Chapter 1

Introduction

One of the most vital ways for safe and secure storage of food and their preservation for future use is the drying of various agricultural products. A burning example is the recent food shortage provoked by the COVID-19 pandemic alone that has affected all parts of the world including the developed, developing, and under-developed countries [1]. A gap between the demand and availability of food has become evident during the pandemic. Under such crisis situations, food storage through drying can help a great deal to overcome the challenges of making food available for nutrition and even boosting the immunity of people. Drying is performed by extracting the moisture from the commodities by various energy-intensive processes [2]. It is noteworthy that the benefits of drying are not limited only to storage of the end product but this also promote quick handling and decreased transportation cost [3,4]. The energy that are involved in drying may be derived from various sources like solar, electricity, biomass, LPG, diesel, petrol, etc. It is a well-accepted fact that non-renewable sources of energy ruin the environment and therefore they are not considered good options. Solar energy is considered as an alternative to non-renewable sources of energy that has got good potential for food-drying applications and additionally, this source is abundant [5].

Open Sun Drying (OSD) is as primitive as human civilization but it is unable to manage several fluctuating environmental conditions and the results are unsatisfactory drying quality [6]. Figure 1.1 illustrates the working concept of drying in open sun [7]. Figure 1.1, Figure 1.3, Figure 1.4, and Figure 1.5 are drawn in AutoCAD. The solar energy of short wavelength falls on the asymmetrical crop surfaces from where a part is reflected back. Depending on the colour of the crops, the remaining part of the radiation is absorbed. The intensity of heat transferred into the crop increases which results in the conversion of the radiation to thermal energy. The blowing of the wind in and out of the crop surface results in loss of heat due to convection. Through conduction, the thermal energy is absorbed in the crop and subsequently it raises the temperature of the crop. The formation of water vapor at the interior of the crop diffuses to the exterior and finally to the ambient by evaporation. Initially, moisture is rapidly extracted from the surface and eventually it slows down [8]. Jain and Tiwari [7] studied the characteristics of different crops like chili, potatoes, cauliflower, onions, etc under OSD. They found that the moisture removal rate was higher in potatoes and cauliflower than the rest under steady-state conditions. Sun drying of basil, mint and parsley was experimentally studied in Turkey [9]. Twelve models were evaluated for the selection of suitable drying models. The Modified Page pertaining to mint and basil leaves, along with Verma *et al.* [10] model for parsley was found to be satisfactory.

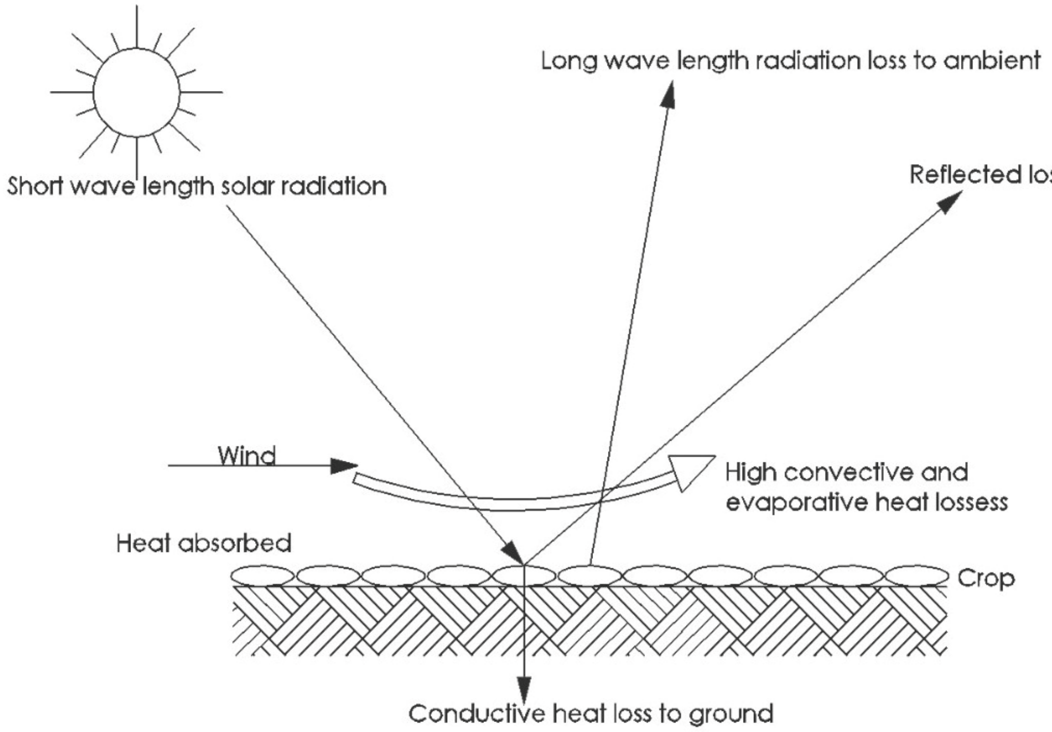

Figure 1.1 Working concept of open sun drying.

