2. Review of Literature

This chapter explores the literature on food drying, particularly focusing on solar drying methods and solar greenhouse drying systems equipped with solar air heaters (SAH), thermal energy storage (TES), and photovoltaic modules (PV) for drying agricultural produce. It delves into drying properties, quality evaluation of agricultural products, thermal efficiency comparisons of various solar greenhouse dryers, and economic and environmental considerations related to these systems.

2.1 Application of solar energy for drying

2.1.1 Solar drying

When assessing solar dryers, three key components are taken into account: the air movement method (passive or active) and the heat transfer mode (direct or indirect, hybrid mode or mixed mode) [33].

Radhakrishnan and coresercher evaluated solar dryers that used phase change materials (PCM) to dry crops, with paraffin wax serving as the PCM for coconut samples. Increasing the PCM amount in conventional solar dryers decreases drying time [34].

A new drying method, Double-pass solar drier, was developed and tested against conventional drying (CD) and traditional sun drying for red chili [35].

Musembi and coresearcher designed and performance evaluation the solar dryer dries 1.0 kg of apples from 86% to 8.12% moisture in 9 hours. This suggests cost savings with scale in solar drying [36].

Fig. 2.1.1 Experimental Set-Up during solar drying

2.1.2 Incorporation of greenhouse effect in drying

In large-scale drying operations, greenhouse drying is pivotal. A greenhouse dryer was developed with natural convection, incorporating sensible heat storage in the drying chamber bed. Four bed types were compared for heat transfer efficiency: gravel, ground, concrete, and black-painted gravel. The black-painted stone bed outperformed others with a 53% heat observe, recommending its use for optimal heat storage by Ahmad and Prakash [37].

Gorjian and coresearcher examined how greenhouse dryers (GHDs) interact with various solar technologies like PV, PVT, and solar thermal collectors. Additionally, it explores improving thermal performance through hybrid setups, and combining SGHDs with other renewable energy sources, all to boost the drying performance of agricultural products [38].

Chauhan and Kumar evaluated a greenhouse dryer with insulated and free convection, showing the advantages of adding a solar collector. The results highlight better room temperatures and increased heat usage, improving the dryer's efficiency [39].

Ahmad and coresearcher presented and assessed a hybrid SGHD for drying bitter gourd flakes in Ranchi, India. It evaluates aspects like drying efficiency, kinetics, properties, economics, and CO_2 reduction. The findings suggest that this hybrid dryer holds the potential to decrease post-harvest losses and support environmental sustainability [40].

The article delves into SGHD for agricultural product drying, design, thermal modelling, energy, and environmental impacts. It discusses the integration of photovoltaic (PV) panels and TES for uninterrupted and off-grid drying processes by Srinivasan and Muthukumar [14].

Khadraoui and coresearcher tested a new SGHD with forced convection for drying red pepper. It's faster than sun drying, cutting drying time by about 7 hours for red pepper and 17 hours for grape. The dryer only shows the falling rate period in its drying curves [41].

Ozgener and Ozgener studied exergy changes during drying in solar greenhouses, analyzing exergy efficiencies. It emphasizes the significance of exergy analysis for understanding drying processes' thermodynamic efficiency, focusing on a passively heated solar greenhouse's drying performance [42].

Singh and coresearcher reviewed various greenhouse solar dryers, which expose products to external challenges such as rain, insects, and animals. By presenting data on existing greenhouse designs, the paper facilitates readers in creating new and modified greenhouse structures for enhanced solar drying applications [3].

Yadav and coresearcher found the utilization of solar greenhouses presents an efficient solution for preventing crop and fruit losses, thereby enhancing the overall agricultural lifecycle. The prototype serves as a valuable tool for conducting experimental validations, specifically focusing on the drying of crops and fruits [43].

