

Moisture removal rate of solar dryers – A review

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ABSTRACT

Agriculture is fighting many tough challenges to successfully meet the demands of the growing population. Not just production but effectively storing and utilizing the produce is also important. Preservation of agricultural products, from deterioration before its use, is essential for various reasons like, the place of production is far from its utility, some of the products may not be producible throughout the year, to meet the unexpected rise in demand, etc. Among various factors, moisture plays a critical role in spoilage of agricultural products. Presence of moisture enables bacteria, yeast, and molds to grow and cause spoilage. Solar dryers enable cheaper, easy and effective way to remove the moisture at the very place of production. Solar dryers effectively capture and concentrate sun's heat to heat the product and evaporate and release the moisture until the moisture comes down to safe level. Various dryer designs were designed and studied that can effectively trap the solar heat inside them. The present work aims to review some of the designs and compare their performance based on their moisture removal rate.

KEY WORDS: Solar dryer, moisture removal, agricultural products.

1. INTRODUCTION

Agriculture is the heart of human life, work and economy. Preservation extends the life of agricultural products before deterioration and helps to meet the shortages in supply and reduce postharvest losses. Most of the fruits and vegetables have a moisture content around 70-85%. They must brought down to their safe storage level which is around 5 to 15%. Figure 1 shows the safe moisture content for different temperatures as reported by Food and agriculture organisation of The United Nations (2011).

Moisture removal Rate: Amount of moisture that can be removed and the rate at which it can be removed depends on the type of material, amount of bound and unbound moisture, whether they are hygroscopic or non-hygroscopic and the physical properties of air used. Hygroscopic materials will always have some residual moisture whereas Non-hygroscopic materials can be dried to zero moisture level. This moisture in hygroscopic material may be a unbound or bound moisture. The bound moisture is held inside material because of closed capillaries or surface forces. The unbound moisture in the material are held by surface tension of water.

The properties of air used to remove moisture is critical especially its moisture level. Moisture is removed as long as there is difference between the vapour pressure of water in the material and the partial pressure of water in the surrounding air. When they reach an equilibrium it is called the equilibrium moisture content (EMC).

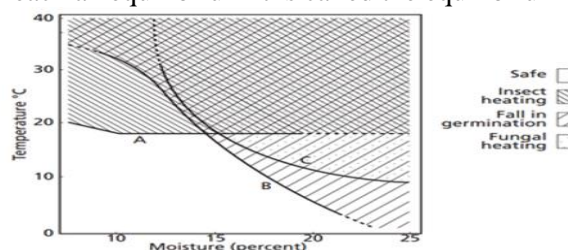


Figure.1. Effect of moisture content and temperature on the storability of crops

Figure.2, shows the typical drying cure presented by Don (2008) explaining the steps involved in drying. Until critical moisture point there is a constant drying rate and after that the drying rate keeps decreasing. For both non-hygroscopic and hygroscopic materials the constant drying rate is same, but decreasing drying rate is different. In the decreasing drying rate region, for non-hygroscopic materials, the drying rate keeps decreasing until the moisture content reaches zero where as for the hygroscopic materials, the decreasing rate is similar until the unbound moisture is fully removed. After that it further decreases until some part of bound moisture is removed.

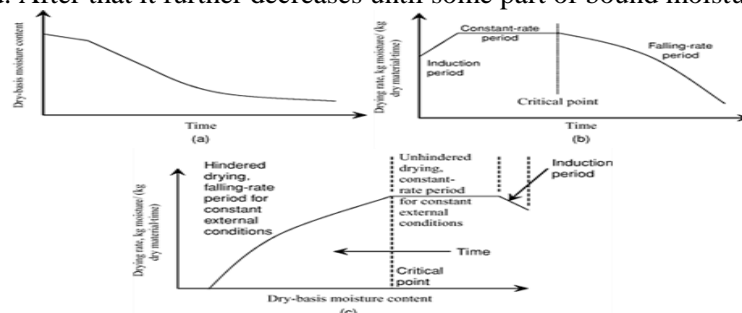


Figure.2. Typical drying curve (a) moisture content (dry basis) as a function of time, (b) drying rate as a function of time, (c) drying rate

Heat required to evaporate the moisture can come from different sources. Solar energy is one such source but is free and clean. Solar driers are widely used to dry agricultural produce as they can be installed closer to the fields and easy to operate.