Generally, OSD do not live to the expectation in terms of the international-quality standards. With the lack of quality involved in OSD, more technical methods for practical use of solar energy for drying have come up, and they are discussed in the subsequent sections. On the contrary, drying in solar dryers has been regarded as an enhanced drying method with good quality in lesser time [11]. As such researchers from the past time have tried to develop different solar dryers that are easy to use, efficient, and environment friendly [12,13]. Over the past decades researchers have developed, designed and experimentally studied various solar dryers for a wide range of agricultural produces like chili [14], ginger [15], turmeric [16], apple [17], carica papaya [18], banana [19], tea [20], and herbs [21]. The dryers that most industries use for commercial purposes are freeze, spray, drum and steam dryers. Solar dryers may be broadly classified into the passive and active types, which may be further categorized into direct, indirect, mixed-mode and hybrid [22], as depicted in

Figure 1.2. Passive solar dryers make use of buoyancy force or wind, or combination of both to heat the air and circulate. Cabinet and greenhouse dryers are examples of passive drying. The air circulation on an active solar dryer is forced by fans, blowers, compressed air etc.

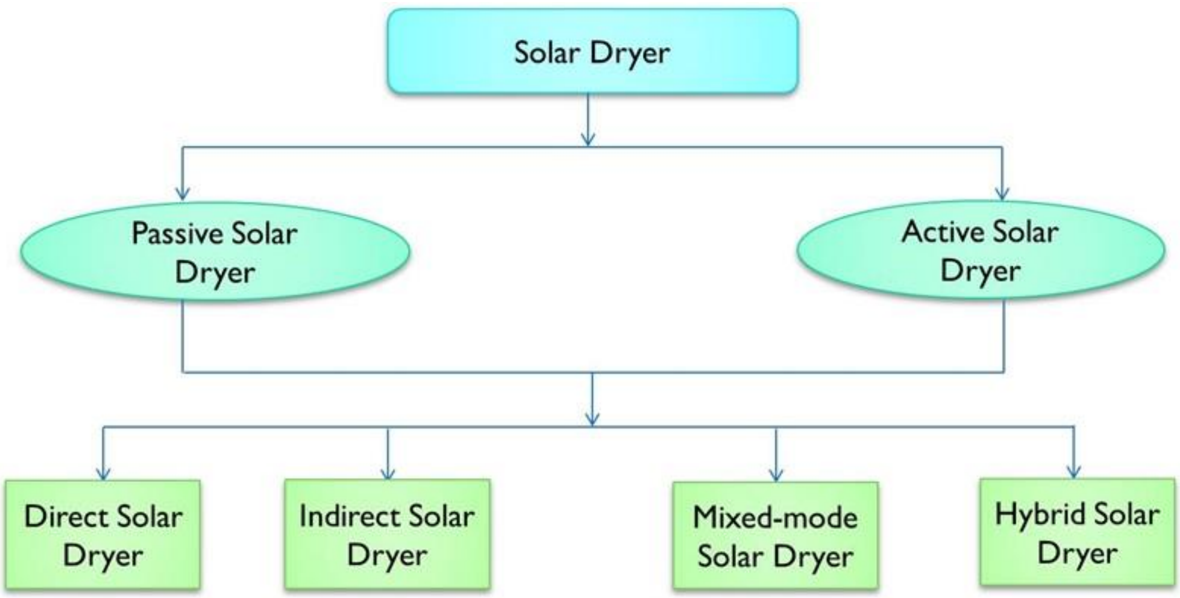

Figure 1.2 Types of solar dryers.

1.1 Direct Solar Dryer

As stated earlier solar dryer serves as a good substitute to OSD. Direct solar dryer (DSD) is generally done in tent or box dryers for different agricultural products. A transparent cover that allows light to pass through is used to lower the heat loss. Direct dryers provide shielding from rain and dust [23]. The layout of a typical DSD is shown in Figure 1.3 [8]. Over the years, researchers have contributed to the development of different types of direct solar dryers for various agricultural products [24,25]. Koua *et al.* [26] also designed a DSD capable of drying plantain banana, cassava, and mango. It was investigated that the evaporation rate per unit time during the constant rate period and the overall resistance to diffusion during the falling rate period for each product. Among the various drying models tested, the Henderson and Pabis model was determined to be the most effective. In a study of direct dryer, Ondier *et al.* [27] conducted experiments on rough rice. This dryer operated effectively at reduced temperature and humidity levels. Rathore and Panwar [28] built a solar tunnel dryer with a hemi-cylindrical shape in India to investigate the drying process of seedless grapes at temperatures ranging from 10 to 28 °C. It required 7 days to reduce the initial moisture content (MC) from 85 % (w.b.) to 16 % (w.b.). The dryer utilized UVstabilized polyethylene sheet as a covering, and an exhaust fan and chimney were incorporated to facilitate air circulation.

