

**DEVELOPMENT OF A FORCED CONVECTION SOLAR CABINET DRYER
WITH THERMAL ENERGY STORAGE**

By

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CERTIFICATION

I hereby certify that this project was carried out by Adeyinka Adeolu of the Department of Mechanical Engineering, Federal University of Agriculture, Abeokuta, Ogun State, Nigeria under my supervision.

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H.O.D

.....

Date

DEDICATION

This project is dedicated to the the Almighty God for His continuous inspiration, blessing, strengthening, supporting and favour and enabling us to complete the project successfully. Also to my parents Mr and Mrs Adeyinka for their love and moral support during the course of project work.

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ABSTRACT

This project introduces a solar drying system that utilises solar energy for drying food substances, reducing agricultural produce wastage and aiding in preservation. The system includes a forced convection solar dryer with thermal energy storage, featuring a solar collector and a drying chamber. Air heated in the collector is channelled into the drying chamber to remove moisture from loaded agricultural produce. A blower efficiently moves the heated air from the solar thermal collector into the drying cabinet. The design considers the location (Abeokuta) and uses meteorological data for specifications.

To enhance drying efficiency and maintain consistency, granite is incorporated as a thermal energy storage material. Granite efficiently absorbs and stores excess heat during sunny periods, providing a reserve of thermal energy for cloudy days or night-time. This stored energy helps maintain the drying process when solar radiation is low.

The dryer's dimensions are 500 mm × 400 mm × 650 mm, constructed from locally available materials like wood, plywood, polyurethane glass, mild steel, and iron net for the trays. The dryer houses three trays placed 100 mm apart. The recorded maximum temperatures in the collector outlet and the top tray of the drying chamber during four distinct experiments under no-load conditions are as follows: 45.7 and 44.6 °C (with blower and no thermal energy storage material), 52.9 and 51.4 °C (with blower and thermal energy storage material), 80.7 and 59.9°C (without blower and no thermal energy storage material), and 74.4 and 62.4°C (without blower and with thermal energy storage material), respectively. These values obtained showed that the dryer is suitable for drying agriculture products like pepper, okra, cassava and plantain.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

Food preservation can be achieved through various methods, and one of them is drying (Leistner and Gorris, 1995). This technique, which has been in use for many years, involves utilising the sun's heat and wind to remove moisture from food, allowing it to be stored for longer periods. While drying is considered the oldest preservation method for agricultural products, it requires a significant amount of energy. However, due to the high cost and limited availability of fossil fuels like coal, there is an increasing focus on exploring alternative and renewable energy resources. In this regard, utilising solar energy to dry fruits and vegetables is an environmentally friendly option with minimal impact on the environment (Pimentel *et al.*, 2008).

In tropical and subtropical regions, including Nigeria, sun drying of cereal grains, fruits, vegetables, and food crops is a common technique for preserving agricultural produce (Chapin *et al.*, 2000). Its design is straightforward, it includes a number of constructional features, and the product that needs to be dried is directly exposed to adverse weather conditions. The quality of the dried items is ultimately impacted by discolouration, dust accumulation, insect and microbial infection, as well as human and animal intervention.

Sun drying can also be labour-intensive and have a limited capacity. For larger-scale operations, it can be time-consuming and expensive to achieve equal drying and prevent contamination due to the physical labour requirements. In Nigeria, sun drying of agricultural produce is not standardized, which can cause variances in the drying process

and the quality of the finished product. The uniformity and marketability of the dried goods may be impacted by this (Ibrahim, Mohamed and Lavernia, 2005).

Several authors have suggested solar drying as an alternative to sun drying for better-quality products. The intermittent effects and weather sensitivity of solar dryers, however, have been significant obstacles to the efficient use of solar energy. As a result, numerous researchers have suggested various arrangements of solar drying systems combined with thermal energy storage components to prevent the re-absorption of moisture. As a result of a change in a material's internal energy, excess heat energy can be stored in fluids and solids as perceptible, latent, or thermochemical heat, or as a combination of these (Bal *et al.*, 2010; Bal *et al.*, 2011; Sharma *et al.*, 2009).

