A review on applications of greenhouse drying and its performance

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Abstract: Limited sources and rising cost of fossil fuels has instigated researchers to look towards renewable energy resources. Among renewable energy resources, solar energy is required to become indispensable in the future, as it is inexpensive, abundant, inexhaustible, environmental friendly and non-pollutant. Most of the people living in developing countries are dependent on agriculture. Agricultural products are dried to increase the storage life, minimize the packaging requirement and reduce the transportation weight. Solar drying for drying agricultural products is being practiced since long back throughout the world. Because of its drawbacks, advance technique, i.e. greenhouse drying, is being adopted for drying crops to reduce the drying time and increase the quality of the food products. Some new methods have also been attempted to increase the drying efficiency of greenhouse. In this paper, a comprehensive review of greenhouse drying of various commodities is presented. Different parameters such as thermal analysis, drying characteristics of crops, energy and exergy analysis, and greenhouse drying performance were discussed. In addition, the economical aspects of greenhouse dryers were also highlighted. This review paper will be helpful to the new researchers to know about the various technical aspects of the greenhouse dryer.

Keywords: greenhouse drying, agricultural products, convective heat transfer coefficient, energy and exergy analysis, economical aspects, drying performance

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1 Introduction

World population is predicted to be about 7.6 billion up to 2020. Looking at this growth of population in the next 25 years, about 50% more food is to be produced. Therefore, agricultural production must be increased to guarantee the food demand for the fast growing population. The population-food imbalance can be solved by increasing the food production or by limiting the population. Another most viable solution to this food problem involves reducing the food losses, which occur during the food production and post-harvest (Brown, 1995). The post-harvest losses are considered to be 30%-40% (El-Sebaii and Shalaby, 2012). Drying (moisture removal process) of agricultural products is one of the important post-harvest processes to save the products from losses. Table 1 presents the recommended levels of safe moisture content and drying temperature for long-term storage of agricultural products (Sharma et al., 1993; Brooker et al., 1993; Tiwari and Ghosal, 2005; Ahmad and Mirani, 2012; Krzyzanowski 2006; Togrul and Pehlivan 2004; Mujumdar 1987; El-Sebaii et al. 2002; Purohit et al., 2006 and Oyoh and Menkiti, 2008), food products (Arun et al., 2014; Ayyappan and Mayilsamy, 2010) and other commodities (Panwar et al., 2014; Aritesty and Wulandani, 2014).

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Table 1 Moisture content details of various commodities

S. No.	Crop	Initial moisture content, % w.b.	Final moisture Content, % w.b.	Maximum allowable temperature, °C
1	Apples	80	24	70
2	Apricot	85	18	65
3	Bananas	80	15	70
4	Brinjal	95	6	60
5	Cabbage, Garlic, Onions	80	4	55
6	Cauliflower	80	6	65
7	Carrots, Green beans	70	5	75
8	Copra	52.2	8	-
9	Coconuts	53.84	7	-
10	Corn	24	14	50
11	Chillies	80	5	65
12	Coffee	65	11	-
13	Fenugreek leaves	89	9	-
14	Fig	70	20	70
15	Ginger	80	8-11	-
16	Groundnuts	40	9	40 – 55
17	Green peas	80	5	65
18	Grapes	80	15 – 20	70
19	Guavas	80	7	65
20	Maize	35	15	60
21	Mulberries, Yam	80	10	65
22	Nutmeg, Sorrel	80	20	65
23	Oil seed	20 – 25	7-9	40 – 60
24	Okra	80	20	65
25	Rice	24	11	30
26	Paddy, raw	22-24	11	50
27	Paddy, parboiled	30-35	13	50
28	Peaches	85	18	65
29	Peanuts	40-55	8-10	-
30	Pineapple	80	10	65
31	Potatoes	75	13	75
32	Prunes	85	15	55
33	Pulses	20-22	9-10	40-60
34	Spinach, Ginger, Turmeric	80	10	-
35	Sweet potatoes	75	7	75
36	Tomatoes	96	7-10	60
37	Wheat	20	16	45

Note: reference sources: Sharma et al. 1993; Brooker et al., 1992; Tiwari and Ghosal, 2005; Ahmed and Mirani, 1012; Krzyzanowski et al., 2006; Togrul and Pehlivan, 2004; Mujumdar, 1987; El-Sebaii et al., 2002; Purohit et al., 2006; Oyoh and Menkiti, 2008; Arun et al., 2014; Ayyappan and Mayilsamy 2010; Panwar et al. 2014; Aritesty and Wulandani, 2014.

Small farmers use the simplest and traditional method of drying, i.e. open sun drying (OSD) for drying of agricultural products to the safe moisture level. In the open sun drying, the product is directly exposed to solar radiations (Belessiotis and Delyannis, 2011). The solar radiation falling on the surface of the product is partly absorbed and partly reflected. The absorbed solar 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 and part of this heat is lost through long wave length radiations to the atmosphere and through to the ground. However, considerable losses occur due to dust, dirt, insects, animals, microorganisms, birds. The product is also discoloured due to ultraviolet radiations. The post-harvest losses are estimated to be 10%-40% (El-Sebaii et. al., 2012).

So, the advanced method of drying, i.e. greenhouse drying is being adopted to overcome the limitations of traditional (open sun) method. The greenhouse is an enclosed framed structure having transparent roofs and walls made up of glass, polyethylene film, etc. (Tiwari, 2003). The working principle of greenhouse technology is shown in Figure 1 (Tiwari 2003) in which product is placed in trays receiving the solar radiations through plastic cover and moisture is removed by natural or forced convection (Esper and Muhlbauer, 1998; Kumar et al., 2006).

