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Research Paper

Thermal modeling and drying kinetics of gooseberry drying inside north wall insulated greenhouse dryer

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HIGHLIGHTS

- North wall insulated greenhouse dryers with solar air heating collector is designed and developed.
- Thermal modeling is done for gooseberry drying under active and passive modes.
- Greenhouse passive drying reduced 41% more moisture content as compare to open sun drying.
- Greenhouse active drying reduced 34% more moisture content as compare to open sun drying.
- Predicted and experimental results were in the range of 0.94–0.1 coefficient of correlation.
- Prakash and Kumar model was selected as best curve fitting technique for drying rate.

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ABSTRACT

The north wall insulated greenhouse dryers with solar air heating collector are used for gooseberry drying under passive and active modes till stagnation in their moisture evaporation. Experiments are performed simultaneously for open sun, passive and active modes to validate thermal models and compare their drying kinetics. The predicted moisture evaporation rate, gooseberry surface and greenhouse room air temperatures show the fair agreement with the experimental observations within the root mean square of percentage deviation ranges from 4.58 to 16.39% and coefficient of correlation ranges from 0.96 to 1 under passive and active mode. For active mode, coefficient of correlation ranges from 0.94 to 0.99 and root mean square of percentage deviation ranges from 3.49 to 12.24%. The passive mode greenhouse dryer was found more effective than other dryers. Based on SSE, R-square, adjusted R-square and RMSE, Prakash and Kumar model was selected as best curve fitting technique for non-linear regression analysis for gooseberry drying under passive mode. The proposed thermal model will be useful tool for designing energy efficient greenhouse drying system for given mass and location.

1. Introduction

Greenhouse dryer is basically a direct type of solar dryer and it has been designed for two modes of air circulation namely passive (natural convection) and active (forced convection) modes [1–4]. Regular greenhouse structure can be use throughout the year either for cultivating or drying the crops which improves the economic benefits [5,6]. An energy efficient greenhouse dryer design according to the crop and climatic condition is another major challenge as, fabrication and experimental work is lengthy and expensive task. Thermal modeling is already proved alternative option to select a proper design, and optimizing the operational and design parameters. Simulation and modeling of design parameters is recommended for getting better and faster results [7].

Kumar and Tiwari explained a thermal model for jaggery drying inside passive mode greenhouse dryer. The thermal model was used to forecast the moisture evaporation rate, jaggery and greenhouse room air temperatures. The coefficient of correlation varied from 0.96 to 1 and 0.90 to 0.98 for moisture evaporation rate and, jaggery and greenhouse room air temperatures, respectively [8]. Jain and Tiwari proposed a mathematical model to reveal the thermal behavior of cabbage and peas inside passive mode greenhouse dryer. The coefficient of correlation and root mean square of percentage deviation ranged from 0.90 to 0.97 and 4.36 to 8.57 respectively for the greenhouse room air and crop (cabbage and peas)

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Nomenclature

A_{cp}	cross sectional area of the crop (m^2)
A_i	surface area of greenhouse including north wall (m^2)
A_{tray}	effective area of tray (m^2)
A_v	area of vent (m^2)
C	constant
C_d	coefficient of diffusivity
E_a	root mean square of percent deviation for greenhouse air temperature (%)
E_c	root mean square of percent deviation for crop temperature (%)
E_m	root mean square of percent deviation for mass (%)
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)
M_{wb}	moisture content wet basis
MR	moisture ratio
M_{cp}	mass of the crop
N'	number of air exchange per hour
N	number of sets
N_0	number of observations in each set
n	number of vent in greenhouse dryer
P(T)	vapor pressure of humid air at temperature T, (N/m^2)
ΔP	partial pressure difference between room temperature and ambient air (N/m^2)
R_a	coefficient of correlation for greenhouse air temperature
R_c	coefficient of correlation for crop temperature
R_m	coefficient of correlation for mass
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)
U_{ex}	percentage of external uncertainty (%)
U_{in}	percentage of internal uncertainty (%)
U_i	overall heat loss (W/m^2°C)
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_o	weight of moisture present in a crop
W_m	weight of undried crop and
W_{bd}	weight of bone-dry material in the crop.
X	characteristic constant
X_m	water content (kg water/kg dry matter)
X_i-X	deviation from the mean
α_{cp}	absorptivity
β	coefficient of volumetric expansion of humid GHD air (1/°C)
τ_i	Transmissivity
γ	solar radiation coefficient
σ	standard deviation,
ρ	density of inside room air (kg/m^3)
η_{ith}	the instantaneous thermal loss efficiency factor

