An Experimental Investigation Of Thermal Desiccant System Integrated With Solar Dryer For Low Energy Dehumidification Process

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THESIS ACCEPTANCE CERTIFICATE

Certified that the final copy of MS/MPhil thesis written by **Mr. Muhammad Zeeshan** (Registration No. **276892**, of **USPCASE** (School/College/Institute), has been vetted by the undersigned, found complete in all respects as per NUST Statues/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for the award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Signature: ______________________________

Name of Supervisor ________________________

Date: ________________________

Signature (HoD): ________________________

Date: ____________________________________

Signature (Dean/Principal): __________________

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Certificate

This is to certify that work in this thesis has been carried out by **Mr. Muhammad Zeeshan** and completed under my supervision at the Centre for Advanced Studies in Energy, National University of Sciences and Technology, H-12, Islamabad, Pakistan.

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Dedication

I would like to dedicate my dissertation work to my family. I special feeling of gratitude to my loving **Father**, **Mother,** and **Aunt** whose words of encouragement and push for tenacity ring in my ears. Their patience and undemanding throughout the completion of this master's research are gratefully appreciated.

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First thanks to Allah who gave me the strength, knowledge, and guidance to complete my research work efficiently. I would like to take some time at the end of this thesis to thank all the individuals without whom this project was never feasible. Although it's just my name on the cover, many individuals have contributed their manner to the studies and I thank them for that.

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Solar Energy Research Lab Sir Areej and Advance Energy Materials Lab Sir Nisar. and thermal shed staff was very cooperative when I fabricated my Experimental Setup thanks to sir Qamar whose guidance and patience were commendable.

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May the Almighty ALLAH richly bless all of you.

Abstract

Drying agricultural products requires a huge amount of energy and the daily increasing price of fuels and the depleting conditions of fossil fuels turned our attention toward renewable energy resources. Solar energy is a gift from God to our country in which almost 300 out of 365 days we receive a tremendous amount of solar radiation. Because of the sinking economy and fluctuation of oil prices worldwide despite putting extra pressure on our import bills it's the best solution to shift to solar energy to cope with this issue. Pakistan being an agricultural country produces a considerable amount of fruits and vegetables each season. But the problem lies with their transportation, spoilage wastage in different ways like insects, etc. So with keeping all these above-mentioned problems an indirectly forced convection desiccant integrated solar dryer was fabricated and tomatoes which are of huge importance in our day-to-day life were dried.

The fabricated system was tested outside the thermal shed located at USPCASE NUST H-12 Islamabad. The system consisted of a solar flat plate collector, drying chamber, solar panel blowers, desiccant bed, solar charge controller, and battery. To increase reflection parabolic reflectors were also used and placed above the drying chamber supported with the help of screws. Experiments were performed during sunshine hours and with the integration of desiccants drying was also conducted during off sunshine hours. With the help of solar panel blowers and battery was charged and during off sunshine hours' experiments were carried out by powering the blowers with the help of the battery. The products were weighed before and after every mode of solar drying during two days period with the help of electric balance. The moisture removal was also calculated at the end of each mode of drying. Similarly, dryer efficiency was calculated with the help of data. The temperatures were measured with the help of 12 channel data logger. The moisture removed after two days of experiments was 56% and overall dryer efficiency was 44%.

Keywords: *Renewable energy, solar flat plate collector, Desiccants, Solar Panel, Solar charge controller, DC brushless fans, Open sun drying, Solar dryer*

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[1] M. Zeeshan and A. Waqas, "Across-the-board over-view of solar dryers ; an extensive scale renewable energy consideration for drying agricultural products,", *2nd, iceans, Confrence procedings, Konya, turkey, 2022.*

[2] M. Zeeshan, and M. U. Haider, "An extensive review of solar collector for drying application ; A smart cities concept," 3rd, *iceans, Confrence procedings, Konya, turkey, 2022. 2022.*

List of Abbreviations and Symbols

ABBREVIATIONS

Solar Drying	SD
Desiccant Drying System	DDS
Open Drying System	ODS
Close Drying System	CDS
Renewable Energy System	RES
Indirect solar dryer	ISD
Drying Chamber	DC
Advance Energy Materials Lab	AEML

Chapter 1. Introduction

1.1 Drying Background and History

The great thing about food preservation is that it was practiced in almost every culture at almost every point in time. Ancient man had to use nature's resources to survive. He put seal flesh on the ice in cold climates to freeze. In hot climes, he exposed food to the sun to dry it. Food naturally starts to spoil as soon as it is harvested. Ancient man's ability to establish roots, settle down, and create communities was facilitated by food storage. Ancient food would have spontaneously dried from the sun and breeze [1]–[3]. Food was actively dried throughout the Middle East and Asia as early as 12,000 B.C., according to evidence. More traces of later cultures can be found, and each would have methods and materials that would reflect their sources of sustenance, such as fish, wild game, domestic animals, etc. Fruits and vegetables have also been preserved by drying since ancient times. Any form of dried fruit they could produce was especially beloved by the Romans. In the middle Ages, "still homes" were purposefully constructed and used to dry fruits, vegetables, and herbs in places where there was little direct sunshine. The heat required to dry foods and, in some cases, smoke them was produced by fire [4]–[12].

According to certain historians, food preservation served cultural as well as nutritional purposes. They cite a variety of special occasion dishes that have been preserved and have symbolic religious or festive implications. More and more individuals in America are residing in urban areas and buying their food from stores. They are no longer living a rustic, independent lifestyle [13]–[16]. A garden is still a welcoming sight for many people, though. Additionally, a bountiful crop of fruits and vegetables is produced every year. The cultural significance of preserved meals is still present today. Preserve no longer means "because we have to," but rather "because we like to."

Numerous approaches for food preservation for later usage are already in use. The traditional method of food preservation is drying. Due to the obvious loss of moisture, the weight and size of the product are reduced, making storage and transportation easier. Drying prevents fungi and bacteria from germinating and growing. For different foodstuffs, there are suggested to dry the moisture content, and for storing them longer [17], [18]. The main goal of a drying process is to provide heat in the most efficient way possible to produce the highest quality product with the least amount of energy expenditure. Air dryers, which utilized a lot of fossil fuels, are used in traditional drying techniques. While, **Table 1.1** Initial, and final moisture content, and maximum allowable temperature for drying for some crops However, rising prices, a scarcity of fossil fuels, and growing environmental concerns put a premium on the use of RERs, such as solar energy, as an alternative source of energy in emerging nations. Heating air electrically for drying is one alternative; however, it is costly and in some cases impractical in rural areas of developing countries [19]. In both urban and rural areas, the use of RERs to encounter energy demand in an environmentally sustainable system has become unavoidable. In the domestic, commercial, and industrial sectors, drying systems based on RERs have been successfully established. Solar systems can fulfill the growing need for energy. Hence, this energy could be put to good use in drying crops [20]–[22].

Table 1.1 Initial, and final moisture content, and maximum allowable temperature for drying for some crops

Products	Moisture content		Max allowable temperature	Drying time (h)
	Initial%	Final%	(^{0}C)	
Onion	85	6	55	48
Tomatoes	95	7	60	36
Grapes	80	15-20	-	15-40
Apple	82	11-14	65-70	24-26
Figs	70	20	70	32
Bananas	80	15	70	15
cassava	62	17	-	-
Copra	30	5	-	-
Tobacco	90	10	-	96
Coffee	65	11	-	288
chilies	80	5	-	48
Ginger	80	10	-	168
Tea	80	3	-	96

By employing the right drying processes, post-harvest losses of agricultural goods can be significantly decreased. The potential applications of solar energy are numerous. Among the procedures used to preserve agricultural produce is solar drying [23]. Previous studies have demonstrated that drying is a labor-intensive process that requires intricate mechanisms of heat and mass transfer between the product and the drying medium. According to the research that has been done thus far on solar drying, it is necessary to create simple, affordable, and effective solar dryers to meet the rising need for food preservation, particularly in developing nations like Pakistan. Numerous solar dryer designs have been investigated for a variety of uses, and plenty of work is still being done in this field [24]–[27].

These systems mostly employ indirect solar energy or are connected to flat plate collectors. During the hours of daylight, the solar flat plate collector gives the hot air a wide range [28].

Many of the agricultural items are dried over a few days at a constant, moderate temperature. In these circumstances, the solar drying system's integrated thermal storage unit is charged during the hours of maximum sunlight and used to provide hot air to the dryer during the hours of minimal sunlight. However, desiccant compounds have been utilized for drying applications [29].

1.2 Thermal desiccant system

By chilling the air below the dew point temperature, condensation can be used to remove moisture from the air. This can be done chemically, or by using air-to-air heat exchangers to bring in dryer outside air. Sorbent materials, which are solids or liquids that can absorb moisture from the air and hold it, are used to perform chemical dehumidification. Sorbents are divided into two categories[30]–[33]:

1.2.1. Adsorbents

Materials that do not undergo a phase shift. On the desiccant's dry surface, moisture is left behind. Adsorbents are typically solids.

1.1.2 Absorbents

Those substances change the absorption process physically, chemically, or combined. The

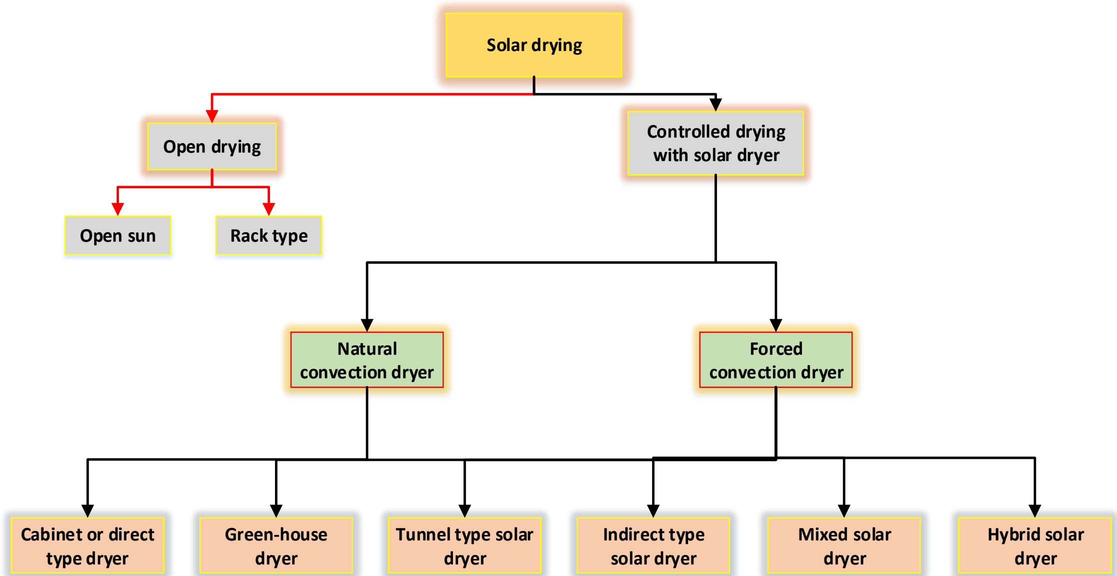

Figure 1.1 Different types of the Solar Dryer.

majority of absorbents are liquids or solids that turn into liquids when they take in moisture [34], [35].

1.3 Solar energy for Drying purposes

Although drying system (DS) and thus preserving horticultural and agricultural harvests is among the oldest applications of solar energy, its enormous potential in the food processing industries has not been fully explored scientifically [36]–[38]. Practically, the most important method for preserving vegetables and fruits is drying. In addition, drying is also the oldest method of removing water from a variety of materials, including wood pulp for papermaking, building materials, and food preservation Fruits and vegetables that have been dried are an extremely important topic [39]. Due to their increased commercial relevance, dried fruits and vegetables have developed into a significant segment of the agricultural industry. The majority of fruits and vegetables are highly perishable since they have a moisture content of more than 80%.[40].Even though drying energy originates from a wide variety of sources, notably fossil resources, natural gas, biomass, electricity, and solar, the subject of this study review tends to fall under the implemented sources such as solar. In the developed world, these methods of thermal drying account for 10–20 percent of total industrial energy consumption [41]. Hydrocarbons cause pollution, and there is no guarantee that they will always be available. Solar energy is a cost-effective and efficient source of long-term strategies for sustainable growth. The earth gets a huge amount of solar energy. It is advisable to replace the traditional process of drying with available sun energy to preserve fruits and vegetables for a long period. Often these agricultural products have high moisture levels once harvested, which causes deterioration due to bacteria and fungi growth. Maintaining agricultural products with safe moisture content eliminates the risk of spoilage under normal conditions [42].

1.4 Categories of solar dryers

The DS is divided into two categories based on how much solar energy is used: One among them is controlled solar drying (CSD). Meanwhile, the other one is open sun drying (OSD).

However, the classification flow chart in **Figure 1.1** depicts various types of solar dryers in detail.

1.4.1 Open sun drying (OSD)

Open sun drying– The items to be dried are scattered out on the ground or in thin layers on trays, mats, and concrete floors, exposing the product to open air and sunlight.

Rack type - The moist food products to be dried is kept in series or parallel racks in this method. Controlling drying parameters such as humidity, velocity, and temperature is challenging in both open and rack types. It has several benefits; including high-quality products, a shorter drying time, dust-free, and large-scale production.