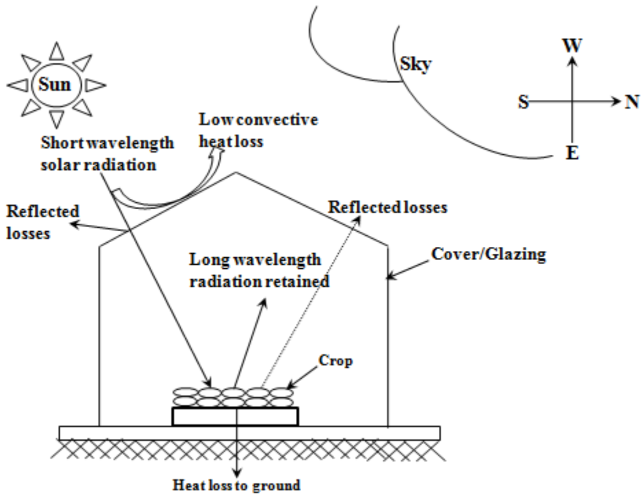

Figure 1 Schematic diagram of greenhouse drying (Tiwari 2003)

A comprehensive review of developments of various greenhouse drying systems has been presented by Prakash and Kumar, (2014a). Prakash and Kumar (2013c) presented a comprehensive review of various design, constructional details and operational principles of solar dryers. Recently a comprehensive review of polyhouse dryers in terms of design and efficiency has also been presented by Sangaithra et al. (2014).

In this review paper, work carried out by different researchers on greenhouse drying for various commodities was presented. Various parameters such as thermal analysis, drying characteristics of products, energy and exergy analysis, and drying performance along with economical aspects of greenhouse dryer is also presented.

2 Research work carried out on various products

Nowadays, the demand for dried agricultural products, food grains, vegetables, fruits, herbs, spices and so on has increased. Traditionally, products are dried in the open sun and are cheap, but the quality of these products is deteriorated by ultraviolet rays, dust, insects, animals, microorganisms, etc. So, the open sun dried products are not meeting the international standards. Off-season cultivation of agricultural products in controlled environment is also increasing. Therefore, the advanced means of drying, i.e., greenhouse drying are being adopted to reduce the losses and to increase the quality of the dried products. Research work carried out by different researchers on greenhouse drying of various products has been discussed in the following section.

2.1 Vegetable drying

Tiwari et al. (2004) determined the convective mass transfer coefficients (CMTC) for jaggery drying under natural and forced convection greenhouse drying modes (Figure 2 and Figure 3). The values of CMTC for jaggery drying were found to vary from 0.55 W/m^2 ^{o}C-1.43 W/m^2 ^{o}C and 0.33 W/m^2 ^{o}C-1.80 W/m^2 ^{o}C under natural and forced modes of greenhouse drying respectively. Jain and Tiwari (2004) evaluated the convective heat transfer coefficients for cabbage and peas drying under open sun, natural and forced convection greenhouse drying modes. The values of convective heat transfer coefficients for cabbage and peas under open sun, natural and forced convection greenhouse modes were reported to be within the range of 25-10 W/m^2 ^{o}C, 17-8 W/m^2 ^{o}C and 38-15 W/m^2 ^{o}C respectively. Jain and Tiwari (2004a) studied the thermal behaviour of cabbage and peas under natural and forced greenhouse modes. Mathematical models were also developed to predict the various temperatures and moisture evaporation under greenhouse drying modes.

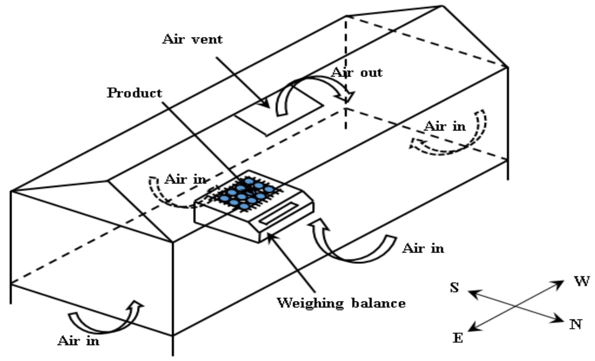

Figure 2 Schematic diagram of natural convection greehouse drying (Tiwari et al., 2004)

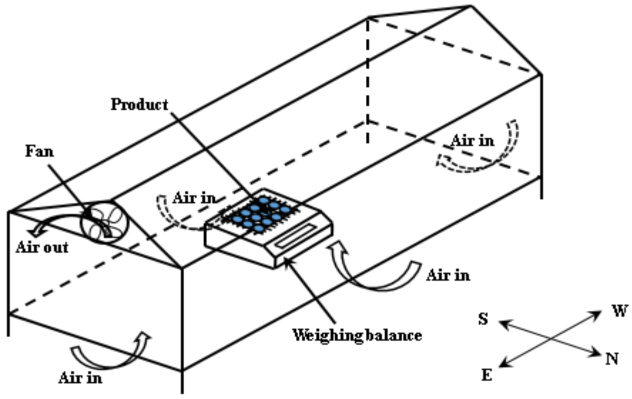

Figure 3 Schematic diagram of forced convection greenhouse drying (Tiwari et al., 2004)

Jain (2005) studied the performance of even span greenhouse with a north wall and packed bed thermal storage for drying of onion. Mathematical model was also proposed to evaluate the performance of crop drying. Sacilik et al. (2006) presented the thin layer drying characteristic of organic tomato in a solar tunnel greenhouse dryer in the climatic conditions of Ankara, Turkey. Tomatoes were dried from initial moisture content of 93.35% (w.b.) to final moisture content of 11.50% (w.b.) in 4 d in solar greenhouse tunnel dryer as compared to 5 d in open sun drying mode. The dried product was reported to be protected from insects, birds, rain and dusts.

Kumar and Tiwari (2007) studied the effect of mass on convective mass transfer coefficients for various masses of onion drying under OSD, natural and forced convection greenhouse drying modes. The values of convective mass transfer coefficient for onion were found to vary from 1.19 -2.75 W/m^2 ^{o}C, 1.28-2.28 W/m^2 ^{o}C and 1.09-3.08 W/m^2 ^{o}C under OSD, natural and forced convection greenhouse drying modes respectively. Sethi and Arora (2009) improved the conventional greenhouse by using inclined north wall reflection (INWR) for faster drying of bitter gourd slices under natural and forced convection modes. The air temperature inside improved greenhouse under natural and forced convection modes were reported to be increased from 1^{o}C to 6.7^{o}C and 1^{o}C to 4^{o}C respectively. Jain et al. (2011) evaluated the convective heat and mass transfer coefficient (CHMTC) for green chilli drying under open sun and under forced convection greenhouse drying (FCGHD) mode. Chilli was blanched with sodium hydroxide and sodium chloride solution. The values of CHMTC were found to be 4.333 W/m^2 ^{o}C and 5.520 W/m^2 ^{o}C for green chilli drying under FCGHD blanched in sodium hydroxide and sodium chloride respectively.

