Abstract

An investigation was carried out the solar greenhouse drying of ginger slices under the climatic conditions of the northeastern region of India. The drying system employed in this study was a solar greenhouse dryer with a parabolic structure integrated with (i) corrugated plate type solar air heating with phase changing material (corrugated SAH with PCM), (ii) Air-circulation system powered through a photovoltaic (PV) module and (iii) sensible heating storage inside the drying chamber. During the experimentation period in summer solar radiation varied from 410-1020 Wm^{-2}, temperature varied from 19-33°C, relative humidity varied from 50-92 %, and air velocity varied from 0.8-8.0 m/s. In winter, solar radiation varied from 200- 590 Wm^{-2}, temperature varied from 15-27 °C, relative humidity varied from 38-75 %, and air velocity varied from 1.0-5.0 m/s. The maximum outlet temperature of the corrugated SAH with PCM was observed as 73 °C which occurred during 12:00 to 13:00 hour of the day, whereas, in a flat type SAH with no-PCM, it was 58 °C at the same hour of the day. The inside temperature of the drying chamber in the developed ISGHD system was found to be 59 °C occurring at 12:00 to 13:00 hour. The ISGHD system gave optimal outcome at a mass flow rate (MFR) of 0.018 kg/s, with drying chamber (i.e., dome) temperatures ranging from 30 to 59 °C and relative humidity from 20 to 86%. Experimental results indicated a relatively adequate drying rate in the developed ISGHD system.

The drying characteristics, encompassing the deviation of moisture content (MC), moisture ratio (MR), and drying rate (DR), were investigated for different thicknesses of ginger slices in the range of 3.0 - 7.0 mm. Initial MC of fresh ginger was 86%, which was subsequently reduced to a safe level of 10% by drying in the developed ISGHD system. For assessing its effectiveness, time taken by various other drying techniques such as open sun drying (OSD), tray drying (TD), refractance window drying (RWD) and solar greenhouse drying (SGHD) to achieve a similar final MC was determined. The drying time taken by the ISGHD system varied across the sample thickness: 29 h, 31 h, and 32 h, for thicknesses of 3.0 mm, 5.0 mm and 7.0 mm. respectively. These drying times were lesser as compared to the methods such as OSD and SGHD which took 54 h and 50 h for 3.0 mm, 59 h, 57 h, for 5.0 mm and 77 h and 54 h for 7.0 mm of ginger slices. Methods with a better control over source temperature (60 ºC in this case) and on the modes of heat transfer such as TD, and RWD needed lesser times of drying viz., 17 h, and 15 h, for 3.0 mm slices; 20 h, and 18 h for 5.0 mm slices; and 22 h, and 19 h for 7.0 mm slices, respectively. Improvement of the drying rate for ISGHD over SGHD is attributed to a relatively higher air temperature resulting from control over source temperature and effective heat transfer from the PCM through corrugated surfaces. While the moisture ratio declined with increasing drying time in all samples, the drying rate improved with rising air temperature in ISGHD system. The drying rate exhibited a decrease

with prolonged ginger drying. The effective moisture diffusivity (D_{eff}), of ginger slices was higher during the drying in ISGHD in the range of 2.5-4.0 × 10^{-10} m^2/s.

The use of PCM within the corrugated type SAH could ensure an efficient drying process as it helped producing warm air even during the off-sunshine hours as it works as a latent heat storage (LHS) system. As a result, drying air temperature could be maintained for a minimum of 3 - 4 hours from the start of off-sunshine hour. Complementary effects were given by the sensible heat storage (SHS) maintained inside the drying chamber which gave 2 - 3 °C elevation of temperature.

In describing the moisture loss kinetics from the ginger slices dried in the ISGHD system, among the ten drying models evaluated, the Page model offered the most comprehensive description, followed by the Logarithmic model and Newton model. However, the 5-10-3 ANN design was also found to be effective for the drying studies of ginger slices. For the description of the quality outcome of the dried slices measurements were done in terms of antioxidant properties, rehydration and shrinkage characteristics, essential oil content, microstructural properties and textural characteristics. A stronger antioxidant potential in the ginger slices dried under the ISGHD was found based on the measured values of the DPPH, total flavonoid content (TFC), and total phenolic content (TPC). In ISGHD, the rehydration ratio was maximized, shrinkage ratio minimized, essential oil yield optimized, and hardness minimized, indicating its superior performance. In FTIR, the wavelength 862 cm^{-1} showed C-H stretching broader band common in drying methods. In XRD analysis, a high peak at a 2θ value of around 23° signifies the amorphous nature with significant crystallinity of ISGHD and RWD drying methods. Additionally, the SEM images of ISGHD samples showed a clear and well-retained fibrous structure.

Utilizing computational fluid dynamics (CFD) was used to simulate the evolution of temperature and airflow profiling within the drying chamber, facilitating validation of hot air drying conditions of the ginger slices. The thermal energy efficiency of SAH and ISGHD varied from 38 to 63 % and 24 to 45%, respectively, at a mass flow rate of 0.018 kg/s, while the exergy efficiency of ISGHD varied from 12 to 35% under the same mass flow rate. The annual capital cost of 6733 INR and an energy payback time (EPBT) of 2.33 years. The developed ISGHD system is a sustainable and cost-effective for rural farmers.