1.4.2 Controlled sun drying (CSD)

On the other hand, revolutionary new dryers with controllable drying parameters are available in the literature. Food quality is affected by the working fluid temperature, humidity, velocity, and other factors during the solar drying of agricultural goods [14], and [18]. Various methods can be used to control these influencing parameters. In addition, in controlled solar drying, solar energy can be kept in the form of heat [31]. The following are the different kinds of solar drying systems that can be controlled:

1.5 Direct solar dryer

In the direct solar dryer (DSD), transparent glasses are used to impart radiation from the sun straightforwardly to the foodstuffs. Losses of Convective must be lessened in these dryers,

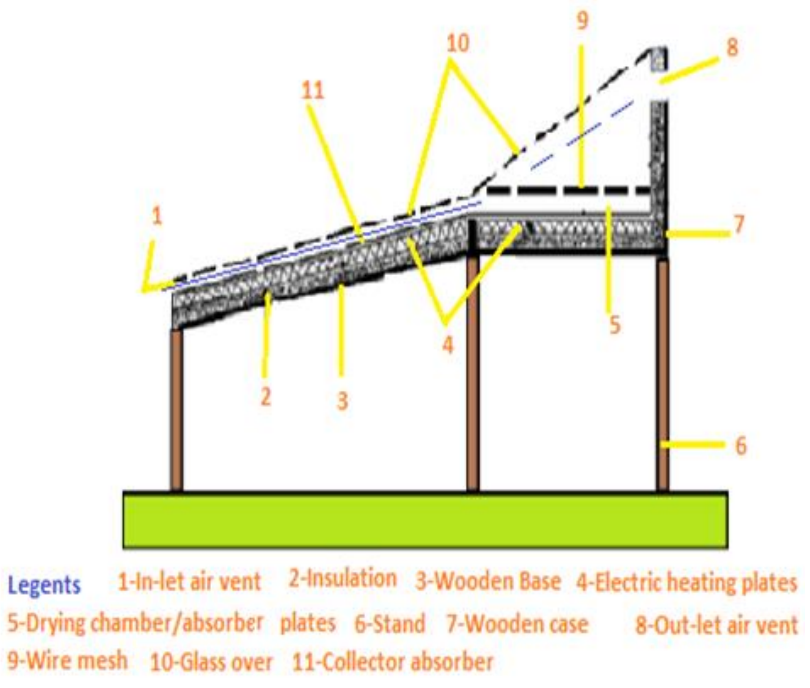

Figure 1.2 A Schematic view natural convection ISD setup.

allowing the drying compartment temperature to be enhanced. Glass-roof solar/ solar cabinet dryers and green-house dryers are examples of direct solar dryers [43].

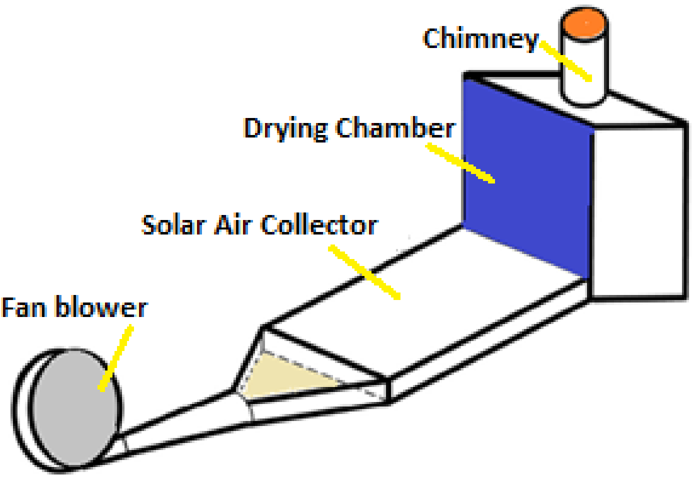

Figure 1.3 Forced convection ISD

1.6 Indirect solar dryer

The literature identifies two types of ISD: (a) Natural convective type and (b) forced circulation type.

1.6.1 Natural convection ISD

Many ISD experiments have been carried out with a simple flat plate and dehumidifier. Without the need for external equipment such as fans or blowers, the air is naturally circulated. A fan's cost and upkeep are reduced by convection [44]. A study of certain ISD with collector and single pass flat plat collector is included in this part, as well as an explanation of the results obtained during natural convection ISD drying. In Jaipur, India conducted experiments and analyzed the cabinet dryer with two shelves and a flat plate collector. Green chili and potato (S. tuberosum) chips were investigated. To improve dryer efficiency, glass and polycarbonate sheets were used as glazing covers [45]. With glass glazing as a cover sheet, the efficiency increased from 9–12% to 23.7 percent, and 18.5 percent with polycarbonate sheets. As a result, the drying time was drastically reduced. **Figure 1.2** depicts a schematic overview of the natural convection ISD setup.

1.6.2 Forced convection setup ISD

The air is forced into or out of the dryer using an electric fan or blower. As a result, in this type of dryer, you can control the drying rate. It's classified similarly to natural circulation, but with the accumulation of a fan/blower. Solar dryers with greenhouse collectors and tunnel-type dryers with integral collectors are two other types of solar dryers [46]. **Figure 1.3** shows a forced convection type indirect solar dryer setup.

1.7 Solar collectors

Solar collectors were constantly being implemented for space heating, timber seasoning, solar ovens, and industrial and agricultural commodity curing or drying. Solar drying of agricultural goods is one of the most important solar collector applications. Considering that solar collectors are the primary apparatus for indirect drying, increasing the number of solar collectors in a drying system can improve its effectiveness,[47] and [48] Furthermore, multiple types of research on solar drying have been published, with an emphasis on solar tunnel greenhouse drying, solar drying of diverse commodities, solar thermochemical processes, and solar drying software applications (SD) [49]. Improvement of sun dryer performance, playhouse drying, and solar greenhouse drying are all examples of SD in Malaysia. Likewise, solar drying with solid/liquid desiccant, solar energy with latent heat, and solar energy with latent heat, thermal energy storage systems. Whereas **Figure 1.4** (F-H) illustrates air-based sun collectors, and **Figure 1.4 (I)** exhibits multiple kinds of water-based solar collectors. For the trying and assessment of numerous modifications to traditional collectors, many theoretical models have been constructed [50]. It's quite difficult to come up with a mutual realistic heat exchange modeling in absorber plates of various configurations [51].

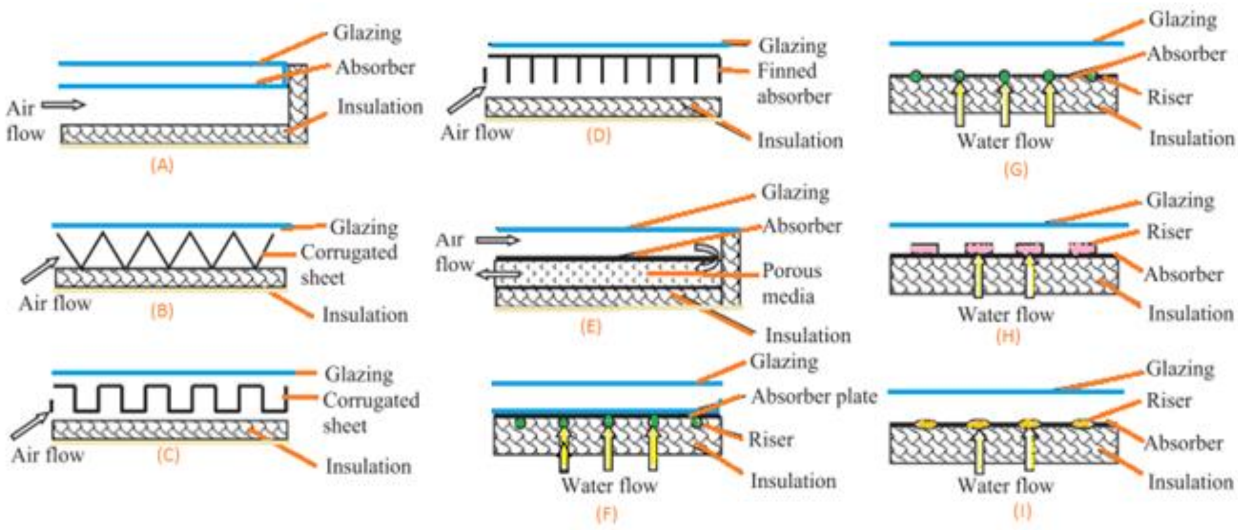

Figure 1.4 Various types of solar collector: A–E: air-based solar collectors, F–H: water-based solar collectors

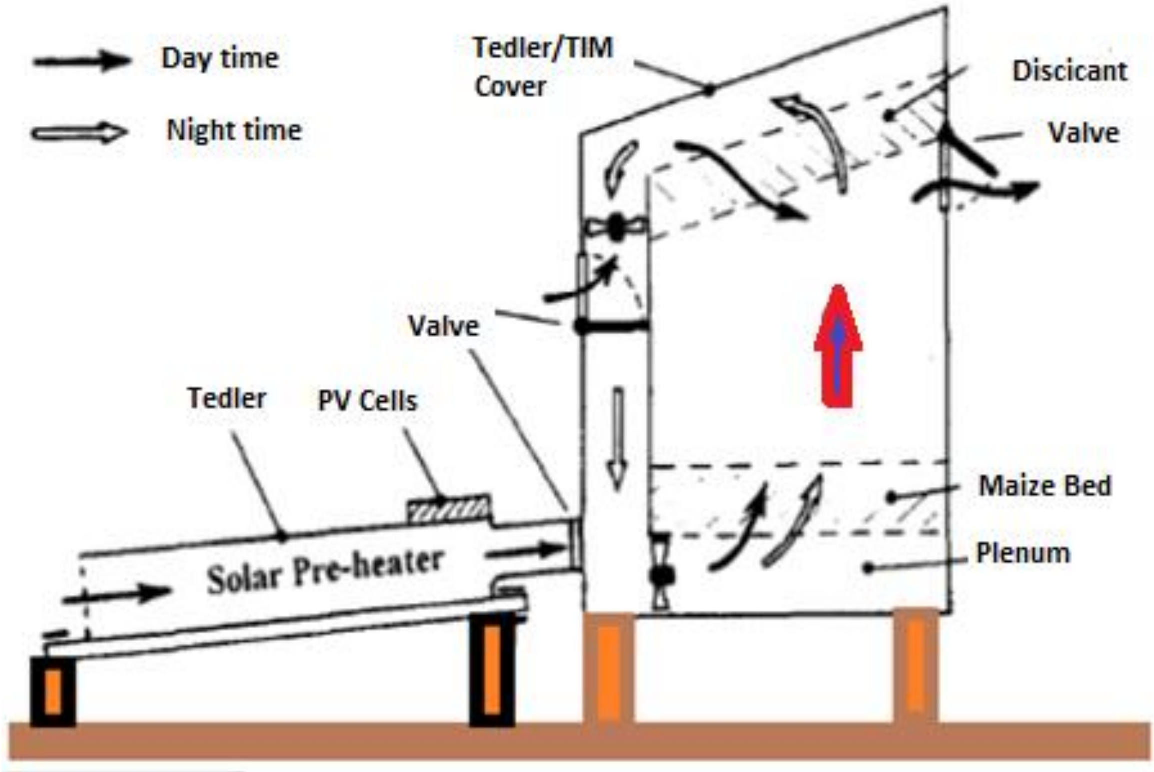

Figure 1.5 Schematic of forced desiccant integrated solar dryer.

1.8 Desiccant Drying

When corn was air dried over a fixed bed of silica gel, Danziger et al. observed that germination of the gel-dried corn remained above 90% while germination of corn dried at 60°C was reduced to 80% [52], [53]. To dry food grains, Odigboh constructed and studied a dehumidification system to lower the relative humidity of damp air through a sorbent bed made of calcium chloride flakes and oven-dried dirt. Lower relative humidities were produced by deeper beds of the sorbent soil mixture as a result of slower airflow rates and longer contact times. The dehumidification system delivered air with a relative humidity range of 85% to 32% [54]–[57]. Ko and McCormick investigated the viability of utilizing desiccants to boost the effectiveness of solar grain drying systems. Ko and McCormick looked into whether desiccants may be used to boost the effectiveness of solar grain drying systems [58]. After 24 hours at 75°C, activated alumina and silica gel, which hold water through physical adsorption, were restored to around 90% of their original capacity. **Figure 1.5** Schematic of forced desiccant integrated solar dryer Comparatively, at 75°C, molecular sieve, and anhydrous calcium sulfate showed only 29%, and 41% moisture decrease, respectively [59]. This study examines the uses of solar energy and desiccant energy storage.

