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Open Sun and Greenhouse Drying of Agricultural and Food Products: A Review

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***Abstract* - Due to high cost of fossil fuels and uncertainty regarding future cost and availability, use of sun drying of various agriculture products, vegetables, fruits, fish, milk products, food products etc. is being practised largely since ancient times for preservation of agriculture products. Despite many disadvantages of natural drying, almost 80 % of farmers are using open sun drying method for drying their crops. Open sun drying, in which the product is spread on ground in open, is the simplest and cheapest method of drying. But there are considerable losses associated with it. So, the advanced method of drying i.e. greenhouse drying can also be used for drying the products and improve the quality. In this paper, a comprehensive review of open sun drying and greenhouse drying of various products are presented.**

***Keywords: Open sun drying, greenhouse drying; Drying; Agricultural products; food products*.**

I INTRODUCTION

Drying is defined as a moisture removal process due to simultaneous heat and mass transfer [1]. It is a traditional method of food preservation, as fruits, vegetables, fish, grains, agricultural products etc [2]. Drying rate depends on external parameters (solar radiations, ambient temperature, wind velocity and relative humidity) and internal parameters (initial moisture content, type of crop, crop absorptivity, and mass of product per unit exposed area). Drying under open sun using the solar radiations for food preservation is practised since ancient times [3]**.** Drying involves a heat and mass transfer phenomenon in which heat energy supplied to the product surface is utilized in two ways: (i) to increase the product surface temperature in the form of sensible heat and (ii) to vaporize the moisture present in product through the provision of the latent heat of vaporization. The removal of moisture from the interior of the product takes place due to induced vapour pressure difference between the product and surrounding medium. The moisture from the interior diffuses to the product surface to replenish the evaporated surrounding moisture. The working principle of open sun drying is shown in figure 1.1 [4]. It is the oldest and most common traditional method to preserve agricultural products, grains, fruits, vegetables, fish etc. [5] in which products are spread on ground directly exposed to solar radiations. The solar radiations falling on the surface is partly reflected and partly absorbed. The absorbed radiations and surrounding air heat up the surface. A part of this heat is utilized to evaporate the moisture from the surface to the surrounding air. The part of this heat is lost through long wave length radiations to the atmosphere and through the conduction to the ground.

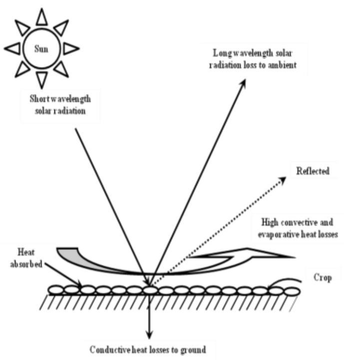

Figure 1.1 Working principle of open sun drying [4]

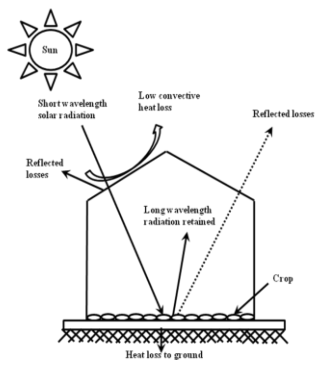

Figure 1.2 Working principle of greenhouse drying **[9]**

However considerable losses may occur due to dirt, dust, insects and microorganism, animals, birds. So the advance technique as greenhouse drying can be introduced in the developing countries to reduce the crop losses and increase the product quality significantly as compared to traditional method of open sun drying [6-9]. Whereas greenhouse is an enclosed structure having transparent walls and roofs, made up of glass, polyethylene film etc [9]. The working principle of greenhouse drying is shown in figure 1.2 in which the product is placed in trays receiving the solar radiations through the plastic cover and moisture is removed by natural convection or forced convection [7]. **Kumar [10]** have given the detailed classification of the greenhouse. Greenhouses are classified into different groups as shown in Figure 1.3. Different shapes of the greenhouse are shown in figure 1.4. Mostly even span and Quonset shape greenhouses are used.

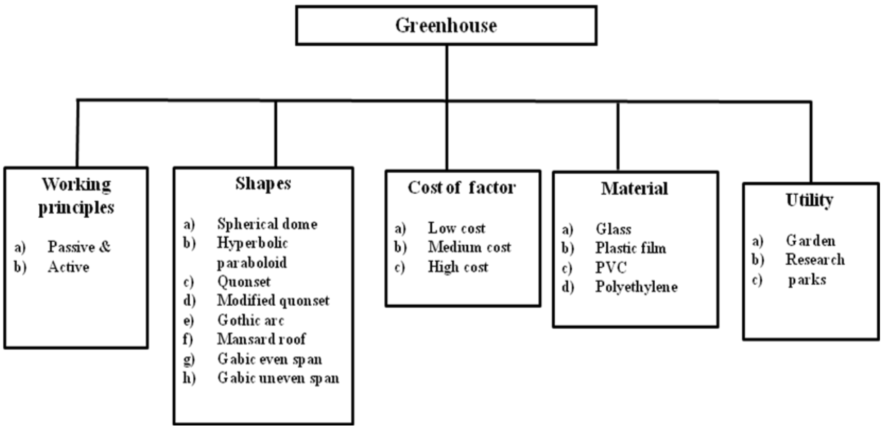

Figure 1.3 Classification of greenhouse based on different parameters [10]