2.1.3 Solar based air heating for supplementation of drying

Babar and coresearcher designed a passive (FPC-SD) for drying mushrooms, for effective drying. The absorber, with an aspect ratio of 2.0 and a depth of 0.25 m, emphasizes the use of passive flat plate collector technology for sustainable mushroom drying [44]. Solar air heaters use solar energy for heat, offering free heating for tasks like space heating. Thermal storage is useful for significant day-night temperature variations. Thermal storage heaters, especially PCM-based ones, are effective for tasks like crop drying, reviewed [45].

Mehta and coresearcher designed a mixed mode tent- type solar dryer and performed under no-load conditions, the collector reached a peak outlet temperature of 86 °C in natural convection mode, while the average outlet temperature throughout the experiment was 75 °C, resulting in a 25.42% efficiency rate. These findings the system's adeptness at utilizing solar energy for drying [46].

Fig. 2.1.2 Schematic diagram of the mixed mode tent solar dryer

2.1.4 Integration of multiple modes of supplementation for greenhouse drying

Khadraoui and coresearcher evaluated a solar dryer with a solar heater using PCM for nighttime use. Adding paraffin wax as PCM significantly improves performance. Without PCM, nighttime conditions in the drying chamber are like ambient conditions, but with PCM, humidity drops by 17-34.5% and the temperature rises by 4-16°C. Solar energy accumulator achieves 33.9% daily energy efficiency and 8.5% daily exergy efficiency [17].

Radhakrishnan and coresearcher integrated phase change materials (PCMs) in solar drying offers an energy-efficient method, especially in post-harvest food processing. This strategy utilizes thermal energy stored in PCMs to prevent food deterioration, improving overall energy efficiency and promoting sustainable food preservation [34].

A natural convection solar greenhouse dryer was utilized in this study to dry coconuts during summer, employing three different sensible heat storage materials. Compared to open sun drying, the concrete-based dryer reduced drying time by 55%, completing the process in 78 hours instead of 174 hours. Sand and rock beds further decreased drying times by 62% (66 hours) and 69% (53 hours), respectively found by Ayyappan et al. [11].

Jouhara and coresearcher reviewed on thermal energy storage (TES) as a vital tool for optimizing energy usage by balancing supply and demand. It particularly focuses on phase change materials (PCMs), which play a key role in addressing energy discrepancies. PCMs are categorized based on their chemical composition and phase transition properties. Various techniques, including cascaded LHS systems and PCM encapsulation, are discussed for improving PCM performance. The review highlights the broad applications of PCMs across industries like construction, power generation, food processing, and automotive sectors. Additionally, it presents a comparison and categorization of modelling tools for analyzing PCM functionality [47].

Banout and coresearcher showed how phase change materials (PCMs) in solar drying can improve food preservation after harvest. It presents a new solar dryer design with black stones for better solar energy absorption, using organic paraffin wax (melting point: 60 °C) as PCM. By adding PCM, drying becomes more efficient, cutting drying time and microbial content in dried coconut compared to traditional sun drying. Adding 100 and 200 g of PCM reduced coconut drying time by about 28 and 52 hours respectively. Solar-dried coconut also has better sensory qualities than sun-dried coconut, including color, taste, flavor, quality, and texture [34].

Tiwari and Tiwari reviewed on incorporating a (PVT) air collector into a drying setup, focusing on detailed thermal modelling. It evaluates thermal efficiency (26.68%), and overall thermal efficiency (56.30%) at MFR of 0.01 kg/s for the air. These results offer crucial insights into the performance of the combined PVT and drying system, benefiting researchers working on thermal modelling for hybrid solar systems [48].

Singh and coresearcher reviewed that hybrid greenhouses enable faster drying rates while preserving the quality of dried products. Greenhouses with auxiliary heating sources perform exceptionally well, allowing operation during off-sunshine hours. Solar collector especially under natural convection, offer faster drying rates with a lower initial investment, making them ideal for small-scale drying operations. Despite higher costs, the ability to dry larger quantities in a shorter time frame justifies the investment in hybrid features [49].

