thin layer drying of tomato slices using a hybrid drying method compared to solar and open sun drying was investigated.

The dryer consists of solar collector, photovoltaic solar panel, battery and drying chamber. The dryer was operated as both a solar-energy dryer and as a hybrid solar dryer. The dryer recorded a raised temperature of 62°C and 54°C in the drying chamber of hybrid dryer and solar dryer respectively.

The moisture content was reduced from 94.22 % to 10 % w.b. in 6 h and 9 h for hybrid dryer and solar dryer respectively. The average drying rate and the efficiency was computed as 0.08kg/h and 71% for hybrid dryer and 0.06kg/h and 65% for solar dryer respectively.

The quality of the tomato dried using the hybrid dryer was superior to those of solar and sun drying methods. From the result it shows that a hybrid solar dryer using PV solar panel suggested a promising process for adoption to preserve tomato which can prevent it from spoilage and post-harvest losses.

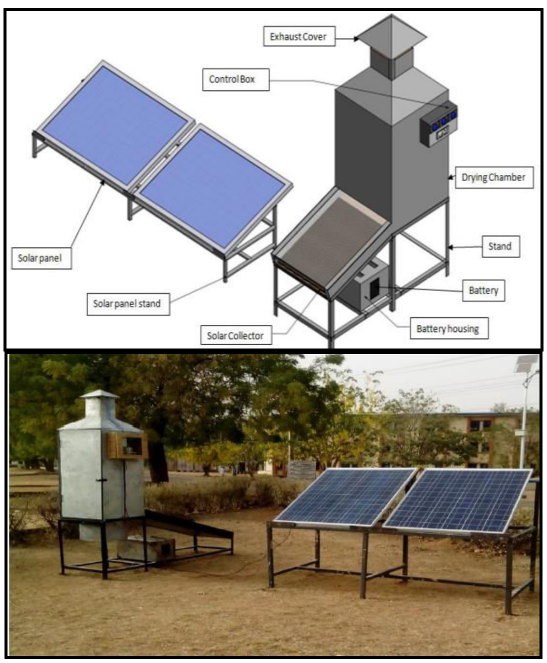


Figure.29 Hybrid photovoltaic solar dryer for tomato drying

Shrivastava *et al.,* (2017) examined the kinetics of fenugreek drying on different trays of an indirect solar dryer (Fig.30). For this purpose, a thin layer of 2 kg of fenugreek was placed on three trays (0.7 m × 0.7 m), to be further dried until there is no variation in its mass. The diffusion coefficient of fenugreek on different trays was also investigated and found in the range of 2.422 × 10^{-8} m^2/s to 3.872 × 10^{-8} m^2/s. An average efficiency of the dryer in peak hours on the first and second days of drying was 38.63% and 7.56%, respectively.

Figure.30 Indirect solar dryer for fenugreek drying

Komolafe and Waheed (2018) designed a 10 kg capacity forced convection solar dryer integrated with thermal energy storage materials for drying agricultural products. The dryer (Fig.31) consists of an insulated solar collector (2.1m × 1.1m), drying chamber, 30W capacity axial fan and photovoltaic components includes of one 200W solar panel, a charge controller, an inverter and 200AH battery.

The maximum collector and drying chamber temperatures obtained from three experiments at no-load conditions with two different thermal and without thermal energy storage materials were 86.2, 91.3 and 80.3°C; and 67.8, 70.8 and 54°C respectively, at the corresponding maximum solar radiations of 716.5, 810 and 724.7 W/m². A full load drying process using cocoa beans with TSMA took two full days, 10 hrs (58 hrs) to reduce initial moisture content of cocoa beans from 0.6 to 0.034 g water/g w.b. The maximum drying temperature and thermal efficiency obtained were 54°C and 48.8% respectively. The dryer was thus viable for drying products within short time with little temperature control mechanism.

