ABSTRACT

Drying of black cardamom is essential for extending shelf life, preserving flavour, and maintaining the commercial value of the spice. However, traditional drying methods such as bhatti drying often lead to uneven drying, higher carbon emissions, quality degradation and longer drying times. In this regard, the present investigation deals with the development of hybrid photovoltaic-thermal (PV-T) solar dryer integrated with thermal energy storage (TES) for black cardamom drying. The study aims to optimise hybrid collector design, operating conditions, and TES central pipe configuration for enhanced heat transfer, followed by drying performance evaluation under seasonal variations and quality analysis of dried cardamom. The cross-flow 30 baffle design achieved a thermohydraulic performance factor of 1.25 and thermal efficiency of 14.94-49.36% higher than channel and twist designs. A double-pass hybrid PV-T collector, with a semi-transparent PV module and cross-flow baffles, achieved 3.57-8.33% higher thermal and 15.44-43.18% higher electrical efficiency than increased transparency configurations. It was also observed that collector inlet air velocity of 16 m/s yielded 37.29-52.07% higher energy and 11.72-17.71% increased exergy performance as compared to 11 and 5 m/s. The TES unit with a helical pipe achieved 7.27-22.75°C higher outlet temperature than a straight pipe with increased pressure drops, while maintaining higher outlet velocity. The hybrid PV-T solar collector and TES unit were integrated with a drying chamber equipped with three axial fans for drying of cardamom, resulting in drying times of 34 and 33 h in winter and summer, respectively. The drying kinetics was best described by Midilli and Kucuk model with the highest effective moisture diffusivity of 1.29×10^{-9} m²/s recorded during summer with axial fan operation. Machine learning based Random Forest algorithm was employed with time and sample temperature as input features to predict the drying behaviour of cardamom. It was observed that as sample temperature increases, its importance in accurately predicting drying behaviour also increases. The hybrid solar dryer achieved 75.57% higher carbon credit-adjusted annual profit than traditional bhatti drying, and the total colour change of the dried samples were 2.38-68.19% lower as compared to conventional dried cardamom. Eucalyptol and terpineol were identified as the abundant essential oil constituents in dried black cardamom. The traditional drying methods led to increased hardness and carbon deposition due to wood-fired drying. The hybrid dryer emitted 0.89-0.97 kg CO_2/kg of dried cardamom, ensuring sustainability, improved quality retention, and economic feasibility.

Keywords: Hybrid PV-T solar dryer, Thermal energy storage, Black cardamom, Thermal performance, Electrical efficiency, Quality attributes, Drying characteristics