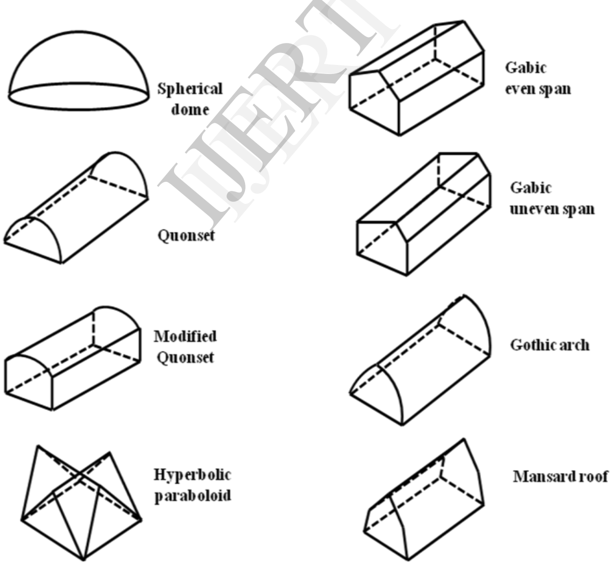

Figure 1.4 Classification of greenhouse based on different shapes **[10]**

In Indian economy, agriculture is an important sector which accounts for 14% of the nation's GDP, about 11% of its export and about half of the population relies on agriculture. During 2011-12, there was record production of food grains at 259.32 million tonnes [11]. Most of the agriculture products, grains, vegetables, fruits, fish etc. are traditionally solar dried for their preservation. But the losses of fruits and vegetables are estimated to be 30–40% during drying in the developing countries [1]. Thus, there is urgent requirement to develop new technique for drying the agriculture products in such a way that the losses can be minimized and the quality of the products can be improved. In this paper, the research carried out by different researchers on open sun drying and greenhouse drying technology used for drying various agricultural products have been reviewed.

II Research advancement on open sun dying of various products

Open sun drying is the simplest way of drying agricultural products, fruits, vegetables, food grains, fish, herbs, milk products etc. In this, the product is spread on ground in thin layer and directly exposed to solar radiations and dried up to the safe moisture content. The safe moisture content of different crops and fruits are given in table 2.1 [12-20] and table 2.2 [17] respectively.

Table 2.1: Moisture content details of various crops [12-20]

S. no.	Crop	Initial moisture content (% w.b.)	Final Moisture content (% w.b.)	Maximum allowable temperature (^{o}C)
1	Paddy, raw	22-24	11	50
2	Paddy, parboiled	30-35	13	50
3	Maize	35	15	60
4	Wheat	20	16	45
5	Corn	24	14	50
6	Rice	24	11	30
7	Pulses	20-22	9-10	40-60
8	Oil seed	20-25	7-9	40-60
9	Green peas	80	5	65
10	Cauliflower	80	6	65
11	Carrots	70	5	75
12	Green beans	70	5	75
13	Onions	80	4	55
14	Garlic	80	4	55
15	Cabbage	80	4	55
16	Sweet potatoes	75	7	75
17	Potatoes	75	13	75
18	Chillies	80	5	65
19	Apples	80	24	70
20	Apricot	85	18	65
21	Grapes	80	15-20	70
22	Bananas	80	15	70
23	Guavas	80	7	65
24	Okra	80	20	65
25	Pineapple	80	10	65
26	Tomatoes	96	10	60
27	Brinjal	95	6	60
28	Peanuts	40-55%	8-10%	
29	Tomatoes	95	7	60
30	Fig	70	20	70
31	Coffee	65	11	
32	Spinach	80	10	
33	ginger	80	10	
34	Turmeric	80	10	
35	Prunes	85	15	55
36	Peaches	85	18	65
37	Guavas	80	7	65
38	Mulberries	80	10	65
39	Yam	80	10	65
40	Nutmeg	80	20	65
41	Sorrel	80	20	65
42	Groundnuts	40	9	

Table 2.2: Initial moisture content of different fruits [17]

Fruits	Moisture content in dry basis
Apricots (non-pre-treated)	4.78
Apricots (sulphured with SO2)	4.00
Apricots (sulphured with NaHSO3)	5.67
Grapes	4.05
Peaches	6.29
Figs	2.29
Plums	3.55

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Anwar and Tiwari [21] studied the drying of six crops (green chillies, green peas, kabuli chana, onion, potato and cauliflower under open sun drying conditions as shown in **figure 2.1.** The schematic diagram of open sun drying is also shown in figure 2.2. Before experiments some treatments (size reduction, peeling and soaking with water in case of kabuli chana) were given to the crops. Kabuli chana were soaked in water for 6 hours to raise the moisture content up to 30% (w.b.). The convective heat transfer coefficients for different crops were found to vary from 3.71 to 25.98 W/m^{2o}C. **Jain and Tiwari [22]** studied the thermal behaviour of

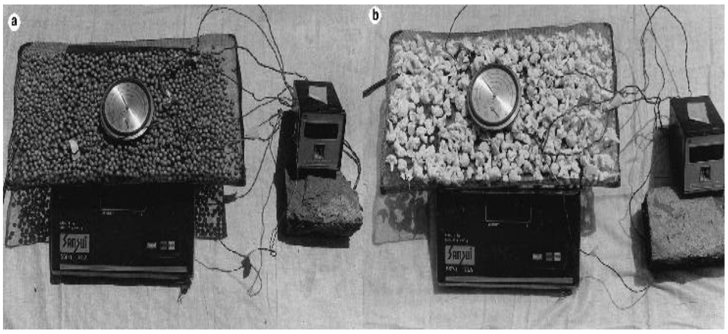

Figure 2.1 Experimental set up for open sun drying: (a) green peas, (b) cauliflower **[21]**

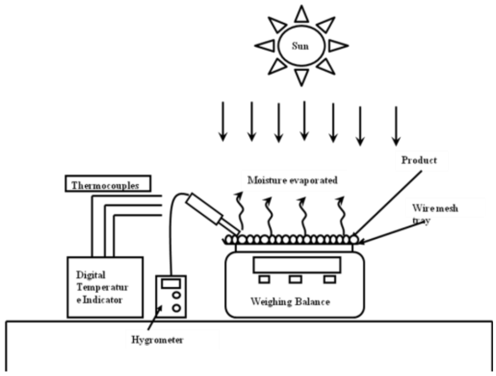

Figure 2.2 Schematic diagram of open sun drying

green chillies, green peas, white gram (kabuli chana), onion, potato and cauliflower under open sun drying condition. A mathematical model was also developed to predict to crop temperature, moisture removal rate and solair temperature. A fair agreement was observed between predicted and experimental results. They used the data of Anwar and Tiwari [21] as input for the determination of experimental constants (C and *n*) and convective heat transfer coefficients (h_c) for various crops. The predicted values of crop temperature, temperature above the crop surface and mass of the crop, by developed model, were found in fair agreement with the experimental values.