Kadam et al. (2011) studied the performance of low cost greenhouse dryer for the drying of onion. Onion slices were pre-treated before drying sodium chloride and potassium metabisulphite. The thermal efficiency of greenhouse dryer was found to be 20.82%. Janjai et al. (2011) developed a large scale modified greenhouse dryer (black concrete floor) having loading capacity of 1000 kg. Chilli, banana and coffee were used to dry inside the modified greenhouse dryer from initial moisture content of 75% (wb) in 3 d, 68% (wb) in 5 d and 52% (wb) in 2 d as compared to 5 d, 7 d and 4 d in open sun drying conditions respectively. The payback period of the dryer was estimated to be 2.5 years.

Shahi et al. (2011) developed and studied the drying of agricultural products (tomato, capsicum, cabbage, leafy vegetables, carrot and apple) in polyhouse type solar dryer in the climatic conditions of Kashmir. The cement concrete floor was painted black for better absorption of solar radiations and north wall was covered with black body to reduce heat losses from the northern side of polyhouse. Payback time of the dryer was reported to be 1.5 years. Janjai (2012) developed a large scale greenhouse dryer with LPG burner (during cloudy and rainy days) and investigated the drying of osmotically dehydrated tomato inside the dryer. The greenhouse air temperature was reported to vary from 35^{o}C to 65^{o}C. The payback period of the dryer was estimated to be 0.65 years.

Bouadila et al. (2014) determined the night time recovered heat of the solar air heater with latent heat storage collector in the greenhouse. A new solar air heater collector (with a compacted layer of spherical capsules) with the latent heat system was operated and installed inside a greenhouse. The collector stored energy during daytime and supplied it during night time to tomato crop inside the greenhouse. The night time heat was reported to be 30% attained of the total requirement of heating. Bouadila et al. (2014a) investigated the effect of phase change material (PCM) on greenhouse temperature. Greenhouse temperature with PCM was found to be 5^{o}C more than the conventional greenhouse temperature. Bouadila et al. (2015) also experimentally evaluated the night time recovered heat of the solar air heater with latent heat storage collector in the greenhouse. Collector stored the solar energy during daytime and supplied it to greenhouse air during night-time for heating. Kooli et al. (2015) determined the effect of nocturnal shutter and the heat provided by a solar air heater with latent heat storage collector inside an insulated greenhouse. Tomato crop was planted in two identical greenhouses (with and without nocturnal shutter) for comparison purpose. Temperature inside the greenhouse with nocturnal shutter was reported to be 2^{o}C higher than the greenhouse without nocturnal shutter. The radiation heat loss rate was reported to be 24% and 61% of the total losses in insulated greenhouses with and without shutter respectively.

It is observed that the vegetables, dried in greenhouse dryer are better in quality as compared to open sun drying. The values of convective heat transfer coefficients for vegetables drying in greenhouse dryer were found to lie in the range of 1.28 W/m^2 ^{o}C-17 W/m^2 ^{o}C and 1.09 W/m^2 ^{o}C-38 W/m^2 ^{o}C under natural and forced modes respectively. The thermal efficiency of the greenhouse dryer was reported to be 20.83%. The maximum payback period of the dryer was estimated to be 2.5 years.

2.2 Fruits/nuts drying

Bala et al. (2003) studied the performance of the solar tunnel dryer (150 kg capacity) for drying of pineapple in the climatic conditions of Mymensingh, Bangladesh. The dryer was operated by a photovoltaic system, making it independent of the electricity grid. Sulfur treated pineapple was dried from initial moisture content of 87.32% (wb) to final moisture content of 14.13% (wb) in 3 d. Ergunes et al. (2005) studied the drying of pre-treated plums (with 1% NaOH solution) in greenhouse and open sun drying modes. Halved-pitted plums were reported to be dried in 6-12 d and 13-22 d in greenhouse dryer and open sun respectively. Elicin and Sacilik (2005) studied the drying kinetics of apples in solar tunnel dryer from initial moisture content of 82% (wb) to final moisture content of 11% (wb). Apples were dried in 28 h in dryer as compared to 32 d in open sun drying. Fadhel et al. (2005) compared the drying of Sultanine grapes in open sun, natural convection solar dryer and solar tunnel greenhouse drying modes. The solar tunnel greenhouse was reported to be most suitable for grape drying. A hybrid photovoltaic-thermal (PV/T) integrated greenhouse dryer (Figure 4) was used to determine the convective mass transfer coefficient for grapes drying in forced mode. The value of convective mass transfer coefficient was reported to vary from 0.26 W/m ^{2} ^{o}C-1.21 W/m ^{2} ^{o}C (Barnwal and Tiwari, 2008).

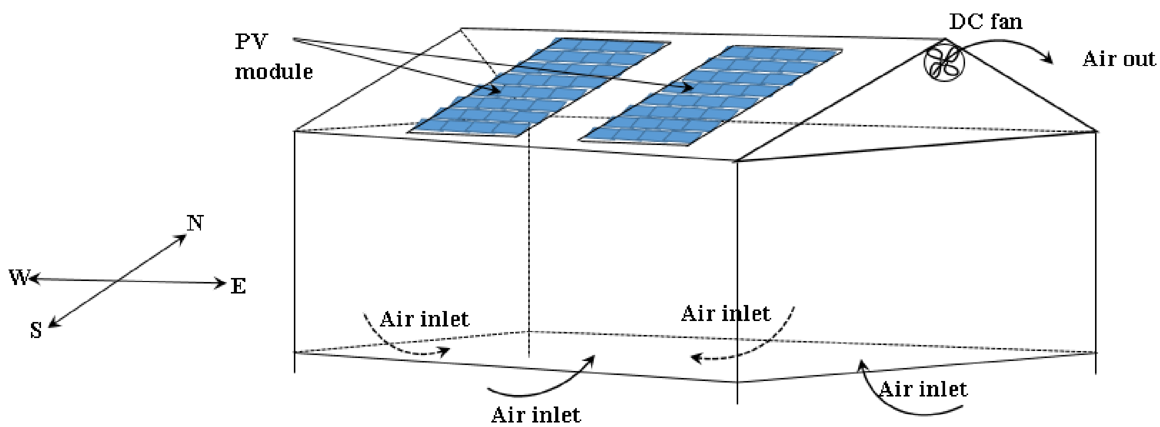

Figure 4 Schematic of PV/T greenhouse dryer (Barnwal and Tiwari, 2008)