Some of the drawbacks of the DSD are as follows:

- Discoloration due to direct exposure to sun.
- Non-uniform moisture removal rate, leading to uneven and slower drying rates.
- Inability to dry large quantity of stock and interruption of drying operations due to rains or clouds.

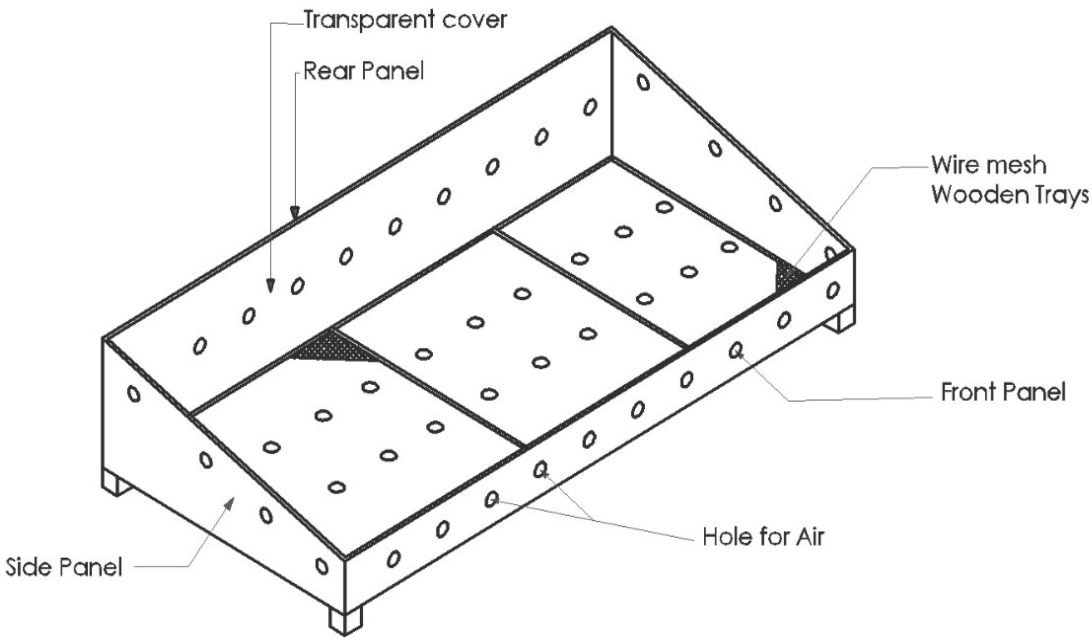

Figure 1.3 Layout of a direct solar dryer.

1.2 Indirect Solar Dryer

The indirect solar dryer (ISD) consists of two main components: a drying chamber and a solar collector. Figure 1.4 shows a layout of an ISD [29]. The SAC concentrates solar energy, while the drying chamber receives hot air from the collector. Within the chamber, the hot air circulates continuously over the agricultural produce, removing moisture. The produce is placed on trays inside the chamber. The SAC is typically made of a transparent cover and an absorber plate, which is inclined based on the location. The absorber plate, coated in black for maximum absorption, absorbs a portion of the solar energy, convecting heat into the chamber. Some of the incident sunlight is reflected back to the environment, some is transmitted through the cover, and the rest is transmitted to the surroundings. As the air temperature inside the cabinet increases, the MC of the product decreases. The ISD addresses some of the limitations of both OSD and DSD. It is important to note that ISD can be implemented in active or passive modes, with or without energy storage. A study of ISD was done to developed a computational fluid dynamics (CFD) model using ANSYS software to analyze parameters like relative humidity, and temperature profiles inside the drying chamber of a passive ISD while drying corn [30]. Téllez *et al.* [31] employed a forced convection ISD to dehydrate red chili peppers. The drying process was within a controlled temperature range of 45 °C, 55 °C, and 65 °C, using an oven. Throughout the study, two different air velocities were utilized: a high velocity (1.4 and 2.6 m/s) and a low velocity (0.7 and 1.48 m/s). Notably, the drying kinetics at 55 °C and 65 °C were quite similar, with drying times of 2.75 h and 3.0 h, respectively. In contrast, the drying process at 45 °C took longer, lasting 6.25 h. Chaouch *et al.* [32] devised an active ISD paired with a pebble sensible heat storage configuration. This storage system was installed at two separate locations: one beneath the drying chamber and the other below the SAC. The inclusion of the storage system resulted in a significant increase in thermal efficiency for both the SAC and drying chamber, with improvements of 28 % and 11.8 %, respectively. Additionally, this system provided an additional hour of heat generation after sunset. To evaluate its performance, the researchers conducted drying experiments using camel meat. Various active and passive indirect solar drying operations have been carried out for different agricultural products, including mango, thyme, mint, and chili [33].