Solar thermal technology has become increasingly popular in agriculture as an effective means of conserving energy. It has gained preference over alternative sources of energy, such as wind and coal, due to its abundance, inexhaustibility, and lack of pollution. Various types of solar dryers have been designed, developed, and tested in different regions of the tropics and subtropics. Two primary categories of these dryers are natural convection solar dryers and forced convection solar dryers. Natural convection solar dryers establish airflow through buoyancy, while forced convection solar dryers utilise a fan powered by electricity/solar module or fossil fuel to create airflow. Solar air dryers are uncomplicated devices that heat air using solar energy and are commonly used in applications that require low to moderate temperatures below 80°C, such as crop drying and space heating. In contrast, solar dryers generate higher temperatures, lower relative humidity, lower product moisture content, and reduced spoilage during the drying process. They also take up less space, require less time, and are relatively inexpensive compared to artificial mechanical drying methods. Therefore, solar drying presents a superior alternative to the drawbacks of both natural and artificial mechanical drying methods.

Solar dryers have proven to be incredibly useful devices in various agricultural and industrial applications, including crop drying, dehydration of fruits and vegetables, fish and meat drying, dairy industries for producing milk powder, seasoning of wood and timber, and drying of textile materials in the textile industry. These dryers effectively utilise solar energy to meet the increasing demand for energy and food supply (Aravindh and Saritha, 2015).

When designing solar dryers for agricultural purposes, the total system cost is a crucial factor to consider. The economic feasibility of using solar dryers in comparison to other available energy sources is a significant consideration that will determine whether or not this technology will gain widespread use (Tiwari, 2016).

The performance of a solar dryer system is dependent on several factors, including the type and design of the dryer, its capacity, the nature of the product being dried, and the prevailing climatic conditions. The efficiency of a solar dryer system can be improved by incorporating appropriate design features. For instance, the drying chamber should be well-insulated to minimise heat losses, and the product to be dried should be spread in thin layers to ensure uniform drying. Additionally, reflective surfaces can be incorporated into the dryer design to enhance the concentration of solar radiation, thereby improving the drying efficiency (Hegde et al., 2015).

While solar drying is an excellent way of utilising renewable energy, it is not without its challenges. One significant disadvantage of solar drying is that it is highly dependent on weather conditions, particularly solar radiation and temperature. Therefore, the drying process can be severely affected by cloudy weather and other adverse weather conditions.

Another limitation of solar drying is that it is not suitable for drying products that are sensitive to heat, light, or oxidation. Additionally, direct sunlight drying of agricultural

products can lead to poor quality and contamination. In comparison, solar dryers generate higher temperatures, lower relative humidity, lower product moisture content, and reduced spoilage during the drying process (Tiwari, 2016).

Furthermore, the initial investment cost for setting up a solar dryer can be relatively high, particularly for larger drying capacities. However, the cost of solar drying can be offset by the significant savings in energy costs, particularly in regions where there is a high demand for energy (Udomkun et al., 2020).

Solar dryers are an effective means of utilizing solar energy in various agricultural and industrial applications. They offer an economically feasible alternative to other available energy sources and have significant advantages over traditional drying methods. While the design of a solar dryer system is dependent on several factors, the incorporation of appropriate design features can significantly improve its efficiency. The limitations of solar drying can be mitigated by careful consideration of the product to be dried and prevailing weather conditions (Matavel et al., 2021).

This study is carried out to increase the drying efficiency of the solar dryer, and it focuses on the design, construction, and performance assessment of a forced convection solar cabinet dryer with thermal energy storage.

1.2 Motivation for the Study

Despite the potential benefits of solar drying with thermal energy storage, the use of this technology is not yet widespread. One reason for this is the lack of affordable and efficient solar dryers that incorporate thermal energy storage. Additionally, many existing solar dryers with thermal energy storage systems have been designed for specific crops or regions and are not adaptable to a wide range of applications. Therefore, there is a need to

design and construct a low-cost, versatile forced convection solar cabinet dryer with thermal energy storage that can be used in different region and for different crops.