Tested a span greenhouse and built-in packed bed thermal storage for drying onions on trays, assessing its effectiveness. Factors like greenhouse dimensions and MFR of air influence crop temperature. TES is vital, especially during non-sunny periods, to stabilize temperatures during drying. The mathematical model proposed serves as a useful tool for assessing crop drying performance in such greenhouse configurations and predicting key parameters like crop temperature, moisture content, and drying rate [50].

Prakash and coresearcher found that solar air heaters (SAHs) harness solar energy for cost-effective heating in commercial and industrial buildings and absorbing solar radiation, warming air as it flows through ducts. In addition to regulating building temperature, SAHs can be used for industrial tasks such as crop drying, tapping into renewable solar energy [51].

Srinivasan and Muthukumar reviewed on use of TES units in solar dryers, which can include SHS, LHS, or a combination of both. It examines the different storage units and materials used across various types of solar dryers, including those with natural and forced convection. The review explores different dryer configurations, dried products, operational factors, and the range of storage materials employed [18].

Malakar and coresearcher designed integrated evacuated tube solar dryer effectively sustains steady drying temperatures despite solar radiation changes. This innovative system provides sustainable and efficient solutions, being adaptable and eco-friendly. Its capability to maintain consistent drying conditions across different temperature ranges highlights its importance for various agricultural uses [21].

Gorjian and coresearcher explored advancement for greenhouse dryers (GHDs) with various solar technologies like PV, PVT, and solar thermal collectors. It explores integrating SGHDs with heat pumps, TES units, and other renewables to enhance thermal efficiency [38].

2.2 Drying kinetics and quality analysis of agricultural produces

2.2.1 Drying kinetics

Thorat and coresearcher identified that drying of ginger slices primarily occurred during the falling rate phase, indicating that moisture elimination was mainly influenced by diffusion. Statistical analysis determined the two-term model as the most accurate in describing the drying kinetics of ginger slices [52].

Ojediran and coresearcher used ANFIS to predict yam slice drying in a hot air convective dryer. It calculated parameters like diffusivity and activation energy, varying air temperature, velocity, and slice thickness. ANFIS accurately forecasted moisture ratio with high correlation ($R^2 = 0.986$) and low error (RMSE = 0.01702). Diffusivity increased with higher air conditions, ranging from 6.382E-09 to 1.641E-07 m^2/s [53].

Murugavelh and coresearcher investigated dried tomato waste using a mixed-mode forced convection solar dryer, reducing moisture from 71.1% to 0.3% in 7 hours, faster than an open solar dryer (15 hours). It showed a low activation energy of 37.46 kJ/mol. Drying kinetics followed the Midilli & Kucuk model with a constant (k) value of 8.135×10^{-5}/s [54].

Arun and Selvan using a solar tunnel greenhouse dryer, coconuts with an IMC of 53.84% (w.b.) reached 7.4% (w.b.) after 56 hours, compared to 147 hours with traditional open sun drying. The dried coconuts were of higher quality, devoid of fungal and bacterial infections, suggesting superior coconut production potential compared to OSD [55].

Borah and coresearcher evaluated four drying methods for ginger and turmeric: integrated drying system (IDS), fluidized bed dryer, electrical oven, and open sun drying. IDS resulted in the lowest crushing strength (1.12 kg), while open sun drying yielded the highest (1.42 kg). Spices dried using IDS maintained the highest quality attributes according to instrumental analysis [56].

Hoque and coresearcher found that the drying rate of ginger rhizomes in both a hybrid solar dryer and a mechanical tray dryer at various temperatures was significantly enhanced by blanching and slicing. The Page equation was found best fit for sliced and blanched ginger. Drying below 70°C, with slicing and blanching, produced the highest quality dried ginger, as indicated by minimal colour changes and improved drying kinetics [57].

An and coresearcher compared various drying methods for ginger slices, finding that air-drying and infrared drying best volatile compounds. Freeze drying, infrared drying, and intermittent microwave & convective drying retained maximum levels of gingerols, phenolics, flavonoids, and antioxidant activities. This highlights the unique advantages of each drying method in maintaining specific quality aspects of ginger slices [58].

