Chapter 2

Literature Review

This chapter explores into the latest research conducted in the field of solar drying systems. The literature discussed in this chapter is categorized into four sections: drying kinetics analysis, energy and exergy assessments, economic evaluations, and environmental considerations. The primary aim of this chapter is to identify areas where further research is needed. Ultimately, this chapter wraps up by outlining the scope of the research conducted within this thesis.

2.1 Drying kinetics analysis

The demand for dehydrated agricultural produces, and medicinal herbs has significantly increased in the recent years [67,68]. A longer shelf life is provided by lowering the MC in agricultural products [69]. It stops the development of bacteria and yeasts, preventing the rotting of harvested goods [70]. A significant amount of energy is devoted to drying processes in a variety of uses, including agricultural, the fabric, pulp, and pharmaceutical and food industries. This energy is primarily derived from fossil fuels. Fossil fuels, however, are beginning to run out and their emissions of carbon dioxide are causing global warming and climate change. The innovative utilization of renewable energy, particularly solar energy, can be an answer to this problem [71]. A significant amount of research works has been conducted by various researchers on solar dryers for evaluating the drying kinetics of the agricultural produces. The adequacy of the Midilli model for predicting the drying behavior has been affirmed in studies on tomatoes by Boughali *et al.* [72] and on thyme by Lahnine *et al.* [73]. In the case of the Two Term model, Yaldiz *et al.* [74] and Lahsasni *et al.* [75] have asserted that this model is the most suitable for fitting the experimental data of the drying process for Sultana grapes and Prickly pears. The Page model demonstrated a remarkable fit with drying curves for thymus [76], raw mango slices [77], and chili peppers [78]. The logarithmic model accurately described the drying characteristics of pumpkin slices [79], long green peppers [80], and apricots [81]. Additionally, Koua *et al.* [26] observed that the drying curves of banana, mango, and cassava aligned well with the Henderson and Pabis model. Çakmak and Yıldız [82] dried seeded grapes from an initial MC of 7 % (w.b.) to a final of 8.26 % (w.b.) in an ISD with solar collector integrated with PCM. The drying kinetics of these seeded grapes were studied for three velocities of air (0.5, 1 and 1.5 m/s) with and without swirling. Out of six different models selected for the study, Midilli showed the most satisfying result. In another study conducted by Dissa *et al.* [83] Amelie and Brooks mangoes were dried using a direct-forced solar dryer. Out of the ten models examined, the Two-term and Approximation of diffusion model were identified as the optimal drying model. The drying rates ranged from 0 to 0.15 $gkg^{-1}s^{-1}$, and the efficiency varied from 0 to 34 %.

In another noteworthy work, Vijayan *et al.* [84] developed a mathematical model to explain how an active solar collector with SHS material (pebble) operates for drying bitter gourd. Out of the different drying models, the Two-term model for solar dryer and Midilli and Kucuk model for OSD were the best-chosen models. The dryer and collector were found to be 19 % and 22 % efficient, respectively. Atalay *et al.* [85] studied the drying of apple in a dryer constituting of a drying cabinet, two solar air collectors, a recuperator system, and fans. The recuperator used for waste heat recovery could recover 50-60 % by utilizing reheated air in the drying unit. The drying characteristics of apples with the thickness (5±2) mm were found at an average temperature range of 50 °C to 60 °C. Out of different models, the Diffusion Approximation model satisfactorily described the drying characteristic of apple. Horuz *et al.* [86] experimentally investigated the kinetics of apricot halves in a microwave-hot air domestic hybrid oven. Amidst the ten drying models, the modified Logistic model which was till that date never been reported had best described the kinetics of the product. A passive solar dryer integrated with biomass was developed for turmeric with initial MC of 831.09 % (d.b.) [87]. The temperature of the dryer was maintained in between 55 °C and 60 °C and ambient was at 28 °C and 30 °C. The Page and Modified Page models were found to be the best fit among ten different drying models available in the literature, which were tested for the purpose. The final MC was reduced to 6.68 % (d.b.) in 14 h and 25 h for the hybrid dryer and OSD, respectively. Essalhi *et al.* [88] experimentally calculated the drying consequence of grapes in an ISD and open sun. The time required for drying in the dryer and OSD was found to be 120 h and 201 h respectively. The drying models were fitted and out of which Midilli model describe the drying kinetics of grapes. Azaizia *et al.* [89] experimentally studied the drying effect of red pepper using a mixed-mode (greenhouse type) using paraffin wax as a phase-changing material. They compared the results with the dryer without using paraffin wax, and OSD. Out of ten different drying models, the most suited one describing the drying kinetics was Midilli and Kucuk for the dryer.

