# 5. Summary and Conclusion

## 5.1 Summary

An integrated solar greenhouse drying (ISGHD) system 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 dome was developed to improve the drying performance and quality of sliced ginger. The performance of the SAH and ISGHD system for drying of sliced ginger, and the quality of the dried ginger slices were evaluated, and the following outcomes for ginger drying were observed.

1. Various weather conditions and ambient parameters influence the solar drying process of agricultural crops and food products. In the northeastern region of India, this influence is quite observable as the duration of sunshine is typically less than that of other regions in the country. A study was conducted to examine the variations in parameters such as solar radiation intensity, ambient air temperature, and relative humidity during the winter (October to February) and summer (March to June) seasons.

2. During summer, strong solar radiation varies from 410-1020 $Wm^{-2}$, temperature from 19-33 °C, relative humidity from 50-92 %, and air velocity from 0.8-8.0 m/s. In winter, solar radiation varies from 200- 590 $Wm^{-2}$, temperature from 15-27 °C, relative humidity from 38-75 %, and air velocity from 1.0-5.0 m/s.

3. During the production of hot air for drying, the maximum outlet temperature of 73 °C was observed in the corrugated type SAH with PCM, whereas the same parameter was estimated as 58 °C in the flat type SAH without PCM is, both of which were observed at 1:00 p.m. Occurrence of the maximum hot air temperature corresponded to the maximum ambient air temperature.

4. When the ambient temperatures ranged from 20 to 35 °C the outlet temperatures in SGHD were 21 to 39 °C, and in ISGHD system were 30 to 62 °C, when observed between the 8:00 a.m. to 4:00 p.m., with the peak occurring at 1:00 p.m. This has resulted in a lower relative humidity of 18 - 68% in ISGHD system against the relative humidity range of 42 - 78% for SGHD, against the ambient air relative humidity of 56 - 93%.

5. The thermal energy storage system in the forms of PCM as latent heat storage (LHS) for inside the SAH and black-painted rock and sand system as sensible heat storage (SHS) inside the SGHD, proved to be helpful in increasing the efficiency of the drying system by providing temperature stability.

6. Corrugated type SAH with PCM facilitated maintaining the drying temperature for 3-4 hours during the off-sunshine hours thereby providing temperature stability. It also reduced the relative humidity after the off-sunshine hours.

7. Corrugated type SAH with PCM could produce outlet temperature in the ranges of 37-71°C for MFR of 0.0067 kg/s; 35-65 °C for MFR of 0.012 kg/s, 32-60 °C for MFR of 0.018 kg/s, and 31-48 °C for MFR of 0.024 kg/s. Optimal temperature conditions are observed at a MFR of 0.018 kg/s, indicating superior efficiency and reduced drying time.

8. Temperature variations within the dome of an ISGHD system across different mass flow rates (MFRs) of air were 33 to 54 °C, 30 to 57 °C, 30 to 59 °C, and 29 to 48 °C for MFRs of 0.012 kg/s, 0.018 kg/s, and 0.024 kg/s, respectively. The parabolic SGHD structure has a higher average temperature than the even-span SGHD structure.

9. During experimentation, the time required to dry ginger to a safe level of moisture content varied based on the drying method applied. For 3.0 mm slices, the drying times are 54 h, 50 h, 29 h, 17 h, and 15 h in OSD, SGHD, ISGHD, TD, and RWD, respectively. For 5.0 mm slices, the drying times are 59 h, 57 h, 31 h, 20 h, and 18 h in OSD, SGHD, ISGHD, TD, and RWD, respectively. For 7.0 mm slices, the drying times are 77 h, 54 h, 32 h, 22 h, and 19 h in OSD, SGHD, ISGHD, TD, and RWD, respectively. The ISGHD could dry the ginger within two sunshine days compared to other solar drying modes, and it is very close to the mechanical drying method.

10. The improved drying rate for ISGHD over SGHD is due to higher air temperature from controlled source temperature and efficient heat transfer from PCM through corrugated surfaces. While moisture ratio decreased with drying time in all samples, the drying rate improved with higher air temperatures in the ISGHD system. The drying rate decreased with prolonged ginger drying. Effective moisture diffusivity ($D_{eff}$) of ginger was higher in the ISGHD system compared to OSD and SGHD, due to the higher temperatures facilitating the mass transfer.

11. Ten drying models were tested for ginger slices, with the Page model exhibiting the best fit, followed by the logarithmic and Newton models. They accurately predicted ginger drying in the ISGHD system, offering the potential for optimizing drying processes.

12. A feed-forward ANN model with an architecture of 5-10-3 showed an excellent agreement between the predicted values and the experimental data, with a low relative deviation value, which has the potential as an estimating tool for the drying behaviour of ginger slices.

