ABSTRACT

Solar drying is considered one of the most promising practises in agriculture as it has several benefits, viz., reducing waste, promoting food security, and conserving the nutritional value of food through value addition at the production site. Harnessing solar power through a solar dryer offers a practical and environment friendly approach to extending the shelf life of perishable agricultural products, resulting in economic benefits, especially for small and marginal farmers. The conventional solar dryers have certain limitations, which are primarily caused by the intermittent and unpredictable nature of available solar radiation. In this context, energy storage by phase change materials (PCMs) can play a crucial role in improvising solar drying technologies. The inherent beneficial characteristics of PCM, including higher storage capacity and constant temperature of operation for absorbing and releasing heat, have already achieved for thermal energy storage, temperature regulation, extended drying time, increased efficiency, flexibility, and reduced energy consumption. There is a substantial amount of research that mainly focuses on the characterization of PCM and simulating the performance of PCM-integrated thermal energy systems. An ample amount of research is also available on industrial applications of PCM, besides agriculture product processing. Despite such developments, the limited study on phase change material integrated solar air heaters for agricultural drying applications is realised probably due to some missing links concerning (i) selection and identification of suitable PCM, (ii) stability and compatibility with container materials, (iii) field performance investigation, and (iii) affordability and sustainability benefits. Keeping this in mind, the current PhD research is taken up to develop phase change material integrated solar air heater for agricultural drying applications through systematic research protocols.

The current research focuses on the identification and selection of PCMs for solar heating and drying applications in the medium temperature range, i.e., 40–90 °C. Seventeen potential PCMs are screened from a comprehensive list of 87 PCMs reported in the literature based on acceptable limits concerning some key properties (*viz*., toxicity, cost, availability, thermophysical characteristics, and corrosivity) as essential criteria. The best three PCM candidates (*viz*., stearic acid, paraffin wax, and acetamide) are then selected based on a multi-attributed decision making that considers melting enthalpy, width of

temperature change, availability, cost, and maximum working temperature as decision variables.

The thermal stability of the selected PCMs is examined through the standard protocols of TGA and DSC. TGA is carried out for all the three fresh PCM samples to check the thermal degradation behaviour of the materials, while DSC (for melting points and latent heat) is investigated for all the selected PCMs at every 100^{th} thermal cycle up to 1000 thermal cycles of heating and cooling. As evidenced from TGA, stearic acid and paraffin wax are more stable PCMs, since both sustained till 120 ºC with a marginal rate of degradation compared to acetamide which started degrading at 110 ºC. However, considering the anticipated level of operating temperature (~90 ºC), all three PCMs are found to be thermally stable for the solar air heater application. More than 90% of the material degradation occurred at 286, 348, and 188 ºC for stearic acid, paraffin wax and acetamide, respectively. These results would be useful to set the permissible limits of operating temperature. The DSC results accounted through the estimation of RPD (relative percentage difference) of onset melting point, peak melting point and latent heat of fusion of all three PCMs corresponding to every 100^{th} thermal cycle are comparable with the corresponding values of PCMs reported in standard literature. Thus, the PCMs are expected to perform satisfactorily with regards to the anticipated cyclic thermal loading of solar heating or drying applications.

The compatibility of the selected PCMs with the container material (*i.e.*, metal specimens like aluminium, stainless steel, mild steel and copper) is studied by standard protocols of corrosion testing, microscopic imaging, and surface roughness profiling. Irrespective of the type of PCM, all test metals experienced corrosion, however, to varying degrees. Copper is more prone to corrosion, followed by mild steel, aluminium and stainless steel. The results are compared with recommended standards for corrosion rates of metal for industrial applications and found to be within acceptable limits and long duration usage. To confirm the results of the corrosion test, surface microscopic imaging and surface roughness profiling are carried out. Microscopic imaging of PCM treated copper and mild steel surfaces exhibited higher surface deformations like cracks and pitting compared to aluminium and stainless steel. Moreover, copper also exhibited the highest average surface roughness and maximum peak-to-valley heights, followed by mild steel, aluminium, and stainless steel. Thus, stainless steel is the preferred material for PCM-based applications over aluminium, mild steel, and copper, in that order.