temperature, respectively. For the moisture evaporation rate, the coefficient of correlation and root mean square of percentage deviation were 0.98 and 2.98 for cabbage respectively and, 0.99 and 4.72 for peas respectively [9]. Sacilik et al. did the mathematical modeling of organic tomato flakes drying inside passive mode greenhouse tunnel dryer. The final moisture content was achieved after five days of drying from 93.35 to 11.50% wet basis for 4.5 kg. The coefficients of correlation and root mean square of percentage deviation were 0.9688 and 15.7 respectively [10].

Kumar and Tiwari performed the thermal modeling of jaggery drying inside active mode even span greenhouse dryer for the optimization of drying factors. It was concluded that inside room air temperature is inversely proportional to number of air exchanges rate. The coefficient of correlation and the square root of percentage deviation were found in the range of 0.96–0.98 and 6.75–12.63 respectively [8]. Condori and Saravia developed a model for the evaluation of moisture evaporation rate during greenhouse drying under active mode. Simulation results had potential to improve drying rate [11]. Jain and Tiwari presented the thermal model to demonstrate the drying behavior of cabbage and peas in active mode greenhouse dryer. The range of root mean square error and coefficient of correlation were 3.88–8.43 and 0.92–0.99 respectively [9]. Janjai et al. offered a thermal model of a PV-ventilated (active mode) greenhouse dryer for drying of peeled longan and banana [12], macadamia nuts [13] and tomato. These models were capable to present the optimal design for the greenhouse system [14]. Panwar et al. performed thermal modeling of a battery operated walk-in-type tunnel dryer (active mode) for surgical cotton drying. Dryer was capable to dry 600 kg cotton with moisture content from 40% to 5% in one day [15].

As per above comprehensive literature review, till now, thermal modeling has been done for conventional greenhouse drying systems. However, there are considerable direct solar radiation and conductive losses from transparent north wall and bare ground inside the greenhouse dryer, respectively. To avoid these losses, greenhouse dryers have been modified for passive and active modes [7,16]. In the present study, greenhouse dryers with opaque north wall are designed and fabricated with solar collector placed inside the floor are introduced under passive and active modes. Experimentations have been conducted for both modes of operation to validate the thermal modeling of developed drying systems. The main objectives of this research work are, (i) to develop the thermal models under passive and active modes, (ii) to perform the experimentations for gooseberry drying, (iii) validate the thermal models, (iv) to explain the thin layer drying behavior and drying kinetics of gooseberry.

2. Material and methods

2.1. Experimental setup

The dimension of the designed roof type even span north wall insulated greenhouse (NWIGD) dryer under passive and active modes is 1.5 m × 1.0 m × 0.5 m. The effective base area of the drying chamber is 1.35 × 0.85 m^2. To cover the basic structure of the drying system, 3 mm thick, UV treated polycarbonate sheet is used. The central height of the drying system is 0.712 m whereas; the height of south and north wall is 0.5 m. The roofs are tilted at 23.5° to allow the maximum solar radiation inside the drying system according to the Bhopal latitude (23.5°). The tray is fabricated with stainless steel wire meshed having the dimension 1.4 × 0.9 m^2. It was placed on the runner at 0.25 m height to ensure sensible intensity of air exchange under and around the crop.

In the passive mode greenhouse dryer, two circular holes of 0.15 m diameter are provided just below the tray for the inlet air, and one rectangular air vent is provided in the middle of the roof