Some of the drawbacks of the ISD are as follows:

- The efficiency of ISD is lesser compared to DSD as the conversion of solar energy into heat SAC and transfer to the drying cabinet involves an additional step resulting in losses.
- The reason cited above further leads to longer drying time.
- Circulation and controlling the heat transfer rate in ISD is challenging as the transfer of heat primarily depends upon the SAC.

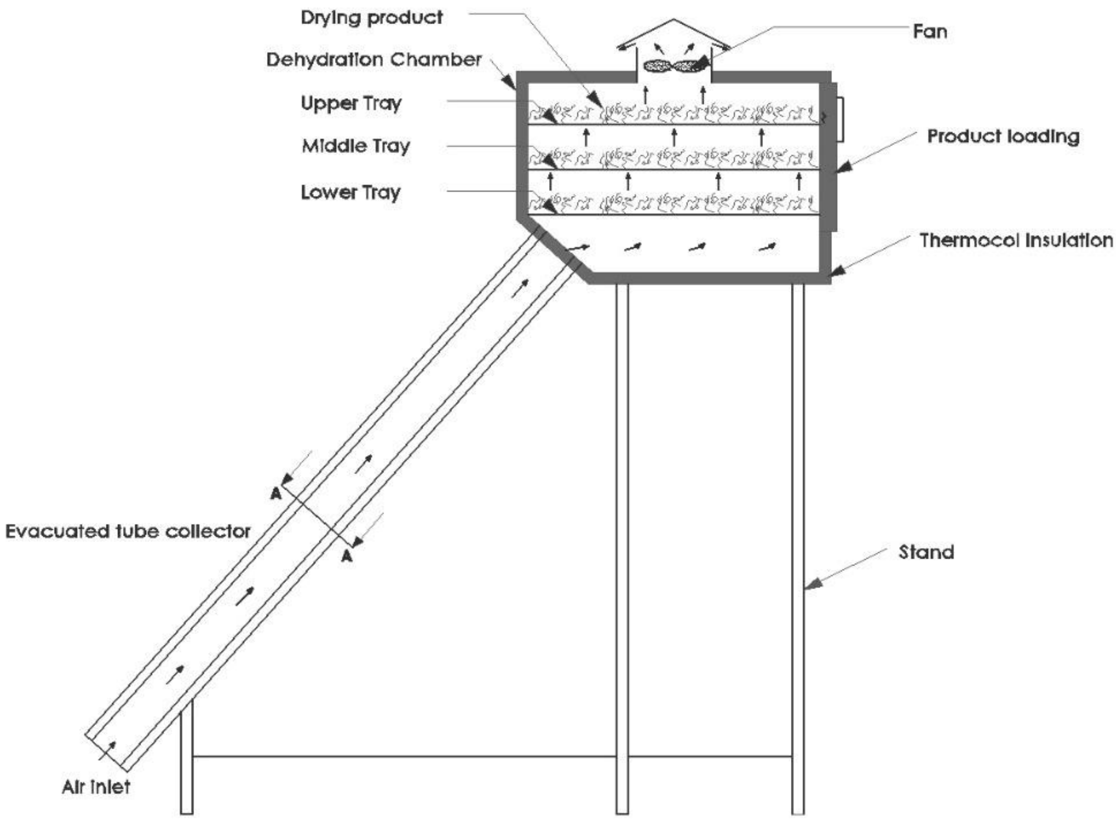

Figure 1.4 Layout of an indirect solar dryer.

1.3 Mixed Mode Solar Dryer

The mixed mode solar dryer (MMSD) gained demand for the ability to overcome some of the limitations to DSD and ISD. Figure 1.5 shows a typical layout of a MMSD [34]. The MMSD integrates both direct solar radiation penetrating the walls of the drying cabinet and heat transfer through the SAC. Due to the dual-directional source, it accelerates the evaporation of moisture from the product within the drying cabinet. MMSD for grapes was designed by Pardhi and Bhagoria [35]. They found the collector efficiency (67.5 %) and the rate of drying (0.38 kg/h). The final MC was found to be 18.6 % from an initial of 81.42 %. Drying in the dryer was found to be superior to OSD. Srittipokakun and Kirdsiri [36] dried pineapple in MMSD. The water content was finally found to be 15 % (w.b.) from 83 % (w.b.). Simate [37] experimentally compared MMSD and ISD of passive mode for maize drying. The length of the collector for ISD was greater than MMSD due to additional direct drying from the sun in the latter. The cost of drying in ISD (16.05 US $ per ton) was more than MMSD (12.76 US $ per ton). However, the capacity of producing dry grain of ISD was found to be more than MMSD. An active MMSD was developed that was used as a greenhouse during the winters. The cost of drying was significantly higher because the fan used for convection was run by solar panel [38]. Murugavelh *et al.* [39] designed a MMSD for drying fruit waste from food processing. The system included a SAC, blower, a cabinet and a chimney. Tomato waste with 71.1 % initial moisture was dried, achieving equilibrium MC in 7 h compared to 15 h in open solar drying. Ekka *et al.* [40] explored the drying process of black ginger using an active MMSD. They carried out the study considering two cases–one with constant mass flow rate of air (0.062 kg/s) and other with two different mass flow rates of air (0.062 and 0.018 kg/s) for the falling-rate period.