After a comprehensive assessment of selected PCMs, including their thermophysical properties and compatibility with container materials, a solar air heater (SAH) with the provision of integrating the selected PCMs is designed using MATLAB code-based simulation tool. The fundamental laws of energy conservation, relevant properties of PCM and system components, and parameters corresponding to anticipated operating conditions are used for the design simulation. Aluminium is considered a PCM container material based on the results of compatibility tests and comparative costs assessed from a market survey. It is observed from the simulation that benefits of increased useful energy is caused by incremental increase in length of the absorber plate which vary with type of PCM and mass flow rate of air. Based on the analysis of results of such variations among (i) three PCMs (stearic acid, paraffin wax and acetamide), (ii) varying length (1 to 3 m) and (iii) varying flow rate (0.018 kg/s to 0.048 kg/s), 1.57 m long absorber plate for air mass flow rate of 0.018 kg/s are considered for development of PCMSAH. The required quantity of PCM is analytically estimated based on the consideration of time constant ($\boldsymbol{\tau_c}$) vis-à-vis melting depth. While 3 hours is the uniform value of time constant for all the PCMs, the melting depth varies among the PCM types. Based on the results of potential melting depth of 1 cm during the operation, 14.56 kg of acetamide, 12.12 kg of stearic acid and 11.30 kg of paraffin wax are recommended for integration with the PCMSAH.

The PCMSAH is fabricated for performance testing initially for no load condition and subsequently for a specified thermal load under experimental condition in Tezpur (Assam, India) with a provision to integrate individual (acetamide, stearic acid, and paraffin wax) PCM container. Experiments are conducted using standard experimental set-up and protocols in the months of April, June, and July in the year 2021 for paraffin wax, stearic acid, and acetamide, respectively. As a control, an identical system without PCM is also used simultaneously for comparative assessment. Part of the test results are used to validate the simulated design by comparing the simulated and observed values of outlet temperatures. In general, close agreement between the simulated and experimental outlet temperatures of PCMSAH is observed, though the degree of agreement varies among the PCMs. The mean relative error between experimental and simulated outlet temperatures for three different PCMs is estimated at 4.50 %, 2.32 %, and 2.63 % for paraffin wax, stearic acid, and acetamide, respectively. Higher outlet temperatures of PCMSAH are observed compared to SAH without PCM due to the effect of latent heat storage. Thus, the benefits of PCMs both during charging and discharging periods of operation are proven, irrespective of the types of PCMs. Moreover, a steady outlet temperature during the low sunshine period is observed for PCMSAH compared to plain SAH. The performance of PCMSAH with respect to three PCMs is also compared using the overall efficiency estimated from experimental data concerning total absorbed and useful components of thermal energy. The PCMSAH using paraffin wax resulted in marginally better performance (45.64 %) compared to stearic acid (45.19 %) and acetamide (40.82 %). The difference in performance might be due to the favourable characteristics of paraffin wax as compared to stearic acid and acetamide. The overall efficiency of PCMSAH with stearic acid is 13.04 % higher than that of SAH without PCM. Similarly, about 7.07 % and 5.77 % higher efficiency are estimated for paraffin wax and acetamide PCMSAHs, respectively, compared to SAHs without PCM. About 2.02 % error is attributed to the uncertainty concerning the estimation of thermal efficiency and is considered acceptable based on the trends available in the literature.

The PCMSAH is subsequently tested for its application as a vegetable dryer using a specially designed drying chamber to handle about 5 kg of raw vegetables daily, which is a representative quantity generated by an individual household in the study region. The experiments are conducted using the PCMSAH integrated with the drying chamber, *i.e.*, the Phase Change Material-Based Solar Dryer (PCMSD).

The tomato is a locally available vegetable in the study region and is therefore, used for experimental drying. The standard drying experiments are carried out using PCMSD and open sun drying on three different dates using paraffin wax, stearic acid, and acetamide. The necessary data pertaining to temperatures at different locations in PCMSD, available solar radiation, and moisture contents of tomatoes are recorded throughout the drying experiment at a regular time interval of 30 minutes. These are used to estimate the required parameters concerning performance, energy-exergy analysis, environmental and economic feasibility for operation of vegetable drying. Irrespective of the type of PCM, the benefits of higher drying rates of PCMSD are demonstrated while comparing the results of open sun drying of raw tomatoes at 93 % (wet basis) or 13.29 (dry basis) moisture content. Ignoring the variations of available solar radiation among the test conditions, acetamide based PCMSD resulted in the highest state of drying (1.89 dry basis, gram/gram) followed by paraffin wax (2.89 dry basis, gram/gram) and stearic acid (3.07 dry basis, gram/gram) whereas, open sun drying during the experiment with acetamide, paraffin wax and stearic acid PCMSD resulted in 4.09, 4.45 and 5.19 of moisture contents (dry basis) at the end of each respective days of experiments.