Amer and coresearcher found that the primary drying chamber of the integrated dryer could hold 32 to 35 kg of fresh chamomile, while a separate chamber had a capacity of 10 to 12 kg for other materials. The dryer maintained the desired air temperature for chamomile drying using a temperature controller. Operating for 30 to 33 hours, the integrated dryer decreased chamomile MC from 72-75% to 6%, contrasting with the 60 hours required for a 9 to 10% reduction with OSD method. The Midili model was identified as the most effective for characterizing chamomile drying kinetics [59].

Hidalgo and coresearcher evaluated a solar dryer for onions, using free and forced air convection with photovoltaic assistance. Drying kinetics analysis revealed consistent and falling rate periods, with convection showing higher drying rates. Straight lines accurately represent constant rate periods. Page models best fit falling rate periods for forced convection. These findings highlight the effectiveness of convection methods in drying green onions and provide valuable diffusivity data for process optimization [10].

Ahmad and coresearcher developed heat storage–based hybrid greenhouse dryer proved highly performed and consistent in drying bitter gourd flakes. The drying kinetics and property analysis demonstrated superior performance compared to OSD, resulting in superior dried products. With a significantly reduced drying time of 8 hours, the hybrid greenhouse dryer emerges as an economically viable and practical solution for small-scale farmers and industries involved in bitter gourd processing [40].

Mani and Thirumalai compared the thermal efficiency of solar greenhouse dryers with even span and parabolic roof designs, operating in active and passive modes. Clad with 200-µm UV stabilized polyethylene sheets, they aim to optimize solar insolation for drying lima beans. The parabolic dryer achieves moisture reduction from 75% to 11% in 28 hours in active mode, while the even-span dryer takes 32 hours. In passive mode, the parabolic dryer achieves this in 32 hours, and the even-span dryer in 36 hours [5].

2.2.2 Quality analysis

The integrated solar biomass dryer dried ginger in 33 hours, compared to 96 hours under natural sunlight. It achieved 18% and 13% higher efficiency in summer and winter, respectively. The hybrid dryer preserved better quality with reduced volatile oil loss [60].

The drying of ginger powder led to notable changes in chemical properties, as observed through FTIR, XRD, and SEM. FTIR analysis showed similar absorption bands across different-sized ginger powders but with reduced intensity in smaller particles. Superfine grinding, especially for 8.34 µm particles, caused shifts in spectra, indicating cellulose structure deterioration. XRD revealed increased crystallinity and peak intensity with a smaller powder size. SEM confirmed that superfine pulverizing effectively altered the original structure of ginger powders [61].

Kondareddy and coresearcher created a (MSD with PCM) to dry blood fruit. The design of the solar collector raised air temperature for drying from 15-18%, maintaining a mean of 60 °C for 10-12 hours. The drying kinetics were well-described by the Midilli model. The color, TPC, TFC, and antioxidant activity of dried and fresh samples were compared [62].

The study dried mature ginger, treated with citric acid, using heat pump dehumidified dryers (40-60 °C) and a mixed-mode solar dryer (62 °C). The highest-quality ginger, with optimal colour and 6-gingerol content, resulted from drying without pretreatment at 40 °C in a heat pump dehumidified dryer. Higher temperatures in the solar dryer, especially for non-pretreated ginger, reduced drying time and preserved high 6-gingerol levels akin to heat-based methods [63].

Deshmukh and coresearcher showed ginger drying from 621.50% to 12.19% (d.b.) in 450 to 480 minutes using a solar dryer. It proved efficient, fast, and energy-free compared to traditional methods, with effective moisture diffusivity at 1.789×10^{-8} m^2/s [27].

Cherrat and coresearcher examined the impact of drying temperatures (40 to 100 °C) on the chemical composition, antioxidant properties, and microstructure of ginger powders. Samples dried at 100 °C exhibited significantly higher levels of polyphenols (24.154 mg GAE/g) and flavonoids (10.564 mg GAE/g). Additionally, antioxidant activity rose from 73.47% at 40 °C to 78.23% at 100 °C [64].