Drying of various products like marrow, aubergine, carrot, green bean, Albanian pepper, green pepper, potato, onion and pear **[23]**,

mulberry, strawberry, apple, garlic, potato, pumpkin, eggplant and onion **[24]**, corn kernels **[25]** have been studied under open sun drying mode.

Togrul and Pehlivan [17] investigated the drying behaviour of apricots pre-sulphured with SO_2 or $NaHSO_3$, grapes, peaches, figs and plums under open sun drying conditions. Twelve models were tested to fit drying rates of the fruits. All the fruits were dried from initial moisture content (table 2.2) to the final moisture content of 15–17% on a dry basis. **Togrul [26]** studied the drying of apricots and determined the convective heat transfer coefficient at different initial moisture contents for apricots subjected to various pretreatment. **Chong et al. [27]** investigated the drying kinetics different sizes (2.0cm×2.0cm, 2.0cm×3.0cm, and 3.0cm×3.0cm) of chiku (Manilkara zapota) and evaluated the effective diffusivities during the falling rate period and temperature period. **Doymaz [28]** investigated the drying behaviour of seeded and seedless grapes from initial moisture content of 78.2% and 79.5% (w.b.) respectively to final moisture content of 22% (w.b.) under open sun drying condition. Different drying models were used and Midilli et al. model was reported to be the best among other models.

Kumar et al. [29] carried out the study for evaluation of convective heat transfer coefficient for papad under open sun drying conditions and indoor forced convection drying mode**.** Papad was dried from initial moisture content of 27-30% per kg of papad weight to its optimum moisture level of 15%. The values of convective hat transfer coefficient for papad was found to be 3.54 W/m^{2o}C and 1.56 W/m^{2o}C under open sun drying condition and indoor forced convection drying mode respectively. **Sahdev et al. [30]** studied the drying of vermicelli of different diameters of 2mm and 1.25mm under open sun drying mode. Vermicelli was dried from initial moisture content of 27% to 30% per kg of vermicelli weight to its optimum storage moisture level of 9%. The average values of convective heat transfer coefficients under open sun drying conditions were found to be 5.61 W/m^{2o}C and 4.13 W/m^{2o}C for vermicelli of 2mm and 1.25mm respectively. It can be seen that the convective heat transfer coefficient strongly depends on the thickness of vermicelli.

Akpinar [31] studied the kinetics of parsley, mint and basil under open sun drying mode**.** Different mathematical models were used to fit the drying curve, among them Verma et al. model was reported to be the best descriptive model for parsley leaves. **Prashad [32]** studied the drying behaviour of *Tinospora cordifolia (Giloe), Curcuma longa L.(turmeric) and Zingiber officinale (Ginger)* in open sun drying condition. The model of Jain and Tiwari (2003) was used to predict the product temperature and moisture removal.

Jain [33] determined the convective heat and mass transfer coefficients of minor fish species like prawn (invertebrates) and chelwa (vertebrates) under open sun drying conditions at different drying times and moisture contents. **Jain and Pathare [34]** studied the drying behaviour of Prawn and chelwa fish under open sun drying mode. They used empirical models for describing the drying process. The initial moisture content of prawn and chelwa fish was observed as 3.621 and 2.676 kg water/kg dry matter respectively. Many researchers have worked relating the mathematical modelling and drying kinetic process of agricultural products to describe the thin layer drying characteristics such as mint [35-36], figs [36-37], banana [38], mango [39], okra [40], green beans [41], pistachio [42], black tea [43-44], rough rice [45], laurel leaves [46], prickly pear pell [47], prickly pear cladode [48], prickly pear fruit [49], golden apple [50], mulberry [51], olive leaves [52], cocoa beans [53], Amranth grains [54], red pepper [55], ginger [56].

Table 2.3: Analysis of open sun drying

S. No	Researcher/s	Year	Commodity	Remarks
1	Anwar and Kumar	2001	green chillies, green peas, kabuli chana, onion, potato and cauliflower	The values of convective heat transfer coefficient were reported to vary from 3.71 – 25.98 W/m^2°C.
2	Jain and Tiwari	2003	green chillies, green peas, kabuli chana, onion, potato and cauliflower	Studied thermal behaviour of various products
3	Togrul	2003	marrow, aubergine, carrot, green bean, Albanian pepper, green pepper, potato, onion and pear	The values of convective heat transfer coefficient were reported to vary from 0.252 – 3.3 W/m^2°C
4	Sahdev et al.	2013	Corn kernels	The value of convective heat transfer coefficient was reported to be 3.91 W/m^2°C and moisture content was controlled upto 16% m.c.
5	Togrul	2005	Apricot	The value of convective heat transfer coefficient was reported to vary from 1.045 – 2.046 W/m^2°C moisture content was maintained from 80%-82.7w.b. and 18.53%-29.81% w.b.)
6	Togrul and Pehlivan	2004	Apricots, grapes, peaches, figs and plums	Moisture content was maintained up to 15 – 17% d.b.
7	Chong et al.	2009	Chiku	Chiku was dried in 3 days.
8	Doymaz	2012	Seeded and seedless grapes	Moisture content maintained upto 22% (w.b.). The midilli et al. model was found to be the most suitable.
9	Akpinar	2006	mulberry, strawberry, apple, garlic, potato, pumpkin, eggplant and onion	The value of convective heat transfer coefficient was reported as 1.861, 6.691, 11.323, 1.136, 8.224, 8.224, 8.224 and 8.224 W/m^2°C for mulberry, strawberry, apple, garlic, potato, pumpkin, eggplant and onion respectively.
10	Prasad	2009	Tinospora cordifolia (Giloe), Curcuma longa L.(turmeric) and Zingiber officinale (Ginger)	The values of convective heat transfer coefficients were reported to vary from 1.57 – 3.89 W/m^2°C, 2.32 – 3.42 W/m^2°C and 1.62 – 3.34 W/m^2°C for Giloe, turmeric and ginger respectively.
11	Sahdev	2012	Vermicelli	The value of convective heat transfer coefficient was reported to be 5.61 and 4.13 W/m^2°C for vermicelli for diameter of 2mm and 1.25mm respectively.
12	Kumar et al.	2011	Papad	The values of convective heat transfer coefficient was reported to be 3.54 and 1.56 W/m^2°C under open sun drying condition and indoor forced convection drying mode respectively and moisture content was maintained till of 15%.
13	Jain	2006	Prawn and chelwa fish	The values of convective heat transfer coefficient were reported to be 0.472 – 9.929 W/m^2°C
14	Jain and Pathare	2007	Prawn and chelwa fish	Prawn took 2 days and chelwa fish took 3 days to dry.
15	Akpinar	2006a	Parsley, Mint and basil leaves	Modified Page (I) model and verma et al. model were found to be most suitable for mint and basil leaves and parsley leaves respectively.