Rathore et al. (2006) presented the drying of amla in a solar tunnel dryer from initial moisture content of 80% to 10% in 2 d. Jairaj et al. (2009) discussed the various methods adopted for grape drying. Janjai et al. (2009) studied the performance of a photo voltaic ventilated solar greenhouse dryer and for drying of peeled logan and banana. Inside greenhouse temperature was reported to be increased up to 60^{o}C. The drying time for peeled logan and banana was found to be 3 d and 4 d respectively as compared to 5 to 6 d in open sun drying condition. The quality of the greenhouse drying products was reported to be high. Rathore and Panwar (2010) developed and studied the performance of a walk-in-type hemi cylindrical solar tunnel dryer with heat protective north wall to dry the seedless grapes (mutant: Sonaka). Grapes were dried from initial moisture content of 85% (wb) to final moisture content of 16% (wb) in about 7 d in dryer where it took about 11 d in open sun drying. Janjai et al. (2010) investigated the performance of a solar greenhouse dryer for drying of litchi flesh.

Litchi flesh was dried from initial moisture content of 84% (wb) to final moisture content of 12% (wb) in about 3 d.

Almuhanna (2012) utilized the solar greenhouse as a solar air heater for drying dates and studied the thermal performance of the solar greenhouse. The daily average overall thermal efficiency of the solar greenhouse during the experiment was reported to be 57.2%. Phusampao et al. (2014) studied the performance of the greenhouse dryer for the drying of macadamia nuts. The nuts were reported to be dried from initial moisture content of 16% (wb) to final moisture content of 3% (wb) in 5 d. Payback time for the dryer was estimated to be one year. Recently Elkhadraoui et al. (2015) investigated the performance of a novel mixed mode solar greenhouse dryer (Figure 5) with forced convection for the drying of red pepper and sultana grape. A flat plate collector was integrated with the greenhouse to increase the greenhouse air temperature. The moisture content of red pepper and Sultana grapes were reduced to 16% (wb) and 18% (wb) in 24 h and 50 h respectively.

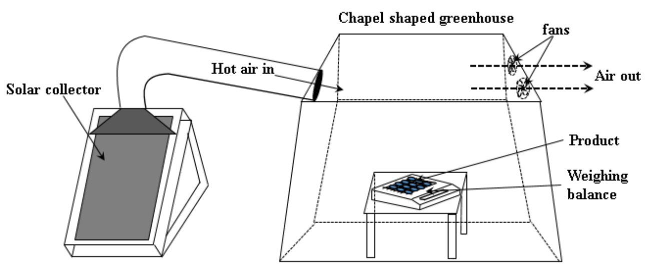

Figure 5 Schematic diagram of mixed mode greenhouse drying (Elkhadraoui et al., 2015)

Greenhouse dryers were integrated with solar collector and PV/T to increase the greenhouse room air temperature. The drying time was significantly reduced. The value of convective mass transfer coefficient for the greenhouse drying of fruits and nuts was found to vary from 0.26 W/m^2 ^{o}C-1.21 W/m^2 ^{o}C. The thermal efficiency of the greenhouse dryer was found to be 57.2%. The payback period of the dryer was also judged to be one year.

2.3 Food products drying

The convective heat transfer coefficients for various shapes and sizes of jaggery pieces were evaluated under natural and forced convection greenhouse drying (Kumar and Tiwari, 2006). The values of the convective heat transfer coefficients were observed to vary from 1.31 W/m^2 ^{o}C-2.75 W/m^2 ^{o}C and 1.04 W/m^2 ^{o}C-3.60 W/m^2 ^{o}C under natural and forced convection greenhouse drying mode respectively. A thermal model was also developed and experimentally validated by Kumar and Tiwari (2006a) to predict the jaggery temperature, greenhouse air temperature and moisture evaporated during jaggery drying under natural convection greenhouse drying condition.

Ayyappan and Mayilsamy (2010) studied the drying of copra in natural convection greenhouse drying mode in the climatic conditions of Pollachi, India. Copra was dried from initial moisture content of 52.2% to final moisture content of 8% under full load in 57 h. The average efficiency of the dryer was reported to be 20%. Quality of copra dried in the dryer was reported to be better as compared to open sun drying. Sadodin and Kashani (2011) studied the numerical performance of a solar greenhouse dryer for drying of copra from 52.2% to 8% moisture content under full load in 55 h. A model was developed for predicting the performance of the dryer which was solved using MATLAB software. The payback period of the dryer was reported to be 2.3 years.

Prakash and Kumar (2012) developed an adaptive-network-based fuzzy system (ANFIS) model to predict the jaggery temperature, greenhouse air temperature and moisture evaporation for drying of jaggery inside natural convection greenhouse drying mode. The developed model was validated experimentally. Prakash and Kumar (2013) also used artificial neural network (ANN) to predict the jaggery mass, solar radiations, ambient temperatures and relative humidity inside natural convection greenhouse drying. ANN model was validated experimentally. Kumar (2013) evaluated the convective heat transfer coefficient of papad for greenhouse drying under natural convection mode. Papad was dried to its optimum safe moisture content of about 14%-15%. The average value of convective heat transfer coefficient was reported to be 1.23 W/m^2 ^{o}C. The behaviour of heat and mass transfer phenomenon during greenhouse papad drying under forced convection mode was also investigated (Kumar, 2013a). The average values of convective and evaporative heat transfer coefficient were found to be 0.759 W/m^2 ^{o}C and 23.48 W/m^2 ^{o}C respectively.

Kumar (2014) determined the effect of size on the convective heat and mass transfer coefficients for khoa for a given mass under natural convection greenhouse drying mode. The average values of convective heat and mass transfer coefficients were found to be increased from 1.59 W/m^2 ^{o}C-2.53 W/m^2 ^{o}C and 39.95 W/m^2 ^{o}C-60.6 W/m^2 ^{o}C respectively. Kumar (2014a) evaluated the effect of size on the convective heat and mass transfer coefficients of khoa for a given mass with greenhouse drying under forced convection mode. The average value of convective heat transfer coefficient was found to vary from 2.15 W/m^2 ^{o}C-3.13 W/m^2 ^{o}C. And the average value of convective mass transfer coefficient was found to vary from 63.23 W/m^2 ^{o}C-93.77 W/m^2 ^{o}C.