2.2 Energy and exergy assessments

Sustaining agricultural products over extended periods or for distant transportation demand significant expenses and labour input. Addressing this challenge, one potential solution is drying of the agricultural products [90]. The energy involved in drying may be derived from various sources like solar, electricity, biomass, LPG, diesel, gasoline, etc. It is a well-accepted fact that non-renewable sources of energy ruin the environment and therefore they are not considered good options. Abundant solar energy is an alternative to non-renewable sources of energy that has got good potential for food-drying applications [5].

Energy is a characteristic of an object or a system that enables it to convert into different forms and perform work. To study the performance of a process, one can analyze energy using the basic principles of thermodynamics. A new type of drying system that combines solar and thermal energy was developed, and a recovery dryer was added to create a hybrid system [91]. The efficiency of a hybrid system was tested with and without a recovery dryer using red chili as the drying material. The evaluation was under two operational modes: hybrid mode (day and night) and thermal mode alone (night). The results indicated that incorporating the recovery dryer increased the overall drying efficiency from 9.9 % to 12.9 % in the thermal mode alone. In the hybrid drying mode without recovery, the overall efficiency was 10.3 %, but it improved to 13 % with the recovery dryer. Baniasadi *et al.* [92] conducted experiments on an active solar dryer with and without storage for drying of apricot slices. The use of phase changing material as a storage, an increased the performance of the solar collector eventually extended the useful drying time. Additionally, the research findings indicated that the drying rate remained uniform across the entire drying cabinet. The dryer showcased a moisture pick-up efficiency of around 10 % and an overall thermal efficiency of approximately 11 %. In another study, Wang *et al.* [93] introduced a solar dryer for drying mangoes that used indirect forced convection with an auxiliary heating device. The results showed that the temperature at various section of the dryer remained stable. The average thermal efficiency of the dryer was between 30.9 % and 33.8 % at a drying temperature of 52 °C. Further, a study was conducted on two active horizontal solar dryers: mixed mode and indirect solar dryer, both equipped with a latent heat storage system, for drying black pepper [94]. The MC was reduced to 0.14 (d.b) from an initial MC of 3.46 (d.b) in 14 h for the mixed-mode dryer and 23 h for the indirect-mode. The overall efficiency of the mixed-mode dryer was 20 % higher than that of the indirect-mode dryer. Iranmanesh *et al.* [95] studied the drying of a solar dryer for apple slices of thickness of 5 mm using water as PCM and modelled with the application of CFD. The system constituted of a cabinet dryer incorporated with trays, a solar collector and TES. Experimental results were performed for 0.025, 0.05 and 0.09 kg/s air flow rates using and without using PCM. The highest overall efficiency of drying was 39.9 % using PCM and 0.025 kg/s air flow rate. CFD simulation and experimental results showed reasonable agreement at various flow rates of air. Mugi *et al.* [96] has conducted a performance study on an ISD for drying beetroot slices. The study was a comparison between the dryer with and without storage. In comparison to those without storage, the dryer with storage demonstrated a significant improvement in drying efficiency, with a substantial increase of 48.63 %. The drying efficiency values for dryers without and with storage were 11.31 % and 16.81 %, respectively.

In the conventional approach, assessing the efficiency of a dryer involves applying the first law of thermodynamics. This provides a measurable representation of energy but overlooks specific information concerning the extent and location of irreversible losses within the system [97]. Exergy study helps to improve the efficiency of solar drying, figuring out how much energy is needed for drying, and finding out the type of energy needed, with a potential to examine the direction of irreversible processes and their consequences [98]. Forced and free convection MMSD were designed and examined with and without storage for pretreated potatoes [99]. Among all the comparisons made, forced convection mixed-mode solar dryer with storage took the least drying time while the free convection without storage took the most time for drying. The experiment studies the energy consumed was (4.10-4.98 MJ), drying efficiency was (25.031-31.5 %) and exergy efficiency was (14.5-80.9 %-68.37 %). In another experiment, Rabha *et al.* [15] studied an active solar dryer for drying of ghost chilli and ginger. Exergy efficiency varied from 21 %-98 % for chilli and 4 %-96 % for ginger, with increasing efficiency over drying time. The highest efficiency was observed during the last few h of consecutive drying days. A passive mode of the indirect solar dryer was used in an experimental investigation by Lingayat *et al.* [19]. The slices of banana were dried between 28 and 82 °C. According to the observations, the exergy loss and efficiency were in the range of 3.36 to 25.2 kJ/kg and 7.38 to 45.3 %, respectively. For drying medicinal plants, an exergy assessment of a solar dryer in free and forced modes integrated with sensible and latent heat storages was performed [100]. The mean exergy efficiency of the drying system was reported to be 30.28 %. Further, Atalay [101] found the exergy efficiency to be 54.71 % in a solar dryer with sensible heat storage for drying of orange slices. Two experiments were conducted, and MC was subsequently reduced to 10.28 % for the first experiment and 10.76 % for the second experiment from an initial of 93.5 %. Similarly, César *et al.* [102], investigated three different modes (mixed-mode natural convection, mixed-mode forced convection, and indirect-mode natural convection) to decrease the MC of pears during drying. Among these modes, the mixed-mode natural convection showed the highest exergy efficiency for the drying cabinet, reaching 65.2 %. On the other hand, the mixed-mode forced convection had the lowest exergy efficiency, measuring 54.4 %.