Results of open sun drying behaviour of different commodities are summarized in table 2.3. From the literature it is found that the values of convective heat transfer coefficients vary significantly with the type of product. It is inferred that the rate of moisture transfer plays an important role in convective heat transfer. The drying process occurs during the falling rate drying period. It is observed that open sun drying of products takes long time for complete drying. It can even take two to three days or even more. Moreover, the qualities of dried products do not meet the international standards. Therefore, need is felt to introduce some advanced solar drying techniques.

III RESEARCH ADVANCEMENT ON GREENHOUSE DRYING

In developing countries, demand for dried agricultural products, vegetables, fruits, marine products, herbs and spices etc. have been increased [57]. Natural sun dried products are cheaper but the quality of these products is low and losses of fruits and vegetables during drying are estimated to be 30–40% of the production [1]. So, the advanced technique i.e. greenhouse drying under both natural and forced convection modes is being used to improve the product quality. In this section some prominent work carried out by different researcher on greenhouse drying of various agricultural and food products have been described. **Condori and Savavia [58]** presented evaporation rate in two different types of forced convection greenhouse dryers (single chamber and double chamber). Analysis of both driers was performed and performance parameter was defined to compare both systems. Two energy sources as air temperature and incident solar radiation were available for active greenhouse dryer. Two new concepts (i) the generalized drying curve and (ii) the dryer performance curve were proposed. Experiments were conducted on proposed dryer to dry sweet pepper Results showed that double chamber greenhouse dryer was 87% more productive than single chamber for the same area. **Manohar and Chandra [59]** presented the natural and forced convection solar greenhouse dryer for drying of rewetted mustard. Mustard was also dried in open sun for comparison purpose. A low cost forced convection tunnel greenhouse dryer (Figure 2.3) was designed, developed and tested on sweet pepper and garlic [60]. **Condori and Saravia [61]** proposed an analytical study of tunnel greenhouse dryer which was proposed by Condori et al. 2001. **Farhet et al. [62]** proposed polyethylene natural convection greenhouse dryer for drying of pepper and applied **Passamai and Saravia'a** model for drying of pepper. **Jain and Tiwari [63]** proposed a greenhouse drying under natural and forced modes to dry cabbage and peas. At the same time open sun drying of these crops were also studied as shown in figure 2.4a. The schematic diagram of natural convection greenhouse drying is shown in figure 2.4b. And experimental set up and schematic diagram of forced convection greenhouse drying is shown in figure 2.5a and 2.5b respectively. **Jain and Tiwari [64]** developed mathematical model to predict the crop temperature, greenhouse temperature and moisture evaporation for open sun drying and greenhouse drying under natural and forced convection of **cabbage and peas**. **Koyuncu [65]** designed and constructed two different types of natural circulation greenhouse dryer. The dryers were tested without load-without chimney, with load (pepper)-without chimney and with load (pepper)-with chimney. In addition, pepper was dried in open sun drying in order to compare the greenhouse dryers with open sun drying. **Sacilik et al. [66]** also investigated the thin layer drying characteristics of organic tomato in a solar tunnel dryer (Figure 2.6) and various mathematical models were used for thin layer drying behavior of organic tomatoes among them approximation of diffusion model was reported to be the most suitable. **Kumar and Tiwari [67]** investigated the drying behavior and effect of mass on convective heat transfer coefficient for **onion flakes** drying under open sun and greenhouse drying modes. Onion flakes were continuously dried for 33 h both in open sun and in roof type even span greenhouse with floor area of 1.2m×0.78m. It was observed that the convective heat transfer coefficient increased by 30–135% as the mass of the onion flakes was increased from 300 to 900 g for different drying modes. **Janjaia et al. [68]** studied the experimental performance of solar drying of rosella flower and chilli using roof integrated solar dryer (Figure 2.7). Field level experiments for deep bed drying of both (rosella and chilli) were performed. Significant reduction in drying time in roof integrated solar dryer as compared to sun drying was observed. **Sethi and Arora [69]** improved the conventional greenhouse solar dryer for faster drying using north wall reflection (INWR) under natural and forced convection mode. Experiments were performed on drying of bitter gourd (*Momordica charantia Linn*) under modified solar greenhouse dryer as well as in open sun drying mode. **Kadam et al. [70]** carried out the systematic study the drying of onion slices in Quonset shape low cost greenhouse (Figure 2.8). **Janjai et al. [71]** developed and tested at field level a large scale solar greenhouse dryer with a loading capacity of 1000 kg as shown in Figure 2.9. Shape of the dryer was parabolic and covered with polycarbonate sheets. The base of the greenhouse dryer was a black concrete floor with an area of 7.5×20.0 m^2. **Janjai [72]** developed a large scale greenhouse dryer with LPG burner and investigated its performance for drying osmotically dehydrated tomato. Solar drying of osmotically dehydrated tomato in solar greenhouse dryer resulted in considerable reduction in drying time as compared with the open air sun drying and the quality of the products dried in the solar greenhouse dryer were reported to be better as compared to the open air dried products. **Artesty and Wulandani [73]** studied the performance of rack type greenhouse effect solar dryer to dry wild ginger from its initial moisture content of 80% wb to 8-11% wb of final moisture content (Figure 2.10). Recently, **Fadhel et al. [74]** studied and compared the thin layer drying characteristics of red pepper by three different solar drying processes (under open sun, greenhouse and solar drier). Different thin layer drying models were used and among them the Logarithmic model was found to be the most suitable model for describing the drying curve.