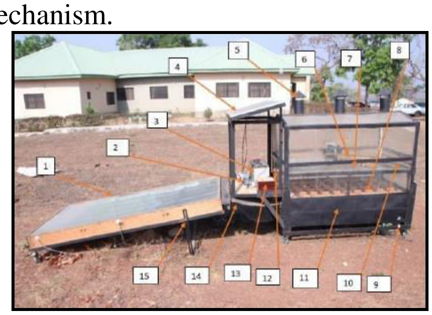


Figure.31 Forced convection solar dryer integrated with thermal energy storage (1. Solar collector box; 2. Charge controller; 3. Battery; 4. Solar cell; 5. Chimney; 6. Stirrer; 7. Drying tray; 8. Thermal storage material; 9. Supporting frame; 10. Drying chamber; 11. Plenum chamber; 12. Thermostat; 13. Stirrer control box; 14. Air duct with blower; 15. Collector box supporting hanger)

A similar an indirect forced convection solar dryer with cocoa beans was developed and conducted a thermal performance by Koua *et al.,* (2018). The dryer (Fig.32) consists of a solar collector, a drying chamber, 2 fans, 2 PV panels and storage battery. Air temperature inside the solar collector increased of 22.1°C with respect to the ambient air temperature. The average solar flux on the collector was 644 W/m². The thermal efficiency of the solar collector varied between 34.9% and 43.4%. The thermal drying efficiency of the indirect solar dryer varied between 14.5% and 20.2%.

Figure.32 Indirect forced convection solar dryer for cocoa beans

Tabassum (2019) developed two types of solar dryer viz. low and high cost solar dryer for small production and large production respectively. The dimension of the low cost dryer for 1 kg cabbage drying in 6 h (Fig.33) is 0.91m L × 0.76m W × 0.61m H with tilted transparent top. The average drying rate for the dryer was 0.428 kg/hr as against 0.300 kg/hr for open sun drying. A direct mode natural convection high cost solar dryer consists of three main parts: solar collector cum drying chamber (1.52m L×1.89m W × 0.91m tilted height), drying trays and outlet chimney. A 500g carrot was dried with initial 86.41% moisture to 1.24% within 5h. The experiments were conducted to dry vegetables and fishes. Microbiological and nutritional values ensure a superior quality of the dried product also. The high cost solar dryer can dry 5 kg carrot or potato within a day.

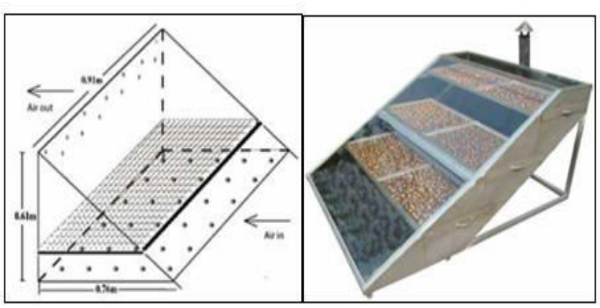


Figure.33 Low and high cost solar dryer for small and large production respectively

Aggarwal *et al.,* (2010) developed an indirect solar drier with solar cell for drying 25 kg of various hill crops (*Punica granatum* L, Ginger, Turmeric and Red chili). The system (Fig.34) consists of solar collector (2.4 m²) and drying chamber with dimension of 1.1 m × 0.7 m × 1.0 m has three removable trays. The bulbs are provided in the solar collector for air heating during clouds and evening and morning for faster drying and reducing drying time. Above mentioned hill crops had been dried in open sun, oven and solar drier for quality comparison. The cost of dried product has been found to be in the range of Rs.5 to Rs.6 per kg.

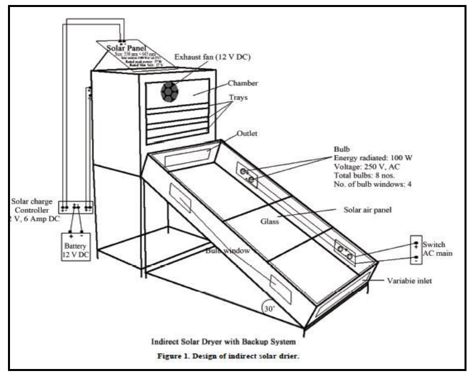


Figure.34 Indirect solar dryer with electric bulb as backup system

Veeramanipriya and Sundari (2019) studied the drying kinetics of forced convection solar dryer (Fig.35) aided with evacuated tube collector for chemically untreated red apple under the climatic conditions of Thanjavur, India. The outlet temperature of evacuated tube collector (59-108°C) was found to be much greater than the ambient temperature (33.5-35.5°C). This enhances the rate of drying in the evacuated tube collector based solar dryer. It takes 5h for apple to reach the equilibrium moisture content whereas it takes 8h for natural sun drying. The efficiency of the solar dryer for drying apple slices is found to be 16.05%.The quality of the dried sample is observed to be better. The use of conventional fuel is minimized and the dryer is found to be eco-friendly.