Arun et al. (2014) studied the drying characteristics of coconuts in a natural convection greenhouse dryer. Coconuts were dried from initial moisture content of 53.84% (w.b.) to final moisture content of 7.4% (w.b.) in 56 h. Greenhouse dried coconuts were reported to be free from fungal and bacterial infections. Arun et al. (2014a) designed and developed a natural convection solar tunnel greenhouse dryer coupled with biomass backup heater (after 5 PM) to study the drying characteristics of coconuts. Coconut fronts, coconut husk and coconut shells were used as fuel for biomass heater. Coconuts were dried from initial moisture content of 53.84% (w.b.) to final moisture of 7.003% (w.b.) in 44 h whereas 56 and 148 h were taken by the dryer without back up heater and open sun drying mode respectively. Coconuts dried in dryer were reported to be free from dust, dirt, damage by birds and infections by bacteria and fungus. Arun et al. (2014b) compared the existing dryer (Arun et al., 2014b) coupled with biomass back up heater (after 5 PM) and without backup heater for drying of coconut and optimized the existing dryer. Coconuts were dried from initial moisture content of 53.84% (w.b.) to final moisture of 7.003% (w.b.) in 44 h by dryer with biomass backup heater whereas 56 h were taken by dryer without biomass backup heater.

Recently Ayyappan et al. (2015) studied the effect of various sensible heat storage materials (concrete, sand and rock-bed) on drying characteristics of coconuts and thermal performance of natural convection solar greenhouse for copra drying. Coconuts were dried from initial moisture content of 52 % (wb) to final moisture content of 7% (wb) in 53, 66 and 78 h using rock-bed, sand and concrete respectively as compared to 174 h in open sun drying mode. The drying efficiency was also reported to be 9.5%, 11% and 11.65% using concrete, sand and rock-bed respectively.

It is concluded from the literature that new methods such as heat storage materials and biomass backup heaters were used for increasing the greenhouse room temperature. Food products dried in greenhouse dryers were observed to be of superior quality as compared to traditional (open sun) method of drying. Different softwares (ANFIS, ANN and MATLAB) have been used for the prediction of various greenhouse temperatures and moisture evaporated. The values of CHTC for drying of food products in greenhouse dryers were found to vary from 1.23 W/m^2 ^{o}C-2.75 W/m^2 ^{o}C and 0.759 W/m^2 ^{o}C-3.60 W/m^2 ^{o}C under natural and forced modes respectively. The average efficiency of the dryer was found to be 20%. The payback period of the dryer was estimated to be 2.3 years.

2.4 Medicinal/spices/herbs/flower plants drying

Manohar and Chandra (2000) studied the drying of rewetted mustard in a natural and forced solar greenhouse type solar dryer. Drying of mustard in natural and forced modes were reported to be 20% and 45% faster as compared to open sun drying mode respectively. Condori et al. (2001) developed a new low cost forced convection greenhouse tunnel dryer for drying red sweet pepper and garlic. The dryer was divided into two chambers, one having partially dried product and another containing fresh product. Two fans were used to circulate the air from first to second chamber. Condori and Saravia (2003) studied the performance of a tunnel greenhouse drier (with single and double chambers) for drying of sweet pepper. Improvement of 160% and 40% was reported in production, compared with the single chamber drying and double drying respectively.

Farhat et al. (2004) carried out the solar drying of pepper in a naturally ventilated tunnel polyethylene greenhouse dryer. Weight reduction of about 83% was reported at the end of the experiment. Improvement in the final product was checked visually and reported to be of good quality. Koyuncu (2006) designed and tested two natural circulation greenhouse dryers for drying of pepper and under no load conditions. The solar absorber surface was painted black to increase the dryer temperature. The dryer was investigated with and without chimney also. The dryer was reported to be two to five times more efficient than the open air dryer.

Janjai et al. (2008) presented the performance of roof integrated solar dryer for drying of rosella flower and chilli and developed a model for drying of chilli. Aritesty and Wulandani (2014) studied the performance of rack type solar greenhouse dryer for drying wild ginger slices. Wild ginger slices were dried from initial moisture content of 80% (wb) to final moisture content of 8%-11% (wb) in 30 h. Fadhel et al. (2014) presented the drying of red pepper (Baklouti) in open sun, under greenhouse and in a solar dryer. Drying time (including nights) for red pepper were reported to be 73 h, 79 h and 118 h in the solar dryer, greenhouse and open sun respectively. Among various thin layer drying models logarithmic model was reported to be most suitable for describing the drying behaviour of red pepper. Nayak et al. (2011) studied the drying of mint in a hybrid photovoltaic-thermal (PVT) forced mode greenhouse dryer. Mint was dried from initial moisture content of 80% (wb) to final moisture content of 11% (wb). The drying efficiency of the hybrid PVT greenhouse dryer was found to be 34.2%.

Panwar et al. (2014) presented the thermal modelling and experimental validation of a walk-in type solar tunnel greenhouse dryer for the drying of fenugreek leaves. Fenugreek leaves were reported to be dried from initial moisture content of 89% (wb) to final moisture content of 9% (wb) in 17 h. The energetic and exergetic performance of fenugreek leaves were also carried out (Panwar 2014). Energy and exergy efficiencies were reported to vary 0.841% to 1.613% and 0.018% to 0.102% respectively. Recently Aghbashlo et al. (2015) developed a new TRNSYS model for simulation of the solar drying process of chamomile flower in a deep bed by integrating an equilibrium drying model and thin-layer drying principles. Elkhadraoui et al. (2015) investigated the performance of a novel mixed mode greenhouse dryer for drying of red pepper. A flat plate solar collector was used to preheat the air entering the greenhouse. The payback period of the dryer was found to be 1.17 years. The life of the dryer was estimated to be 20 years.

It was observed that the drying efficiency of the hybrid dryer was evaluated, as 34.2%. Energy and exergy efficiencies were found to be 1.613% and 0.102% respectively. The payback period of the dryer was found to be 1.15 years.