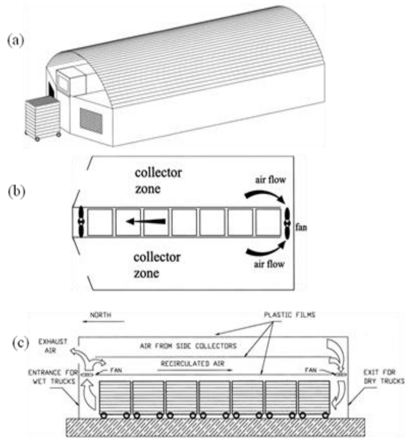

Figure 2.3: Face view (a), plant view (b), and operational scheme(c) of forced convection tunnel greenhouse dryer **[60]**

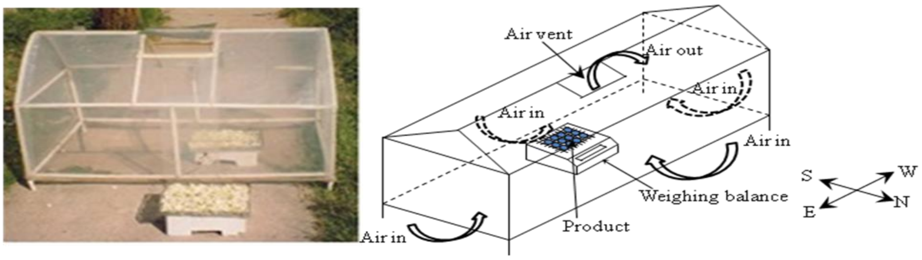

Figure 2.4 Experimental set up of open sun and natural convection greenhouse drying and schematic diagram of greenhouse drying with natural convection drying mode [63].

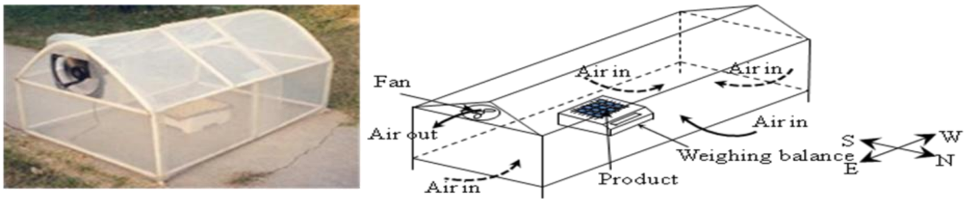

Figure 2.5 Experimental set up and schematic diagram of forced convection greenhouse drying [63].

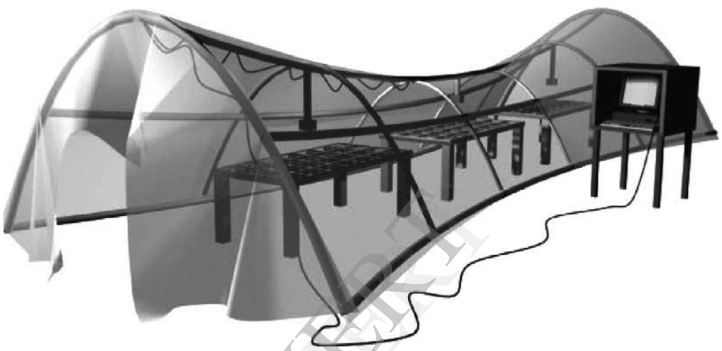

Figure 2.6: Schematic diagram of solar tunnel dryer [66])

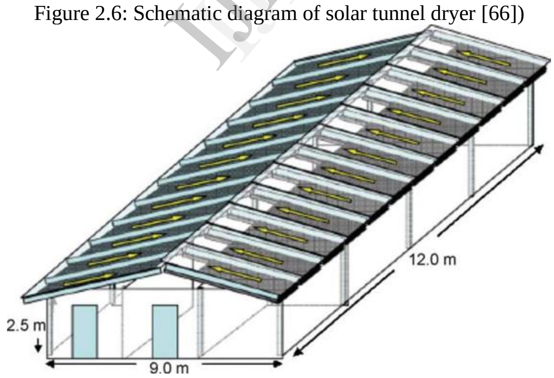

Figure 2.7: Illustration of Roof integrated solar drying system **[68]**

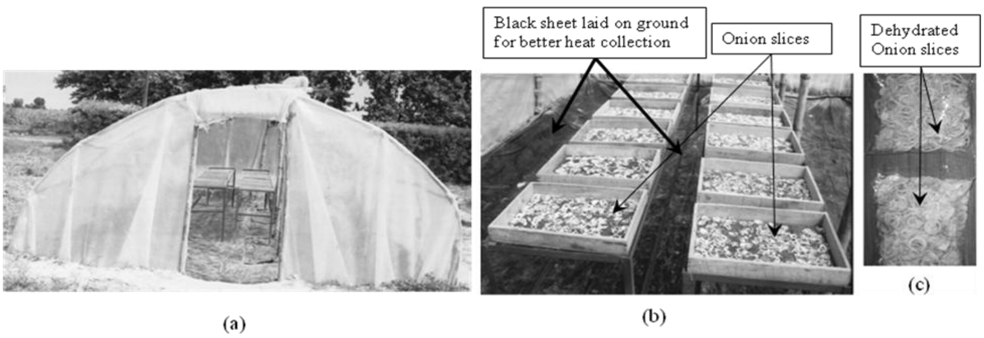

Figure 2.8: Quonset shape low cost greenhouse for drying of onion slices (a); Onion slices drying in trays (b); and dehydrated onion slices packed in polypropylene (c) **[70].**