This study aims to design, construct, and evaluate the performance of a forced convection solar cabinet dryer with thermal energy storage. The research will focus on determining the optimal design parameters and the effectiveness of the thermal energy storage system. The results of this study will provide valuable information for the development of affordable and efficient solar dryers with thermal energy storage systems,

1.3 Problem Statement

Drying is a common method of preserving agricultural products, such as fruits, vegetables, and spices. However, conventional drying methods, such as open-air sun drying, have several drawbacks, such as low efficiency, high dependence on weather conditions, and exposure to dust, insects, and microbial contamination. Solar dryers are devices that use solar energy to dry products in a controlled environment, but they often suffer from low and fluctuating temperatures, especially during cloudy days or at night. Therefore, there is a need to develop a solar dryer that can maintain a high and stable temperature for effective and consistent drying of products. One possible way to achieve this is to integrate a thermal energy storage system into the solar dryer, which can store excess heat during peak sunshine hours and release it when needed.

1.4 Aim and Objectives of the Study

The aim of this study is to design, build, and assess the performance of a forced convection solar cabinet dryer with thermal energy storage for drying agricultural products.

The objectives of this project are :

1. Design a forced convection solar cabinet dryer with thermal energy storage.

2. Construct a forced convection solar cabinet dryer with thermal energy storage.
3. Evaluate the efficiency of the thermal energy storage system in the solar cabinet dryer.

1.5 Justification of the Study

To the best of our knowledge, there is a limited body of research focusing on solar dryers incorporating granite as a thermal energy storage material for agricultural product drying. This research project aims to bridge this gap by developing a unique forced convection solar cabinet dryer that is not only cost-effective but also versatile in accommodating different types of crops and adaptable to various geographic regions.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Drying

Drying is among the techniques used to preserve agriculture, marine and herbal products since many years ago. It has several advantages including sustaining the product flavour, nutrients and quality, enhancing appearance, extending shelf life for consumer utilization, reducing packaging and shipping capacity. Removal of moisture through drying process can also prevent mold and bacteria from cultivating and ruining the food. Besides in agriculture sector, drying process is also widely applied in timber industry where drying of wood planks is carried out to remove moisture before further processing. Air-drying and kiln-drying are two types of wood drying techniques used in wood processing. In industrial sector, drying is one of the important process in food, chemical, textile, cement and pharmaceutical products production. Industrial drying is an energy-intensive process. At this point of time, both domestic and industries rely on open solar and conventional fuel for drying process.

Traditional drying, which is often carried out outdoors on the ground, is the technique most frequently utilised in developing nations since it is the easiest and least expensive way to preserve food. Some disadvantages of open air drying are: exposure of the foodstuff to rain and dust; uncontrolled drying; exposure to direct sunlight which is undesirable for some foodstuffs; infestation by insects; attack by animals, etc. (Madhlopa *et al.*, 2002).

Over the past 20 years, solar dryers, which have the potential to significantly lessen the aforementioned drawbacks of open air drying, have drawn a lot of interest as a way to improve conventional drying (Bassey, 1989).

There is a growing global awareness that renewable energy can significantly benefit farmers in developing countries and increase their productivity (Waewsak *et al.*, 2006). Among renewable energy sources, solar thermal technology is increasingly being recognized as an effective energy-saving solution in agriculture applications. It is preferred over other alternative sources such as wind and shale due to its abundance, non-exhaustibility, and non-polluting nature (Akinola and Fapetu, 2006; Akinola *et al.*, 2006).

2.1.1 The drying process

Drying processes are essential in preserving agricultural products, and they involve the simultaneous removal of moisture through heat and mass transfer (Ertekin and Yaldiz, 2004). Overall, solar thermal technology, specifically solar air heaters, presents a promising and eco-friendly solution for agricultural drying processes, which play a crucial role in preserving and increasing the productivity of agricultural products. Solar air heaters are a type of simple device that utilizes solar energy to heat air. They are widely used in applications that require low to moderate temperatures, typically below 80°C, such as crop drying and space heating (Kurtbas and Turgut, 2006).