2.5 Fish/pork drying

Sarkar and Tiwari (2005) developed a thermal model for greenhouse fish pond system. Tiwari et al. (2006) determined the convective heat and mass transfer coefficient (CHMTC) for prawn drying under natural convection greenhouse drying mode. The value of CHMTC for greenhouse prawn drying was found to vary from 1.23 W/m^2 ^{o}C-9.2 W/m^2 ^{o}C. Das and Tiwari (2008) evaluated the CHMTC for fish drying under forced convection greenhouse drying mode. The value of convective heat and mass transfer coefficient for fish drying under forced convection greenhouse drying mode was reported to vary from 1.5 W/m ^{2} ^{o}C-21 W/m ^{2} ^{o}C.

Tiwari et al. (2009) studied the energy and exergy analysis of greenhouse fish drying. Energy analysis was used to predict fish surface temperature, greenhouse room air temperature and moisture evaporated for the drying of fish under natural and forced convection greenhouse drying modes. Boonyasri et al. (2011) experimentally investigated the performance of pork drying in semi cylindrical roof solar greenhouse dryer. Pork was dried from initial moisture content of 210% (db) to final moisture content of 70% (db) in 260 min as compared to 320 min in open sun drying condition. The payback period of the dryer was estimated to be 1.15 years.

It is seen that the values of CHMTC for the drying of fish were found to vary from 1.23 W/m^2 ^{o}C-9.2 W/m^2 ^{o}C and 1.5 W/m ^{2} ^{o}C-21 W/m^2 ^{o}C under natural and forced convection greenhouse drying modes respectively. Thermal model for greenhouse fish drying was also developed. The payback period was estimated to be 1.15 years.

2.6 No load analysis

In order to utilize the drying capacity of the greenhouse dryer, it has been experimented under no-load conditions. Lokeswaran and Eswaramoorthy (2013) presented the experimental and numerical analysis of a natural convection greenhouse dryer under no-load condition. A model was developed in pre-processor GAMBIT and analyzed using the Fluent 6.3.26 software. The experimental results were validated using computational fluid dynamics software Fluent 6.3.26. Kumar et al. (2013) studied the performance of active and passive greenhouse dryer under no-load conditions. Maximum temperature in natural and forced convection modes was reported to be 40.6^{o}C and 41.6^{o}C respectively. Prakash and Kumar (2013a) developed and tested modified solar active (forced) greenhouse dryer with opaque northern wall under no-load condition. The greenhouse was tested under two conditions, firstly covering inside floor with a black sheet and secondly without covering the inside floor. Prakash and Kumar (2013b) presented the ANFIS modeling of the modified active greenhouse dryer under no-load condition. The north wall of the greenhouse was made opaque using a mirror. Prakash and Kumar (2013c) presented the thermal analysis of a new developed modified active greenhouse dyer under no-load conditions. Black polyvinyl chloride (PVC) sheet on the concrete floor and a reflecting mirror on the north wall were used to minimize the heat losses.

Prakash and Kumar (2014) designed and developed a modified natural convection greenhouse dryer and conducted experiments under no-load conditions. The north wall of the greenhouse was made opaque by a mirror and floor was covered with black PVC sheet. Joudi et al. (2014) attempted to heat the single slope greenhouse air using solar air heater (SAH) system under no load condition at Baghdad, Iraq. SAH covering 45% of the greenhouse roof area was observed to provide the daily heating load of the greenhouse. Recently Prakash and Kumar (2015) studied the thermal performance of passive greenhouse dryer with different floor conditions (barren floor, floor covered with black PVC sheet and black painted floor) under no-load condition. The dryer with black PVC floor was reported to be more effective. The embodied energy of the dryer was also determined and its value was reported to be 480.2776 kWh.

It is observed that the greenhouse dryers have been modified (by covering the greenhouse floor with black PVC sheet, reflecting mirror on the north wall and by using solar air heater) to increase the greenhouse air temperature which shortened the drying time of the products. Different softwares have also been applied for validation of the results. Energy analysis in terms of embodied energy was also calculated and found to be 480.2776 kWh.

3 Theoretical considerations used for the analysis of greenhouse drying system

3.1 Heat and mass transfer analysis for greenhouse drying system

Heat and mass transfer analysis for greenhouse drying have been carried out by many authors in natural and forced convection modes. The convective heat transfer coefficient (h_c) is evaluated by Equation 1 and Equation 2 Tiwari et al. (2004); Kumar et al. (2011); Tiwari (2003)

$$Nu = \frac{h_c X}{K_v} = C(Gr\,\mathrm{Pr})^n \quad \text{For natural convection} \tag{1}$$

$$Nu = \frac{h_c X}{K_v} = C\,(\mathrm{Re}\,\mathrm{Pr})^n \quad \text{For forced convection} \tag{2}$$

The rate of heat utilized to evaporate moisture is given as Equation 3 (Malik et al., 1982; Kumar and Tiwari, 2006)

$$\dot{Q}_e = 0.016\, h_c \left[P(T_p) - \gamma\, P(T_e)\right] \tag{3}$$

The evaporative heat transfer coefficient (h_e) can be evaluated by using the following Equation 4 (Kumar et al., 2012):

$$h_e = 0.016\, h_c \left[\frac{P(T_p) - \gamma\, P(T_e)}{T_p - T_e}\right] \tag{4}$$

Different researchers have determined the values of h_c and h_e for the drying of various commodities under natural and forced modes of greenhouse drying. A brief analysis of work carried out on different commodities is summarized in Table 2.