Performance Parameters in Solar Drying: The capital investment of solar dryers are generally high. Tiwari (2016) expressed that in order to compete with other commercial dryers, one must come up with efficient designs. Some of the parameters that influence effective drying are available solar heat, ambient air temperature and humidity, thermal conductivity, absorptance, size and shape of the product. Higher heat from sun, surface area and thermal conductivity and ambient air temperatures will result in faster drying. But increase in the humidity of the ambient air reduces the diffusion of moisture from the product into air which eventually slows down the drying process.

Moisture content on wet basis is given as the ratio of weight of moisture (m_w) present in the material per unit of wet material (Sengar, 2012).

$$M_{wb} = \frac{m_w}{m_w + m_d} \quad (\text{or}) \quad M_{wb} = \frac{W-D}{W} \text{ kg per kg of mixture}$$

Moisture content on dry basis is given as the ratio of water content present in the material to the weight of dry material (m_d).

$$M_{db} = \frac{m_w}{m_d} \quad (\text{or}) \quad M_{db} = \frac{W-D}{D} \text{ kg per kg of mixture}$$

Where, W and D refer to the wet mass and dry mass of the material.

Collector efficiency is the amount of solar insolation that is transferred to the air.

$$\eta_c = \frac{\dot{m} C_p (T_{af} - T_{ai})}{I_c A_c}$$

Where, \dot{m} , C_p , I_c and A_c refers to the mass flow rate of air, specific heat of air, solar insolation on the collector and area of the collector respectively. T_{af} and T_{ai} refer to the final and initial temperature of air across the solar collector.

Drying efficiency is the amount of solar insolation used to remove the moisture by evaporation.

$$\eta_d = \frac{w H_{fg}}{I_c A_c}$$

Where, w is the amount of moisture removed and H_{fg} is the latent heat of vaporisation of water.

Various technologies are used in both domestic and industry to preserve food product by removing the moisture in them. Of them solar drying is widely used for its simplicity, cost and ease of operation in poor countries. The function of a dryer is to remove the moisture, within certain period, from the product and bring it down to a desired level that prevents deterioration. There are different methods used to dry agricultural products using the energy from the sun. They can be classified generally under sun drying, greenhouse drying and solar drying. Solar drying further can be classified as natural circulation, forced circulation and mixed mode dryers. Generally, natural drying is done in open space where the moisture in the product evaporates using solar energy and the moisture diffuses into the ambient air.

Direct and Green House Drying: The products are directly exposed to sun and the produce gain heat from solar radiation. The moisture in the products evaporate and diffuse into the ambient air. Continuous drying during cloudy or rainy days can be achieved using greenhouse dryers. They are also equipped with auxiliary heating systems like LPG or biomass etc. Figure.3 and 4, shows open drying and green house drying given by Sadeghi (2012) and Janjai (2012).

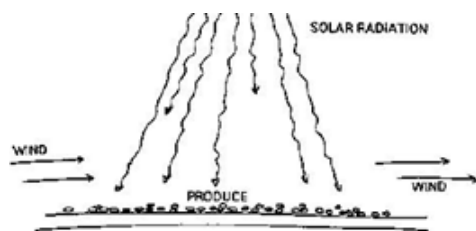


Figure.3. Open sun drying

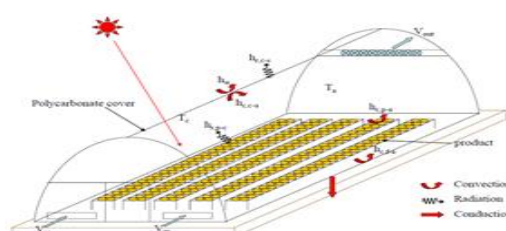


Figure.4. Greenhouse drying and energy

Drier Designs and their Performance: Natural drying is slow and requires more surface area. Various factors like insufficient drying, loss due to insects, birds and rodents, adverse weather, insect infestation, etc. contributes to high crop loss. Solar dryers apart from serving the purpose, says Ekechukwu (1999) that they also safe guards the grains and crops from such loses.

Industrial drying though faster compared to natural drying but is costly and uses non-renewable energy sources. The primary function of a solar dryer is to increase amount of heat available to the product by trapping the solar heat. It also safeguards the products from external weather, birds etc.

