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Thermo-environomical and drying kinetics of bitter gourd flakes drying under north wall insulated greenhouse dryer

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ABSTRACT

The greenhouse dryers consist opaque and insulated north wall with solar air heating collector at the bottom. It has been used for bitter gourd flakes drying under natural and forced modes. Thermal models were developed for the both modes of drying. Experiments were performed concurrently for open sun, natural and forced modes to compare their thermal modeling and drying kinetics results. Energy analysis includes; embodied energy, CO_2 emission, CO_2 mitigation and economic evaluation were done for both modes of drying. The predicted values of bitter gourd flakes and room air temperature, and moisture evaporation rate showed the fair agreement with the experimental observations within the root mean square of percentage deviation ranged from 3.25% to 5.82% and 2.83% to 5.26%, and the coefficient of correlation ranged from 0.98 to 0.99 and 0.99 to 1 under natural and forced modes, respectively. The final moisture ratio was achieved 0.12 after 15 h, 0.14 after 16 h and 0.25 after 21 h under forced, natural and open sun modes respectively. Crop drying under forced mode is found significantly faster than other modes of drying. The Logarithmic model was selected as best curve fitting technique for non-linear regression analysis for forced mode. The energy payback time of developed dryers under natural and forced modes is 1.68 and 2.35 years, respectively. The net CO_2 mitigation of bitter gourd flakes drying is 33.04 and 36.34 t under natural and forced modes, respectively.

1. Introduction

Open solar drying is an economical and ancient technique of food preservation. It is widely used and a general practice of drying of fruits, vegetables, fish, meat, forest products and seeds for preservation without using any conventional energy. However, it has some drawbacks such as possibility of degradation of product due to microbiological reactions, insect infestation, overheating and de-coloration (Chauhan et al., 2015, 2017; Dev et al., 2015).

In order to get better quality of dried agricultural products many conventional and non-conventional energy based dryers came into existence. But conventional energy based dryers utilizes energy like petroleum products (Petrol, Diesel and Kerosene) and electricity which increases the cost of dried product and creates the environmental pollution problems also. Therefore, to save the environment and reduce the drying cost, solar dryers were appeared (Kumar et al., 2014; Prakash and Kumar, 2013; Sharma et al., 2009). Solar dryers use solar energy which is freely available and pollution free. Solar dryers minimize the all the problem related to conventional energy based drying. Solar dryers are broadly classified into two types; direct and indirect solar dryers (Singh et al., 2015a; Ekechukwu and Norton, 1999). In direct solar dryers, solar radiation passes through a transparent cover and strike over the drying tray. The transmitted solar radiation are absorbed by the crop surface, which increases its temperature and moisture removal occurs. In indirect solar dryers, incoming ambient air is heated using solar air heater and further, heated air is directed into the drying chamber. Once the heated air comes in contact with the crop, moisture contents start evaporating (Chauhan and Kumar, 2016a, 2016b; Singh et al., 2015b).

Greenhouse drying is a direct type solar drying. The greenhouse effect is used to produce heat inside at micro level. Greenhouse dryer is a solution of all deficiency faced during the open sun drying. It reduces the losses and improves the quality of dehydrated product. In the greenhouse drying system, the drying product is kept on the tray and moisture removal occurs either by forced or natural mode of operation. It can be used throughout the year to make it more cost effective (Ekechukwu and Norton, 1999; Kumar et al., 2014). Natural mode greenhouse drying system works on thermosyphic effect, whereas forced mode greenhouse drying system has provision of exhaust fan installation to ventilate the humid air from the drying chamber. Forced

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Nomenclature

A_{cp}	cross sectional area of the crop (m^2)
A_i	surface area of greenhouse wall (m^2)
A_{sc}	solar collector area
A_{tray}	effective area of tray (m^2)
A_v	area of vent (m^2)
C	constant
C_d	coefficient of diffusivity
EPBT	energy payback time
E_{ao}	annual thermal output energy (kWh)
E_{em}	embodied energy (kWh)
E_{ao}	annual energy output (kWh)
E_{do}	daily output energy (kWh)
E_{di}	daily input energy (kWh)
f (t)	time-dependent derivative
g	acceleration due to gravity (m/s^2)
h_{cvt}	convective heat transfer coefficient of the air ($W/m^2\,°C$)
I_i	global solar radiation (W/m^2)
L_a	losses of energy by consumer in domestic appliances
L_{td}	losses of energy per unit in transmission and distribution
MR	moisture ratio
M_{cp}	mass of the crop (g)
M_{final}	final moisture content
$M_{initial}$	initial moisture content
m_{ev}	total moisture evaporated
N′	number of air exchange per hour
N	number of sets
N_0	number of observations in each set
N_{dy}	number sunshine days
N_{hr}	number of sunshine hours per day
n	number of vent in greenhouse dryer
n′	life span of dryer (years)
P(T)	vapor pressure of humid air at temperature T, (N/m^2)
ΔP	partial pressure difference between room and ambient air temperature (N/m^2)
Rh_{am}	ambient relative humidity (%)
Rh_{gh}	inside greenhouse relative humidity (%)
T_{am}	ambient temperature (°C)
T_{cp}	crop temperature (°C)
T_{gd}	ground temperature (°C)
T_{rm}	temperature inside the North wall insulated greenhouse dryer (°C)
t	ton
U_i	overall heat loss ($W/m^2\,°C$)
U	uncertainty
V	velocity of exhaust air (m/s)
v_{in}	inlet air speed (m/s)
v_o	outlet air speed (m/s)
W	X_m/X_{m0}dimensionless water content
W_{bg}	weight of moisture present in a crop
W_{ud}	weight of undried crop and
W_{bd}	weight of bone dry material in the crop (g)
wb	wet basis
X	characteristic constant
X_m	water content (kg water/kg dry matter)
α_{cp}	absorptivity
β	coefficient of volumetric expansion of humid GHD air (1/°C)
τ_i	transmissivity
λ	latent heat of vapourisation (kJ/kg)
γ	solar radiation coefficient
σ	standard deviation
ρ	density of inside room air (kg/m^3)
η_d	daily efficiency (%)