Figure 2.9: solar greenhouse dryer of loading capacity of 1000kg **[71]**

Figure 2.10 Rack type greenhouse solar dryer **[73]**

Fadhel et al. [75] investigated the drying behaviour of **Sultanine grape** variety under three different solar grapes drying processes i.e. open sun drying, natural convection solar dryer and solar tunnel greenhouse drying mode. **Ergunes et al. [76]** presented two different drying methods (greenhouse dryer and open sun drying) for drying of plums and recommended the greenhouse solar dryer for successful prune production in rural areas. **Elicin and Sacikik** [77] also studied the drying kinetics of organic apples in a solar tunnel dryer for dehydration of apples. **Rathore et al. [78]** presented a hemi-cylindrical shaped walk-in type tunnel dryer to dry one ton of amla pulp. **Barnwal and Tiwari [79]** designed and developed a hybrid photovoltaic-thermal (PV/T) self greenhouse dryer (Figure 2.11) of 100 kg capacity to dry **Thompson seedless grapes** (Mutant: Sonaka). **Janaji et al. [80]** presented the experimental and simulated performance of a PV-ventilated solar greenhouse dryer for drying of peeled logan and banana. **Rathore and Panwar [81]** presented a walk-in type hemi cylindrical solar tunnel dryer (STD) with heat protective north wall to dry seedless grapes (Figure 2.12). **Janjai et al. [82]** investigated the drying of litchi flesh in solar greenhouse dryer and developed a mathematical model for predicting the performance of litchi flesh. **Almuhanna [83]** attempted a new approach of utilizing a solar greenhouse (gable even span; Figure 2.13) as a solar air heater for drying dates.

Figure 2.11 Hybrid photovoltaic-thermal (PV/T) integrated greenhouse dryer
[79]

Figure 2.12: Solar tunnel dryer (with thermocouple positions) and inside view of tunnel dryer with grapes **[81]**

Figure 2.13: Solar greenhouse dryer, [83]

Tiwari et al. [84] evaluated the convective heat and mass transfer coefficients for **prawn** under natural convection greenhouse drying. The comparative study for drying of pork under open sun and solar greenhouse drying was carried out by **Boonyasri et al. [85].**

A new approach of papad drying under greenhouse has been reported by **Kumar [86]** and the behavior of heat and mass transfer during forced convection greenhouse drying of **papad** has been investigated by the author (Figure 2.14). Papad of 180 mm diameter and 0.7 mm thickness was prepared and papad of 23.5 g weight was taken for each run of drying. The average values of convective and evaporative heat transfer coefficients were reported as 0.759 W/m^{2o}C and 23.48 W/m^{2o}C respectively.

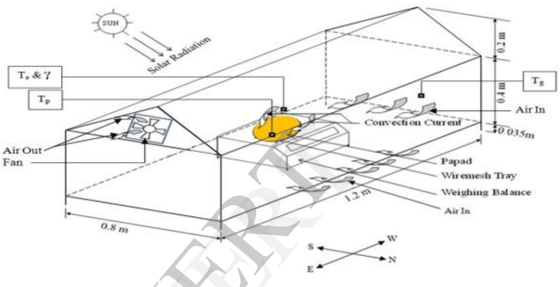

Figure 2.14 Schematic view for papad under forced convection greenhouse drying mode **[86]**

The convective heat and transfer coefficients for **jaggery** drying **(Tiwari et al. [87])** were calculated under natural and forced convection greenhouse drying. **Kumar and Tiwari [88]** studied the effect of various shapes and sizes of **Jaggery** for different mass (2.0 kg and 0.75 kg) on convective mass transfer coefficient. Sample size of 0.03×0.03×0.01 m^3, 0.03×0.03×0.02 m^3 and 0.03×0.03×0.03×m^3 as thin layers were used for the experimentation. Further the results were improved by **Prakash and Kumar [89]** by generating ANFIS (adaptive-network-based fuzzy inference system) to predict the jaggery temperature, the greenhouse air temperature and the moisture evaporation for drying of jaggery inside the greenhouse under natural convection mode. **Prakash and Kumar [90] also** presented ANN (artificial neural network) to predict the mass of the jaggery drying inside natural convection greenhouse drying condition.