Khan *et al.,* (2020) developed a cabinet type solar dryer (Fig.36) having a base of 63.5cm × 134cm with the capacity of 5 kg ginger at Kota. Temperature variations at various sections in the device were measured on a number of days. The solar dryer, fabricated with locally available materials (plywood, G.I. sheet, polystyrene sheet) was an economically affordable system.

Figure.35 Evacuated tube collector based forced convection indirect solar dryer

The thermal efficiency of a full load system was found to be 29.1%. An experimental study showed that, on the first day, 45% of moisture was removed in the dryer while only 7.06% moisture was removed in open sun drying. The maximum drying rate was recorded on the first day of full load conditions i.e.0.318 kg/h.

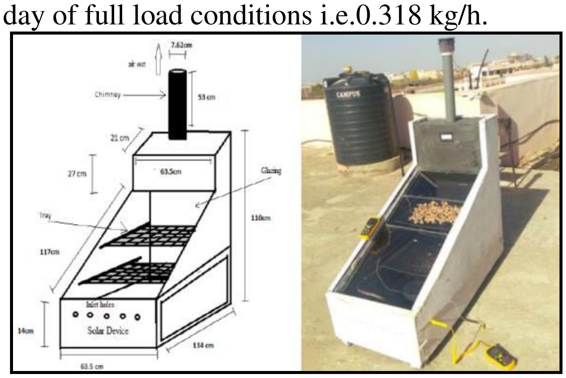


Figure.36 Cabinet type solar dryer for 5 kg ginger

A study was conducted by Arun *et al.,* (2020) to determine the user flexibility to choose among different agro-products and simultaneously ensure the drying uniformity inside an active multi-tray indirect-mode solar cabinet dryer (Fig.37) (MTISCD). Drying uniformity and flexibility in product selection is the primary concern for the end-user in solar drying application.

The MTISCD is made of stainless steel and can hold up to a maximum of 20 kg. The work considered unripe untreated banana and bitter gourd with IMC of 64% (wb) and 93% (wb), respectively.

The present work tries to assess the influence of a tray-sequencing pattern on the drying behaviour at different combinations of flake thickness (0.002-0.004 m), multi-tray spacing (0.1-0.15 m), tray mesh size (0.01-0.015m), and mass flow rate (0.015-0.03kg/s).

For all the tested combinations, the proposed peculiar tray sequencing aided to achieve drying uniformity for banana flakes within 10 h and bitter gourd by 18 h. Energy utilization ratio (45.3%-47.9%) decreased with an increase in mass flow rate. Among the tested combination, 0.03 kg/s, 0.002 m thickness, 0.15 m spacing, and 0.01 m mesh size resulted in higher average energy efficiency (15.34%).

Table.3 Tray sequencing pattern used for drying banana flakes and bitter gourd slices inside MTISCD (T stands for tray)

Time (Hrs.)	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5
08:00	T1	T2	T3	T4	T5
10:00	T1	T2	T3	T4	T5
12:00	T2	T1	T3	T4	T5
14:00	T3	T4	T5	T2	T1
16:00	T4	T5	T3	T2	T1

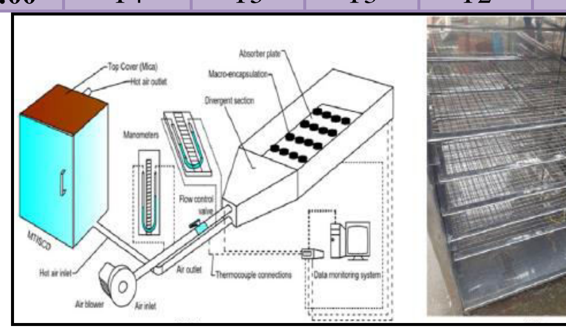


Figure.37 Multi-tray indirect-mode solar cabinet dryer (MTISCD)

An experimental study was performed by Suherman *et al.,* (2020) on hybrid solar dryer (Fig.38) combined with LPG as an auxiliary heater for cassava starch to support the drying process. It was found that from three temperatures (40, 50 and 60°C) used, only drying at 60°C that met the requirements of cassava starch's safe moisture content limit. It is found that higher temperature will lead to faster and more effective drying. The fastest moisture reduction occurred at the first tray, followed by the second and the third tray. The value of drying rate was found to be high at high level of moisture content, then gradually decreased as moisture content decreased. The drying process of cassava starch mostly happens in the falling rate period. From comparison with open sun drying, hybrid solar dryer was found to be more effective; with the highest effectivity factor value recorded was 6.4 at 11:00 am.