Some of the drawbacks of the MMSD are as follows:

- MMSD are primarily dependent upon the solar radiation and its performance increases with increase of radiation.
- MMSD results in inconsistent drying during fluctuation of solar radiation leads to wastage of the product.
- The temperature within the MMSD is difficult to control.

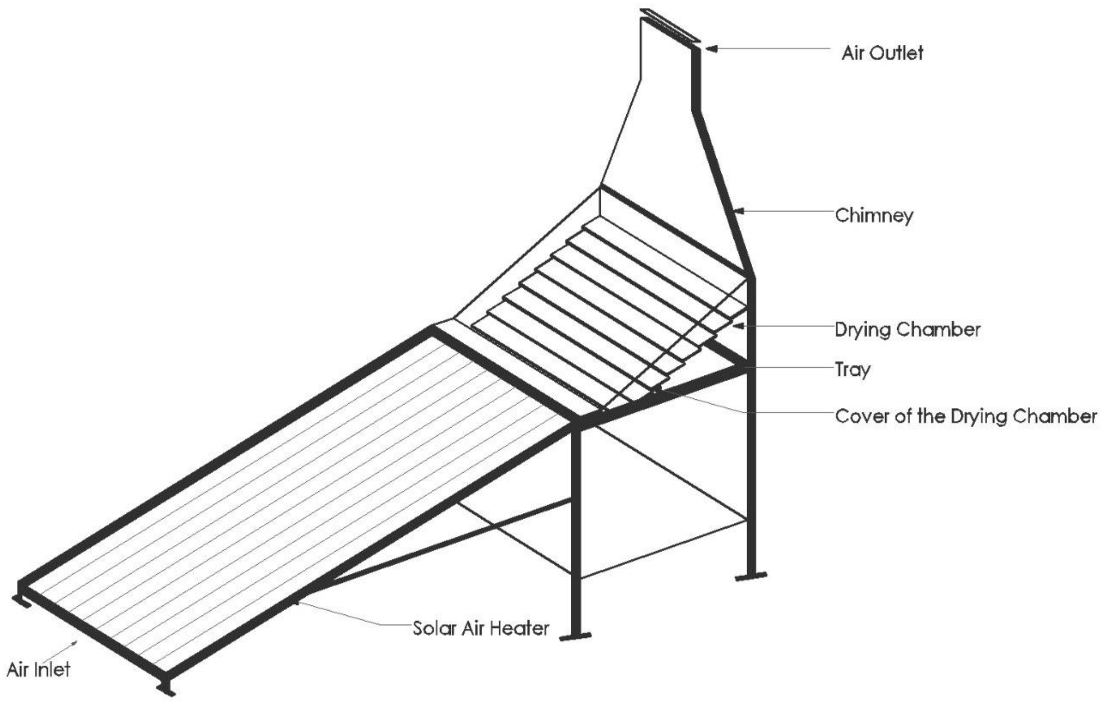

Figure 1.5 Layout of a mixed-mode solar dryer.

1.4 Hybrid solar dryer

A hybrid solar dryer (HSD) can be used to solve the drawbacks of other solar dryers to a very large extent. It is a combination of ISD or MMSD generally integrated with thermal energy storage or an auxiliary heating device. The thermal energy storage used is either a sensible or latent type. Here the heat is stored during the daytime and released when there isn't sufficient radiation of the sun to dry the process [41]. The auxiliary heating systems includes the electric heater, LPG, biomass back up heater, etc. HSD often runs in single mode or in combination [42].

1.4.1 Thermal Energy Storage

The utilization of Thermal Energy Storage (TES) remains a longstanding method that is highly sought after in the advancement of effective solar drying systems. The integration of HSD with TES effectively addresses the concerns related to the security and preservation of food. Thermal energy can be stored primarily in the form of sensible heat storage (SHS) and latent heat storage (LHS).