Physically held water is the only type of water that is eliminated during the drying process. Dried products are becoming increasingly popular due to their extended shelf life, varied product offerings, and reduced volume. By enhancing the quality of products and refining process applications, the potential for expansion of the dried goods market is significant. Implementing dryers in developing countries can help reduce post-harvest losses, ensuring the availability of food in those regions. Post-harvest losses are often estimated to be as

high as 40% and even up to 80% under unfavourable conditions, with a significant portion attributable to inadequate and/or untimely drying of food products like grains, pulses, tubers, meat, and fish (Bassey, 1989; Togrul and Pehlivan, 2004).

There are three drying process stages: the increasing rate period, the constant rate period, and the decreasing rate period. The increasing rate period occurs as the drying material gains heat energy from the drying fluid initially with moisture diffusion to the surface of the drying material for evaporation. Then the surface of the drying material becomes saturated. The rate of water evaporation balances the rate of heat transfer; hence the drying rate and drying material surface temperature remain constant. The decreasing rate period commences when the surface saturation can no longer be maintained. This decreasing rate period can be further divided into two stages: (a) the first falling-rate period, when the saturated surface remains; (b) the second falling-rate, when the drying material surface becomes entirely unsaturated, and the drying rate is determined entirely by the rate of internal moisture movement until the end of the drying process.

2.2 Solar Dryers

The preservation of food and vegetable products is a well-established practice that has been utilised for centuries in order to maintain their flavour, appearance, and overall quality. Historically, the process of drying food grains involved exposing them to direct sunlight, firewood, fossil fuels, or coals, which not only incurred high costs but also resulted in the release of carbon emissions. These conventional methods are often unreliable, unhygienic, and can compromise the quality of the preserved food items. Therefore, the adoption of a solar dryer that operates on free and clean energy presents a superior alternative for achieving higher value addition in food preservation. Solar dryers not only offer cost savings and environmental benefits but also provide a reliable and

hygienic means of preserving food products without compromising their nutritional value or taste. By utilising solar energy to power the drying process, solar dryers offer a sustainable and efficient solution for food preservation, thereby contributing to the improvement of food security and sustainable agriculture (Behera *et al.*, 2022).

According to Natarajan *et al.* (2022), the following factors have been observed to impact the drying process, they are:

- Type of solar dryer
- Modes of solar drying
- Air velocity, temperature and relative humidity
- The surface area of the produce
- Weight, shape, thickness and size of products in the dryer
- The biological characteristics of the products like skin, bound moisture, etc.

Solar dryer heats and removes moisture from products while preserving the nutrients and quality. The overall processes involve heat transfer by radiation from the direct sunlight, by convection from the atmosphere to the wet product, by conduction from product's surface to the product interior and/or by conduction from the drying trays inside the drying chamber that is in contact with the products.

Kumar *et al.* (2016) deliberated on three types of solar dryers namely; direct, indirect and hybrid, in terms of their present status, design, development and performance evaluation. Solar dryers can be categorized into different types based on how solar radiation is utilized in the drying process. The first classification is the direct type, where solar radiation directly reaches the products undergoing drying. In this setup, the products are exposed to the sun's rays, harnessing its heat to facilitate the drying process. On the other hand, the indirect type of solar dryers functions differently. Here, the solar radiation is not directly

incident on the products but is instead directed towards a separate solar collector. The solar collector absorbs the radiation and converts it into heat energy. This heat energy is then transferred to the surrounding air within the collector. The heated air is subsequently conveyed to the drying chamber, where it interacts with the products to remove moisture and promote drying (Kumar et al., 2022).

In addition to the direct and indirect types, there is a third classification known as a hybrid solar dryer. The hybrid solar dryer combines solar energy with additional energy sources to enhance the drying process. These supplementary energy sources can include biomass, electricity, thermal storage systems, or even mechanical heat pumps (Heydari, 2022). By incorporating these alternative energy sources, the hybrid solar dryer ensures a more reliable and efficient drying process, especially in situations where solar radiation alone may be insufficient or inconsistent. The hybrid solar dryer offers flexibility and adaptability by utilizing multiple energy sources to optimize the drying conditions. It can enhance the drying performance, shorten drying time, and maintain the quality of the dried products. This approach highlights the versatility of solar drying technology, enabling it to harness the benefits of solar energy while leveraging other energy sources for enhanced efficiency and reliability (Kamarulzaman *et al.*, 2021).