Various sophisticated dryer designs are being designed and studied that can effectively trap the solar heat inside them. Dryers can be high temperature or low temperature dryers. High temperature dryers are used where fast drying is necessary. Low temperature dryers are used as long-term bulk storage dryers.

Indirect-natural convection driers: Bukola (2008) developed a simple passive mixed mode dryer as shown in Fig.5 to dry yam chips of about 4 mm thickness. The dryer reached a maximum temperature of 57°C and was able to bring down the moisture level to its desired value in 14 hours. Sengar developed a low cost natural circulation drier to dry Kokum fruit. They reported a maximum drying efficiencies of 9.88% and 7.66 % for salted and unsalted Kokum fruits.

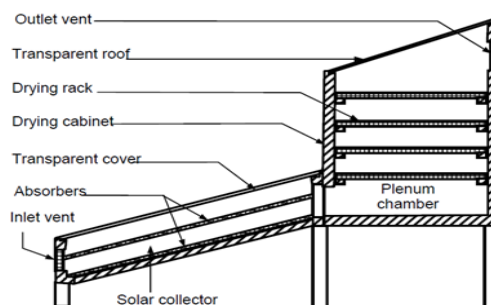


Figure.5. Mixed mode solar drier

Indirect-forced convection driers: All solar driers can have additional components or systems to supplement the solar collectors to meet the heating requirement whenever there is a need like a fall in intensity of sunlight etc. Fudholi (2013) added an auxiliary heating system as shown in Fig.6, add heat apart from what was gained through solar collector. Prasad and Vijay (2005) developed solar-biomass hybrid drier to dry ginger, turmeric and guduchi. They compared the results with solar only and open-sun drying. The hybrid drier was able to dry the materials almost twice faster than solar-only and 6 times faster than open-sun drying. In forced convection, sallam (2015) found that, the rate of drying was the same in both direct and indirect drying. This is because both the temperatures and the air velocity above the trays were almost the same. In natural convection system, the total drying time of the direct solar dryer was less compared to the indirect drier. This may be due to the greenhouse effect. Greenhouse effect in direct systems tends to increase air temperature inside the direct solar dryer thereby reducing the drying time.

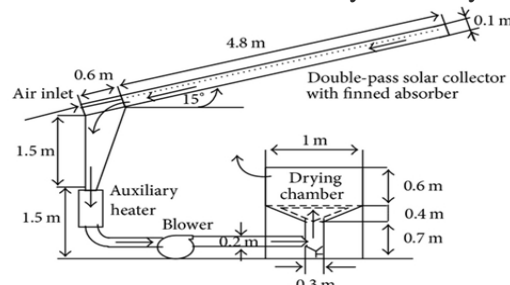


Figure.6. Schematic of solar drier with auxiliary heater

Mohanraj and Chandrasekar (2008 and 2009) designed and tested the performance of an indirect forced convection solar drier with sand and gravel fillings between the absorber and insulation as shown in Fig.7. They dried copra and chilli in a chamber. The drier efficiencies were found to be 24% and 21%.

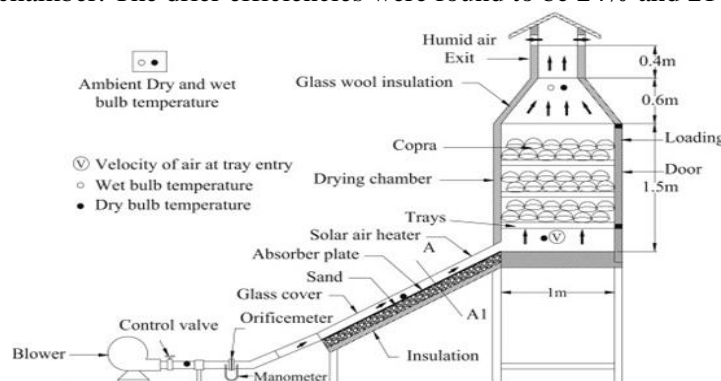


Figure.7. Schematic of solar drier used by Mohanraj (2009)

Shanmugam and Natarajan (2007) developed a forced circulation solar dryer and integrated a desiccant bed with reflective mirrors as shown in Fig.8. They tested its performance by drying 10 mm thick green peas and pineapple slices. Every additional feature proves to decrease the drying time. For example green peas took 31 hours to dry when a simple solar dryer was used. But it dried in 21 and 19 hours when a desiccant is used with and without reflectors respectively.