2.3 Performance evaluation of solar drying process

2.3.1 Computational modelling of drying Process

Togrul and Pehlivan identified the best mathematical model for apricot solar drying. After analyzing drying curves and considering factors like temperature, velocity, and humidity, the logarithmic model proved most effective. This sheds light on the dynamics of apricot drying, highlighting the model's ability to capture drying behaviour under different conditions [65].

Subin and coresearcher utilized computational fluid dynamics (CFD) simulations to evaluate and choose the optimal roof covering material for commercial greenhouses. It compared the effectiveness of different configurations of polyethylene and polycarbonate sheets. Additionally, the analysis included simulations of cooling and heating systems to improve the greenhouse's climate control [66].

Macadamia nuts were efficiently dried in a greenhouse solar dryer within five days, producing top-quality dried products. Simulation using the finite difference method accurately represented heat and moisture transfer during drying, aligning closely with experimental results. This simulation method aids in designing and optimizing solar greenhouse dryers by Phusampao et al. [67].

Alimohammadi and coresearcher examined how different fluids affect a parabolic trough solar collector's thermal efficiency. It used CFD to predict thermal changes and conducted experiments with an airflow rate of 0.025 kg/s. Comparing simulated and predicted outcomes, the CFD method reliably and precisely forecasts the PTSC performance with different working fluids [68].

Román-Roldán and coresearcher investigated and used 3D computational fluid dynamics software ANSYS Fluent for temperature and velocity distribution in an SGHD drying chamber, considering solar radiation effects. Two models, real and reduced height, aligned well with experimental temperature data. The real model showed a turbulent kinetic energy (TKE) range of 1.27 to 6 m^2/s^2, averaging 1.6 m^2/s^2. The improved model, with 36.5% volume reduction, exhibited 2.4 times higher average TKE (3.8 m^2/s^2), averaging temperature of 316.5 K, and increased air velocity (0.9 m/s at 1.0 m height), ensuring over 95% uniform temperature distribution for efficient drying [69].

Rani and Tripathy utilized 3D computational models to examine airflow, temperature, and heat transfer in solar drying of pineapple slices. Using COMSOL Multiphysics, the simulations compared flat plate and finned collectors in mixed solar dryers. The finned collector outperformed the flat plate, achieving 10% moisture content reduction in pineapple slices 2.5 hours faster. Inadequate air distribution in the flat plate dryer created vortices and localized heating, while the finned collector offered better airflow distribution and a uniform temperature profile, impacting drying homogeneity [70].

CFD simulations yielded promising results in efficiently drying local products, with close agreement between simulation and experimental data. RMSE values for temperature and relative humidity remained consistently low, confirming simulation accuracy. These findings highlight the reliability of CFD in optimizing drying processes for local products, enhancing overall efficiency, investigated [71].

2.3.2 Energy and exergy Analysis

Prakash and coresearcher found that the energy and exergy efficiencies fluctuate with the operating mode. In natural convection, they are 11.47% and 2% respectively. In induced forced convection, they increase to 56% and 10.43% respectively. Adding a reflector further boosts efficiencies to 86.19% and 17.617% respectively [51].

Mugi and Chandramohan investigated on forced convection indirect solar dryers (ISDs) with divergent ducts and CPU fans achieved higher efficiencies compared to natural convection ISDs. Forced convection ISDs showed average solar air collector and dryer efficiencies of 74.98% and 24.95%, respectively, while natural convection ISDs had slightly lower efficiencies at 61.49% and 20.13%, respectively [7].

Murugavelh and coresearcher introduced a mixed-mode type solar tunnel dryer for fruit waste drying. It includes a blower, solar collector, greenhouse chamber with trays, and chimney. Exergy efficiency ranged from 38.53% to 67.58%, averaging 52.21%, peaking during maximum solar radiation. It efficiently uses solar energy for drying various agro-biomass and fruit waste [54].