Numerous thermal and physical characteristics have been compiled. Desiccants were comparable with phase change materials, rock-bed storage, and water systems for energy storage, according to a cost analysis. The characteristics information was supplied for both traditional and desiccant-related energy storage [60], [61]. Costs connected with handling different materials and renting containers must be taken into account in the cost analysis for energy storage [9], [13], [15]. At the achievable moderate flat-plate collector temperatures, the commercially available liquid sorbents calcium chloride, lithium bromide, two solid desiccants, activated alumina, and silica gel are more easily generable [12]. Although they were much more expensive, lithium bromide and silica gel had better mass transfer and storage characteristics [31]. Bio-desiccants could be used in a small number of cycles. Corn with a moisture content of 25% was placed in a drying bin with a 0.75 m diameter and 0.40 m depth that required 12 m^2/min of dry air (dB) [35]. The first batch of corn was dried using the outside air. After 24 hours, the average moisture content in the bin dropped to 22.4% from the original grain moisture content of 25% (dB) [62]. Using natural air to dry did not significantly alter the moisture content [32]. In the second batch, the drying of the maize was combined with the use of a flat plate solar collector and began at midnight. To dry sultana grapes, Yaldish et al performed thin layer drying tests in an indirect forced convection sun drier [1]. A blower pushed heated air heated by a solar air heater through the product. To estimate solar drying curves, the coefficient of determination of eight different thin layer mathematical drying models was evaluated. The temperature and velocity of the drying air were projected to have an impact on the model constants and coefficients by the regression models [3]. The schematic diagram of the desiccant bed solar dryer system is depicted in **Figure 1.6**. The thin layer sun drying behavior of sultana grapes was adequately represented by the two-term drying model. Additionally, the impact of drying air velocity and

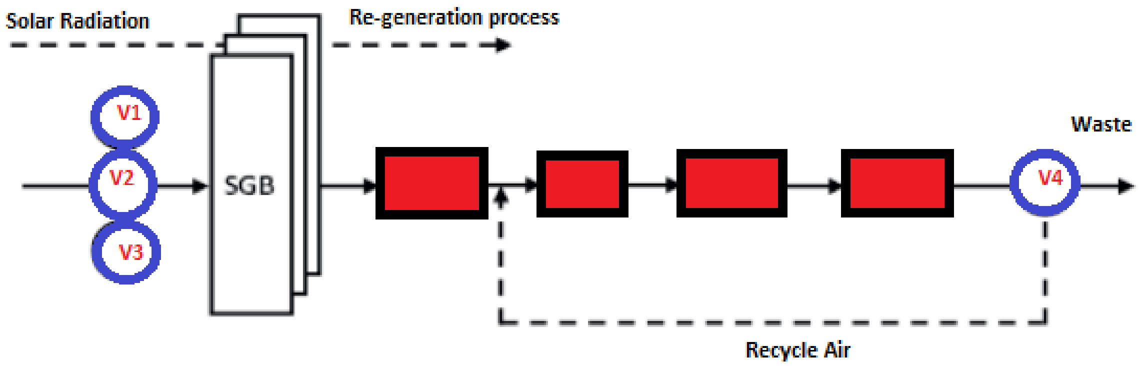

Figure 1.6 Schematic of the desiccant bed solar dryer system Concept

temperature on the two-term model's coefficients was investigated. The drying air temperature range used in the model was 32.4 to 40.3 ºC, and the velocity range was 0.5 to 1.5 m/s [63], [64].

1.9 Main objective

- Designing of the solar dryer.
- To create an integrated sun drying system using forced convection and desiccant for agricultural products.
- To research the dryer's and solar flat-plate collector's performance.

1.10 Statement of the Problem

Solar dryers with forced convection achieve faster drying rates than those with natural convection. However, they frequently perform below par. One cause of this is insufficient airflow dispersion, which leads to insufficient drying. Grain is drying unevenly due to air in certain dryer places. Sometimes, the fan is either large or undersized, which results in inadequate airflow (and velocity). resulting in increased energy use and, in some situations, grain blowing uphill. Additionally, using grain layers of the wrong thickness results in subpar performance. When exposed to air, some areas of the grain layer that are too thick do not dry evenly. which is moisture-saturated.

1.11 Summary

Agricultural product drying is a time-consuming and energy-demanding practice. However, uneconomical, and depletion of fossil fuels as well as environmental jeopardies fascinate the utilization of solar energy as a substitute source, predominantly in emergent countries. Escalating environmental concerns prompted the use of renewable energy resources (RERs) in the drying of agricultural foodstuffs [65]. As a consequence, the solar dryer (SD) is a reasonably effective approach for drying agricultural products in a highly uniform manner [66]. However, over the last few decades, considerable several research has been established to dry food and agriculture products using an SD. This review paper focuses on the substantial achievements devoted to the development of solar drying technology available today, as well as the state-of-the-art developments in solar drying. Furthermore, the comparison of advantages/disadvantages of In-direct type solar dryers (ITSDs) is also part of this paper [67].

1.12 Thesis layout

The structure of the remaining thesis is as follows; chapter II, explains the detailed Literature review. The proposed methodology and experimental setup were explained in chapter III. However, the results and discussions were depicted in chapter IV. Furthermore, the thesis is concluded in chapter V.

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Chapter 2. Literature Review

2.1 Drying an extensive literature review

Many different solar dryer designs have been investigated for a variety of uses, and a lot of work is still being done in this field. These technologies mostly employ indirect solar energy or are connected to flat plate collectors. During the hours of daylight, the solar flat plate collector gives the hot air a significant temperature variation. While many agricultural items are dried over a few days at a constant, moderate temperature. In these circumstances, the solar drying system's integrated thermal storage unit is charged during the hours of maximum sunlight and used to provide hot air to the dryer during the hours of minimal sunlight. However, it has been made possible to use desiccant materials for drying applications. The 15 products' drying characteristics are investigated using several thin layers of drying mathematical models [1]–[3]. In this chapter, the information available in the literature on;

- Solar flat plate air collector
- Solar dryer
- The use of desiccants for drying applications.

Fruits and vegetables were traditionally processed by being left to dry out in the sun. The pace of dehydration throughout this procedure was slow, and dust, insects, and unexpected rain all harmed the quality. Mechanical dryers powered by fossil fuel or electricity could be utilized to prevent these issues. But given the current situation, when traditional energy sources are quickly running out, it is imperative to make better use of solar energy. With this in view, several types of solar dryers have been designed and developed around the world. In this section, various dryers described in the literature are discussed along with their design specifics and performance metrics, such as product initial and final moisture content, drying capacity, loading density, tray area and number, drying time, drying rate, and pickup efficiency, and dryer thermal efficiency. A solar cabinet dryer for drying apricots, cabbage, onions, grapes, and tomato slices was developed [4]. The system consisted of a rectangular container, insulated at its base and covered with a double-layered, transparent roof. The size of the dryer constructed was 1.93 m x 0.66 m cross-section, with a tray area of 1.1 m^2. The framework was built using rough lumber and masonite hardboard sheets. Wood shavings and 26 excelsior packings were used as insulation. The use of this dryer resulted in a reduction in the overall drying time when compared to the open sun drying by 50% for apricots, 67% for cabbage, 50% for onions, 75% for grapes, and 50% for tomato slices. The maximum dryer thermal efficiency of this system was 20%. To enhance radiation on the drying surface, a low-cost home solar dryer with a special parabolic trough reflector architecture was created in [5]–[7]. The dryer has a parabolic trough reflector area of 3.3 m^2 and a total drying surface area of 1.1 m^2. The perforated aluminum panel sheeting and aluminum angle used to frame the product drying trays were made of aluminum. Mango slices loaded with loading capacities of 3.7, 3.8, and 4.3 kg/m^2 were 9.5 mm thick. For the first 5.5 hours of the solar day, the drying rates for these three loadings ranged from 0.48 to 0.55 kg moisture/m^2. Due to barriers preventing internal moisture diffusion through the product, the latter drying period's lower drying rate of 0.02 to 0.011 kg moisture/ m2.h was attained. Ref [8] reviewed solar drying in highly mechanized, agricultural systems. Ref [9]mentioned that neither the temperature required nor the quantity of heat necessary in high-temperature batch type or continuous flow dryers could be reached with solar collectors. High-temperature drying equipment could not be cheaply powered by solar energy. Low-temperature storage drying systems, which have become more important in the last ten years for drying hay and grain, were thought to be better suited for solar energy. Solar energy is extremely advisable, and it is used in tropical and subtropical nations. When compared to conventional drying techniques, the use of solar crop dryers seems to be a solution to reduce mass losses while also greatly enhancing product quality. There were significant interests in lowering the high amount of fossil fuels utilized for crop drying in highly mechanized agricultural systems. Studies revealed that high-temperature continuous flow dryers could not be economically powered by solar energy. Solar energy was thought to be better suitable for low-temperature drying in storage. The necessary temperature rise could be achieved with inexpensive solar collectors. Solar collectors heated the drying air, which dramatically sped up the drying process and decreased drying time. Utilizing sun dryers to dry crops reduced mass losses dramatically and increased product quality. Ref [10] designed a low cost, solar cabinet dryer, which could be used to dry 10 to 15 kg of fruits and vegetables. The dryer that was created was a mild steel rectangular box that measured 2.08 metres by 0.82 metres by 0.24 metres. For storing the item to be dried, two wooden and wire mesh frames (0.96 m x 0.76 m x 0.05 m) were installed above the bamboo. A double-sloped 0.3 mm PVC roof was provided for the dryer. At the peak of the slanted roof, three aluminium chimneys that were painted black served as hot air escapes. In the chimneys, regulating valves were installed so that the air flow could be changed. The moisture content of the red chilies was reduced from 86.3 to 4.1% within 9 days by the solar drying method whereas it took 18 days to dry 12 kg by open sun drying. In contrast to open sun drying, where the drying curve was flat, the solar dryer's drying rate accelerated dramatically as the moisture content dropped below 62%. In comparison to the open sun drying method, the average solar energy consumption efficiency was 12% in the solar dryer. In ref [11] developed a multi-purpose, solar tunnel dryer for drying sultana grapes and dried from an initial moisture content of 78% on wet basis to a final moisture content of 18% on wet basis. A modest fan, a solar air heater, and a tunnel drier made up the system. Because air bubble foil operated at high temperatures, which were necessary for drying grapes, it was chosen as the cover material. The dryer was used nonstop for the first two days to avoid unfavorable product deterioration and discoloration. The moisture was removed during this time using a reasonably high airflow rate of 1200 m3/h because it was evaporating quickly. The airflow rate was decreased to 600 m3 per hour after two days of drying, which raised the temperature at the collector output. In the tunnel dryer, sultana grapes were dried in 5 days as opposed to 7 days in the open sun. 1200 m3 per hour were forced through the collector and dryer using an energy source that ranged from 70 to 100. Ref [12] designed and developed a forced convection solar dryer for drying sultana grapes, green beans, sweet peppers and chili peppers. The solar air collector comprised a 0.57 m x 2.03 m helical absorber, black-painted aluminium wires with a diameter of 1 to 1.5 mm, and a polyester plate with glass wool as the clear cover. Dimensions of the drying room were 0.51 m x 1.05 m x 1.29 m. The drying chamber has the following measurements: 0.51 m x 1.05 m x 1.29 m. An electrical heater was used to test the solar air heater and assist in determining the ideal inlet air temperature for the working fluid. The drying time for sultana grapes, green beans, sweet pepper and chilli pepper using solar dryer were 5, 2.5, 5 and 2.5 days whereas with open sun drying it took 11, 9.5, 10.75 and 5.2 days, respectively [13].

2.2 Solar collectors-based drying

During the last 30 years, different designs of solar flat plate air collectors have been proposed and discussed in the literature. The design of an efficient and suitable flat plate air collector is one of the most important factors, which control the economy of solar drying. All the designs of solar flat plate air collectors studied so far are classified into two categories. The first type has a non-porous absorber plate and air flowing above the absorber plate (type-I), below the absorber plate (type-II), or on both sides of the absorber (type-III). Type-I is the simplest design, which is mainly used in raising the temperature of the ambient air by 15 to 25^{o}C. For higher temperatures, type-II of conventional design or type-III with double channels is very efficient. The airflow can be single, double, or even triple pass. Economic studies have indicated that single-glazed conventional heaters without a concentrator are suitable for domestic and agricultural applications, which require air temperatures ranging from slightly above ambient temperature up to 70°C. They are relatively cheap, easy to construct, and inexpensive to maintain. A conventional flat plate solar air collector is typically a rectangular flat passage between two parallel smooth plates. The upper plate is nominally painted black to enhance the absorption of incident solar radiation and is sometimes covered with a selective coating to increase the efficiency of solar absorption. A single glass cover is customarily used to reduce the heat loss from the absorber, while sufficient insulation around the sides and at the base of the collector is necessary to minimize heat loss to the surroundings. A mixed-flow type fan or blower is usually employed to provide a continuous airflow at the required rate and to overcome flow resistance across the collector air channel beneath the absorber plate. The single flow channel brings the air stream into thermal contact with the hot absorber to heat the air as it passes through. The important characteristic of the thermal behavior of solar air collectors is the depth of the flow path of the air also called the flow channel depth. It is because both the pressure drop in the duct as well as the forced convective heat transfer coefficient depends on the flow channel depth. The collector performance can also be improved by employing higher flow rates but at the cost of additional pumping power. It has also been documented in the literature that different materials (absorber, plate coating, glazing, insulation, and ducting) of different shapes, dimensions, and layouts can improve the thermal performance (outlet temperature and collector efficiency) of solar collectors. The heat output of the collector changes greatly depending on the amount of solar radiation hitting it, and the amount of solar radiation fluctuates greatly depending on the location and time of year [14]. studied how duct depth and length affected the flat plate solar air collector's efficiency and pumping power. At airflow rates of 50, 75, 100, 200, and 300 $kg/m^2.h$, the duct depth was examined for lengths of 0.05, 0.10, 0.15, and 0.2 m, respectively. As duct depth increased, the efficiency of the collector declined along with it, as did the pumping power. The efficiencies were approximately 38, 47, 51, 61, and 66% for 50, 75, 100, 200, and 300 $kg/m^2.h$, respectively. At 0.2 m duct depth, they were reduced to 19, 24, 28, and 39 %. The efficiency of the collector increased with an increase in duct length and mass velocity. Ref [15] developed an analytical criterion for determining the optimum flow channel depth of conventional flat plate solar air collectors for particular pumping power, giving the minimum depth required to maximize heat transfer from the absorber plate to the moving air.