2.3 Economic evaluations

In order to examine the feasibility of the dryer, an economic assessment is necessary [103]. A solar system was experimentally studied for drying 200 kg of pineapple at a constant mass flow rate [104]. The MC decreased to 9.7 % (w.b.) from an initial 82 % (w.b.) in 8 h. With a capital investment of 550,000 INR, the payback span of the drying system was estimated to be 0.54 year. A 210 kg capacity forced convection dryer of capital cost of 1250 USD was experimentally studied in Borj Cedria, Tunisia [105]. The drying time was reduced significantly compared to OSD with a payback period of 1.6 years. Jain and Tewari [106] constructed a dryer for drying of leafy herbs with paraffin wax as its PCM for TES at Jodhpur, India in the month of June. The solar drying system consisted of a solar flat plate collector (1.5 m^2), a packed bed of PCM comprising of 48 numbers of cylinder tubes of 0.75 m length and 0.05 m diameter, a drying plenum with six trays (0.50 m × 0.75 m) of 10-12 kg of capacity and LHS on a passive draft system with absorber plate of 23° inclination. The drying with PCM as TES continued for 5-6 h after the sunset. Additionally, the temperature was maintained at 6 ℃ more than the ambient till midnight. The thermal efficiency was found to be 28.2 % with a payback period of 1.5 years. In another noteworthy work, a solar dryer with 100 kg capacity was developed [3]. The set-up consisted of a drying cabinet, a SAC of water type, a heat exchanger and storage system. The SAC efficiency ranged from 21 to 69 % with drying time of 4 days. The payback period was calculated to be 1.37 years. Yahya *et al.* [107] did the performance and economic analysis of a solar-biomass dryer for drying of rice. The set up comprised of the solar collector, a heat pump (with R-22 as the working fluid), a fluidized bed, a cyclone, and a centrifugal blower (3.7 kW power). The MC was reduced to 14 % (w.b.) from an initial value of 27.72 % (w.b.). The temperature and relative humidity were maintained at average values of 80.9 ℃ and 8.14 %, respectively.