13. Quality analysis of dried ginger and ginger powder, such as rehydration ratio, shrinkage ratio, texture, colour properties, essential oil content, and antioxidant properties (including DPPH, TPC, and TFC), as well as FTIR, XRD, and SEM analyses, indicated that these property values were more favourable with ISGHD, as compared to the property values in slices obtained by RWD, TD, SGHD, and OSD.

14. The corrugated type SAH with PCM reached its peak thermal efficiency of 38%-63% at 0.018 kg/s flow rate, while the ISGHD dryer achieved maximum thermal efficiency of 33%-45% at the same MFR, showing best performance at the intermediate flow rates. The ISGHD dryer's maximum exergy efficiency was observed at 0.018 kg/s flow rate, ranging from 12% to 33%. Overall, the ISGHD demonstrated energy efficiency ranging from 32% to 45%, and exergy efficiency ranging from 12% to 33%.

15. The annual capital cost of the dryer (Capacity of 4.0 kg/batch and area of $1.2 \times 1.0$ m$^2$) has been found to be 6733 INR, and the energy payback time (EPBT) of the dryer is 2.33 years. The developed dryer (ISGHD) is sustainable and cost-effective for rural farmers.

## 5.2 Conclusion

This study investigates the solar greenhouse drying process of ginger slices in the northeastern region, highlighting the influence of weather conditions and ambient parameters. Notable variations in climatic conditions in the summer and winter impacting the solar radiation and relative humidity were observed. The use of phase change material within the solar air heater helped maintaining temperature stability during off-sunshine hours and resulted in an improved efficiency. Additionally, sensible heat storage within the drying chamber too improved the system efficiency. Corrugated type SAH with PCM demonstrates superior outlet temperature ranges, indicating enhanced efficiency of air heating system, which in turn resulted in a relatively rapid rate of ginger slice drying. Similarly, the integrated solar greenhouse drying system (ISGHD) achieves optimal thermal energy and exergy efficiencies at intermediate flow rates, with improved drying times for ginger slices compared to other drying methods. Quality analysis reveals ISGHD as a better option in terms of various properties. Overall, ISGHD system and corrugated type SAH with PCM exhibited promising energy and exergy efficiencies, suggesting their potential for practical application in solar drying operations.

## 5.3 Scope for Future Work

The future scope for integrated solar greenhouse drying system lies in widespread adoption in agriculture. Research should prioritize enhancing solar energy capture efficiency, optimizing greenhouse design for diverse climates, and incorporating innovative technologies for automated control. Further exploration into thermal energy storage, biomass-fired air heating, and scaling up applications in different regions can enhance implementation and positively impact sustainable agriculture. Ongoing innovation aims to advance eco-friendly and cost-effective methods for agricultural produce drying, benefiting farmers and supporting global food security.

### 5.3.1 Biomass fired air heater

The future scope for research in drying agricultural produce within solar greenhouses, supported by biomass-fired air heaters, offers a compelling avenue for advancing sustainability in food preservation, as shown in (Fig. 5.1).

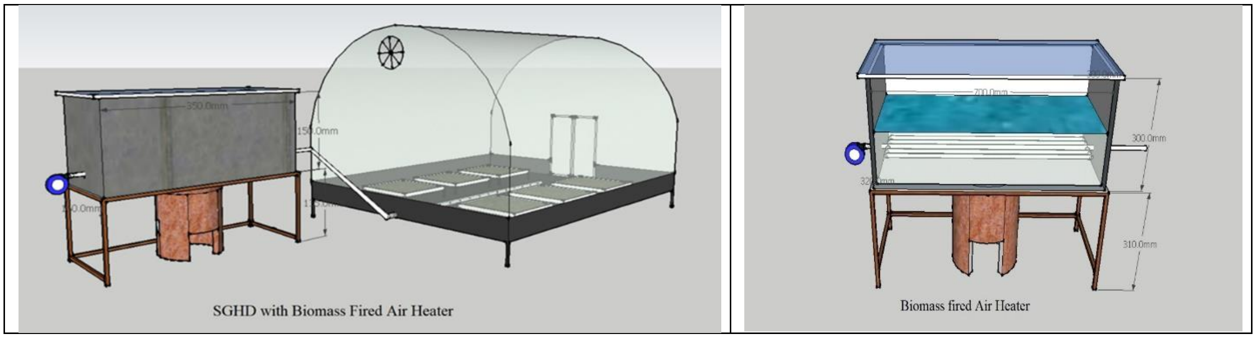


**Fig. 5. 1 Scheme of solar greenhouse drying system assisted with biomass-fired air heater**

Enhancing the thermal energy storage (TES) systems is a pivotal area that facilitates better management of energy resources and prolonged drying operations. Extending drying hours into the night presents another crucial focus, demanding innovations in supplementary heating and insulation techniques to optimize resource utilization.