Ref [16] established a straightforward formula for estimating the ideal depth to length ratio of a channel for a flat plate collector to heat air at a known mass velocity. An ideal ratio of (D/L) opt = 2.5x10-3 was proposed for the typical flat plate collector's variable flow operation. [84] Mentioned that the average value for the useful energy-to-optimum channel geometry ranged from 81 to 96%. Additionally, lowering this ratio below its ideal level led to a modest improvement in thermal efficiency. In a separate study, the ideal channel design for solar flat plate air collectors operating in constant and variable flow with airflow above (type-I), below (type-II), and on both sides (type-III) of the absorber plate was examined. [17] tested a 10 m x 1 m collector in the mass velocity range of 0.005 to 0.03 $kg/m^2/s$. For the aforementioned collectors, a channel depth to length ratio of 0.0025 was suggested as the ideal value for both constant and variable flow operations. [18] A solar air collector with a single pass double duct channel that measures 0.74 m by 0.44 m and has a duct depth of 0.075 m as well as a full-scale model that measures 12.6 m by 6.75 m and has an overall duct depth of 0.28 m were both put to the test. The air mass flow rate, relative humidity, air mean temperature, and efficiency for top-to-bottom channel depth ratios of 0.364:1, 1.08:1, and 3.42:1 were calculated using the laboratory model. 464 W/m^2 was the steady-state incident solar radiation. Under these circumstances, the air's mass flow rate and relative humidity were 0.0164, 0.0123, and 0.0139 kg/s and 35, 35.8, and 39.8%, respectively. At mass velocities between 0.005 and 0.055 kg/m2/s, the efficiency and outlet temperature of a flat plate, finned, and V-corrugated solar air collectors were examined. The flat and finned plate collector's flow channel depth was 25 mm, while the V-corrugated collector's flow channel depth was 50 mm. The absorber plate has measurements of 1.8 m by 0.7 m. The three collectors' ideal operational mass flow rates were 0.030, 0.029, and 0.031 $kg/m^2.s$ when efficiency and outlet temperature were taken into account.

The efficiency and outlet temperature of a flat plate, finned and V-corrugated solar air collectors at the mass velocity range of 0.005 to 0.055 $kg/m^2/s$ were investigated. The flow channel depth of the flat and finned plate collector was 25 mm and for the V- corrugated collector was 50 mm. The dimension of the absorber plate was 1.8 m x 0.7 m. The optimum operating mass flow rate of these three collectors considering the efficiency and outlet temperature was 0.030, 0.029, and 0.031 $kg/m^2/s$.The efficiency and the outlet temperature at these conditions are 62, 65, 68.5%, and 48, 50, 53 ^oC, respectively [19]. In a single-pass mode, the efficiency of the flat plate collector was 30, 45, 55 and 62%, respectively at 0.01, 0.02, 0.03 and 0.04 $kg/m^2/s$. The V-groove collector gave the experimental efficiencies and outlet temperatures as 41, 51, 60, 66, 71% and 62.9, 57, 50, 43.8, 40.6 ^oC, respectively at 0.011, 0.02, 0.03, 0.042 and 0.054 $kg/m^2/s$ [20].

At mass velocities between 0.005 and 0.055 $kg/m^2/s$, the efficiency and outlet temperature of a flat plate, finned, and V-corrugated solar air collectors were examined. The flat and finned plate collector's flow channel depth was 25 mm, while the V-corrugated collector's flow channel depth was 50 mm. The absorber plate has measurements of 1.8 m by 0.7 m. The three collectors' ideal operational mass flow rates were 0.030, 0.029, and 0.031 $kg/m^2.s$ when efficiency and outlet temperature were taken into account. To enhance the rate of heat transfer [21] experimentally investigated and compared the performance of flat plate-packed bed absorbers with iron screen matrices of different geometrical parameters and plane collectors. The collector was 1.55 m × 0.44 m x 0.05 m in size. The plane collector's absorber was made of a GI sheet. The plane collector's efficiency ranged from 31% at 0.0159 kg/m^2 to 38% at 0.0318 $kg/m^2/s$ and was increased from 21 to 61% with packed bed absorbers. The solar air collector efficiency of the single-pass, glazed and unglazed types was studied by [22]. The single glazing was constructed using fiberglass- reinforced polyester sheet. The air passages consisted of galvanized steel decking, which was obtained in 0.6 m x 10.7 m sections. The system was designed to heat air to 90 ^oC for industrial crop dehydration applications. The collectors have tested in single-pass fashion in the unglazed tests and, single and double-pass mode in the single-glazed tests of various lengths so that the pressure drops and convective heat transfer rate could be varied independent of collector operation temperature. [23] tested their system with mass velocity ranging from 0.0013 and 0.027 kg/m^2 .s. The collector efficiency of the single-pass glazed and unglazed 21.3 m long collector was 68 and 50 %, respectively at the mass velocity of 0.027 $kg/m^2/s$. The collector efficiency of the glazed, double-pass solar air collector for this mass velocity was 85 %. The thermal performance of solar air collectors with ducts filled with wire screen matrices that have been blackened was examined in [24]. The shape of wire screens (5.5 to 14 mesh per inch), mass velocities (0.0159 to 0.0318 kg/m), and input solar energy fluxes were among the many influencing factors covered by the experiments. Two symmetrical rectangular pipes measuring 1.55 m by 0.44 m by 0.05 m made up the collector. For each collector, an absorber plate made of a 24-gauge G.I. sheet with an exposed area of 0.649 m^2 was used. With a mass velocity of 0.0318 $kg/m^2/s$ $kg/m^2/s$, the packed bed collector's highest efficiency was 61%, compared to the maximum efficiency of 39% for the plane collector. The maximum and minimum values of the collector heat removal factor were 0.990 and 0.870, respectively and for the plane collector, the value was only 0.691. Ref [25] has examined the efficiency of six different types of conventional solar flat plate air collectors (Model 1: single plastic glazing, black painted hardboard absorber, and front pass; Model 2: single plastic glazing, black painted flat plate absorber and front pass; Model 3: single plastic glazing, black painted zigzag plate absorber and front pass; Model 4: single plastic glazing, black painted flat plate absorber and back pass; Model 5: single plastic glazing, black painted zigzag plate absorber and back pass; Model 6: double plastic glazing, black painted flat plate absorber and back pass). Crop drying treatments were utilized at temperatures that were obtained that were more than 40 ^{o}C above the ambient temperature. At mass velocities of 0.018 kg/m^2.s, these six collectors had collector efficiencies of 42.11, 45.88, 44.23, 39.76, 39.05, and 36.94%, respectively. At the aforementioned mass velocities, these collectors' average output temperatures were 40, 40.94, 40.5, 29.5, 39, and 38.87 ^{o}C, respectively. Amongst the above six models, model 2 was the most efficient collector and the least efficient one was model 6. [26], [27] explored a solar air heater and cum storage system integrated within a rock bed for agricultural purposes. With a range of air mass velocity, glazing count, rock bed depth, and heat decay characteristics of the rock bed with night insulation cover in addition to glass coverings, experimental observations of fluid temperature, energy storage, and other measures for system performance were reviewed. Their experimental setup included a 4 m^2 flat plate air heater that was coupled to a 1.75 m x 1.75 m integrated rock bed storage and collection system. A metallic plate with a thickness of 0.0091 m made up the air heater. The total energy measured by the solar heater rose as the number of glazing was raised from one to two. Their findings demonstrated that the relatively cheap solar collectors with integrated storage devices could be constructed using materials that were both readily available and affordable. Their integrated, augmented rock system had a 52.8% total efficiency with a mass flow rate of 165.6 kg/h and a rock bed depth of 0.2 m, outperforming both the integrated rock storage and collection system and the widely used traditional solar heater. [28] evaluated the effectiveness of a solar air collector with dimensions of 0.57 m x 2.03 m, painted black helical type aluminium wires with a diameter of 1 to 1.5 mm, and a clear polyester panel with glass wool. In their system, the collector efficiencies varied from 57 to 75% at 0.042 kg/m^2, 28 to 79% at 0.055 kg/m^2, and 59 to 81% at 0.070 kg/m$^{2.}$ The temperatures at the collector's inlet and outflow ranged from 35.7/42.2 to 45.5/60.6 ^{o}C at 0.042 kg/m^2.s, from 33.7/41.4 to 54.0/63.5 ^{o}C at 0.055 kg/m^2.s, and from 36.3/48.1 to 44.5/57.2 ^{o}C at 0.070 kg/m^2/s. Their system's combined efficiency with the drying unit was between 57 and 81% at 0.055 kg/m^2.s. [29] developed and tested a single-glazed, solar matrix air collector, which had physical and technical advantages over the conventional collector. Due to its tiny hydraulic diameter, Matrix has a high heat transfer area-to-volume ratio and a high heat transfer coefficient. This collector was comprised of two parallel sheets of fine-mesh copper wire screens that had been black oxidised or black galvanised for industrial use. The key features of this design included improved performance, extensive flexibility, long durability, and a cost-effective, light weight construction. The channel height of the collector has no impact on its thermal performance at a low mass flow rate of 0.01 kg/s. Low heights for the upper channel between 20 mm and 30 mm were advised for better thermal performance of the collector at higher mass flow rates greater than 0.025 kg/s. The performance of several types of solar air collectors developed in India. All of the solar air collectors for porous and non-porous absorbers were investigated. Three different transparent coverings made of 30 mm polyethylene, 30 mm thick polyethylene with aluminium foil, and 60 mm thick polyethylene were tested in the porous absorber collector. With a flow rate of 770 m3 per hour, the maximum collector efficiency of these collectors was 52.33, 55.88, and 67.85%, respectively. The nonporous single-glazed single-pass air collector's heat removal factor and plate efficiency factor were 0.75 and 0.96, respectively, at 0.0158 kg/m^2 s. Enein et al. (2000) investigated how flat plate solar air collector performance was impacted by channel length, width, and depth, as well as mass flow rate and storage materials. The flat plate collector included an absorber plate with its upper side painted matte black to boost the system's absorptivity and a glass cover with strong solar radiation transmission. The absorber plate gave out 24 thermal energy to the heated air as it travelled between the glass cover and the absorber. Under the absorber plate was where the storage material was put. Maximum collector outlet temperatures of 44°C and 53°C, respectively, were attained with a collector cross sectional area of 0.05 m x 1 m when the collector's length was changed from 0.5 to 20 m. The maximum outlet was achieved when the collector's breadth ranged from 0.5 m to 5 m (depth = 0.5 m and length = 1 m). The air channel depth was changed from 0.03 to 0.20 m, and it was found that as the channel depth increased, the outlet temperatures of 54 and 52 ^oC somewhat reduced. In the aforementioned study, air moved at a mass flow rate of 0.00117 kg/s. With a collector dimension of 1 m x 1 m x 0.05 m, maximum temperatures of 53 and 45 ^oC, respectively, were observed when testing various air mass flow rates ranging from 0.00117 to 0.00468 kg/s. The thermal performance of the air heater with the sensible heat storage material was much higher (57%) than that without storage (53%), according to their findings. For drying, it was discovered that the storage material's optimum thickness should be around 0.12 m. The performance of a single-glazed flat plate solar air collector with paraffin-type, phase change, energy storage system we discussed. The dimension of the collector was 1.635 m x 0.945 m with an effective glazing area of 1.34 m^2 [30]–[31]. Modules of phase change material comprised of thin rectangular blocks that were each 1.637 metres long and 0.1575 metres apart were created. Using shared air input and discharge header manifolds, the area in between each module pair served as an air heater. The heated air's peak temperature rise was about 15 ^{o}C, while the peak cumulative, usable efficiencies and maximum airflow rate were about 0.058 kg/s and 22%, respectively. Five solar collectors with 0.9 x 0.4 m measurements. Based on the collector's surface geometry and the length of the airflow line, air collector efficiency was improved. Heat transfer and pressure loss both increased as surface roughness increased. The number of absorber slices in the collector was altered by pressure loss from the optimal slice number for heat transmission. The efficiency of the collector could be improved by increasing the mass flow rate of air due to an enhanced heat transfer [32].