Table 2 Values of C and n for drying of various commodities in greenhouse drying modes

S. No.	Crop	Author	Year	C	n	h_c (W/m^2 ^{o}C)	h_e (W/m^2 ^{o}C)
1	Onion	Kumar and Tiwari	2007	0.512 – 1.120	0.137 – 0.271	1.09 – 3.08	
2	Cabbage and Peas	Jain and Tiwari	2004	0.95 – 1.03	0.13 – 0.36	8 – 38	
3	Grapes	Barnwal and Tiwari	2008			0.26 – 1.21	
4	Green chilli	Jain et al.	2010	0.972 – 1.004	0.233 – 0.404	1.900 – 7.967	
5	Jaggery	Kumar and Tiwari	2006	0.93 – 1	0.02 – 0.31	1.31 – 3.60	
6	Papad	Kumar	2013, 2013a	0.92 – 0.996	0.15 – 0 .194	0.759	23.48
7	Khoa	Kumar	2014, 2014a	0.89 – 0.99	0.16 – 0.26	1.53 – 3.14	61.92 – 94.58
8	Prawn	Tiwari et al.	2006	1.00 – 1.47	0.22 – 0.26	1.23 – 9.2	
9	Fish	Das and Tiwari	2008	1.00 – 1.47	0.22 – 0.26	1.23 – 21	

From Table 2, it is concluded that the values of experimental constants C and n generally lies in the range of 0.512-1.47 and 0.02-0.271 for the greenhouse drying of different commodities respectively. And the value of the convective heat transfer coefficient varies from 0.759 W/m^2 ^{o}C-38 W/m^2 ^{o}C. The values of evaporative heat transfer coefficient lies between 23.48 to 100 W/m^2 ^{o}C for different food commodities.

3.2 Drying models for solar greenhouse system

Mathematical modeling of the dehydration process is very useful in designing and optimization of the greenhouse dryers (Berlin and Blazquez, 1986; Brook and Bakker-Arkema, 1978; Vagenas and Marinos-Kouris, 1991). To evaluate the performance of the product dried in greenhouse, many authors have proposed mathematical models (Yaldiz et al. 2001; Fadhel et al., 2014; Panwar, 2014; Prakash and Kumar, 2014b) which are summarized in Table 3.

Table 3 Model implemented and suggested

S. No.	Author	Year	Commodity	Model name	Model
1	Yaldiz et al.	2001	Sultana grapes	Two term	$MR = a\exp(-k_0 t) + b\exp(-k t)$
2	Fadhel et al.	2014	Red pepper	Logarithmic	$MR = a\exp(-k t) + c$
3	Panwar	2014	Kasuri Methi (Fenugreek) leaves	Verma et al.	$MR = \exp(-kt) + (1-a)\exp(-g_c t)$
4	Prakash and Kumar	2014b	Tomato flakes	Prakash and Kumar	$MR = at^3 + bt^2 + ct + d$

The moisture ratio (dry basis) of the product is evaluated as Equation 5 (Elkhadraoui et al., 2015; and Panwar, 2014)

$$MR = \frac{M_t - M_e}{M_i - M_e} \tag{5}$$

3.3 Energy and exergy analysis of greenhouse drying

It is always worthy to remove maximum moisture from the products up to its safe level with the use of minimum amount of energy. Nayak and Tiwari (2008) carried out the energy and exergy analysis for the performance of photovoltaic/thermal (PV/T) integrated greenhouse in the climatic conditions of Delhi, India. The exergy efficiency of PV/T integrated greenhouse was found to be 4%. Ozgener and Ozgener (2009) investigated the drying performance of a passively heated solar greenhouse. Exergy efficiencies were derived as a function of drying time and temperature of the drying air. The average exergy efficiency of drying process was reported to be 63%-73%. The solar heated greenhouse was proposed for pre-drying during low solar energy gain.

3.3.1 Energy analysis

Energy efficiency can be determined by Equation 6 Panwar (2014):

$$\eta_{Energy} = \frac{E_{out}}{E_{in}} \times 100 \tag{6}$$

where

Energy input can be evaluated by Equation 7 Panwar (2014):

$$E_{in} = \sum I \times A \quad \text{(W)} \tag{7}$$

Energy output can be calculated by Equation 8 Panwar et al. (2013):

$$E_{out} = M_a C_a \left(T_g - T_{amb}\right) \quad (W) \tag{8}$$

3.3.2 Exergy analysis

The exergy input to the greenhouse dryer is the solar radiation exergy, i.e. radiation to work conversion (Patela, 2003; Tiwari and Mishra, 2012). Exergy efficiency is given by Tiwari and Mishra (2012). (See Equation 9, Equation 10 and Equation 11 please).

$$\eta_{solar} = \frac{Ex_{out}}{Ex_{in}} \times 100 \tag{9}$$

where

$$Ex_{in} = \sum\left(I \times A\right) \times \left[1 - \frac{4}{3}\left(\frac{T_{amb}}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4\right] \tag{10}$$

and exergy output is given by

$$Ex_{out} = M_{ao} C_a \left[\left(T_{go} - T_{ref}\right) - \left(T_{amb} + 273\right) ln \frac{T_{go} + 273}{T_{ref} + 273}\right] \tag{11}$$

A brief analysis of energy and exergy analysis of greenhouse drying of different commodities is given in the Table 4.

Table 4 Energy and exergy efficiencies for greenhouse drying of various commodities

S. No.	Commodity	Author	Year	Energy efficiency, %	Exergy efficiency, %
1	Kasuri methi (fenugreek) leaves	Panwar	2014	2.72-28.01	69.43-90.76
2	Jackfruit leather	Chowdhury et al.	2011	48.21	41.42
3	No-load	Nayak and Tiwari	2008	-	4

3.4 Greenhouse dryer performance

Greenhouse dryer performance can be evaluated in terms of efficiency factor. The drying efficiency of the greenhouse dryer is evaluated as the ratio of energy used to evaporate the moisture from the product to the energy supplied to the greenhouse dryer through solar radiations. It can be calculated as Equation 12 (Ayyappan et al., 2015; Nayak et al., 2011; Boonyasri et al., 2011).

$$\eta = \frac{m_{ev}\ \lambda}{I\ A} \times 100 \qquad (12)$$

A brief analysis of greenhouse performance evaluated by the authors is summarized in Table 5.

Table 5 Summary of greenhouse efficiency of drying of various commodities

S. No.	Product	Author	Year	Dryer efficiency, %
1	Pork	Boonyasri et al.	2011	55.7
2	Mint	Nayak et al.	2011	34.2
3	Coconut	Ayyappan et al.	2015	11.65
4	Jackfruit leather	Chowdhury et al.	2011	48.21-65.30

4 Economical aspects of greenhouse technology

To know the importance and utilization of greenhouse dryers, it becomes very important to study its economic aspects. The temperature inside the greenhouse can be maintained to the optimum level for a given crop or product for higher yield. Greenhouse (controlled environment) drying is more beneficial and profitable as compared to traditional open sun drying because of better quality product and reduced drying time.