The average solar collector and biomass furnace efficiency were calculated to be 50.5 % and 77.5 %, respectively. The average SEC, drying and pick up efficiency were 4.76 kWh/kg, 15.4 % and 43.8 %, respectively. The payback period of the HSD was approximately 1.6 years. Kareem *et al.* [108] examined a drying system integrated with a SAC with granite grits as a storage material below the absorber plate to dry screwpine leaves. The drying time in this system was 28 h whereas in an OSD method, it took 53 h. The reported drying and collector efficiencies were 36.0 % and 58.7 %, respectively. The estimated payback period for this integrated system was 0.75 year. A 10 kg capacity MMSD was experimentally studied in Guwahati, India for drying of stevia leaves [109]. The study estimated the payback period of the proposed system to be 0.65 year. An active ISD with pebbles as SHS material was developed to study the drying of bitter gourd slices [110]. The drying time was found to be 7 h from an initial mass of 4000 g to final mass of 723 g. The average exergy efficiency was calculated to be 28.74 % for 0.0141 kg/s mass flow rate and 40.67 % for 0.0872 kg/s. The study regarding environmental impact showed that for a period of 35 years, the CO_2 mitigation was found to be 33.52 tons and earned a carbon-credit value in the range of INR 10894 to 43756. The payback period was found to be 2.21 years. In East Africa, where post-harvest fruit loss is common, two solar dryers were created: the improved solar dryer and the solar photovoltaic and electric dryer [111]. Economic analysis reveals that the improved solar dryer is more cost-effective, with a payback period 2.4 times shorter than that of the solar photovoltaic and electric dryer. This makes the improved solar dryer a superior choice for farmers and agro-processors in Uganda and East Africa without access to electricity. The performance and economics of a V-grooved air collector with rotating trays in a solar cabinet dryer for drying potato chips in Bhubaneswar, Odisha was studied [112]. The results were compared to a flat plate air collector with rotating trays in the same dryer. The utilization of the V-grooved collector resulted in a payback period of 0.48 years for the newly designed dryer. In their research, Singh *et al.* [29] employed evacuated tubes in an indirect solar drying system for turmeric and fenugreek leaves. They determined the payback period to be approximately 555 days for turmeric and 604 days for fenugreek leaves. A cabin-style solar dryer with an additional heating element was employed to dehydrate four different types of items, including apples, kiwis, banana slices, and quince julienne strips [113]. Among these products, quince strips incurred the highest production cost per kilogram, approximately $1.137 per kg, while the most cost-effective option was apple slices at around $0.478 per kg. Another study examined the qualitative and economic evaluation of a forced convection drying setup used for tomato slice dehydration within a Tunisian agricultural greenhouse, taking into account the local climate [114]. The overall efficiency was calculated as 42 % for the dryer, while the solar air collector demonstrated an efficiency of 62 %. To assess the quality of both fresh and dried tomatoes, a color analysis was conducted. The economic analysis revealed that the payback period was estimated to be 1.82 years.

2.4 Environmental considerations

Solar crop processing represents the latest and most effective technological advancement for developing nations, designed to address a multitude of challenges. The introduction of solar drying technologies to farmers has the potential to instigate significant change, ultimately eradicating hunger and poverty in these nations. A primary advantage of employing solar dryers is the reduction of global warming through diminished greenhouse gas emissions, notably carbon dioxide. Various methods have been employed to quantify the extent to which solar dryers can contribute to emission reduction. Solar energy utilization in the drying process, not only conserves significant amounts of traditional fuel but also mitigates carbon emissions. The extent of fuel reduction hinges on the design and type of solar dryer, with hybrid systems such as greenhouse-style solar dryers with natural circulation showcasing a fuel consumption decrease of 20 to 40 % [12]. The environmental study of solar dryers provides a great deal of information regarding $\mathrm{CO_2}$ emissions [4,115]. Chauhan *et al.* [116] developed greenhouse solar dryers for drying of bitter gourd in active and passive mode. The energy payback period for these dryers operating in passive and active modes were 1.68 years and 2.35 years, respectively. In terms of carbon dioxide reduction, the drying process for bitter gourd flakes results in a net mitigation of 33.04 tons and 36.34 tons under passive and active modes, respectively. In another study Beigi *et al.* [117], the environmental impact of paddy drying in a convective dryer was assessed through an analysis of equivalent specific $\mathrm{CO_2}$ emissions were evaluated. Energy and exergy analyses were conducted under various conditions. Specific $\mathrm{CO_2}$ emissions ranged from 3.83 to 8.42 $kg_{CO_2}\ per\ kg_{water}$, with lower temperature and lower airflow rates resulting in a reduced carbon footprint. An investigation into the drying kinetics of potato slices was undertaken in a convective dryer utilizing waste heat [118]. The exergo-environmental analysis of the proposed dryer indicates $\mathrm{CO_2}$ emissions of 184.46 kg/year and a $\mathrm{CO_2}$ mitigation of 17.24 tons over a 20-year life cycle. This suggests that the successful industrial application of the proposed drying system could be a significant step towards the development of energy-efficient and environmentally sustainable food drying systems. Hadibi *et al.* [119] conducted an assessment of a hybrid solar dryer that utilized electric resistance in the drying chamber to dry garlic cloves. The evaluation consisted of energy, exergy, and environmental analyses. The solar dryer had an energy payback period of 0.32 years and was capable of mitigating 140 tons of CO_2 at an air velocity of 6.9 ms^{-1}. Vijayan *et al.*[110] developed a pebble-based active indirect solar dryer to study the drying of bitter gourd slices. The energy payback time and CO_2 mitigation was calculated to be 2.21 years and 33.52 tons, respectively. In addition, Atalay and Cankurtaran [120] evaluated the energy payback period (EPPD) of a large-scale solar dryer assisted by thermal energy storage, reporting an EPPD of 6.82 years, CO_2 emission of 2.581 tonnes/year, and CO_2 mitigation of 99.6 tons for a 20-year lifespan, which also aligns with the outcomes of the present study. A forced convection solar dryer developed, incorporating a heat exchanger placed within the dryer itself, which also serves as the drying platform [121]. With an evacuated tube collector, the dryer has the potential to mitigate CO_2 emissions by 88.12, 50.49, and 135.04 tonnes over its lifespan for tomato, ginger, and bottle gourd, respectively. In contrast, the conventional dryer, lacking a collector, only mitigates CO_2 emissions by 49.58, 26.57, and 41.22 tonnes for these same crops during its lifetime. Additionally, the energy payback time for tomato, ginger, and bottle gourd is 0.69, 1.79, and 2.87 years less than that of the conventional dryer, respectively. Mishra *et al.* [122] performed a comprehensive assessment on greenhouse dryer in both active and passive operational modes when there was no load present. In the active mode, the energy payback period for the solar dryer was determined to be 1.5 years, while in the passive mode, it was found to be 1.1 years. A performance analysis was done for an indirect solar dryer in three scenarios, testing it during spring and summer seasons for drying *Momordica charantia* [123]. The dryer had an energy payback period of 1.42 years and could potentially reduce CO_2 emissions by 23.88 kg/year, mitigate 20.13 tons of carbon, and earn carbon credits worth $100.642 to $ 402.569 over a 35-year lifespan. A comparative study was done for drying of groundnut in a simple and modified greenhouse dryer [124]. A greenhouse dryer with natural convection was enhanced by incorporating a latent heat storage unit containing beeswax as the phase change material. The energy payback period for modified greenhouse dryer was 2.28 years, while for simple greenhouse dryer, it was 1.27 years. Modified greenhouse dryer showed greater CO_2 reduction and earned a higher total carbon credit. The environmental results in Gupta *et al.* [125] suggest that the photovoltaic-thermal solar dryer, when functioning in the forced convection drying mode, exhibits superior environmental sustainability compared to the natural convection drying. The calculated payback period for the solar dryer is 1.40 years in the forced mode and 1.70 years in the natural mode. Importantly, these payback periods are notably shorter than the expected system lifespan of 30 years.