2.3 Desiccant drying

Ref [33] The germination rate of corn dried with air desiccated over a fixed bed of silica gel was reported to be around 90% but drying at 60°C reduced germination rates to 80%. To dry food grains, they looked into the dehumidification system, which lowers the relative humidity of damp air through a sorbent bed made of calcium chloride flakes and oven-dried soil. Lower relative humidifies were produced by deeper beds of the sorbent soil mixture as a result of slower airflow rates and longer contact times. The system delivered 85% to 32% relative humidity dehumidified air. Researchers examined the viability of utilizing desiccants to boost the effectiveness of solar grain drying systems [34]. After 24 hours at 75°C, activated alumina and silica gel that was physically adsorbing water was restored to roughly 90% of their original capacity. At 75°C, molecular sieve and anhydrous calcium sulfate only showed a 29 and 41% moisture decrease, respectively. After 24 hours of heating at 150°C, complete regeneration was established. When heated over 815°C to cause the residual moisture in silica gel and other comparable sorbents to evaporate, the adsorptive capacity is diminished. Due to the high temperature required for generation, it was decided to renew liquid desiccants using a high-temperature concentrating solar collector after researching various forms of desiccants. In ref [35] evaluated the solar regeneration of silica gel and its use in grain drying. With a 26% (dB) moisture content, three lots of 75.4 kg of silica gel were recycled using solar power. The drying process took 280 hours for a lot of 1520 kg of corn with a surface moisture content of 23.5% (wb) and a depth of 0.66 m. The lot was dried using a 40:60 mixture of ambient and desiccated air. Another lot with a moisture content of 24.2% (wb) was dried concurrently for 350 hours using only ambient air. Using the same airflow rate of 3.68 m3 per minute, two lots containing 1520 kg of milo with an 18.5% (wb) moisture content and a 0.53 m depth were dried until the surface moisture content was below 16.2%. (wb). The required drying times were 330 hours with ambient air and 210 hours with a 60:40 blend of ambient and desiccated air. Final average moisture concentrations ranged between 12.6 and 14.4% (wb). It stressed the value of supplying solar energy during the intermittent use of fossil fuels and that desiccants were a prospective medium particularly suited for drying applications [36]–[38]. A crop or food product may be dried on a small or large scale using both liquid and solid desiccants. This study examines the uses of solar energy and desiccant energy storage. Numerous thermal and physical characteristics have been compiled. Desiccants were comparable with phase change materials, rock-bed storage, and water systems for energy storage, according to a cost analysis. The characteristics information was supplied for both traditional and desiccant-related energy storage. Costs connected with containers and material handling for different types of materials would need to be included in the cost analysis for energy storage. At the achievable moderate flat-plate collector temperatures, the commercially available liquid sorbents calcium chloride, lithium bromide, two solid desiccants, activated alumina, and silica gel are more easily regenerable. Although they were much more expensive, lithium bromide and silica gel had better mass transfer and storage characteristics. Bio-desiccants had the potential for limited cycle applications [39], [40]. Four drying batches using liquid desiccants to increase the efficiency of solar grain drying systems [41], [47] drying bin of 0.75 m diameter and 0.40 m depth, which required 12 m3 /m2 .min of dry air, was filled with corn of moisture content 25% (dB). In the first batch, the ambient air was used for corn drying. The initial grain moisture content was 25% (dB), and after 24 h, the average moisture content in the bin reached 22.4%. Using natural air to dry did not significantly alter the moisture content. In the second batch, the drying of the maize was combined with the use of a flat plate solar collector and began at midnight. At 4 p.m., the first batch's moisture content was 11.5% (db). The second batch began at 4 p.m. with a moisture content of 25% (db), and by noon, it had risen to 20.4%. (db). It was found that drying using solar-heated air dried clothes more quickly than drying with ambient air. The liquid desiccant system and the corn-drying model were combined in the third batch. The desiccated air dried the corn bin. The third batch was dried in 45 minutes between 2 and 9 p.m. The fourth batch started at 9 p.m and the average moisture content reached 18.3% on a dry basis by noon. An external energy source was used in the fourth batch. During this test, the air entered the drying bin at a constant temperature of 60°C. Six batches could be dried within 24 h. Each batch could be dried in 4 h with a slight difference in the final average moisture content. [48] developed solar crop dryer using forced ventilation and solar regenerated, bentonite-CaCl2 based desiccant unit [49]. The integrated desiccant unit was positioned directly above the grain bed, and a flat plate solar air collector was attached to the drying bin. The dryer was made to work in two different ways: desiccant drying at night using forced air circulation across the grains and through the desiccant bed and drying during the day using solar-heated air and independent simultaneous regeneration of the desiccant bed. After sundown, the dryer's inlet and exit windows were sealed, forcing a solar, battery-powered fan to circulate air between the grain and the desiccant beds. To maintain a higher temperature, transparent insulating material was added to the drying bin, although it had no beneficial effects on desiccant regeneration. Their experimental analysis showed that of the entire drying load, drying with solar heated air accounted for about 75% and drying with a solar regenerated desiccant bed for about 25%. the potential for aerating stored grain in the humid tropics employing solid betonies, $CaCl_2$-based desiccant dehumidifiers. In tests, the solar-regenerated open-cycle packed bed desiccant dehumidifier showed that a unit with a collector area of 0.921 m^2 and containing 32.5 kg of desiccant could continuously maintain an air flow rate of 2 m3 /min while lowering its relative humidity by 40% and raising its temperature by about 40 ºC [50]–[52].

2.4 Summary

The following was indicated by the literature review. A solar drying system with integrated desiccant could dry agricultural products when the sun wasn't shining. Scientific drying techniques could raise the product's quality. There were not many publications available for using reflective mirrors in solar drying applications Various drying applications may call for the usage of various desiccant compounds. Desiccants possessed the capacity to store heat energy and dry out the air. The best solar air collectors for drying applications are those with flat plates. The drying behavior of numerous agricultural products was predicted using mathematical models of thin layer drying. to carry out the experiments necessary to comprehend how green peas and pineapple slices dry at various air mass velocities.

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Chapter 3. Materials and methodology

3.1 Description of the Experimental Setup

A forced convection solar dryer integrated with desiccant is manufactured in our research work. The parabolic reflector was also added to increase reflection. The system was manufactured with the help of locally available resources present in the Thermal shed. After managing the resources and with the help of a technician it was manufactured. The system consisted of a solar flat plate air collector, drying chamber, DC brushless fan motor, parabolic reflector, solar panel, solar charge controller, and battery. The latter part of this chapter

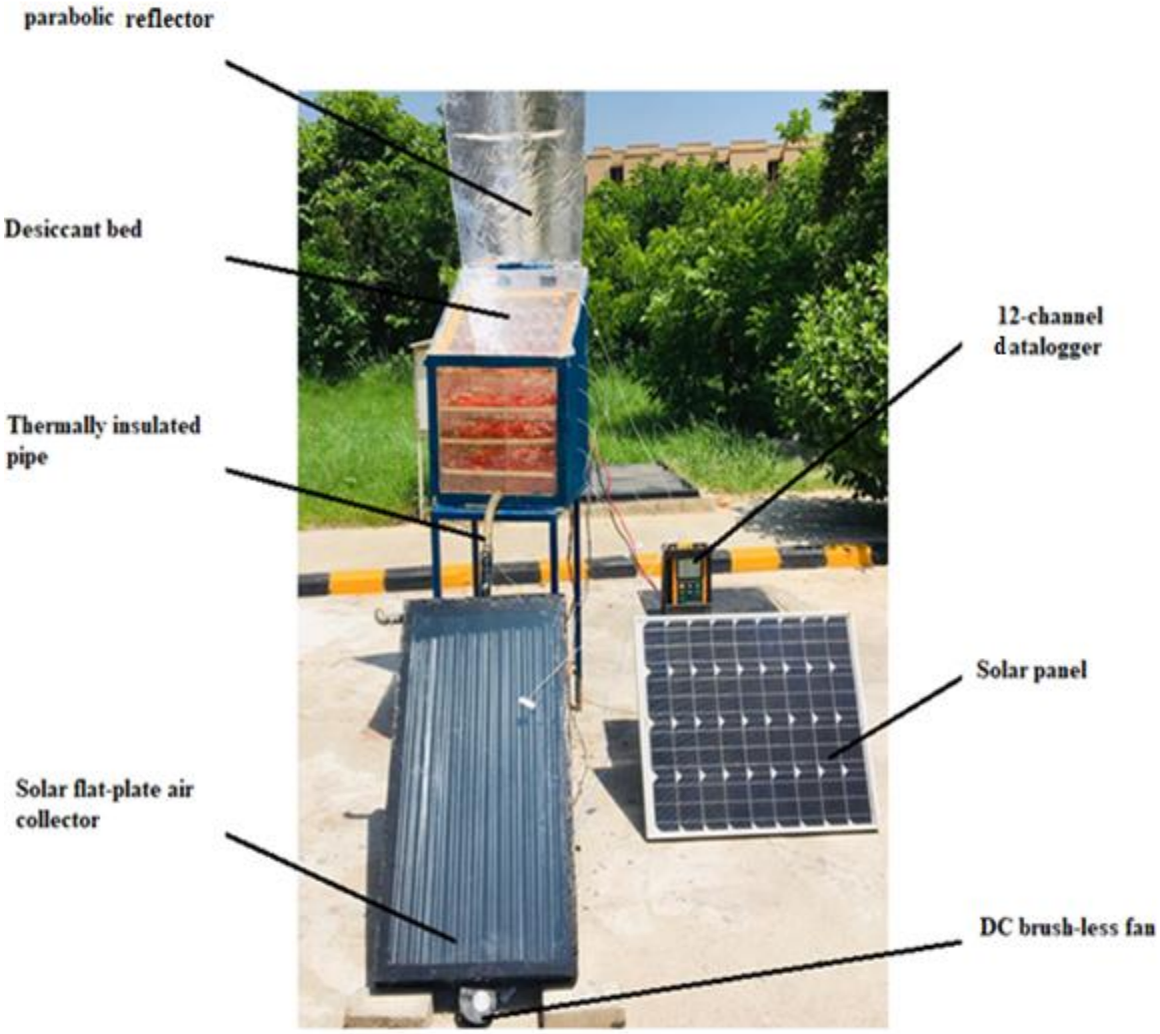

Figure 3.1 Pictorial view of the Experimental Setup

covers the details of the various components, fabrication, and the procedure with which we have carried out the experiments.

Figure 3.1 shows the complete diagram of the experimental setup and the site on which experiments were performed. A DC brushless fan motor was used to supply air at the required air flow rate and this fan was powered by a solar panel. The other two fans were placed behind the desiccant chamber and their function is to supply the required air during the off sunshine hours to continue drying. A single glazed solar flat plate air collector was used for gaining useful solar energy from solar radiation. The pipe was used to connect the solar air collector with the drying chamber. The drying chamber consisted of 4 trays to hold the products which were to be dried. The air heated from the solar air collector was forced into the drying chamber to absorb moisture from the products. A small door was made with wood and acrylic glass and was supported by four screws for loading and unloading the drying products. Acrylic was used so that some heat can also pass from this. The drying chamber was covered with aluminum foil from the inside to increase reflection. A solid $CaCl_2$ solar regenerated desiccant unit was placed at the top of the drying chamber. Cylindrically shaped molded desiccants were placed at the top of the desiccant bed. The fans which were charged with the help of solar panels during sunshine hours were used to supply air inside the drying chamber during off sunshine hours. Copper thermocouples were fixed at different positions to measure temperatures.

3.1.1 Solar flat plate air collector

Solar flat plate collectors are used to collect useful heat energy from the sun and they are beneficial for various applications. They can be used directly or by connecting fans depending on the application. In applications related to solar crop drying these are more effective in giving temperature complexity and proved to me more techno-economic as compared to concentrated collectors. A simple solar collector consists of an absorber plate that is painted black to absorb the maximum amount of sunlight and transfer it to a working fluid. It is advisable to use a duct for air circulation. In the case of forced circulation drying applications, airflow through the collector is achieved by fans or a blower. In our case, we used a DC Brushless fan motor which was powered by a solar panel. Details of the Single Glazed Solar Flat Plate Air Collector are depicted in **Table 3.1**.

Table 3.1 Details of Single Glazed Solar Flat Plate Air Collector

Type of air collector	Non porous conventional type
Gross dimensions	100 cm * 50 cm
Area of absorbing surface	45cm* 90cm
Absorber material	Steel
Number of glazing	1
Glazing material	Plain window glass
Spacing between glazing and absorber	6cm
Back insulation	55mm
Side insulation	40mm
Location of the test	USPCASE NUST H-12 Islamabad
Longitude	73.0479 E
Latitude	33.6844 N
Height	507m

Table 3.2 Details of the Drying Chamber

Type of drying chamber	Indirect type with forced circulation
Dimension of the drying chamber	0.48m * 0.48m
Number of drying trays	4 with an area of 0.47m* 0.47m
Material used for construction	Locally available wood
Number of parabolic reflector	1
Air duct	Pipe connecting the air collector and drying chamber
Mode of air flow	Air flow in the upward direction through the drying material

A flat plate of dimension (100) *(50) was used in our work. A (50) mm copper sheet which was painted black was used as an absorber plate to absorb incident solar radiation. A () mm thick plain glass was used as a transparent cover to reduce the upward heat losses parallel to the absorbing surface. The collector frame was made locally available. For the insulation aluminum foil was used for back and side insulation.

3.1.2 Drying Chamber

The drying chamber which is the most important part of the system is constructed from a locally available resource like wood. The proper distance was made for the placement of trays on the inner side. The dimensions of the drying chamber are (0.48 m * 0.48m *0.55m) having a roof with a slope of 30degree. That roof was used as a desiccant bed on which desiccants were placed which helps in drying during off sunshine hours. The inner walls were covered with aluminum foil to increase reflection. The drying trays of dimensions (0.47m * 0.47m). The drying chamber was in a position to hold 4 trays were fabricated firm wire mesh.

The shelves were kept on a wooden frame fixed on the inner walls of the wooden box and were 100mm apart. The drying chamber also consisted of two DC Brushless fan motors of 12V to draw ambient air through the desiccant bed to continue drying during off sunshine hours. And they were powered through the same solar panel. The desiccant bed was placed at the top of the drying chamber to hold desiccants.

During the daytime, plywood was placed at the bottom of the desiccant bed so that moist air coming from the drying chamber would not interact with the desiccants. During off-sunshine hours' plywood was placed at the top of the desiccant bed to avoid heat losses through the upper surface. Another addition introduced to the drying chamber is the parabolic reflector to increase the intensity of incident solar radiation. A detail of the Drying Chamber is mentioned in **Table 3.2**.

3.1.3 Desiccant preparation

Solar drying is effective during sunshine hours but the problem is if the objective is to continue drying during off sunshine hours then a thermal energy storage system should be installed in some way or the other. In this regard, researchers have been experimenting with different techniques to carry out drying experiments in the hours of no sunshine. In recent

(a) (b)

Figure 3.2 (a) Desiccants placed on the Desiccant Bed. (b) Pictorial view of Desiccants

research carried out by various researchers' desiccants are the material which stands out as the solution to this problem. The desiccants are used to absorb heat during the sunshine hours and that heat can be used in off sunshine hours. Almost 60-70 percent of the drying is carried under sunshine but the remaining is carried with the help of desiccants. In our case, we carried out experiments during sunshine hours and in the off sunshine hours 2-3 hours, we used desiccants with the help of DC Brushless fan motors located on the back side of the desiccant bed to provide that heat to the drying chamber to continue drying. Based on the research work solar regenerated calcium chloride-based desiccant was made in a lab. The composition of solid desiccant was 60% betonies, 10% CaCl2, 20% Vermiculite and 10% cement. We made 0.5kg of desiccant in Advance Energy Materials Lab in USPCASE NUST H-12 Islamabad. Care was taken to avoid damage while mixing and molding and an adequate amount of water was added during the process. The desiccant was molded in the form of cylinders and with the help of a Uni-axial hydraulic press. Then after pressing these desiccants were dried in an oven dryer at a temperature of 200C for the next 24 hours. The mass of each desiccant was 10g and we used 50 such pallets of a combined weight of 0.5kg for carrying out our experiments. Below fig shows the desiccants made in a lab. **Figure 3.2** (a) Desiccants placed on the Desiccant Bed. (b) Pictorial view of Desiccants.

