Abstract

Solar energy stands out as the most viable long-term source for supplying the rising energy needs. Vegetables, fruits, medicinal herbs, and agricultural products all benefit greatly from drying to preserve them for future purposes. Solar energy stands out as the most utilized energy source for drying, either applied directly or indirectly in the drying of food and agricultural products particularly in rural areas. Nevertheless, the intermittent and uncertain availability of solar energy can impact the reliability and application of solar dryers. This limitation may be overcome by integrating thermal energy storage or auxiliary heaters into the system.

The present study focuses on the drying of *Garcinia pedunculata* and *Curcuma amada* in an improved solar dryer. In the first experiment, a free convection corrugated solar dryer for *Garcinia pedunculata* was studied and compared with conventional open sun drying. *Garcinia pedunculata* is a local seasonal medicinal fruit in Northeast India. The experiments were performed in two batches. The moisture content of *Garcinia pedunculata* in the dryer was reduced to 7.22 % (w.b.) for the first batch and 7.1 % (w.b.) for the second batch in 28 h from the initial of 88 % (w.b.) of moisture content. Subsequently, it was reduced to 10.18 % (w.b.) and 10.08 % (w.b.) for the first and second batch respectively in 55 h in open sun drying. Midilli and Kucuk model was found to be the most suitable for the developed dryer and Two-Term model for open sun drying for both the batches. The average thermal efficiencies of the solar air collector (SAC) for the first and second batch were evaluated as 33.29 % and 33.33 % respectively. The average specific energy consumption and average thermal efficiency of the dryer were estimated as 68.00 $kWhkg^{-1}$ and 10.69 % respectively for the first batch 65.54 $kWhkg^{-1}$ and 10.77 % respectively for the second batch. For the developed solar dryer, the payback period was calculated as 0.6 year.

In the second experiment, an improved active solar dryer with and without integrated sensible heat storage (SHS) was proposed. A unique feature of this dryer is its movable walls from the sides of the dryer to transform it to an indirect or mixed-mode as and when necessary. Drying kinetics of *Garcinia pedunculata*, the dryer performance and economic analysis of dryer were evaluated in the indirect solar dryer without SHS (Exp. I), mixed-mode solar dryer without SHS (Exp. II), indirect solar dryer with SHS (Exp. III), mixed-mode solar dryer with SHS (Exp. IV), and open sun drying (OSD). The dryer's average efficiencies were 18.12 %, 22.37 %, 21.74 %, and 24.46 % for Exp. I, Exp. II, Exp. III, and Exp. IV, respectively. The moisture content of *Garcinia pedunculata* was reduced to 12.09 % (w.b.) from 87.99 % (w.b.). The overall drying

time for Exp. I, Exp. II, OSD, Exp. III and Exp. IV were 31, 26, 53, 28, and 10 hours, respectively. From the eleven drying models, the Two-Term model was the best-fitted model for Exp. I, Exp. II, OSD and Exp. III, and Midilli and Kucuk model was for Exp. IV. The final products fragrance and colour are better for Exp. IV. Developing this dryer for Exp. I, Exp. II, Exp. III and Exp. IV, the price required was around 25,000, 27,000, 26,000, and 28,000 INR (1 US$=74.57 INR), respectively, while the economic payback periods are 1.6 years, 0.9 year, 1.4 years, and 0.59 year, respectively.

In the third experiment, the four combinations were considered, indirect-mode solar dryer without storage (ID-WOS), mixed-mode solar dryer without storage (MX-WOS), indirect-mode solar dryer with storage (ID-WS), and mixed-mode solar dryer with storage (MX-WS) to study the exergy and environmental effects. For ID-WOS, MX-WOS, ID-WS, and MX-WS, respectively, the drying durations were 30 h, 25 h, 28 h, and 8 h, and the drying efficiencies were 18.55 %, 24.03 %, 20.32 %, and 29.94 %. In ID-WOS, MX-WOS, ID-WS, and MX-WS, the average exergy efficiency was determined as 47.08 %, 65.10 %, 52.46 %, and 68.07 %, respectively. Environmental impact was studied for all four cases. The energy payback periods for ID-WOS, MX-WOS, ID-WS, and MX-WS, were 1.47, 1.61, 1.48, and 1.62 years, respectively. The study indicated that MX-WS outperformed the other three configurations in all aspects.

In the fourth experiment, a thorough investigation of the dryer working in the indirect configuration with modification to check the adaptability and performance was done. To evaluate practical application of the dryer, a product other than *Garcinia pedunculata* was chosen. The drying kinetics, energy, exergy, quality, and economic studies of the solar dryer with and without energy storage was conducted for *Curcuma amada*. The original configuration of a SAC has been modified by adding gravels beneath the absorber plate. *Curcuma amada* samples had initial moisture of 87.4 % (w.b.) and achieved an equilibrium moisture level of 4.4 % (w.b.) within 8 h in the dryer equipped with waste beverage canned absorber plate and storage (SDCWS) and for dryer without storage (SDCWOS) it took 26 h. Out of the eleven drying models tested, the Midilli and Kucuk model exhibited the most favorable fit for *Curcuma amada* in both the experiments. The average efficiencies for the collector and dryer were 67.26 % and 21.88 %, respectively, in SDCWOS. In contrast, the efficiencies for the collector and dryer were 87.95 % and 29.63 %, respectively, in the SDCWS. Exergy parameters such as in, out, loss, efficiency, improvement potential, waste exergy ratio, and sustainability index were estimated for both the configurations. Quality analysis was

further carried out for both SDCWOS and SDCWS in terms of total polyphenol content, total flavonoid content and color. The estimated energy payback periods were 1.7 years for SDCWOS and 0.47 year for SDCWS, considering a 20-year lifespan. In all assessed aspects, the SDCWS configuration showed more favorable outcomes.

It may be concluded that the Mixed-mode solar drying with corrugated absorber plate SAC, SHS, and Indirect solar drying integrated with canned absorber plate SAC, SHS, showed improved thermal efficiencies, lesser payback periods and lesser drying times. Application of such improved solar dryers have potential to change positively for sustainable advancement of agricultural drying techniques within rural areas.