2.5 Numerical work on improved solar dryer

Tedesco *et al.* [126] designed a passive ISD with a chimney and numerically evaluated the solar collector, drying chamber, and chimney. They compared the results with experimental drying of apples. A numerical model was developed to investigate the performance of a wood dryer using an indirect hybrid solar dryer with TRNSYS software [127]. An environmental analysis was conducted, with a particular focus on the reduction of carbon dioxide emissions resulting from the integration of the solar collector into the dryer system. The results demonstrated a significant annual decrease of approximately 34 % in CO_2 emissions due to this integration, highlighting its positive impact on environmental sustainability. Yadav and Chandramohan [128] numerically developed a TES with paraffin wax as its PCM for an ISD. The study was conducted for two cases: one with TES with fin and other without fins up to 10.00 pm. For four different air velocities (1, 2, 3 and 4 ms^{-1}), CFD analysis was done and compared. For the two cases, it was found that air velocity of 1 ms^{-1} showed better result compared with the other velocities. Further, at the air velocity of 1 ms^{-1}, average temperature of PCM with fins was found to be 3.7 K higher than the one without fins. The maximum percentage of the former showed a gain of 52.2 % higher than the latter. Alimohammadi *et al.* [129] studied both numerically and experimentally the effect of parabolic trough solar collector along with four fluids, namely, water, glycerine, engine oil and nanofluid (Al_2O_3, 4 %) aided with paraffin as PCM on a solar dryer for apple slices. The study highlighted the different aspects of the usage of the four fluids. The input thermal energy of the dryer was 17.3, 18.46, 17.76 and 16.80 MJ, respectively for nanofluid, oil, glycerine and water. The collector efficiency assisted with the afore mentioned fluids were 69.9 %, 73.4 %, 71.9 % and 63.8 %, respectively. With respect to water, the engine oil, glycerine and nanofluids, the overall efficiencies of the dryer were 20.2 %, 12.4 % and 9.7 %, respectively. A numerical simulation was conducted to model the performance of a cocoa bean dryer under different convection scenarios: natural, forced, and a combination of forced and natural convection [130]. The aim was to assess their efficiency in a tropical climate. The analysis revealed a calculated payback period of 2.19 years. However, it was suggested that by raising the price of a kilogram of properly dried cocoa beans and utilizing the dryer for drying other products when cocoa beans are not in season, the payback period could be reduced. A numerical and comparison of three different designs of solar dryer was studied [131]. The use of both Plexiglas and glass led to a 25 % reduction in drying time, with a modest 57 % rise in expenses. The drying time achieved with the semi-greenhouse-style setup using the combined plastic and glass approach was on par with that of the single-glazing greenhouse style but at a more economical cost. A study on numerical works provides insights into potential directions for future research and improvements to experimental findings. Incorporating numerical simulations study into the experimental framework could facilitate a cohesive understanding of how these methodologies complement each other in future study.