Prakash and Kumar [91] also presented ANFIS model for the modified forced convection greenhouse during under no load condition. **Prakash and Kumar [92]** developed and tested a laboratory scale modified solar active (forced convection) greenhouse dryer with opaque northern wall. A comprehensive review of various designs, construction and operating principles of different solar drying systems have been described by **Prakash and Kumar [93].**

The convective heat transfer coefficients for khoa pieces (**Kumar et al. [94]**) were evaluated in a controlled environment under natural and forced convection greenhouse and open sun drying modes which were found to vary from 0.54-0.91 W/m^{2o}C, 0.86-1.09 W/m^{2o}C and 0.54-1.03 W/m^{2o}C respectively. An empirical model was also developed to predict the convective heat transfer coefficient for khoa as a function of drying time. 100 g of khoa sample of 1.5 cm thickness was taken for the experimentation and dried till no variation in its mass was recorded. Further **Kumar [95]** studied the effect of size on the convective heat and mass transfer coefficient for khoa drying under natural convection greenhouse mode (Figure 2.15) for a given mass (100 g). Samples of khoa pieces of dimensions 0.025×0.02×0.015 m^3, 0.0375×0.03×0.015 m^3 and 0.075×0.06×0.015 m^3 were used for drying in roof type even span greenhouse of 1.2×0.8 m^2effective floor area and air vent of 0.043 m^2 was provided at the roof. The khoa sample was dried till no variation in its mass was recorded. The average values of convective heat transfer coefficients were found to be 2.53 $W/m^{2o}C$, 1.95 $W/m^{2o}C$ and 1.59 $W/m^{2o}C$ for khoa pieces of size 0.025×0.02×0.015 m^3, 0.0375×0.03×0.015 m^3 and 0.075×0.06×0.015 m^3 respectively. The average value of convective heat transfer coefficient was observed to be increased by 59.12% when khoa sample size was decreased from 0.075×0.06×0.015 m^3 to 0.025×0.02×0.15 m^3. And the average value of mass transfer coefficient were found to be 60.0 $W/m^{2o}C$, 50.25 $W/m^{2o}C$ and 39.95 $W/m^{2o}C$ for khoa pieces of size 0.025×0.02×0.015 m^3, 0.0375×0.03×0.015 m^3 and 0.075×0.06×0.015 m^3 respectively. The average value of mass transfer coefficient was observed to be increased by 51.69% when khoa sample size was decreased from 0.075×0.06×0.015 m^3 to 0.025×0.02×0.015 m^3.

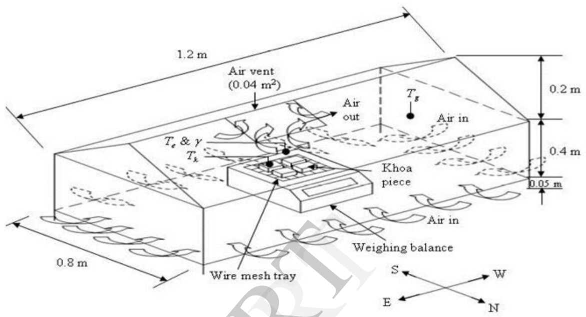

Figure 2.15: Schematic diagram of the experimental set up [95]

Kumar et al. [96] discussed the effect of various operating parameters on the performance of greenhouse dryer under unloading conditions. **Tiwari et al. [97]** presented the energy and exergy analyses for fish drying under natural convection greenhouse drying mode. **Nayak and Tiwari [98]** also carried out the energy and exergy analysis for the prediction of performance of a photovoltaic /thermal (PV/T) collector integrated with a greenhouse (Figure 2.16). **Ozgener and Ozgener [99]** investigated the drying performance of a passively heated solar greenhouse.

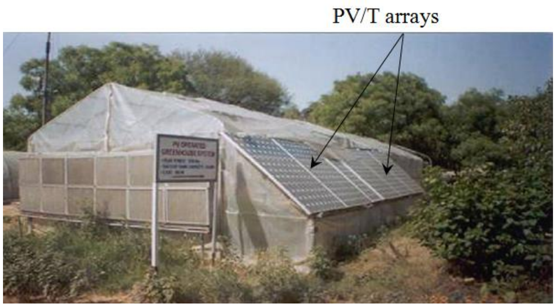

Figure 2.16 Experimental set up of PV solar integrated greenhouse [98]

Ayyappu and Mayilswamy [100] designed and developed a natural solar tunnel dryer (10m×4m×3m) for copra. **Sadodin and Kashani** [101] investigated the solar greenhouse tunnel drying of copra. The roof of the greenhouse was made of semi-circular (Figure 2.17). Results of greenhouse drying of different commodities are summarized in table 2.5.