Solar Dryer integrated with sensible heat storage

When design, material, availability, and cost are count on, solar dryers with SHS are much simpler than those with LHS. The medium for SHS can be of two types: solids (pebble, brick, concrete, etc), and liquid (water, molten salts, petroleum oils, etc). The stored energy in SHS is charged and discharged in due course of time. The installation of HSD in rural areas with SHS are trouble-free as the materials are easily available and designs are not very complicated. A significant amount of experimental research works has been conducted by various researchers on HSD with SHS. Mohanraj and Chandrasekar [43] designed an active solar drying system for copra. This HSD had sand placed in between the absorber plate and insulation layer of the air heater. The overall HSD comprised of a solar air heater, a fan for circulation of air and a chamber for drying of copra. The dryer efficiency was found to be 24 %. After drying the copra for 82 h from an initial MC of 51.8 % (w.b.) to final of 9.7 % (w.b.) at the upper tray and 7.8 % (w.b.) at the lower tray. The dried copra was graded as per Bureau of Indian Standards. Potdukhe and Thombre [44] experimentally studied the drying of fenugreek leaves and chilli by using Thermic oil as SHS material in a passive ISD. The efficiency for drying of chilli (8.35 %-21 %) and fenugreek seeds (13.4 %-15.2 %) were calculated. The time for drying was saved to 40 % using SHS despite the 10 % increase in cost. In another study for drying of chilli, 40 kg of the produce was dried in an active (centrifugal blower) solar dryer using gravel as its SHS material. The initial MC (72.8 % w.b.) and final MC (9.1 % in w.b.) was reported with a drying efficiency of 21 % in 24 h [45]. Ayyappan and Mayilsamy [46] used rock bed as SHS for drying copra in a passive mode of solar dryer. The MC of the coconut was reduced to 7.1 % (w.b.) from an initial MC of 52 % (w.b.). The drying in the innovated solar dryer took 54 h compared with 153 h in OSD. The use of SHS increased the temperature of the dryer by 7-12 ℃ than the temperature of the ambient. Ayyappan *et al.* [47] compared different SHS materials. The drying times of Copra in a greenhouse dryer using concrete, sand, rock bed, and OSD were noted to be 78 h, 66 h, 53 h, and 174 h, respectively. The concrete-based dryer had a 9.5 % efficiency. With the usage of sand and rock, the dryer efficiency was reported at 11 % and 11.65 %, respectively. A dryer was experimentally studied for drying *Vitis vinifera* and *Momordica charantia* using rock bed, sand bed, and aluminium fillings as SHS material under the weather conditions of Negamam, India [48]. Among these SHS materials, the usage of sand took the minimum time for drying of both *Vitis vinifera* (28 h), and *Momordica charantia* (5.3 h). Abubakar *et al.* [49] developed a MMSD with and without TES and examined it in the environmental conditions of Zaria in Nigeria for drying of yam slices. The SHS material used in the dryer was gravel. The system constituted of a solar collector (0.65 m length and 0.43 m wide), a drying chamber (0.50 m length and 0.43 m wide), and a chimney (0.7 m high). The drying rate was found to be 2.71×10^{-5} kg/s and 2.35×10^{-5} kg/s with and without TES, respectively. The efficiencies of collector and drying were 67.25 % and 28.75 %, with TES and 40.10 % and 24.20 %, without TES. Using the SHS material, the dryer efficiency increased by 4.55 %. Bhardwaj *et al.* [50] experimentally studied the chili drying by using both SHS and phase-changing material in an indirect solar dryer. The MC was reduced to 4.85 % (w.b.) from an initial of 86.50 % (w.b.). The time required for drying was 21 h (dryer with storage), 96 h (dryer without storage), and 150 h (OSD).

Solar Dryer integrated with Latent Energy Storage

Latent heat storage (LHS) or phase changing material (PCM) are widely used TES in recent times. PCM shows promising results in storages/capturing of the thermal energy and has gained importance in the research field solar-drying technology. An experimental study was conducted for a solar dryer with HS 58 as its LHS material [51]. The insulation that accompanied the TES tank was glass wool of 10 cm thickness. HS 58 were enveloped in polyethylene spherical balls inside TES tank. At 70 ℃, the charging experiments were conducted, and discharging was done at ambient temperature. The experiments were carried out for three mass flow rates of 200, 300 and 400 kg/h. It was found that heat was exchanged uniformly, and the optimum capacity of the storage system was utilized at the mass flow rate of 200 kg/h and utilize the optimum capacity of storage system. Shalaby and Bek [52] dried *Ocimum basilicum* and *Thevetia neriifolia* in a newly developed ISD with PCM. The

PCM used was paraffin wax that was melt at 49℃. For 5 hours after sunset, the use of PCM increased the temperature of the drying by 2.5-7.5 ℃ above the ambient temperature. The drying time was found to be 12 h for *Ocimum basilicum,* and 18 h for *Thevetia neriifolia*. The experiment was maintained at a mass flow rate of air within a range of 0.0664-0.2182 kg/s. Bahari *et al.* [53] prepared a TES with combinations of paraffin wax and Al_2O_3 nanoparticles at three levels (0.5, 1 and 1.5 w/w) for solar drying of agricultural produces. Usage of Al_2O_3 nanoparticles enhanced the usage of paraffin in regard to their thermal properties. The highest amount of thermal energy that was absorbed was found to be 6109, 6445 and 6089 kJ, respectively for Al_2O_3 composites with 0.5, 1 and 1.5 (w/w) nanoparticles. Without any nanoparticles, the energy storage was 3393 kJ. From the economic point of view 1 % (w/w) nanoparticles of Al_2O_3 was preferred. Atalay [54] analysed the cost and energy of TES systems for solar drying. The study was for both sensible (pebble) and latent (paraffin wax) storage systems. 10 kg of lemon was used for drying and the results for both the systems were compared. The performance analysis revealed that the average thermal energy accumulated during charging for LHS and SHS was 49.52 MJ and 52.59 MJ, respectively. The drying time for the 5 mm thick lemon slices were 6.27 h for SHS and 6.23 h for LHS from a MC of 94.8 % (w.b.) to 10 % (w.b.). The experimental analysis showed that the average energy efficiencies for the afore mentioned storages was 68.2 % and 68.55 %, respectively. From an economic point of view, the study stated that the SHS had 10.47 % lower cost than the LHS.