mode greenhouse drying system provides better control and optimum drying conditions inside the dryer with the help of fan or blower (Prakash and Kumar, 2015; Tiwari et al., 2004).

Natural mode greenhouse dyer is referred for comparatively low moisture content crop (Prakash and Kumar, 2014a). Janjai et al. (2011) introduced a thermal model to examine the drying performance for banana chilli and coffee. A reasonable agreement was found with root mean square differences 12.9%, 14.6% and 11.4% for, chilli coffee and banana, respectively. The payback period of greenhouse dryer was 2.5 years. Turhan (2006) proposed a thermal model for greenhouse pepper drying and compared results with open air drying. The greenhouse dryer was found 2–5 times more efficient and produced 5–9 °C more temperature than open air condition. Kumar and Tiwari (2006a) offered a thermal model for 0.75 and 2.0 kg of jaggery under natural mode greenhouse dryer to compute the moisture evaporation rate, jaggery and greenhouse room air temperatures. The coefficient of correlation was ranged from 0.96 to 1 for the mass evaporation and 0.90–0.98 for crop and greenhouse room air temperatures, respectively. Sacilik et al. (2006) carried out mathematical modeling of solar tunnel dryer for thin layer of organic tomato flakes. Developed model reduced the initial investment of dryer during fabrication and processed better quality dried products. Jain and Tiwari (2004) performed a mathematical modeling of peas and cabbage drying. The coefficient of correlation was ranged from 0.98 to 0.99 for the crop mass and, 0.77–0.97 for crop and greenhouse room air temperatures.

Forced mode greenhouse dyer is referred for high moisture content crop (Prakash and Kumar, 2014a). Tiwari et al. (2016) developed a mathematical model for a hybrid photovoltaic-thermal greenhouse dryer to predict the crop, solar cell and greenhouse temperatures and results were validated with experimental outcomes. The theoretical and experimental outcomes were in good coefficient of correlation as 0.92, 0.96, 0.99 and root mean square percentage deviation 4.64%, 0.96%, 0.97% for crop, solar cell and greenhouse temperatures respectively. Panwar et al. (2013) did thermal modeling of a battery operated tunnel dryer for drying of surgical cotton. The dryer capacity of the dryer was 600 kg and the moisture content of cotton was reduced from 40 to 5% in one day. Janjai et al. (2009) proposed a thermal model of a PV-ventilated tunnel dryer for drying of longan and banana. The root mean square difference of longan and banana was 6% and 9% for moisture content and, 3% for temperature prediction. The payback period was 2.3 years. Smitabhindu et al. (2008) introduced a mathematical model for forced mode solar-assisted dryer for banana drying. The optimized recycle factor and collector area were found 90% and 26 m^2, respectively. Kumar and Tiwari (2006b) performed the thermal modeling of jaggery drying under forced convection mode for the optimization of operating parameters. The greenhouse air temperature was decreased with increasing the number of air changes per hour. The coefficient of correlation was in the range of 0.96–0.98. The square root of percentage deviation was varied from 6.75% to 12.63%. Jain and Tiwari (2004) demonstrated a thermal model to explain the drying behavior of cabbage and peas in forced mode greenhouse dryer. The range of root mean square error was 3.88–8.43 and coefficient of correlation was 0.92–0.99. Condori and Saravia (1998) developed a model for estimation of evaporation rate in the forced mode greenhouse dryer with provision of single and double drying chambers. The simulation results showed that the double chamber greenhouse dryer enhanced the drying potential by 90%.

The fabrication of experimental setup and testing is costly and tedious task. Therefore, thermal modeling can help to optimize the design aspect and important operational factors. With the help of thermal