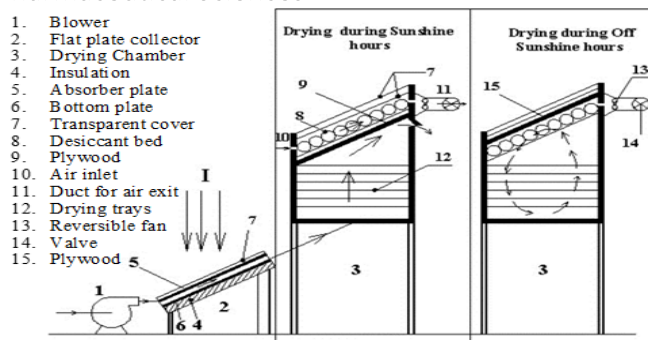


Figure.8. Schematic of solar drier with desiccant and reflectors

Indirect-hybrid system driers: Not just components even different systems were integrated with solar system in drying. Prasad and Vijay (2005) developed solar-biomass hybrid drier to dry ginger, turmeric and guduchi as shown in Fig.9. They compared the results with solar only and open-sun drying. The hybrid drier was able to dry the materials almost twice faster than solar-only and 6 times faster than open-sun drying.

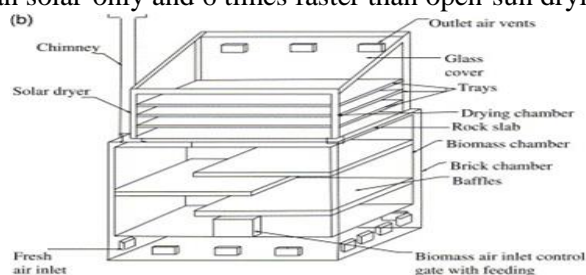


Figure.9. Schematic of solar – biomass hybrid drier

Yahya (2016) used biomass and heat pump systems, as shown in Fig.11, along with solar panels in drying chilli and achieved 98% reduction in moisture in 11 hours. Ceylan and Gurel (2016) designed and tested an indirect, forced circulation, mixed-mode fluidized bed drying system as shown in Fig.10. A solar drier system can be synchronised with any other heating systems and will contribute to the reduction in cost in terms of energy.

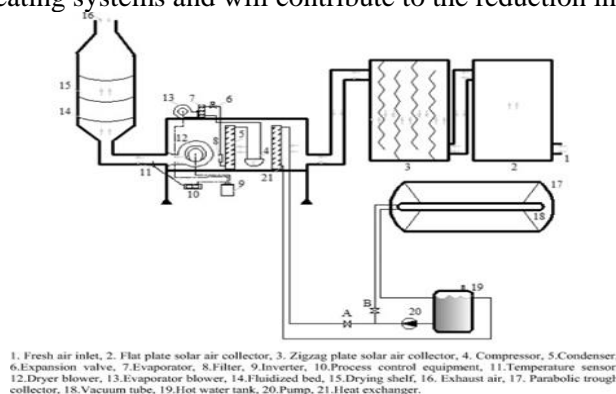


Figure.10. Schematic of mixed-mode fluidized bed drying system

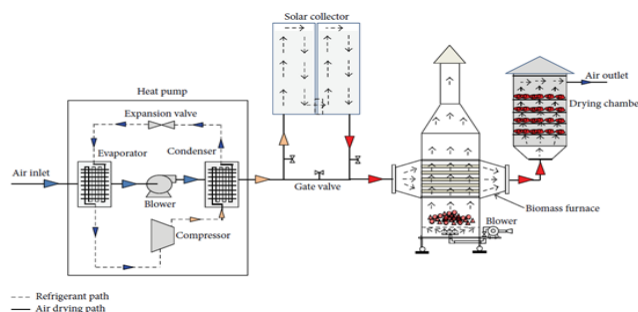


Figure. 11. Solar assisted heat pump dryer integrated with biomass

Moisture Removal Rate of Various Drier Models: Tiwari (2016), has tabulated various agricultural commodities, fruits, vegetables and crops that are dried using various dryer models and their performance. Solar driers models performances are compared with each other based on their moisture removal rate, collector efficiency and overall efficiency. Different kind of solar driers and their performances are compared and shown in Table.1.