The use of solar dryers as an efficient and environmentally friendly method of food preservation has grown in recent years. In this situation, a double-pass solar air collector, heat pump, and photovoltaic unit were used to build and create a new type of solar dryer that would improve the drying performance for carrot slices (Şevik, 2013). To achieve the best drying conditions, the system was created to deliver a constant drying air temperature with PID (proportional–integral–derivative) control and variable air volume. The double-pass solar air collector (DPSAC), which was used to dry the carrots, supplied the necessary thermal energy. The drying cabinet's air inlet temperature was used to control

the air velocity, which was controlled between 0.4 and 0.9 m/s. At a drying air temperature of 50 °C, it took 220 minutes for the initial moisture content of 7.76 g water/g dry matter (dry basis) to be reduced to 0.1 g water/g dry matter (dry basis) (Şevik, 2013). According to experimental findings, depending on the system's operating circumstances, the double-pass collector's thermal efficiency ranged from 60% to 78%. Furthermore, it was discovered that the system functions pleasantly in typical ambient air conditions without the requirement for the heat pump. Overall, the solar dryer system's utilization of a heat pump, photovoltaic unit, and double-pass solar air collector revealed the possibility for effective and long-lasting food preservation utilizing solar energy. The tuning of system settings to enhance the drying performance for various food products can be explored in further research (Şevik, 2013).

The utilisation of different types of solar dryers for drying various types of vegetables in different environmental conditions has been documented. In comparison to the open sun drying method, the samples obtained through solar drying were of higher quality and exhibited faster drying rates due to the enclosed chamber's effect during the drying process. Furthermore, the enclosed chamber provided protection against external factors such as dust, pests, and birds that could negatively impact the dried samples' quality. Additionally, the samples obtained through solar drying were aesthetically more pleasing than those obtained through open sun drying. The drying air temperatures typically ranged between 40 and 60°C, which helped prevent the samples from cooking in the dryer. However, it has been observed that high temperatures could lead to a decrease in sample quality, despite reducing drying time. Therefore, it is important to maintain the temperature within the range where both drying time and sample quality meet the required standards (Natarajan *et al.*, 2022).

The utilisation of dryers in developing nations can reduce post-harvest losses and substantially contribute to the availability of food in these regions. Although estimates vary, these losses are often reported to be around 40%, and in severe cases can approach 80%. Improper or delayed drying of food items such as cereal grains, pulses, tubers, meat, and fish is a significant factor contributing to these losses (Bassey, 1989; Togrul and Pehlivan, 2004).

Fadhela *et al.* (2005) used three different solar drying methods for drying sultanine grapes, namely natural convective, tunnel greenhouse and open drying. The moisture content of dried grapes was reduced from 80 to 16% within 77 h in the solar dryer, 119 h in the greenhouse dryer and 250 h in open sun drying. It was also mentioned that the dried grapes from the greenhouse dryer were superior when compared to other drying methods.

Romano *et al.* (2009) fabricated a modular solar cabinet dryer for apple and carrot drying. For this operation, various sizes and forms of apples and carrots were analysed. The moisture content of dried apples in the solar cabinet dryer was in the range of 26–85% on a wet basis. It was mentioned that the energy required to remove the moisture from the carrot and apple sample was 7428.28 and 3300.19 kJ/kg, respectively. It was also mentioned that the air to water removal from the apple and carrots was 126.93 and 928.56 m³.

Pangavhane *et al.* (2002) studied the qualitative analysis of three different dryers, namely new natural convection, open and shade dryer for grapes drying. It was observed that the shade drying of grapes took 15 days and open sun drying took only seven days, then finally solar dryer took four days for grapes drying. The drying period of the sample was reduced by 43% compared to the open sun drying method.

Eissen *et al.* (1985) developed a low-cost solar dryer for grapes drying and overcomes the grapes low quality and mass losses dried from the open sun drying method. It was mentioned that the solar dryer was possible to reduce the drying time and importantly, the quality of dried grapes sample was improved compared to the open sun drying method.

Al-Juamili *et al.* (2007) fabricated a cabinet solar dryer for apricots, beans and grapes drying with a total collector area of 2.4 m². The moisture content of dried apricots was reduced from 80 to 13% on a wet basis. It was mentioned that 25 to 30% of RH air exists from the dryer and there was no need for high-speed air inside the dryer.