3.1.4 Solar panel

To make our system renewable we come up with the idea to use solar panels so that during the daytime it uses sunlight and in the off sunshine hours can be used to charge the battery to continue operation. The details of the solar panel are listed in **Table 3.3**.

3.1.5 Battery

Figure 3.3 (a) depicts the utilized battery. The battery which was charged with the help of a panel to be used in the off sunshine hours was available in Technology Center Lab. The details of the battery used are listed in **Table 3.4**.

3.1.6 Solar charge controller

Figure 3.3 (b) depicts a solar charge controller that was used to keep the battery from overcharging and to regulate the current and voltage coming from the solar panel to the battery. The detail of the solar charge controller mentioned in **Table 3.5**.

Table 3.3 Details of PV Module

Company	**SUNTECH**
Model	STP060S-12/Sb
Rated maximum power	60W/P max
Output tolerance	+_ 5%
Current max	3.41 A
Voltage max	17.6 V
Short circuit current I sc	3.84 A
Open circuit voltage	22 V
Nominal operating cell temperature	45 +- 2C
Weight	6.2 KG
Dimensions	771*665*30
Series fuse rating	15 A
Cell Technology	Mono-Si
All technology STC	25 C
AM	1.5 A
E	1000W/m*2

Table 3.4 Details of Battery Features

Company	**LONG**
Model	WP18-12SHR
Cycle use	14.4-15V(25C)
Standby use	13.5-13.8 (25C)
Initial current	5.4A MAX

Table 3.5 Details of the Solar Charge Controller

Company	**Land Star**
Model	LS1024EU
Voltage	12/24V
Current	10A
USB Output	5V 1.2A

(a) (b)

Figure 3.3 (a) View of the Battery (b) Solar Charge Controller

3.2 Methodology

Drying experiments were carried out for drying of vegetables here in my case we tried tomatoes the experiments were conducted in two modes. First, the drying was carried out under sunshine hours after with the help of desiccants during sunshine hours experiments were also conducted. The solar radiation was measured by a pyrometer. Temperatures at different positions were measured with the help of a 12-channel thermocouple data logger. Model TM-500. All thermocouples were provided by Solar Energy Research Lab at the USPCASE NUST H-12 Islamabad. The temperatures were measured at 8 locations.

T1 → → Absorber temperature

T2→ → Glass temperature

T3→ → Collector outlet Temperature

T4→ → Bottom tray 1

T5→ → Upper tray 2

T6→ → Upper tray 3

T7→ → Upper tray 4

T8→ → Desiccant bed temperature

All temperatures were recorded every 30-minute intervals and they were saved. The ambient temperature and humidity were measured by a temperature and humidity sensor which was also provided by the department. The mass of tomatoes before the start of experiments on Day 1 10 –August 2022 were measured by electric balance available at the Advance Energy Materials Lab (AEMS). The mass at the end of sunshine hours was again measured to know how much moisture has been removed as a result of solar drying. Then, again by setting the product in trays with the help of loading and unloading the trays with the help of an adjustable door supported by screws. Then off sunshine hours' experiments were performed in the period between 5:50 pm to 7:20 pm after every 30 minutes temperatures were recorded with the help of a data logger. Then after 7:20 pm products were unloaded from trays and again they were weighed and measured how much mass has been removed as a result of off sunshine hours' experiments. During off-sunshine hours the ambient air was supplied by DC Brushless fan motors located at the back side of the drying chamber. At night time plywood

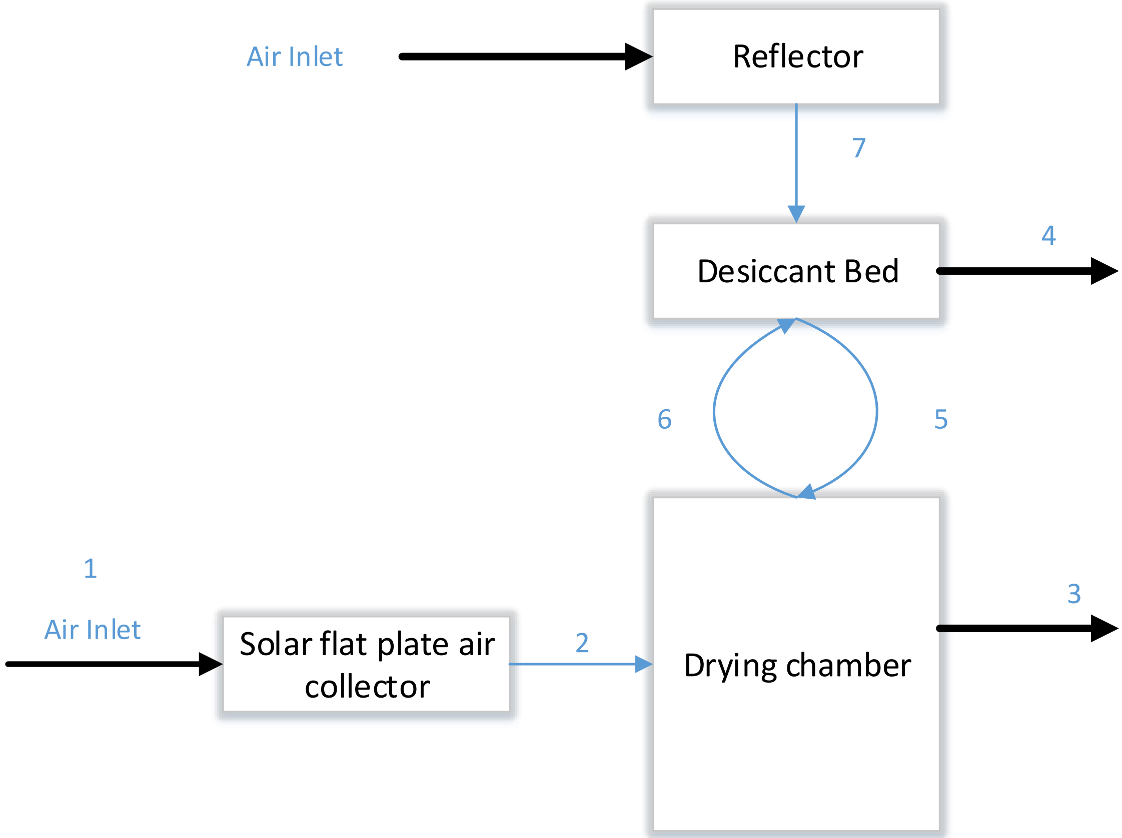

Figure 3.4 Flow chart of proposed methodology.

sheet was placed above the desiccant bed to avoid heat losses. The fans were powered by a battery which was charged during the daytime with the help of a solar panel. This was the procedure for carrying out the experiments on the first day of drying. Parabolic reflectors were also provided at eh top of the drying chamber to increase solar reflection. The next day again weight was measured before and after sunshine hours experiments and again unloaded and weighed for off sunshine hours.

Due to the unavailability of the electric balance in the lab on the second-day products were weighed in the facility available at the cafeteria located near USPCASE NUST. The same methodology was repeated for the next day's experiments. All drying experiments were completed within two days 10-11 August 2022. On the second day, the weather changed sunshine was not at its peak but still, we performed experiments, and winds and rain interrupted for 1 hour but we covered the system's electric components like the battery and solar charge controller, and then after the rain stopped we again carried experiments till 4:45 pm. And the same method was applied or off sunshine hours' experiments were performed till 7:30 pm and weighed again and this comes down to the end of the drying experiments. The flow chart diagram for different modes of drying experiments is shown in **Figure 3.4**.

3.2.1 Drying Characteristics

The quantity of moisture present in the products can be expressed as either on a dry basis or wet basis.

The moisture present on the wet basis is the mass of moisture content present in the product per unit mass of untried matter in the product[63], [64], [120]. It is expressed in equation 1

$$M_{wb} = \frac{W_0 - W_d}{W_0} \tag{1}$$

The moisture content on a dry basis is the mass of the moisture content present in the product per unit mass of dry matter in the product and is expressed as

$$M_{db} = \frac{W_0 - W_d}{W_d} \tag{2}$$

Where,

$$M_f = \frac{W_{wet} - W_d}{W_d} \tag{3}$$

Another view is to measure the instantaneous moisture at any given time and is expressed as

$$M_{tdb} = \left[\frac{(W_{0db} - 1)W_0}{W_t} - 1\right] \times 100\% \tag{4}$$

And

$$M_{twb} = 1 - \left[\frac{(1 - W_{0wb})}{W_t}\right] \times 100\% \tag{5}$$

The moisture loss is expressed by the equation 6

$$M_L = M_{final} - M_{intial} \tag{6}$$

Chapter 4. Results and Discussion

4.1 Case studies

A series of experiments have been conducted in our fabricated system for the drying of tomatoes in the sunshine and off sunshine hours. All temperatures in eight different locations were measured with the help of 12 channel data logger provided by Solar Energy Lab present in USPCASE NUST H-12 Islamabad. All readings were recorded after equal intervals of 30 minutes throughout the experimental day. The drying experiments were carried out in 2 modes a) solar drying during sunshine hours and b) desiccant drying during off sunshine hours. The initial and final weight of the products was measured with the help of a petri dish and beaker present in the Advance Energy Materials Lab (AEMS). Now we will explain all the results one by one in detail.

4.1.1 1st Experimental Day

The initial weight of tomato = 2000 g

Beaker before=100.960 g

Beaker after= 101.3524 g

Difference = 0.3924 g

Petri dish weight before = 5.5744 g

Table 4.1 Variations of mass of tomatoes and moisture loss at day 1 sunshine hours drying experiments.

Day	Mass of Tomatoes at 12 PM	Mass of tomatoes at 5 PM	Moisture loss from Tomatoes (g)
1	2000 g	1270.2722 g	729.7278 g

Table 4.2 Variations of mass of tomatoes and moisture loss at day 1 off sunshine hours drying experiments.

Day	Mass of tomatoes at 5:50 PM	Mass of tomatoes at 7:20 PM	Moisture loss from tomatoes (g)
1	1270.2722	1142.8269g	127.4454g

Petri dish weight after = 5.8143 g

Difference = 0.2399 g

The weight measuring capacity of the beaker was 150 g so we added the weight according to the limit of 150 g it takes a longer time but we try our best to meet the requirement which with the beaker can give accurate values. So it took 14 steps to weigh all the tomatoes at the end of day 1 sunshine hours' experiments started from 12:00 PM – 5 PM. Variations of mass of tomatoes and moisture loss at day 1 sunshine hours drying experiments are depicted in **Table 4.1**

The weights were as 54.333g ,74.125g, 73.960g, 70.445g, 113.145g ,103.7382g, 108.368g, 99.097g, 100.009g, 109.6292g, 112.8269g, 106.9211g, 068.7663g.

Total weight at the end =1269.6399g

So, with the help of the above weight measured we calculated the amount of moisture removed at the end of sunshine hours on Day 1.

Moisture lost= 2000- (1269.6399 +petri dish + beaker)

Moisture lost = 2000-(1269.6399 +0.2399+0.3924)

Moisture lost= **729.7278g**

We can explain this in the below table for more convenience

Table 4.3 Variations of mass of tomatoes and moisture loss at day 2 sunshine hours drying experiments.

Day	Mass of tomatoes at 9:45 AM	Mass of Tomatoes at4:45 PM	Moisture loss from Tomatoes (g)
2	1142.8269	965.10	177.8269

Table 4.4 Variations of mass of tomatoes and moisture loss at day 2 off sunshine hours drying experiments.

Day	Mass of Tomatoes at 5:50 pm	Mass of Tomatoes at 7:20 pm	Moisture loss of Tomatoes (g)
2	965.10g	880g	85.1g

Then off sunshine hours' experiments were conducted from 5:50 PM-7:20 PM. Their initial and final weight was also measured in the same manner and temperatures were recorded after equal intervals of 30 minutes. Variations of mass of tomatoes and moisture loss on day 1 off sunshine hours drying experiments are shown in **Table 4.2**.

The initial mass of tomatoes = 1270.2722 g

The final mass of tomatos= 1142.8269g

Moisture loss= 1270.2722-1142.8269g

Moisture loss= 127.4454g

4.1.2 2nd Experimental Day

Due to the absence of peak sunshine on 11 august sun was present only from 9:45 - 12:45 AM then rain interrupted for just 1 hour then solar radiations dropped but continued the experiments by just covering the electrical accessories in the fabricated system like covering the data logger, solar charge controller, etc. So we adopted the same procedure by measuring the temperatures every 30-minute intervals. Variations of mass of tomatoes and moisture loss at day 2 sunshine hours drying experiments are mentioned in **Table 4.3**.

The initial mass of tomatoes = 1142.8269g

The final mass of tomatoes= 965.10g

Moisture loss= 1142.8269g-965.10g

Moisture loss = 177.8269g

Then we again performed experiments from 5:50 -7:20 pm with the help of desiccants during off-sunshine hours. Then we again measured the mass of tomatoes at the end of day 2 and that was the end of the experiments. Variations of mass of tomatoes and moisture loss on day 2 off sunshine hours drying experiments are depicted in **Table 4.4**.