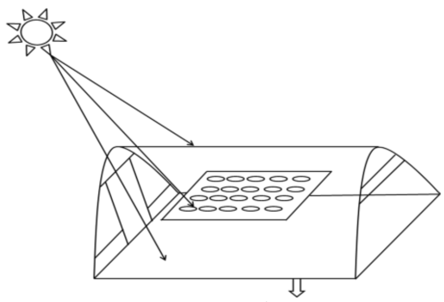

Figure 2.17: Schematic diagram of solar tunnel dryer **[101]**

Table 2.5: Analysis of greenhouse drying

S. no.	Researcher	Year	Agricultural products & vegetables	Remarks
1	Condori and Saravia	1998	Sweet pepper	Proposed different concepts of forced greenhouse driers
2	Manohar and Chandra	2000	Rewetted mustard	Greenhouse drying was reported to be 20% to 45% faster than open sun drying mode.
3	Condori et al.	2001	Sweet pepper and garlic	presented low cost tunnel greenhouse dryer under forced convection
4	Condori and Saravia	(2003)	Sweet red pepper	Proposed tunnel greenhouse dryer
5	Farhet et al.	(2004)	Pepper	Proposed polyethylene natural convection greenhouse dryer
6	Jain and Tiwari	2004	Cabbage and Peas	The values of convective mass transfer coefficients were reported to be 17 – 8 W/m^{2o}C.
7	Jain and Tiwari	2004 a	Cabbage and Peas	Mathematical model was developed.
8	Koyuncu	(2006)	Pepper	The greenhouse dryer was found to be 2-5 times more efficient than open sun drying
9	Sacilik et al.	(2006)	Organic Tomato	Moisture content was maintained upto 11.50%
10	Kumar and Tiwari	2007	Onion	The value of convective heat transfer coefficient was reported to be increased by 30 – 135% with increase in mass.
11	Janjai et al.	2008	Rosella flower and chilli	Proposed roof integrated solar dryer
12	Sethi and Arora	2009	Bitter gourd	Proposed modified solar greenhouse dryer having inclined reflected north wall. Moisture content was maintained upto 7% db.
13	Kadam et al.	2011	Onion slices	Thermal efficiency was reported to be 20.82%.
14	Janjai	2012	Osmotically dehydrated tomato	Presented a large scale greenhouse dryer with LPG burner
16	Artesty and Wulandani	2014	Wild ginger	Moisture content was maintained up to 8 – 11%(wb).
17	Fadhel et al.	2014	Hot red pepper	Studied and analyzed the drying of red pepper by three different solar processes (open sun, greenhouse and solar dryer).
19	Fadhel et al.	2005	Sultanine grapes	Moisture content was maintained up to 16%.
18	Ergunes et al.	2005	European Plume (Prunus domestica L.)	Greenhouse dryer took 6 – 12 days to dry halved pitted plums as compared to 13 – 22 days in open sun.
20	Elicin and Sacikik	2005	Apple	Moisture content was maintained up to 11%.
21	Rathore et al.	2006	Amla pulp	Moisture content was controlled up to 10%.
22	Barnwal and Tiwari	2008	Thompson seedless grapes	The value of convective heat transfer coefficient was reported to vary from 0.26 – 1.21 W/m^{2o}K.
23	Janjai et al.	2009	Peeeld logan and banana	Peeled Logan and banana were dried in 3 and 4 days respectively.
24	Janjai et al.	2010	Licthi flesh	Moisture content was maintained up to 12% (wb).
25	Rathore and Panwar	2010	Seedless Grapes	Moisture content was maintained up to 16% (wb).
26	Janjai et al.	2011	Banana, chilli and coffee	Banana, chilli and coffee were dried in 5, 3 and 2 days respectively under solar greenhouse dryer.
27	Almuhanna	2012	Dates	The thermal efficiency of the solar greenhouse was reported to be 60.11%.
28	Tiwari et al.	2006	Prawn	The value of convective heat transfer coefficient was reported to vary from 9.2 – 1.23W/m^{2o}C.
	Boonyasri et al.	2011	pork	Moisture content was maintained up to 70% (db).
29	Tiwari et al.	2009	Fish	Energy and exergy analyses of fish drying were carried out.
30	Tiwari et al.	2004	Jaggery	The convective heat transfer coefficients were reported to be 0.73 – 1.41W/m^{2o}C and 0.80 – 1.47 W/m^{2o}C for sample of 800g and 0.55 – 1.22 W/m^{2o}C and 0.91 – 7.07 Wm^{2o}C for 2000g sample under natural and forced convection greenhouse mode respectively.
31	Kumar and Tiwari	2006	Jaggery	Effect of shape and size of Jaggery for a given mass (2.0 kg and 0.75 kg) on convective mass transfer coefficient have been studied.
32	Prakash and Kumar	(2012)	Jaggery	ANFIS (Adaptive-Network-Based Fuzzy Inference System) model was used to predict jaggery and green house temperature and jaggery mass during drying.
33	Prakash and Kumar	2013	Jaggery	ANN was proposed to predict the hourly jaggery mass under natural convection greenhouse drying mode.
34	Kumar et al.	2011 a	Khoa	The values of convective heat transfer coefficients for khoa under open sun, greenhouse drying under natural convection and forced convection modes were reported to be 0.54 – 1.03 W/m^{2o}C, 0.54 – 0.91 W/m^{2o}C and 0.86 – 1.09 W/m^{2o}C respectively.
35	Kumar	2014	Khoa	The values of convective heat transfer coefficients for khoa were reported to be increased from 1.59 W/m^{2o}C to 2.53 W/m^{2o}C and 39.95 W/m^{2o}C to 60.6 W/m^{2o}C respectively for decreasing the size of khoa pieces.
36	Kumar	2013	Papad	The values of convective and evaporative heat transfer coefficients for papad were reported as 0.759 and 23.48 W/m^{2o}C respectively.
37	Kumar et al.	2013	No load condition	Forced convection greenhouse drying was found to be 31% more efficient than natural convection greenhouse drying.
38	Prakash and Kumar	2013-a	Unload condition	Presented ANFIS model for the modified forced convection greenhouse during under no load condition.
39	Prakash and Kumar	2013-b	Unload conditions	Modified solar active greenhouse dryer with opaque wall was tested in laboratory scale.
40	Prakash and Kumar	(2013)	Review	Proposed solar photovoltaic thermal dryer for remote rural village farm application in most developing countries
41	Prakash and Kumar	2014	Review	Comprehensive review of various greenhouse drying systems was carried out.
42	Nayak and Tiwari	2008	Energy and exergy analyses	Energy and exergy analyses of a photovoltaic /thermal (PV/T) collector integrated with a greenhouse were carried out.
43	Ozgener and Ozgener	2009	Exergy analysis	The average exergy efficiency of the drying process was observed to be 63–73%.
44	Ayyappu and Mayilswamy	2010	copra	Moisture content was maintained up to 8%
45	Sadodin and Kashani	2011	copra	Moisture content was maintained up to 8% and developed a mathematical model.

Greenhouses of different shapes have been used for drying of various products under different environmental conditions. Photovoltaic/thermal greenhouse dryer are also used by a few researcher. Products dried under greenhouse were observed to be of good quality as compared to open sun drying. The greenhouse dryers were observed to be 2-5 times more efficient than open sun drying mode.

IV Summary

One of the important applications of solar energy is the drying of agricultural products, fruits, vegetables, fish, food products etc. as it is free of cost and is abundant. Almost 80% of the farmers are adopting open sun drying for their crops. But the losses to agricultural products due to outside environment are remarkable. From the literature, it has been observed that greenhouse technology significantly improves the quality of the products and reduces the drying period. Therefore, advanced method of drying i.e. greenhouse drying should be adopted to overcome the limitations of traditional open sun drying method. This review paper focuses on available various greenhouse structures and their constructional and working principle.

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