Adu and Bodunde (2012) developed a tent-type solar dryer for okra drying in which the top of the dryer was covered with polythene. The final desired moisture content of okra under tent dryer and open sun drying was attained in 23 and 30 h, respectively. Compared with open sun drying, the dried products from the solar dryer were better in terms of colour, aroma, taste, texture, and overall acceptability.

Ehiem *et al.* (2009) fabricated an industrial vegetable and fruit dryer for tomato drying. It was mentioned that the thermal efficiency and drying quantity of the dryer was reported as 84% and 258.64 kg. It was also mentioned that the drying rate of a dryer was 40 g/h at RH of 35%, the average temperature for drying tomatoes was 50°C. It was reported that the drying time of the dryer was improved and it was recommended to industrial users.

Romano *et al.* (2009) fabricated the modular solar cabinet dryer for carrot drying. It was mentioned that the total solar energy fall on the collector surface and air to remove moisture from the carrot was found to be 753.2 kJ/m² and 928.56 m³. It was found that the moisture content of carrots reduced from 71 and 13% within six days. It was found that the temperature inside the cabinet dryer was negatively correlated with the humidity of air ($R^2 = 0.91$) and climatic conditions influenced the drying time.

Ogheneruona and Yusuf (2011) developed a direct type solar dryer for tapioca drying. It was observed that the mean drying air temperature was 32 °C, relative humidity was 74% and global solar radiation was 13 MJ/m² per day. It was found that the moisture content of dried tapioca decreased from 79 to 10% on a wet basis within 20 h.

Forson *et al.* (2007) experimentally investigate the mixed-mode solar dryer for cassava and other crops drying. It was determined that the moisture content of dried cassava was reduced from 67 to 17% on a wet basis within 30 to 36 h. It was found that the drying efficiency of the mixed-mode solar dryer was found to be 12.3 (partial loading of the sample) and 12.5% (fully loading sample).

Moy *et al.* (1980) fabricated three different solar dryers, namely direct, indirect and combined mode of the dryer with the attachment of two reflector mirrors. The loading capacity of a density was 7.3 kg/m³. It was reported that the direct type solar dryer with a reflector was much efficient and the mixed-mode solar dryer (MMSD) also equally efficient but slightly less than the direct type dryer and the least one was indirect mode solar drying.

Bolaji (2008) developed a cabinet dryer for drying yam chips and shelled corn. It was mentioned that the drying air temperature and the intensity of radiation were important influencing factors for the rate of moisture removal from the sweet potato samples. It was found that the liquid concentration of dried yam and shelled corn was found to be 150 and 70 kg/m³. It was reported that the moisture removed from the sample in the solar dryer was much higher compared to the open sun drying method.

Singh and Kumar (2012) developed a laboratory-type mixed-mode solar dryer and cabinet dryer for drying a sample of cylindrical-shaped potato and 16 drying kinetics curves acquired over the different drying operations. The dryer performance index with consistent

data for all examined conditions obtained a high degree of independence of processing conditions. It was mentioned that the root mean square and standard error of mixed-mode solar dryer dried potato was in the range of 0.030 to 0.036 and 0.001 to 0.003. It was also mentioned that the root mean square and standard error of cabinet dryer dried potato was in the range of 0.025 to 0.031 and 0.001 to 0.003.

Nasri and Belhamri (2018) developed an indirect type solar dryer for drying potato in three differently-shaped dryers, namely cubical, cylindrical and rectangular parallelepiped to determine the drying kinetics internal coefficient of diffusion and experimental curves in every case. It was mentioned that the effective moisture diffusivity of dried potato varied from 15.5×10^{-9} to 1.9×10^{-9} m²/s. It was also mentioned that the exponential model gave better agreement with experimental results.

Natarajan and Elavarasan (2019) developed a double slope direct type-solar dryer for potato drying. The experiment was conducted for two days. At the end of the first and second day, moisture removed from the potato sample in the solar dryer was 52.2 and 51% on a wet basis, and moisture removed from the open sun drying potato was 42.9 and 43.9% on a wet basis, respectively. It was reported that the quality of dried potato in the solar dryer was better than the open drying method.