1.4.2 Solar-Biomass

Arun *et al.* [55] developed an HSD for drying of coconut in Tamil Nadu, India. The dryer was of greenhouse type and the biomass was used as a backup (after 5 p.m). The fuel that was used for the backup were all derived from different parts of coconuts, like their fronts, shells and husk. The coconuts were dried from an initial MC of 53.84 % (w.b.) to 7.003 % (w.b.) in 44 h in the integrated dryer and in 148 h in OSD. The dryer seemed to be advantageous with superior quality of dried products. Neba and Nono [56] introduced a solar biomass dryer model, its design and a software for simulation named DryDSim. The dryer was simulated for the experimental results of green pepper. The design was done to obtain the maximum productive design for various agricultural produces and cost-effective systems. Yahya *et al.* [57] developed and studied a HSD for drying of paddy. The system comprised of two solar collectors (1.8 m^2 area), a fluidized bed and a biomass furnace. The temperature of the drying air was maintained at 61 ℃ to 78 ℃. From an initial MC of 20 %

(w.b.), the final MC of paddy was 14 % (w.b.) in 1281 s for 61 ℃ and 796 s for 78 ℃. The average specific energy consumption (SEC) (4.76 kWh/kg for 61 ℃ and 4 kWh/kg for 78 ℃), average thermal efficiencies (13.45 % for 61 ℃ and 16.28 % for 78 ℃) and average exergy efficiencies (47.6 % for 61 ℃ and 49.5 % for 78 ℃) were calculated. In addition to the aforestated experimental results, the study calculated the solar fraction and biomass fraction to be 21.15 % and 26.83 %, respectively for 61 ℃, while 15.01 % and 42.22 % respectively for 78 ℃. Tarigan [58] investigated a HSD for drying of agricultural produces. The system consisted of a solar collector, a biomass-backup heater, and a drying chamber. The thermal energy storage was of sensible type (bricks). CFD analysis exhibited that 56 ℃ was the most satisfactory drying temperature. Manrique *et al.* [59] developed a HSD for drying of coffee beans. The MC of coffee beans were reduced to 12 % (w.b.). The system comprised of a drying unit, a heat exchanger, a PV/T system, and a combustion chamber. The specific thermal and electric consumption were calculated to be 6.9 MJ and 1.4 MJ per kg of coffee, respectively.

1.4.3 Solar-LPG

Janjai [60] developed an active solar-gas dryer for drying of fruits and vegetables (100 kg load capacity). This greenhouse system was 8.0 m wide, 20.0 m of length and 3.5 m high. The dryer was tested to dry tomatoes in Thailand. The drying time was 2-3 days less than an OSD. The payback was calculated as 0.65 years. Cesar *et al.* [61] investigated a HSD for drying of tomatoes of 94 % (d.b.) of initial MC. The system consisted of solar collector with a V-corrugated Al-coated black absorbing plate, a drying chamber with 10 trays of drying area 0.42 m, and an LPG system. The drying experiments were conducted for three modes, namely, solar-LPG, only solar, and LPG modes. The efficiencies were calculated as 71 %, 86 % and 24 %, respectively. However, the solar-gas and only gas systems showed similar drying rates in constant period. Additionally, they also showed same efficiency with 20 % less fuel intake in solar-gas than only gas system. A solar-LPG dryer was developed for drying of rice [62]. The investigation was done for two tests, one for 104 kg of rice (50.1 ℃ and 21.73 % RH), and the another for 200 kg (46.9 ℃ and 21.7 % RH). The former took 5 h to reach 14.3 % (w.b.) MC from an initial of 28.4 % (w.b.) with a drying efficiency of 22.4 %. However, the latter took 8 h to reach the final MC 14.3 % (w.b.) from 27.6 % (w.b.) with a drying efficiency of 31.7 %. Zoukit *et al.* [63] designed an active HSD for drying of tomatoes. The study was considered for three modes: solar, gas and solar-gas. The flow of air inside the dryer was predicted with CFD simulation. The RMSE and RMSE % were found to 2.1 ℃ and 2.5 % RH for the simulation, and 2.7 ℃ and 2.4 % RH with the experiments, considering steady state. The thermal efficiencies were calculated as 4 %, 37 % and 40 %, respectively for the solar, gas and solar-gas modes.