The initial mass of tomatoes= 965.10 g

The final mass of tomatoes = 880g

Moisture loss= 965.10g-880g ,Moisture loss=85.1g

4.1.3 Total moisture loss of tomatoes at the end of day 1.

M.L= Initial mass – Final mass, M.L=2000g -1142.8269g

M.L=857.1731g

% Moisture content loss in tomatoes at the end of Day 1

% M.C= (Initial Mass-Final Mass)/ (Initial Mass) *100

% M.C= (2000-1142.8269)/ (2000) * 100

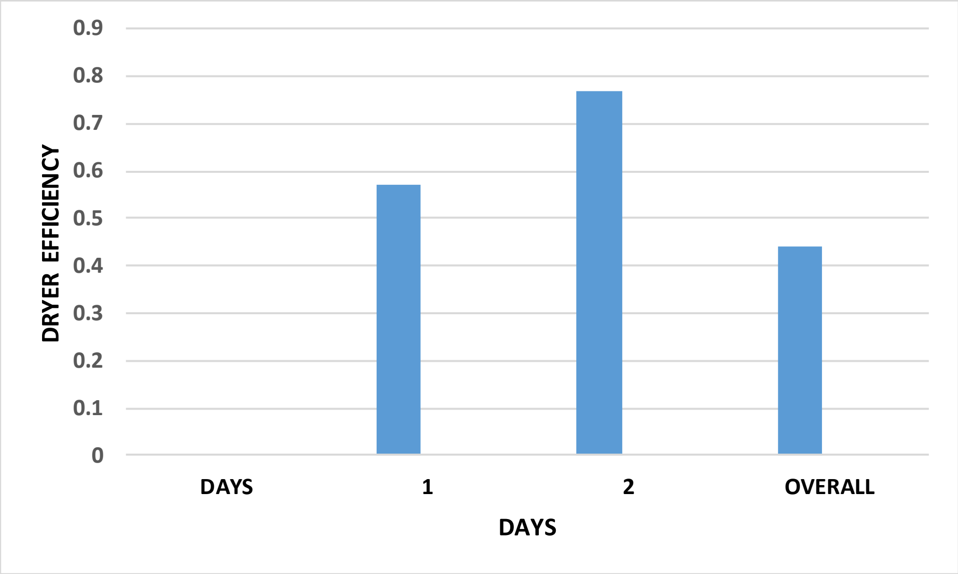

Figure 4.1 Days v/s dryer efficiency of tomatoes at the end of experiments.

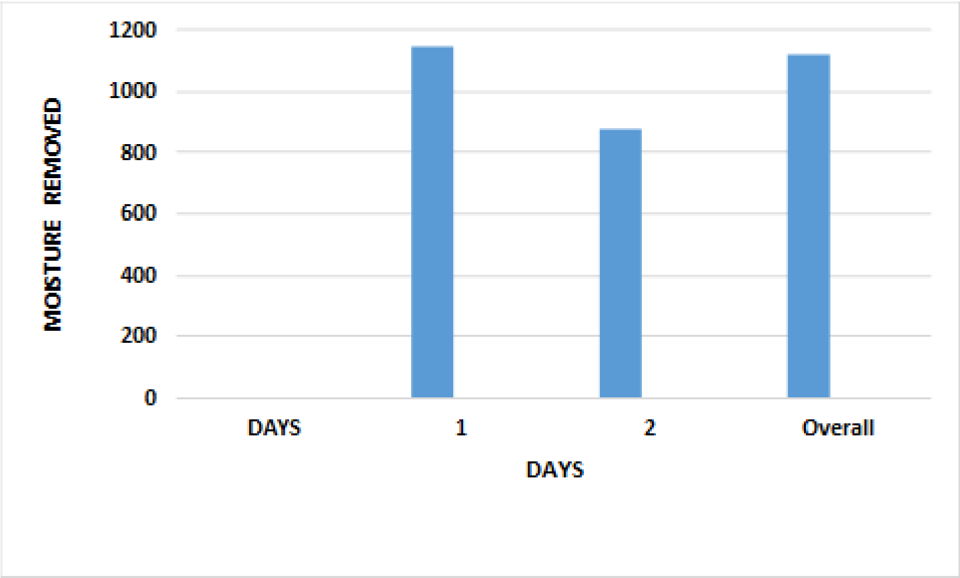

Figure 4.2 Time v/s moisture removed of experiments.

% M.C= 42.8586% Day 1

4.1.4 Total moisture loss of tomatoes at the end of Day 2.

M.L= Initial mass – Final mass

M.L=1142.8269g-880g

M.L=262.8268g

% Moisture content loss in tomatoes at the end of Day 2

% M.C= (Initial Mass-Final Mass)/ (Initial Mass) *100

% M.C= (1142.8269-880)/ (1142.8269) * 100

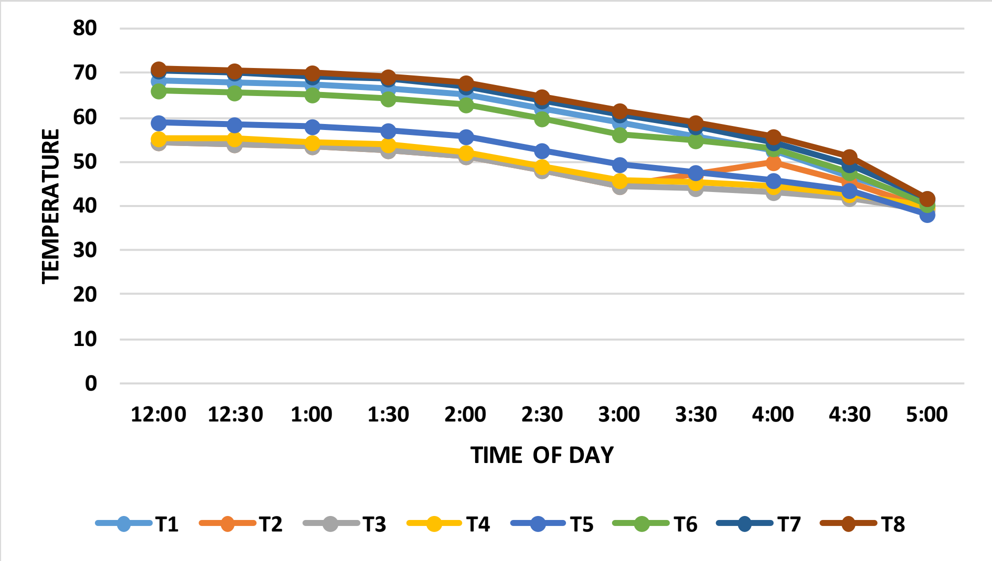

Figure 4.3 Time V/s Temperatures Sunshine Hours Day 1.

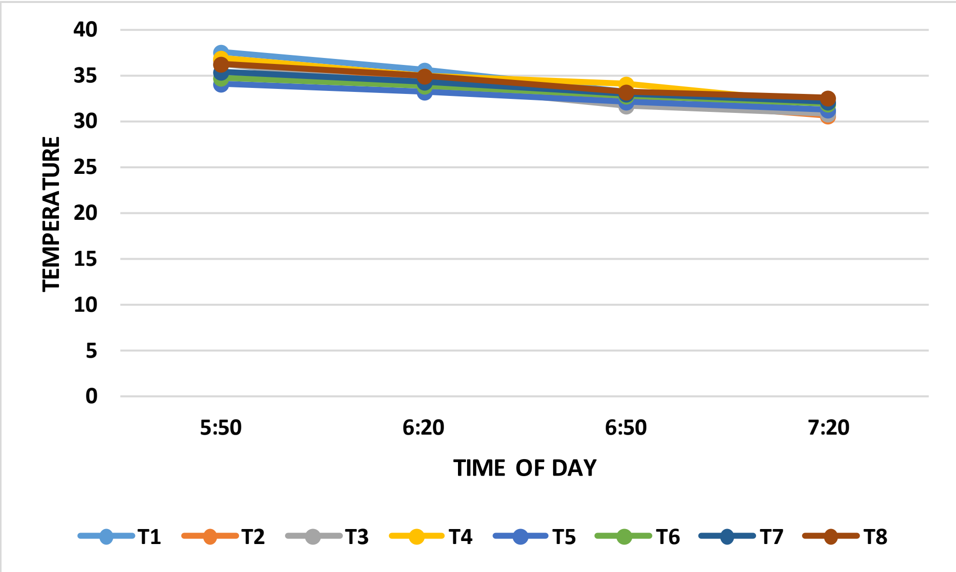

Figure 4.4 Time V/s Temperatures Day 1 Off-sunshine Hours.

% M.C= 22.9979% Day 1

4.1.5 Overall loss of moisture at the end of Experimental days reading from 10 August 2022- 11 August 2022.

M.L= Initial mass – Final mass

Initial mass = 2000g

Final mass=880g

M.L= 1120g

% M.C= (Initial Mass-Final Mass)/ (Initial Mass) *100

% M.C= (2000g – 880g)/(2000g) * 100

%M.C=56%

4.1.6 Total moisture content loss at end of two days of drying from 10 August – 11 August 2022

M.L= Initial mass – Final mass

Initial mass = 2000g

Final mass=880g

M.L= 1120g

% M.C= (Initial Mass-Final Mass)/ (Initial Mass) *100

% M.C= (2000g – 880g)/(2000g) * 100

%M.C=56%

4.2 Discussion

Figure 4.1 shows the dryer efficiency of tomatoes at the end of the experiments. The dryer efficiency at the end of day 1 was 57.14 % at 7:20 pm. And at the end of drying it increased to 77 %. The overall efficiency after experiments comes down to 44%. At the end of drying, experiments moisture comes down to 880g which was 2000g at the start of experiments.

Figure 4.2 shows the amount of moisture which is been removed during day 1 and day 2 and the overall moisture removed at the end of the experiments. At the start of day 1 2000g of tomatoes were placed in the dryer and at the end of day 1 1142.9269g were left which were again dried the next day and at the end of day 2 drying the moisture was removed and

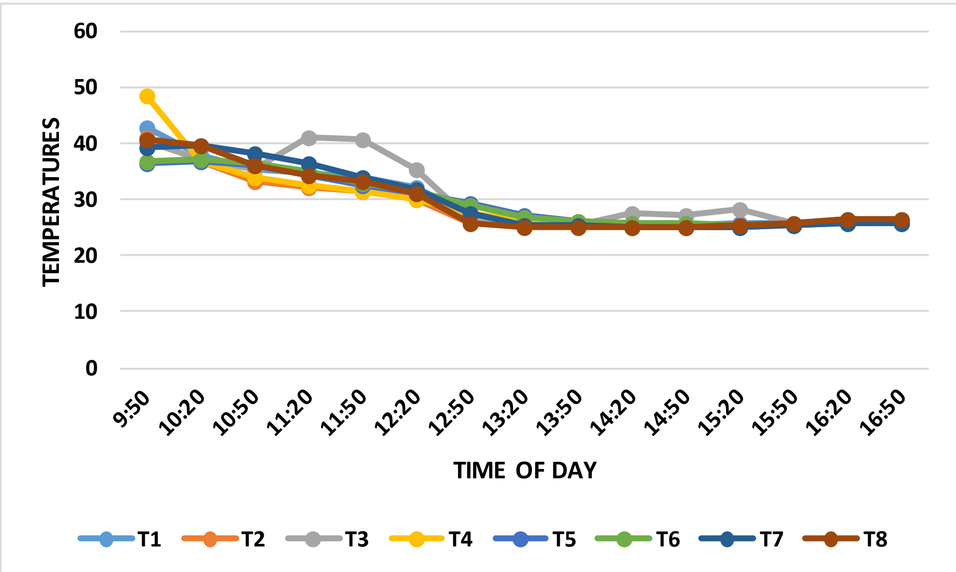

Figure 4.5 Time V/s Temperatures Day 2 Sun-Shine Hours.

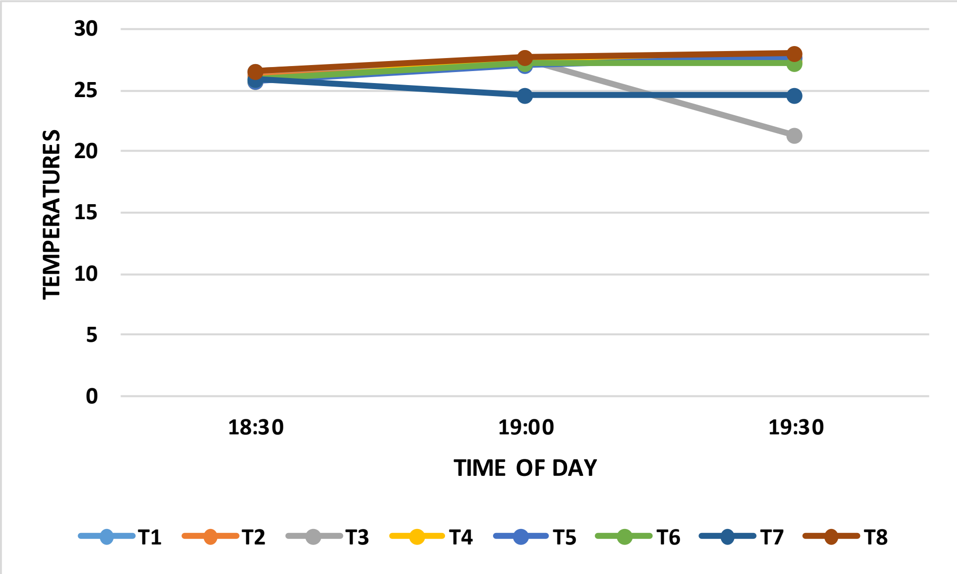

Figure 4.6 Time V/s Temperatures Off-Sunshine Hours Day 2.