A solar cabinet dryer comprising a solar air heater and a drying cabinet was used to dry pumpkin, green pepper, stuffed pepper, green bean, and onion in thin layers. The drying process was conducted with three different air velocities to investigate their effects on drying time. Fresh materials were also dried using natural sun drying methods. Various moisture ratio models were employed to analyse the drying curves of the products, and the models were evaluated based on their determination coefficients. The study found that drying air temperature could be increased to approximately 46°C, and the drying air velocity had a significant impact on the drying process. The drying time for the solar

drying method ranged between 30.29 and 90.43 hours for different vegetables, while it was between 48.59 and 121.81 hours for natural sun drying. The thin layer drying models satisfactorily explained the drying curves, with very high determination coefficients. These findings indicate the potential of solar cabinet dryers for efficient and effective drying of various agricultural products (Bayındırli *et al.*, 2016)

A mathematical model of direct sunlight and solar drying of some fermented dairy products (kishk) was created by Bahnasawy and Shenana in 2004. Solar radiation, heat convection, heat received or lost from the dryer bin wall, and latent heat of moisture evaporation were the major factors in the equations that described the drying system. At a variety of relative humidity levels, the model was able to forecast the drying temperatures. It can also forecast moisture loss from the product at a variety of relative humidity levels, temperatures, and air speeds.

Pangavhen *et al.* (2002) presented a novel convection solar dryer design, development, and performance testing. The solar dryer was specifically designed to achieve optimal dehydration temperatures ranging from 50 to 55°C, suitable for drying grapes, as well as various fruits and vegetables. The system effectively facilitated the natural flow of hot air, leading to enhanced drying rates. The drying airflow rate was found to increase naturally with ambient temperature due to thermal buoyancy within the collector. The collector efficiencies varied between 26% for a mass flow rate of 0.0126 kg/s of air and 65% for a mass flow rate of 0.0246 kg/s, demonstrating its capability to heat the drying air adequately. Compared to open sun drying methods, the drying time for grapes was significantly reduced by 43%. The findings from this study highlight the effectiveness of the proposed convection solar dryer in achieving optimal drying conditions and significantly improving the drying process for grapes and potentially other agricultural products.

In a separate study, Sebaili *et al.* (2002) investigated an indirect type natural convection solar dryer for various crops, including grapes, figs, onions, apples, tomatoes, and green peas. The investigation involved both experimental and theoretical analyses. Drying constants specific to the selected crops were obtained from experimental results and correlated with the drying product temperature. The study proposed a linear correlation between the drying constant and product temperature, providing valuable empirical data for the crops examined. Additionally, the empirical constants of Henderson's equation, which were not previously available in the literature, were derived for all the materials studied. The proposed empirical correlation demonstrated its effectiveness in describing the drying kinetics of the selected crops.

In a study conducted by Gallali *et al.* (2000), the results of an investigation on dried fruits and vegetables, including grapes, figs, tomatoes, and onions, were reported. The investigation involved chemical analysis of various parameters such as vitamin C, total reducing sugars, acidity, moisture, and ash content. Additionally, sensory evaluation data, including colour, flavour, and texture, were considered. A comparison was made between products dried using solar dryers and those dried under natural sun drying conditions. The findings of the study indicated that the utilization of solar dryers offered several advantages over natural sun drying, particularly in terms of drying time.

This research provides valuable insights into the quality and sensory attributes of dried fruits and vegetables, highlighting the benefits of employing solar dryers as an efficient and time-saving alternative to natural sun drying.

An overview of current evaluation techniques and the criteria often taken into account for evaluating solar food dryers was presented by Leon *et al.* (2002). These factors can be divided into four categories:

(i) dryer physical characteristics; (ii) dryer thermal performance; (iii) dried product quality; and (iv) dryer price and payback period.

2.3 Forced Convection Solar Dryers

Forced convection solar dryers can be utilised successfully. However, to operate the fans, they need electricity, which is regrettably absent in many rural locations. Due to their extremely low incomes, potential dryer users are unable to afford energy even when it is available.