Dutta and coresearcher analyzed how different MFRs of air (0.0072, 0.014, 0.02, and 0.024 kg/s) affect the energy performance of a mixed-mode corrugated solar air heater through experiments. Higher flow rates led to higher thermal efficiencies but lower outlet temperatures, resulting in decreased temperature differentials [72].

Subramani and coresearcher evaluated a cost-effective greenhouse dryer's efficiency through energy and exergy analyses, comparing it with open sun drying. Using two cover sheets UV polyethylene and drip lock drying trials were conducted for ivy gourd and turkey berry. Results showed superior performance of the greenhouse dryer, thermal efficiencies of up to 30.64% and exergy efficiencies of up to 0.09%, especially under active mode for ivy gourd drying [6].

Malakar and coresearcher) designed a solar dryer with an evacuated tube absorber and heat pipe was designed for garlic cloves. It reached a peak collector efficiency of 42.56% and dryer efficiency of 56% at 2.0 m/s airflow. At this rate, exergy efficiency was 56.59%, with a minimum exergy loss of 4.74 W at 1.0 m/s airflow [20].

Kondareddy and coresearcher modified solar dryer with TES was created for blood fruit, increasing drying time by 19%. It improved drying rates and preserved product quality compared to a tray dryer. Energy and exergy analyses, along with payback period calculations, the MSD's superior performance, with EPT of 1.23 years and substantial CO_2 emission reductions [62].

Silva and coresearcher investigated on a mixed solar cabin dryer and achieved thermal efficiency of 21% and exergy efficiency ranging from 10% to 66%, averaging at 23%, with corn reaching 13% moisture content in 8.5 hours, in contrast to 24 hours with natural sun drying [73].

Ndukwu and coresearcher assessed energy and exergy sustainability in drying product moisture, considering environmental and economic factors. Energy consumption ranged from 5.52 to 35.12 MJ, and Exergy efficiency varied between 5.6% and 95.13% during sunshine hours [74].

2.4 Environmental analysis and cost analysis

To evaluate the dryer's economic viability and sustainability, it's crucial to examine various indicators across economic, energy, and environmental domains. Energy considerations involve analyzing embodied energy and specific energy consumption [14].

Kingphadung and coresearcher compared greenhouse solar drying to hot air drying for preserved fruit production in Thailand, finding both methods cost-effective. However, greenhouse solar drying was favoured by small entrepreneurs aiming to produce mango product [75].

In India, small-scale cashew nut processing often relies on energy-intensive drying methods. To address this, renewable energy dryers, including solar, biomass, and hybrid options, were evaluated for economic viability. A solar-biomass hybrid dryer emerged as the recommended solution for small-scale cashew nut processing [76].

Lakshmi and coresearcher reviewed and evaluated a mixed-mode forced convection solar dryer for stevia leaf drying, finding it suitable for commercial use with high product acceptability and a favourable payback period of 0.65 years, indicating low-risk commercialization [12].

2.5 Summary of chapter II

This chapter provides a concise literature review that enhances our understanding of the development and application of integrated solar greenhouse drying (ISGHD) system. It covers studies on solar air heating systems (SAHs) with phase change materials (PCMs), focusing on the research gap in thermal storage systems (latent heat storage - LSH and sensible heat storage - SHS) in dryers and solar air heating systems (SAHs). Additionally, it explores the use of photovoltaic (PV) modules in drying systems. The review delves into solar greenhouse drying assisted with SAH, PV modules, PCMs, and thermal energy storage (TES) applications. Aspects covered include ginger drying kinetics, product quality, artificial neural networks (ANNs), drying modelling, thermal analysis, and performance evaluation. The Energy and exergy analyses of various solar greenhouse dryers and other solar dryers are discussed, along with computational fluid dynamics (CFD) analysis for simulating and validating experimental data. Furthermore, environmental and cost considerations for dryers are examined.