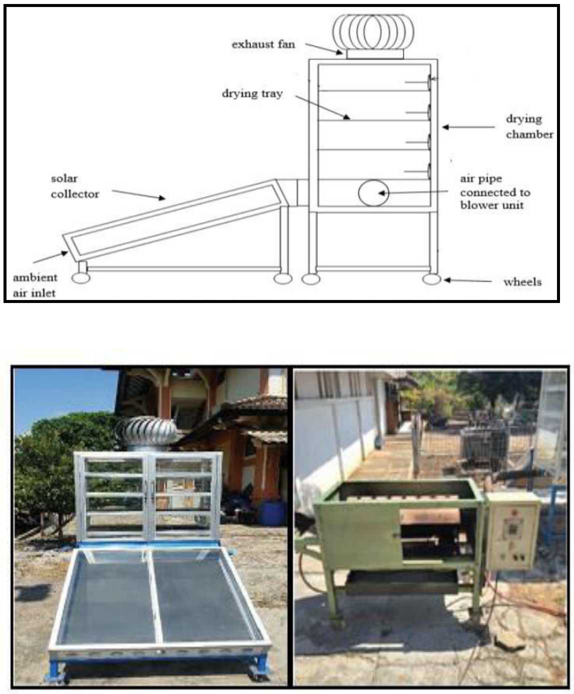


Figure.38 Hybrid solar dryer with blower-burner unit

The solar tunnel dryer (STD) (Fig.39) was evaluated with and without load condition for Keshuda flowers (*Butea monosperma*) in winter and summer seasons and its economic evaluation was calculated by Sengar *et al.,* (2022). During winter and summer season, the maximum temperature inside STD was 50-54°C and 51-59°C at 2 p.m. and at the same time solar intensity was around 850 W/m² and 960 W/m², ambient temperature was around 34°C and 38°C, and inside relative humidity was around 30% and 12% during no load test respectively. It is observed that the drying time of Keshuda flowers required 15 h inside the dryer as compared to 27 h in open sun drying method in winter. In summer, Keshuda flowers required 13 h inside the dryer as compared to 21 h in open sun drying method to reduce moisture content up to 10% (w.b.) inside the dryer and in open sun drying. Collection efficiency and pick up efficiency of solar tunnel dryer was found as 59.37% and 16.62% respectively whereas system drying efficiency varies between 12.31-21.20%. The average 33.00% saving in time was observed using STD over open sun drying method. The Net present worth, payback period and Benefit-Cost ratio was found as ₹ 10,52,119/-, 6.2 months and 2.67 respectively.

Figure.39 Solar tunnel dryer for keshuda drying

Recommendations for future work

The solar drying system is an energy efficient technique in the drying processes. Many experimental studies reported the various methods used for drying of agro-horticultural products using solar dryer. Thus, the efforts have been taken to review to briefly discuss the recent research and development on solar and other types of dryer technologies for roselle (*Hibiscus sabdariffa* L.) drying and to review some important work carried out across the world. After reviewing the available research papers, solar, sun, electric oven, freeze, shade, microwave, cross flow, infrared and other drying technologies are available for drying of roselle leaves and calyces. Efforts also have been made to review the available solar dryer technologies, for drying of other agro-products. It is observed that among the different types of solar dryers, the indirect forced convection solar dryer may be highly suitable or superior (El-Sebaii *et al.,* 2012) for industrial, commercial and large scale applications due to its various important points like speed and quality of drying, easily incorporating back-up (LDO, LPG, PNG, electrical) unit, easily eliminating the tray reshuffling or stirring, scope of integrating with existing drying system and chamber (cabinet type, tunnel type, continues type, tray type, etc.), possibility of uniform drying, attached any types of solar air heating unit (roof-integrated, glazed, unglazed or both, PV-thermal), reduce drying area needed, reduces labour cost, good controls and automation is possible, reduce the drying time, same drying is possible, it enhance both food value and marketability of dried food, large capacity drying is possible, stand alone technologies may be designed, on farm operation is possible without grid power. They are faster, safer and more efficient than traditional sun drying techniques. This may be helpful to generate the employment at village level as well as value addition in products. Based on very good ideas and concepts available in all research paper, an efficient and engineered indirect forced circulation solar dryer for roselle fruits and leaves drying by incorporating most of the above said advanced techniques may be planned to develop. This dryer may be useful for any of the agro-industrial products.