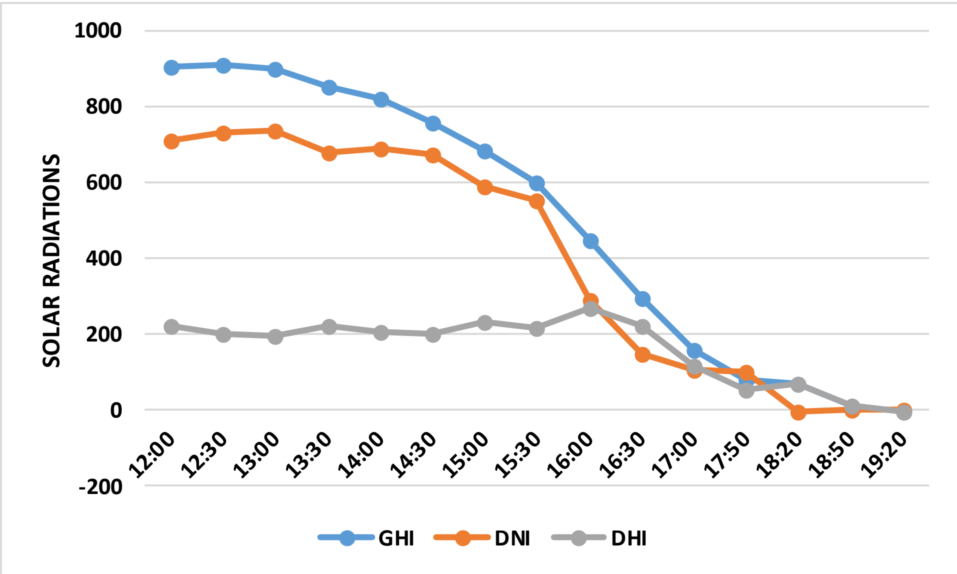

Figure 4.7 Day 1 V/s Solar Radiations.

reduced to 880g. during day 2 due to less sunshine and rain interrupted less moisture was removed as compared to day 1. But still managed to remove moisture at the off sunshine hours due to desiccants integrated drying. The below graphs show the variations of time vs. moisture removed throughout two days of drying.

Figure 4.3 explains the temperature variations during sunshine hours on day 1 10 august 2022. The maximum temperature achieved in the absorber plate was 68.4 ^{2}C and with time due to the decrease of solar radiations, it decreased to 41.2C. Similarly, the temperature at the desiccant bed which was supported by parabolic reflector in order to increase the reflection. So the maximum and minimum temperature achieved at the desiccant bed was 71.1 and 41.6 respectively. All reading was recorded at equal intervals of 30 minutes.

While in **Figure 4.4** the temperatures were measured after 30-minute intervals during off sunshine hours. The maximum and minimum absorber temperature achieved during that span was 37.6 ^{0}C and 31.2 ^{0}C respectively. Similarly, the maximum and minimum temperature at the desiccant bed was 36.3C and 32.7 ^{0}C. The experiments were performed from 5:50- 7: 20 PM and then products were unloaded.

Figure 4.5 shows the variations in temperatures during the second day of experiments. The temperatures were not as high as compared on the first day due to less sunshine and then an

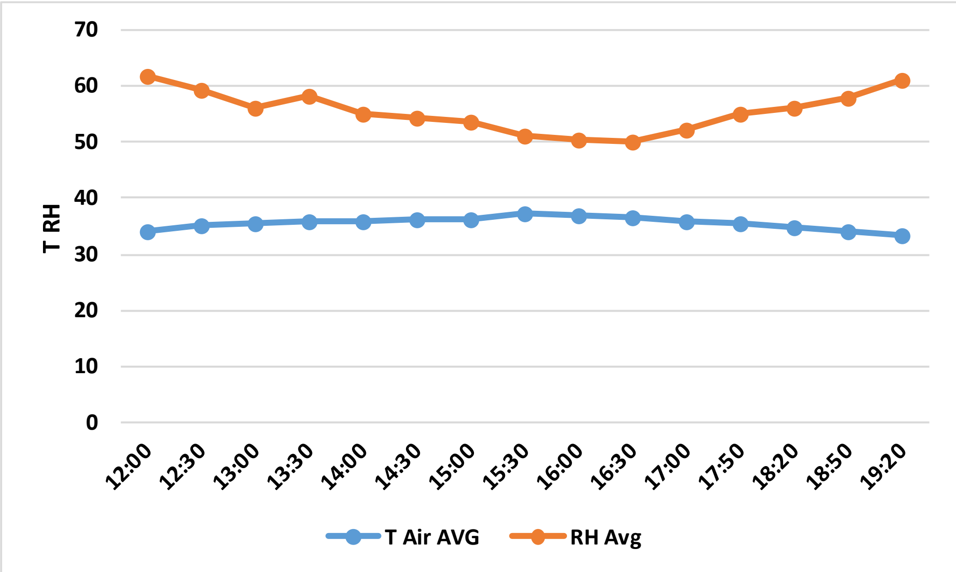

Figure 4.8 The variations of Temperatures and Relative Humidity on Day 1.

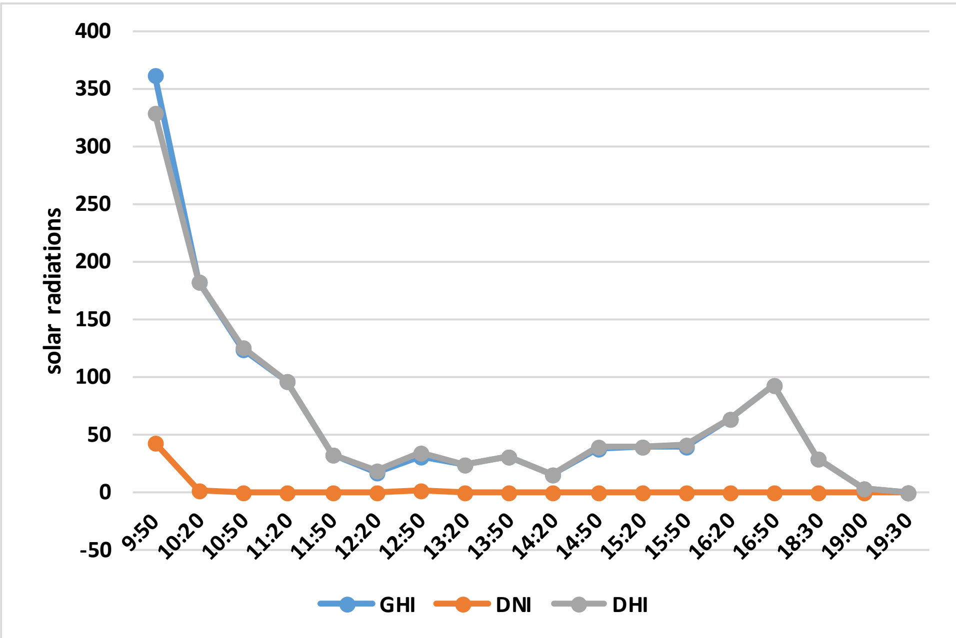

Figure 4.9 The variations of solar radiations v/s time throughout the Day 2.

hour run was interrupted. The maximum and minimum absorber plate temperatures achieved were 42.8C and 26.6 ^{0}C. Similarly, desiccant bed temperatures were not as high as the previous day and maximum and minimum temperatures achieved were 40.9 ^{0}C and 26.6 ^{0}C. The experiments were performed from 9:50 AM - 4:50 PM and temperatures were measured after 30 minutes intervals with the help of 12 channel data logger.

Figure 4.6 shows the variations of temperatures during off sunshine hours of day 2, 11 august 2022. The temperature which was achieved was less as compared to the previous day due to change in weather conditions. The maximum and minimum absorber plate temperatures achieved were 26.6C and 27.4 ^{0}C. Similarly, the desiccant bed temperatures were 26.6C and 28 ^{0}C. The experiments were performed between 18:30-19:30.

Figure 4.7 shows the variations of global horizontal irradiance, direct normal irradiation, and diffuse horizontal irradiance. The global horizontal irradiance, direct normal irradiation, and Diffuse horizontal irradiance were measured with the help of a pyrometer provided by the department. The maximum global horizontal irradiance, Direct normal irradiation, and Diffuse horizontal irradiance were 913.6979, 740.2537, and 269.9213 W/m^2. They were recorded after every 30 minutes.

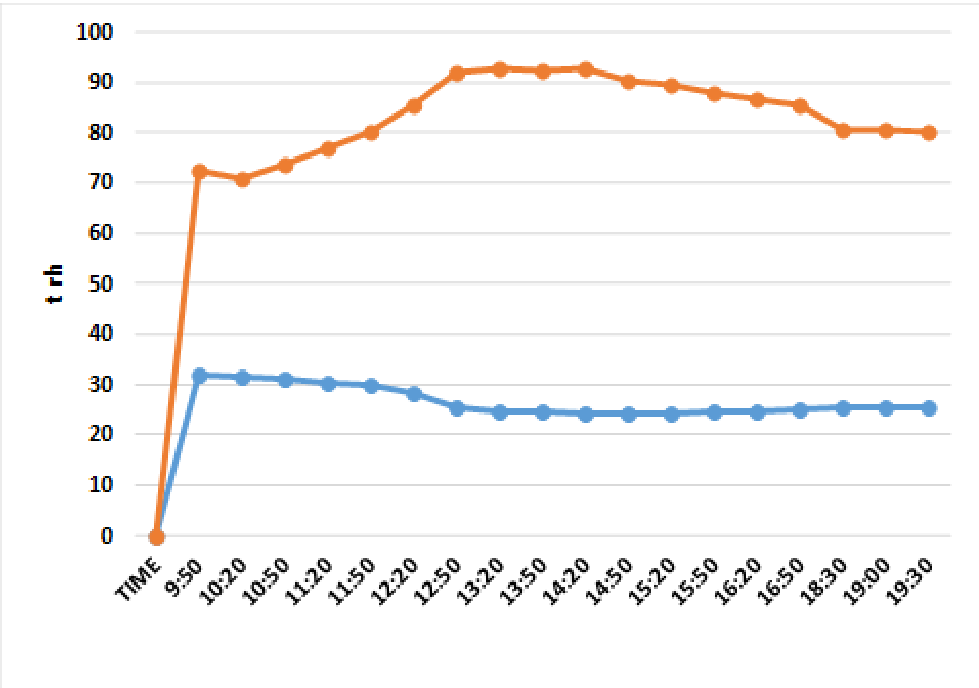

Figure 4.10 The variations of temperatures and relative humidity of Day 2.

Figure 4.8 depicts the temperature and relative humidity measured after regular intervals of 30 minutes throughout day 1. The maximum relative humidity recorded was in the morning and evening. Over time RH decreased till evening and then again increased during off sunshine hours experiments and again achieved maximum values. The global horizontal irradiance, direct normal irradiation, and diffuse horizontal irradiance were measured with the help of a pyrometer provided by the department. These values were less than on day 1 due to changes in sunshine and rain interruption. The maximum global horizontal irradiance, Direct normal irradiation, and Diffuse horizontal irradiance were 363.035, 42.91039, and 330.1161 W/m^2. They were recorded after every 30 minutes and shown in **Figure 4.9**.

In **Figure 4.10** the temperature and relative humidity was measured after regular intervals of 30 minutes throughout Day 2. The ambient temperatures and relative humidity were recorded after equal intervals of 30 minutes. At the start temperature increase but then due to changes in weather starts to decrease. On the other hand, relative humidity first increased and then shows a different pattern.

Chapter 5. Conclusions and Recommendations

5.1 Conclusions

The indirect forced convection solar dryer integrated with desiccants was fabricated and its experiments were conducted in the USPCASE NUST H-12 Islamabad. All fabricated setup was made with the help of laboratory staff and me. The daytime experiments were carried out with the help of sunshine and with the integration of desiccants drying was performed in the hours of no sunshine. The desiccant drying was carried out for 1-2 hours. In the daytime fabricated setup was placed outside the thermal shed at the USPCASE NUST H-12 Islamabad. All temperatures in different locations were measured within an equal interval of 30 minutes and recorded with the help of 12 channel data logger which was provided by Solar Energy Lab. The desiccant drying was carried out with the help of two Dc brushless fans located at the backside of the drying chamber which blows ambient air to continue drying. The moisture removed at the end of drying days was measured with the help of an electric balance present at the Advance Energy Materials Lab (AEMS) located inside USPCASE NUST.

Before the start of the experiments, 2kg of tomatoes were weighted and placed inside the drying chamber consisting of 4 trays. Then after sunshine hours experiments they were again reloaded and weighed. The moisture removed at the end of day 1 sunshine hours' experiments was reduced to 1270.2722g then they were again loaded for another mode of drying based on desiccants and at the end of 1.5-hour moisture was reduced to 1142.869g.

The same experiment was performed the next day and due to less sunshine and rain interrupted less moisture was removed during the sunshine hours. They were weighed and at the end of sunshine hours it reduced to 965g and after desiccant drying, it finally comes down to 880g.

Similarly, dryer efficiency was calculated separately for day 1. It comes out as 57.14% and similarly day 2 efficiency was 77%. But the overall efficiency was reduced to 44%. In the same manner moisture content which was removed was also calculated on day 1 which was 42.8586% and on day 2 it was 22,9979. Overall moisture content removed was 56%.

5.2 Recommendations

The following are recommended for further study

1. The optimum operating conditions determined from this study should be adopted by users of the dryer to maximize MRR and drying efficiency.

2. Some other desiccants can be tried and tested for this type of desiccants.

3. Because this type of dryer can be for industrial purposes as there is enough availability of solar panels so they can be incorporated to avoid grid electricity and with the help of blowers, they can perform experiments related to their requirements.

4. The simulations can also be done with the help of MATLAB software and its economical evaluation can also be done with the help of different software.