2.6 Summary of the literature review

This chapter provides an extensive investigation of recent advancements in solar drying systems across various dimensions, categorized into four pivotal areas: drying kinetics analysis, energy and exergy assessments, economic evaluations, and environmental study. Diverse drying kinetics models have been applied to predict the drying behavior of agricultural products effectively. Energy and exergy assessments highlight the significance of utilizing solar energy, with hybrid systems showcasing improved efficiency and reduced environmental footprint compared to conventional methods. Economic evaluations reveal the cost-effectiveness of solar drying systems, with rapid returns on investment and significant savings observed in various studies. Furthermore, environmental study highlights the potential of solar dryers to mitigate greenhouse gas emissions and promote sustainable development, particularly in regions with limited access to conventional energy sources. Overall, the chapter emphasizes on the multifaceted benefits and promising potential of solar drying systems in addressing contemporary challenges in agricultural product processing, sustainability, and environmental conservation.

2.7 Scope of the present work

In the present research work, drying of *Garcinia pedunculata* using a newly developed free convection corrugated solar dryer (FCCSD) was studied. The FCCSD demonstrated efficiency through useful heat gain and thermal efficiency measurements. Drying models were applied, with FCCSD and an open sun drying (OSD) system assessed for moisture content reduction rates. As the efficiency of the dryer and specific energy consumption (SEC) was assessed, the recorded inlet and outlet temperatures, along with relative humidity, played a pivotal role in understanding its performance. Additionally, an economic analysis was performed to highlight the potential savings and construction costs, emphasizing the importance of assessing viability for various agricultural products.

Next, the drying kinetics of *Garcinia pedunculata* using different configurations of solar dryers, including indirect solar drying without solar heat storage (SHS), mixed-mode solar drying without SHS, indirect solar drying with SHS, and mixed-mode solar drying with SHS was studied. The average efficiencies along with SEC values of the dryer were calculated for each experimental set, revealing the dryer that gave the highest efficiency and lowest SEC. The overall drying times for each experimental set were observed to find the mode that showed the shortest drying time. Various drying models were evaluated to identify the best fit for each mode of experiment. The construction cost of the dryers and their economic payback periods were calculated to find out the attractive economic payback period, indicating its economic viability over time.

Again, in this study, four-mode solar dryer was developed and tested for drying *Garcinia pedunculata*. The dryer distinctive feature of the dryer is its ability to transform the drying cabinet into different modes by sliding the walls. The four modes considered were 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). Drying durations and efficiencies varied for each mode, showcasing the adaptability of the dryer. The average exergy efficiency was assessed for ID-WOS, MX-WOS, ID-WS, and MX-WS. Exergy studies provided insights into the true potential of the solar system, indicating varying exergy efficiencies across the configurations. The study also considered the environmental impact of all four configurations. Environmental considerations, including CO_2 emissions, mitigation, and embodied energy, were also investigated over a 20-year lifespan.

Further, an indirect solar drying system integrated with a waste beverage canned absorber plate has been studied. The primary distinction and innovation in the present system is focused on the arrangement of the solar collector compared to the other solar dryers available in the literature. This collector incorporates waste beverage cans those were integrated into an aluminium absorber plate. Moreover, there is a lack of information regarding the drying kinetics, energy, exergy, quality, and economic assessment of such a solar dryer aided by solar energy storage while dehydrating *Curcuma amada*. Gravels were chosen as a solar thermal energy storage from a construction site. The availability of the present drying system and previous research indicate its effectiveness in reducing drying time, improving process uniformity, and temperature control.

The research focused on assessing the suitability and efficiency of the dryer for another product by studying the drying process of *Curcuma amada*. Furthermore, both *Garcinia pedunculata* and *Curcuma amada* are subject to seasonal availability. Adapting the system to dry crops available at different times of the year facilitates year-round operation, thus maximizing its utilization and benefits.