Among the different types of dryers, hybrid solar dryers are better in the following ways:

1. Maintenance of hygiene: Accumulation of dirt, infestation of pest, bacterial pollution is eliminated in hybrid drying.
2. Superior quality of products: As the drying operations are done in controlled conditions in hybrid dryers, the quality of the final products are finer.
3. Less wastage: There is not much to discard from the final product as the quality is restored in hybrid dryers.
4. Continuous operation: Hybrid solar dryers continuously work even after the sun sets and on rainy days. They are generally assisted by their back-up's life thermal energy storage, biomass, gas, electricity, etc.

1.5 Motivation and research objectives

Assam, a northeastern state in India, is enveloped by hills, major rivers like Brahmaputra and Barak, and their tributaries, as well as dense forests and tea gardens. Consequently, the climatic conditions are marked by regular rainfall, elevated humidity, low average annual solar radiation, and prolonged rainy days. In the summertime, solar radiation experiences fluctuations due to the presence of clouds in the sky, yet the average daily solar radiation is ample on sunny days. The combination of climate and soil conditions renders Assam well-suited for cultivating a diverse range of agricultural products.

However, certain agricultural food products like *Garcinia pedunculata* (GP) and *Curcuma amada* are seasonal but have high nutritional or medicinal values that can be beneficial if these are made available round the year through some appropriate food-preservation process [64–66]. The development of an enhanced solar dryer with TES for drying of the products aims to address these issues, anticipating the production of consistently high-quality products that offer increased value and income for local farmers. Consequently, this research has been conducted through a methodical approach, aiming to achieve the following objectives:

(i) Evaluation of a free convection corrugated type of solar dryer for *Garcinia pedunculata*: An investigation on kinetics, energy, and economic aspects.

(ii) Evaluation of a PV-driven innovative solar dryer with and without sensible heat storage for *Garcinia pedunculata*: An investigation on kinetics, energy, and economic aspects.

(iii) Evaluation of a PV-driven innovative solar dryer with and without sensible heat storage for *Garcinia pedunculata*: An investigation on exergy and environmental aspects.

(iv) Evaluation of a PV-driven innovative solar dryer for *Curcuma amada* without and with gravels as thermal energy storage: An investigation on kinetics, energy, exergy, quality and economic aspects.

Structure of the Thesis

The thesis is organized into six chapters. The organization of each chapter is described as follows:

Chapter 1: Introduction

The thesis is structured into seven chapters. The current chapter encompasses the introduction and the background. The subsequent chapters are organized as outlined below.

Chapter 2: Literature Review

This chapter provides a concise overview of existing literature, focusing on the examination of drying kinetics analysis, energy and exergy assessments, economic evaluations and environmental considerations. Subsequently, this chapter is concluded with the scope of the current research.

Chapter 3: Evaluation of a free convection corrugated type of solar dryer for Garcinia pedunculata: An investigation on kinetics, energy, and economic aspects.

In this chapter, thermal performance studies *Garcinia pedunculata* in an efficiently developed free convection corrugated solar dryer is studied and compared with the conventional open sun drying. The study was primarily done on the basis of drying kinetics of *Garcinia pedunculata*, energy efficiency and payback period of the dryer. This chapter further provides the specifics of the developed dryer, including the fabrication details of its various components.

Chapter 4: Evaluation of a PV-driven innovative solar dryer with and without sensible heat storage for *Garcinia pedunculata*: An investigation on kinetics, energy, and economic aspects

In this chapter, four configurations of solar dryer and open sun drying are evaluated and compared. Drying kinetics of *Garcinia pedunculata*, the dryer performance and economic analysis of dryer were evaluated in the indirect solar dryer without SHS (Exp. I), mixed-mode solar dryer without SHS (Exp. II), indirect solar dryer with SHS (Exp. III), mixed-mode solar dryer with SHS (Exp. IV), and open sun drying.

Chapter 5: Evaluation of a PV-driven innovative solar dryer with and without sensible heat storage for *Garcinia pedunculata*: An investigation on exergy and environmental aspects

This chapter provides a great deal of information on the utilization of energy performance and the energy payback period of the dryer. The estimation of exergy in, out, loss, efficiency and the environmental parameters are studied in detail for the four modes. The four combinations 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).

Chapter 6: Evaluation of a PV-driven innovative solar dryer for *Curcuma amada* without and with gravels as thermal energy storage: An investigation on kinetics, energy, exergy, quality and economic aspects

In this chapter, the drying kinetics, energy, exergy, quality, and economic studies of a solar dryer with and without energy storage is studied for drying *Curcuma amada*. The drying of *Curcuma amada* was studied in order to check the adaptability and effectiveness of the dryer for another product. Additionally, both *Garcinia pedunculata* and *Curcuma amada* exhibit seasonal availability. Adapting the system to dry crops accessible at different times of the year enables year-round operation, thereby maximizing its utilization and benefits.

Chapter 7: Conclusions and future scopes

In this chapter, conclusions, opportunities for enhancing the developed solar dryer, and future prospects are discussed, followed by a reference section.