Table.1. Moisture removal rate comparison of various driers used to dry agricultural produce

	Initial Moisture (% wet basis)	Final Moisture (% wet basis)	Duration (hours)	Moisture removal rate (kg/kWh)	Dryer description	Temp. (°C)	Collector (Drier) Efficiency (%)	Reference
Yam chips		85 reduction	14		Mixed mode-free convection, chamber drying	57		Bukola (2008)
Ginger	319	11	192		Open sun			Prasad (2005)
Turmeric	359	8.8	270					
Guduchi	257	9.6	290					
Ginger			72		Solar only		(29.1)	
Turmeric	(dry basis)	(dry basis)	95				(22.44)	
Guduchi			120				(13.5)	
Ginger			33		Natural convection, solar-biomass hybrid drier	67	(15.59)	
Turmeric			35				(14.74)	
Guduchi			50				(7.5)	
Kokum-Ripened	85-93	10	15		Indirect, rotary natural convection with chamber drying	57	70.97 (9.88)	Sengar (2012)
Salted unsalted			21				(7.66)	
Kokum-Un-Ripened	85-93	10	32		Indirect, rotary natural convection with chamber drying	57	70.97 (4.72)	
Salted unsalted			27				(4.20)	
Copra (coconut)	51.8	9.7	82		Indirect, forced Convection with sand packing. Chamber drying	60	24	Mohanraj (2008)
Chilli	72.8	9.1	24	0.87	Indirect forced Convection with Gravel packing. Chamber drying	60	21	Mohanraj (2009)
Chilli		98% reduction	62		Open sun drying			Yahya (2016)
			11	0.14	Solar assisted heat pump dryer integrated with biomass furnace	70.5	(9.03)	
Chilli	80	10	65		Open sun drying			Fudholi (2013)
			33	0.19	Indirect, forced convection drier with auxiliary heater.	55	74% (13)	
Chilli								
Low air velocity	80-85	5-10	16		Forced convection drier	44	55	Margarita (2017)
High air velocity			21			44	72	
Green Peas	80	5	31		Indirect forced Convection		43	Shanmugam (2007)
Pineapple slices			34		Chamber drying		49	
Green Peas			21		Indirect forced Convection with desiccant bed.	76	48	
Pineapple slices			32		Chamber drying			

Green Peas			19		Indirect forced Convection with desiccant bed and reflectors. Chamber drying	86	53	
Pineapple slices			28					
Mint Leaves	567 (dry basis)	17 (dry basis)	11		Indirect, forced circulation, mixed-mode fluidized bed drying	57	78	Ceylan (2016)
whole mint	75-85	5	32		NaturalDirect	55.1		Sallam (2015)
			32		Natural-indirect	46.5		
			30		Forced-Direct	38.4		
			30		Forced-Indirect	38.7		

It can be observed that though addition of auxiliary systems improved the moisture removal rate, it has also reduced the overall energy efficiency of the systems. For example, as observed by Prasad (2005), the ginger's moisture removal time has reduced from 72 hours to 33 hours but the efficiency drops from almost half i.e from 29% to 15%. This may be because of increase in heat loss and poor thermal conductivity of air. Efficiency is also a matter of the type of products used. The efficiency of the collector drops by 50% when an un-ripened fruit is dried compared to drying a ripened fruit. As Margarita (2017) observed that it is possible to circulate air at relatively low velocities and still obtain the same temperature in the drier. Certain design modifications may not produce any significant performance improvement as observed by Shanmugam and Natarajan (2007). Pineapple slices doesn't show great improvement with the addition of desiccants. So a onetime least cost design like reflecting mirrors, itself may serve the purpose. The moisture removal rate and drier efficiency are significantly affected by the type of product dried. Each products may have few drier deigns where they will produce the output with minimum energy consumption.

2. CONCLUSIONS

Solar drying reduces the drying time at least by half from sun drying.

The drying rate of forced convection systems are higher than natural convection systems. This is because of the improved convection coefficient associated with increase in air velocity.

For forced convection systems, weather the drier is direct type or indirect type doesn't make a big difference. But direct type natural solar dryers have less drying time compared to indirect type natural solar driers.

The drying time has decreased with the addition of auxiliary systems like biomass systems but the overall drying efficiency also decreased. This may because of increase in heat loss as the medium used is only air whose thermal conductivity is low.

By comparing various models for a similar products it can be observed that each solar driers models must be selected based on the type of product to be dried. Concentrating only on heat may result in loss of energy and high investment and maintenance costs.

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