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Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

References

Aggarwal, R. K.; Sharma, M. M. and Sharma, A. K. (2010) Indirect Solar Drier with Electric Back up System for Quality Hill Products. *Natural Resources*, Vol.2010(1):88-94 https://doi.org/10.4236/nr.2010.12009

Alonge, A. F. and Jackson, N. I. (2014) Development of an indirect forced convection solar dryer for cassava chips. *Journal of Agricultural Engineering and Technology* (JAET), Vol.22(4):89-100.

Amoasah, B.; Appiah, F. and Kumah, P. (2018) Effects of Different Drying Methods on Proximate Composition of Three Accessions of Roselle (*Hibiscus sabdariffa*) Calyces *International Journal of Plant and Soil Science*, Vol.21(1):1-8. Article no.IJPSS.38550. https://doi.org/10.9734/IJPSS/2018/38550

Amoasah, B.; Appiah, F.; Tandoh, P. and Amoateng, E. (2019) Effect of Different Drying Methods on the Mineral Content of Three Accessions of Roselle (*Hibiscus sabdariffa*) Calyces. *Asian Journal of Advanced Research and Reports*, Vol.5(3):1-10. Article no. AJARR.48965 https://doi.org/10.9734/ajarr/2019/v5i330133

Arroyo, S. F., Inmaculada C. Rodríguez-Medina, RaúlBeltrán-Debón, Federica Pasini, Jorge Joven, Vicente Micol, Antonio Segura-Carretero, Alberto Fernández-Gutiérrez (2011) Quantification of the polyphenolic fraction and in vitro antioxidant and in vivo anti-hyperlipemic activities of *Hibiscus sabdariffa* aqueous extract, *Food Research International* 44:1490–1495. https://doi.org/10.1016/j.foodres.2011.03.040

Arun, K. R.; Kunal, G.; Srinivas, M.; Sujith Kumar C. S.; Mohanraj, M. and Jayaraj, S. (2020). Drying of untreated Musa nendra and Momordica charantia in a forced convection solar cabinet dryer with thermal storage. *Energy*. Vol.192(2020):1-13. Article no. 116697 https://doi.org/10.1016/j.energy.2019.116697

Ashaye, O. A. (2013). Studies on moisture sorption isotherm and nutritional properties of dried Roselle calyces. *Int. Food Res. J.*, Vol.20(1):509-513.

Babalola, S. O., Babalola, A. O. and Aworth, O. C. (2001). Compositional attributes of the calyces of Roselle. *J. Food Technol. Afr.*, Vol.6(4):133-134. https://doi.org/10.4314/jfta.v6i4.19306

Chavda, T. V. and Kumar, N. (2008) "Solar Drying of Agro Products" Published in IREDA NEWS. Vol.5(2,3 and 4):44-48. April – December, 2008.

Chavda, T. V. and Rathore, N. S. (2017) Book on "An Engineered Prototype Solar Dryer for Rose Petal – Value addition through drying on commercial scale" Publisher: LAP LAMBERT Academic Publishing. [ISBN: 978-3-330-34465-5]

Chavda, T. V., Kumar, N., (2009). Solar dryers for high value agro products at SPRERI. Proceedings of the *International Solar Food Processing Conference*.

Chavda, T. V., Prem Singh, Sagar Agravat and Philip, S. K. (2017). "Design, development and demonstration of a Shallow solar tunnel dryer for non-electrified areas". *Journal of Applied and Natural Science,* Vol.9 (4): 2461-2468. https://doi.org/10.31018/JANS.V9I4.1554

Chavda and Tilak V. (2013) “Solar Tunnel Dryer for Amla” Processed Food Industry Vol.16(10): 25-26, August 2013. [ISSN No. 09721649]

Daniel, D. L., B. E. Barragan Huerta, I. Anaya Sosa, M. G. Vizcarra Mendoza (2012) Effect of fixed bed drying on the retention of phenolic compounds, anthocyanins and antioxidant activity of roselle (*Hibiscus sabdariffa* L.), *Industrial Crops and Products,* Vol.40:68– 276.