The energy analysis and exergy analysis considering (i) PCMSAH (*i.e*, collector) alone and (ii) the integrated system *i.e*., PCMSD are carried out using the data derived from the tomato drying experiments and based on standard procedure. Overall, energy efficiency of collectors (*i.e*., PCMSAH alone based on the total heat gained by air) operated using three different PCMs is estimated as 60.77 %, 69.14 % and 66.06 % for paraffin wax, stearic acid and acetamide, respectively. The different levels of performance observed during the PCMSAH test and drying tests might be due to differences in operating conditions. However, the overall efficiency of the integrated drying system (*i.e.*, PCMSD based on energy spent on removal of moisture during the drying process from absorbed solar energy by the PCMSAH) is estimated at 6.61 %, 6.84 % and 7.40 % for paraffin wax, stearic acid and acetamide, respectively. Specific energy consumption *(SEC)* of PCMSD (energy required for removal of unit mass) with reference to tomato drying are also estimated as 11.94, 10.62, and 9.56 kWh/kg for paraffin wax, stearic acid, and acetamide, respectively. The acetamide based PCMSD maintained the lowest *SEC* because it exhibited the highest overall drying efficiency among the three PCMs. The results of exergy analysis of the PCMSD collector (PCMSAH) indicated marginal variations in overall exergy efficiency among the systems operated using paraffin wax, stearic acid, and acetamide are 2.66 %, 2.78 % and 2.94 %. The evaluated values of exergy efficiency of the drying section of PCMSD with paraffin wax range from 2.12–83.47 %, stearic acid range from 1.25–78.52 % and acetamide range from 8.15–90.29 % and the overall exergy efficiency of the PCMSD dryer are 43.33 %, 37.74 % and 45.64 % for paraffin wax, stearic acid and acetamide respectively. The destruction of exergy inside the PCMSD (consisting of intermediate conduit and drying chamber) is attributed by different thermal losses in the conduit and the drying chamber including inefficiency of heat and mass transfer during dehydration the product. In the current study little attention was given to the product (tomato) specific design of the drying chamber which might be the cause for exergy destruction. Further, inadequate provision of moisture migration from the drying chamber might be another concern. The product specific design accompanied by the measures for prevention of thermal heat losses (insulation and optimum convection) are some of the suggested areas of improvement.

The economic analysis is carried out considering the data pertaining to different PCMSD components as per prevailing market rates and using standard procedures. The potential for enhanced income from dried tomatoes produced by PCMSD by a typical farm family is estimated, as there are potential higher earnings from valorised food products. The economic analysis of the PCMSD is evaluated by the annualised cost method. Annual income and economic payback period are estimated based on relevant parameters (capital costs, first annual cost, salvage value, annual maintenance cost, and annual power cost for the operation of PCMSD) and several other considerations (*viz.*, quantity, prices, interest rate, discount rate, and inflation rate). The capital cost of the acetamide integrated system is higher (41,428.00 INR) as compared to both paraffin wax and stearic acid integrated systems (~38,000.00 INR) due to differences in the prices of PCM. The range of variations in the annualised cost of operations of PCMSD with reference to three PCMs is marginal and in the range of 10,334.00 to 10,846.00 INR. Similarly, the variations in potential annual income among the three PCMs are also marginal (*i.e.*, 76,553.00 to 77,065.00 INR) caused by variations in PCM prices. Overall, it is estimated that the investment in the system could be paid back within about half a year if operated for the entire year to convert raw tomatoes into value-added products. Thus, PCMSD could be considered an economically feasible technology. Finally, the important parameters for the environmental sustainability of PCMSD is assessed as per the net-zero requirement. The embodied energy, CO_2 emission, mitigation potential, potential carbon credit earnings and energy payback period from PCMSD are assessed using standard protocols. The amount of embodied energy required in manufacturing of the PCMSD with all the three PCMs are 1357.04, 1382.67 and 1609.81 kWh for paraffin wax, stearic acid and acetamide respectively. The yearly CO_2 emission, CO_2 mitigation and range of carbon credit earned for PCMSD with (i) paraffin wax is 184.74 kg/year, 5329.14 kg and $ 26.65 to $ 106.58 (2201.73 INR to 8806.94 INR), (ii) stearic acid is 188.23 kg/year, 5276.80 kg and $ 26.38 to $ 105.54 (2180.11 INR to 8720.45 INR) and (iii) acetamide is 219.15 kg/year, 4812.98 kg and $ 24.06 to $ 96.26 (1988.48 INR to 7953.94 INR) respectively. Finally, the energy payback period of PCMSD with different PCMs are estimated as estimated as 2.51 years for paraffin wax, 2.56 years for stearic acid and 2.98 years for acetamide respectively. Despite of the certain limitations experienced during the progress of the research all the objectives *viz.*, (i) PCM for solar drying application: Selection and assessment for thermal stability and compatibility. (ii) Design, development, and performance analysis of PCM integrated solar air heater (SAH). (iii) Performance study of phase change material solar dryer (PCMSD): Energy, exergy, economic and environmental analysis could be achieved with useful information in the area of application of PCM in solar drying technology for agricultural product processing.