The life cost of a dryer depends on various factors such as (Tiwari, 2003):

a) Initial investment and operating cost of greenhouse

b) Maintenance and annual cost of the product dried in the greenhouse.

c) Life of greenhouse and its salvage value

The economic evaluation of greenhouse dryers for drying of various commodities performed by different authors is summarized in Table 6.

Table 6 Economical analysis of greenhouse drying of commodities

S. No.	Commodity	Author	Year	Mode of greenhouse drying	Payback period (Years)	Estimated life of greenhouse dryer (Years)	Remarks
1	Strawberry	Banaeian et al.	2011	Data was collected	-	-	The benefit-cost ratio was found to be 1.74. Mean net return = 0.59 kg/$
2	Pork	Booayasri et al.	2011	Forced	1.15	-	Maximum capacity of dryer was estimated to be 40 kg.
3	Chilli, banana, coffee	Janjai et al.	2011	Forced	2.5	2.5	Maximum loading capacity of the dryer was estimated to be1000 kg.
4	Macadamia nuts	Phusampao et al.	2014	Forced	-	1	Loading capacity was 750 kg. Dried nuts of 13,000 kg were estimated to be produced annually.
5	Fenugreek leaves	Panwar et al.	2014	Natural	22 d	-	Loading capacity of dryer was estimated to be about 100 kg.
6	Red pepper and grapes	Elkhadraoui et al.	2015a	Mixed Forced mode	1.6	20	Solar collector was used to preheat the air entering the greenhouse. Loading capacity of dryer was estimated to be 80 kg (pepper) and 130 kg (grapes).
7	Red pepper	Elkhadraoui et al.	2015a	Mixed forced mode	1.17	20	Studied and compared the thin layer drying characteristics of red pepper in new greenhouse dryer and under open sun

4 Conclusions

About 80% of the world population live in developing countries and are dependent on agriculture. Agricultural products, just after harvesting, are dried to the safe moisture level. Solar energy is the most promising power source of energy for drying of agricultural products. Most of the farmers adopt open sun drying because it is abundant, inexpensive and non-pollutant. But the open sun dried products are also subjected to remarkable losses due to environment (dust, rain, ultra-violet rays, birds, animals etc.). But losses of fruits and vegetables are estimated to be 30%-40% during drying under open sunlight. The post-harvest losses can be reduced by adopting advanced means of drying, i.e. greenhouse drying. The greenhouse dryer can be operated in natural and forced mode as required. Studies reveal that the greenhouse dried products are of superior quality and colour as compared to open sun drying. Many authors have studied and presented various parameters of greenhouse. In this manuscript, an attempt was made to discuss state-of-the-art for each aspect. The following conclusions are drawn from this technical review.

1. The maximum values of CHTC were observed to be 17 W/m^2 ^{o}C and 38 W/m^2 ^{o}C under natural and forced greenhouse drying modes respectively.
2. Maximum greenhouse drying efficiency was observed to be 65.30%.
3. The maximum values of energy and exergy efficiencies were found to be 48.21% and 90.76% respectively.
4. Minimum and maximum payback period was found to be 22 d and 2.5 years respectively.
5. The benefit-cost ratio was calculated as 1.74 and net return was estimated to be 0.59 kg per dollar.
6. Various drying models have been suggested and implemented to study the drying behaviour of the products. These models would be helpful in designing and optimization of the greenhouse dryers.
7. Hybrid greenhouse dryers (with PV/T) were also used and its efficiency was found to be 34.2% and can be attempted in remote areas where there is scarcity of electricity.
8. Greenhouse is integrated with solar collector and its payback period was observed to be 1.17 years.
9. Modified greenhouses are also being adopted to increase the performance.
10. Very little work on usages of heat storage and phase change materials is carried out, and the future studies can be carried out.
11. Therefore, future researchers should be targeted on hybrid sustainable greenhouse dryer which can be introduced in rural regions to reduce the spoilage and improve the quality of the dried products so that the farmers get the significant agricultural return on their efforts.

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Nomenclature

A = Area of greenhouse (m^2)

A_t = Area of tray, m^2

a, b, c, d, g, h, g_c, *k,* k_0 = Drying models Constants

C = Experimental constant

C_a = Specific heat of drying air J/kg/K

C_v = Specific heat of humid air, J/kg ^oC

Gr = Grashof number = $\beta g X^3 \rho_v^2 \Delta T / \mu_v{}^2$

g = Acceleration due to gravity, m/s^2

h_c = Convective heat transfer coefficient, $W/m^2\,^oC$

h_e = Evaporative heat transfer coefficient, $W/m^2\,^oC$

I = Solar radiation intensity on greenhouse, W/m^2

K_v = Thermal conductivity of humid air, W/m ^oC

n = Experimental constant

N = Number of observations in each set

M_{ao} = Mass flow rate of drying air at outlet of dryer, kg/s

m_{ev} = moisture evaporated, kg

M_{ev} = Mass evaporated, kg

M_e = Equilibrium moisture content of the product (dry basis)

M_i = Initial moisture content of the product (dry basis)

M_t = Moisture content of the product at time t (dry basis)

MR = Moisture ratio

m_a = Mass flow of drying air, kg/s

Nu = Nusselt number = $h_c X / K_v$

Pr = Prandtl number = $\mu_v C_v / K_v$

Re = Reynolds number = $\rho_v V X / \mu_v$

$P(T)$ = Partial vapour pressure at temperature T, N/m^2

$\dot{Q}_e$ = rate of heat utilized to evaporate moisture, J/m^2 s

T_{amb} = Ambient temperature, K

T_g = Drying air temperature, K

T_p = Temperature of product surface, ^oC

T_e = Temperature just above the product surface, ^oC

t = Time, s

ΔT = Effective temperature difference, ^oC

T_{go} = Air temperature at greenhouse outlet, ^oC

T_{ref} = Reference temperature, ^oC

T_s = Sun surface temperature = 6000 K

V = Air velocity inside the greenhouse, m/s

X = Characteristic dimension, m

Greek symbols

β = Coefficient of volumetric expansion, 1/K

γ = Relative humidity, %

λ = Latent heat of vaporization, J/kg

μ_v = Dynamic viscosity of humid air, Ns/m^2

ρ_v = Density of humid air, kg/m^3