Denise Rubinho dos Santos Martins, Eliana Janet Sanjinez-Argandona, Nailene de Freitas Ortega, Vitor Garcia, Vinicius Soares de Oliveira and Claudia Cardoso (2020) Production and characterization of *Hibiscus sabdariffa* by spray dryer using different sprinkler nozzles and carrier agents. *Journal of Food Processing and Preservation*. Vol.44(23):14493-14499. https://doi.org/10.1111/jfpp.14493

Dominguez-Lopez, A., Remondetto, G. E. and Navarro-Galindo, S. (2008). Thermal kinetic degradation of anthocyanins in a roselle (*Hibiscus sabdariffa L. cv. ‘Criollo’*) infusion. *International Journal of Food Science and Technology*, Vol.43:322–325. https://doi.org/10.1111/J.1365-2621.2006.01439.X

El-Sebaii, A. A. and Shalaby, S. M. (2012) Solar drying of agricultural products: A review. *Renewable and Sustainable Energy Reviews*, Vol.16(2012):37-43. https://doi.org/10.1016/j.rser.2011.07.134

Fudholi, A.; Othman, M. Y.; Ruslan, M. H.; Yahya, M.; Zaharim A. and Sopian K. (2011) Design and testing of solar dryer for drying kinetics of seaweed in Malaysia. *Recent Researches in Geography, Geology, Energy, Environment and Biomedicine*, Vol.July 2011:119-124.

Gautam, R. D. (2004). Sorrel–A lesser-known source of medicinal soft drink and food in India. *Natural Product Radiance*, Vol.3(5):338-342.

Hahn, F., G. Hernandez, J. Hernandez, C. Perez and J. M. Vargas (2011). Optimization of Roselle drying time and drying quality. *Can. Biosyst. Eng.*, Vol.53:3.1-3.8.

Hanem, A. Abd Elghany, Zeinab A. El Swaify and Zeinab A. Abd Elhafez Asian (2022) Effect of different drying methods and storage time on quality of roselle calyxes (*Hibiscus sabdariffa L.*) plants. *Journal of Research in Medical and Pharmaceutical Sciences*, Vol.11(4):1-14.. https://doi.org/10.9734/ajrimps/2022/v11i430194

Hussein, J. B.; Hassan, M. A.; Kareem, S. A. and Filli, K. B, (2017) Design, Construction and Testing of a Hybrid Photovoltaic (PV) Solar Dryer. *International Journal of Engineering Research and Science* (IJOER). Vol.3(5):1-14. https://doi.org/10.25125/engineering-journal-IJOER-MAY-2017-4

Islam M M. (2019) Food and Medicinal Values of Roselle (*Hibiscus sabdariffa* L. Linne Malvaceae) Plant Parts: A Review. *Open Journal of Nutrition and Food Sciences* Vol.1(1):14-20.

Ismail, S. and M. I. Mohammed (2014). Roselle calyx (zoborodo) as a substitute to organic indicator (methyl orange), *Sci. Afr.,* Vol.13(1):99-102.

Jairaj, K. S.; Singh, S. P. and Srikant, K. (2009) A review of solar dryers developed for grape drying, *Solar Energy*, Vol.83:1698-1712. https://doi.org/10.1016/j.solener.2009.06.008

Janjai, S. (2012) A greenhouse type solar dryer for small-scale dried food industries: Development and dissemination, *International Journal of Energy and Environment* Vol.3(3):383-398.

Janjai, S. and Tung, P. (2005) Performance of a solar dryer using hot air from roof-integrated solar collectors for drying herbs and spices; *Renewable Energy*, Vol.30(14):2085-2095. https://doi.org/10.1016/j.renene.2005.02.006

Khan, M., Sengar, N. and Mahavar, S. (2020) Fabrication and testing of a low cost passive solar dryer. 18th *International Conference on Sustainable Energy Technologies* SET, 20-22 August 2019 held at Kuala Lumpur, Malaysia.pp.21-28.

Komolafe, C. A. and Waheed, M. A. (2018) Design and fabrication of a forced convection solar dryer integrated with heat storage materials. *Annales de Chimie Science des Matériaux*. Vol.42(1):22-39. https://doi.org/10.3166/acsm.42.22-39

Koua Kamenan Blaise, Koffi Ekoun Paul Magloire and Gbaha Prosper (2018) Thermal performance evaluation of an indirect solar dryer. *Instrumentation measure metrologie*, Vol.17-n° 1/2018:131-151. https://doi.org/10.3166/i2m.17.131-151

Kumar, N., Sagar Agravat, Tilak Chavda, H. N. Mistry (2008) “Design and development of efficient multipurpose domestic solar cookers/dryers” *International Journal of Renewable Energy*. Vol-33(10):2207-2211. [ISSN NO. 0960-1481]

Lalit M. Bal, SantoshSatya, S. N. Naik, Venkatesh Meda (2011) Review of solar dryers with latent heat storage systems for agricultural products, *Renewable and Sustainable Energy Reviews* Vol.15(2011):876–880. https://doi.org/10.1016/j.rser.2010.09.006

Langova, J., D. Jaisut, R. Thuwapanichayanan, C. Phowong, J. Stencl, D. Jovanovic, J. Fryc and V. Vlasek (2013). Modelling the moisture sorption isotherms of Roselle (*Hibiscus sabdariffa* L.) in the temperature range of 5–35°C. *Acta Univ. Agric. Silvic. Mendel. Brun.*, Vol.196(6):1769-1777. https://doi.org/10.11118/actaun201361061769

Lema A A, Nor H M, Kandaker M M, Nur F H N, Dogara A M. (2022) The Effects of Various Drying Techniques on Physicochemical and Nutritional Qualities of (*Hibiscus sabdariffa* L.) Roselle Calyx. *Plant science today*, Vol.X(X):1-8. (Early Ac-cess). https://doi.org/10.14719/pst.1796

Maskat M. Y., Lung. C. K., Momeny E. Khan. M. J. Siddiqui. S. A. (2014) Temperature and Feed Rate Effects Properties of Spray Dried *Hibiscus sabdariffa* Powder. *International Journal of Drug Development and Research*. Vol.6(4):28-34.

Meza-Jimenez, Jorge; Juan J. Ramı´rez-Ruiz, Guadalupe Luna-Solano, and Isaac Andrade-Gonz-alez (2009) Low-Cost Solar Thermodynamic Drying System for the Dehydration of Roselle (*Hibiscus sabdariffa* L.). *Drying Technology*, Vol.27:621–624.

Minh, N. P. (2020) Technical Parameters Affecting the Spray Drying of Roselle (*Hibiscus sabdariffa*) Powder *J Pure Appl Microbiol*. Vol.14(4):2407-2416. https://doi.org/10.22207/JPAM.14.4.18

Mohanraj, M. and Chandrasekar, P. (2009) Performance of a forced convection solar drier integrated with gravel as heat storage material for chili drying *Journal of Engineering Science and Technology*, Vol.4(3):305-314.

Padmanaban, G.; Palani, P. K. and Dharmalingam, S. (2016) Reaction of Developed Solar Dryer on Amla. *International Journal of Advanced Engineering Technology*. Vol.7(2):326-328.

Philip, S. K. and Chavda Tilak (2003) Technical bulletin on “Agro – industrial application of forced circulation solar dryer” Published by All India Coordinated Research Project on Renewable Sources of Energy for Agricultural and Agro-based Industries of Indian Council of Agricultural Research, New Delhi.

Plotto, A. 2007. Post-Production Management for Improved Market Access for Herbs and Spices. Post-harvest compendium. Edited by Mazaud, *et al.,* FAO.

Prenesti, E., Berto, S., Daniele, P. G., and Toso, S., (2007). Antioxidant power quantification of decoction and cold infusions of *Hibiscus sabdariffa* flowers. *Food Chemistry*, Vol.100:433–438. https://doi.org/10.1016/j.foodchem.2005.09.063

Saeed, I. E. (2010). Solar drying of Roselle (*Hibiscus sabdariffa* L.) Part II: effects of drying conditions on the drying constant and coefficients, and validation of the logarithmic model. *Agr. Eng. Int.*: *CIGR Ej.*, Vol.12:1-21.

Saeed, I. E., K. Sopian and Z. Abidin (2008). Drying characteristics of Roselle: study of two-term exponential model and drying parameters. *Agr. Eng. Int.: CIGR Ej.,* Vol.10:1-27.

Sandopu Sravan Kumar, Prabhakaran Manoj, Nandini P Shetty, Parvatam Giridhar (2015) Effect of different drying methods on chlorophyll, ascorbic acid and antioxidant compounds retention of leaves of *Hibiscus sabdariffa L. Jounrla of the Science of Food and Agriculture*, Vol.95(9):1812-1820. https://doi.org/10.1002/jsfa.6879

Sengar, S. H.; Chavda, T. V.; Alok Singh and Burbade, R. G. (2022) Solar drying of Butea monosperma (keshuda) flowers for herbal colour. *Indian Journal of Agroforestry*, Vol. 24(1):72-77.

Sharma, A., Chen, C. R., Nguyen Vu Lan, 2009, Solar Energy Drying Systems: A Review, *Renewable and Sustainable Energy Reviews*, Vol.13:1185-1210. https://doi.org/10.1016/j.rser.2008.08.015

Shrivastava, Vipin; Kumar, Anil and Baredar, Prashant (2017) Kinetics of fenugreek drying in an indirect solar dryer. *Heat Transfer Research*, Vol.48(9):787-797. https://doi.org/10.1615/HeatTransRes.2016011738

Singh, Sukhmeet; Parm Pal Singh, S. S. Dhaliwal (2004) A Multi-shelf portable solar dryer. *Renewable Energy*. Vol.29(2004):753–765. https://doi.org/10.1016/j.renene.2003.09.010

Sudarmayanti, Baiq Arie dan Yunus, M. (2011) Budidaya Tanaman Rosella (*Hisbiscus sabdariffa L.*) dan Keunggulannya, http://ntb.litbang.deptan.go.id/ind/index.php?option=com_contentandview=articleandid=412:budidaya-tanaman-rosella-hisbiscus-sabdariffa-l-dan keunggulannyaandcatid=53:artikelandItemid=49, May12th2011,10:36

Suherman Suherman, Evan Eduard Susanto, Asif Widodo Zardani and Nur Haniza Roviqoh Dewi (2020) Performance study of hybrid solar dryer for cassava starch. Conference Paper in AIP Conference Proceedings of 2nd International Conference on *Chemical Process and Product Engineering* (ICCPPE) 2197, 080003. https://doi.org/10.1063/1.5140943

Suherman, B. Fajar, H. Satriadi, O. Yuariski, R. S. Nugroho and A. Shobib (2012). Thin layer drying kinetics of Roselle. *Adv. J. Food Sci. Technol.*, Vol.4(1):51-55.

Tabassum, S., Bashar, M. S., Islam, M. S., Sharmin, A., Debnath, S. C., Parveen, S., Khanom, S. A. A. and Khanam, M. (2019) Design and development of solar dryer for food preservation. *Bangladesh Journal of Scientific and Industrial Research*, Vol.54(2):155-160. https://doi.org/10.3329/bjsir.v54i2.41672

Tee, P., Yusof, S. and Mohamed, S. (2002) Antioxidative properties of roselle (*Hibiscus sabdariffa L.*) in linoleic acid model system, *Nutritionand Food Science*, Vol.32(1):17-20. https://doi.org/10.1108/00346650210413951

Tjukup Marnoto, Endang Sulistyowati, Budiyastuti, P., Sumarwoto, P S, M. Syahri, Bambang Sugiarto. Yusuf Hanafi, Girman, Kristianingrum. Drying of Rosella (*Hibiscus sabdariffa*) Flower Petals using Solar Dryer with Double Glass Cover Collector. *International Journal of Science and Engineering* (IJSE), Vol.7(2)2014:150-154 https://doi.org/10.12777/ijse.7.2.150-154

Tsai, Pi-Jen; McIntosh, John; Pearce, Philip; Blake Camden, Brian R. Jordan, (2002). Anthocyanin and antioxidant capacity in Roselle (*Hibiscus sabdariffa* L.) extract, *Food Research International,* Vol.35:351-355.

Veeramanipriya, E. and A R. Umayal Sundari (2019) Drying Kinetics of Forced Convection Solar Dryer for Fruit Drying. *International Journal of Innovative Technology and Exploring Engineering* (IJITEE), Vol.8(6):323-327.

Vlachos, N. A., T. D. Karapantsios, A. I. Balouktsis, and D. Chassapis (2002) Design and testing of a new solar tray dryer. *Drying Technology*, Vol.20(5):1239–1267. https://doi.org/10.1081/DRT-120004050

Yahya, M., Ahmad Fudholi, Hadyan Hafizh, Kamaruzzaman Sopian (2016) Comparison of solar dryer and solar-assisted heat pump dryer for cassava. *Solar Energy*, Vol.136(2016) :606–613. https://doi.org/10.1016/j.solener.2016.07.049

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