Yao *et al.* (2022) discussed the advantages of using a fan or air blower as a supportive energy source in comparison to a chimney in practical drying activities, particularly for distributed-type solar dryers. While they acknowledged that a fan relies on non-renewable energies, they highlighted the fan's superior capability in generating pressure difference compared to a chimney. Specifically, they mentioned that a fan can generate pressure differences ranging from 100 to 500 Pascal (Pa), whereas a chimney typically produces only 0.5 Pa. Due to this significant disparity in pressure difference, the active mode, which involves the use of a fan, is preferred over the passive mode (using a chimney) in practical drying activities. This preference stems from several advantages associated with the active mode, including higher efficiency, effectiveness, and controllability.

They explained that the higher drying fluid flow resulting from the use of a fan enhances the moisture carrying capability of the system. Consequently, this increases the drying rate, as the drying materials are exposed to a higher airflow carrying capacity. Additionally, the active mode helps to minimize the exposure time of the drying materials to the high temperature of the drying fluid, which is especially beneficial in high-temperature drying scenarios. By utilising a fan, it becomes possible to maintain a stable airflow rate within the drying chamber, which contributes to regulating the temperature during the drying

process. This controlled airflow helps to stabilise and maintain the desired temperature conditions within the chamber.

The forced drying airflow circulation facilitated by the fan is particularly advantageous when dealing with larger drying materials. The increased airflow circulation ensures that the drying treatment is effectively applied to the entirety of the larger materials, contributing to more efficient and thorough drying.

Mohammadhossein *et al.* (2022) investigated a new design of forced convection solar dryer. The metal of the sewing machine bobbin and also pipes containing PCM (phase change material) were used as a barrier on the absorber plate. The results showed that using bobbin absorber plate and PCM in the dryer improves the average collector efficiency and the average dryer efficiency by 28.5% and 52.1% respectively compared to flat absorber plate without PCM, 26.4% and 36.3% compared to bobbin absorber plate without PCM, and 12.2% and 12.9% compared with flat absorber plate with PCM.

Mohanraj and Chandrasekar (2008) fabricated and tested an indirect forced convection solar drier integrated with sensible heat storage material and tested it for copra drying. It reduced moisture content (wet basis) from 52% to 7.8% and 9.5% in 66 h for trays at bottom and top respectively. System pick-up efficiency varied between 45% and 13%. Copra obtained was graded as 76% milling copra grade 1 (MCG1), 18% MCG2 and 6% MCG3. Specific moisture extraction rate was estimated to be 0.84 kg/kWh. In sun drying, moisture content reduced from 52.3% (wet basis) to about 9.2% in 7 days. Copra obtained was graded as 53% MCG1, 24% MCG2 and 23% MCG3.

Tiwari *et al.* (2009) developed a mathematical model of greenhouse fish (prawn) drying to predict the moisture evaporation, fish surface temperature and drying temperature under natural and forced convection modes. The average fish surface temperature under natural

and forced convection was 46.85 °C and 45.6 °C, respectively. The average green-house dryer temperature under natural and forced convection was reported as 48.53 °C and 46.4 °C, respectively. The developed models were validated with values obtained from experimentation. The final desired moisture content under natural and forced convection modes were attained in 12 h and 9 h, respectively. The instantaneous exergy efficiency of passive and active modes was 0.287% and 0.133%, respectively. The study concluded that overall performance was better in forced convection mode (Das and Tiwari 2008).

Pangavhane and Sawhney (2002) reviewed different types of solar dryers for grapes. Solar drying of grapes has proved that it was economically and technically feasible. It was reported that the forced convective dryer with auxiliary heat was recommended for better control and reliability for large-scale grape drying.

McDoom *et al.* (1999) studied forced convection solar crop dryer for cocoa beans and coconut drying. It was found that the moisture content of dried cocoa beans decreased from 98 to 8% on a dry basis within 18 h, where it was about 12 h by using the heater. It was reported that there was 29–31% energy saving by reuse of hot air and varying the degree of venting.

Hossain and Bala (2007) studied Mixed Mode Forced Convection Solar Tunnel Dryer (MMFCSTD) for numerical and experimental analysis of red and green chillies drying. It was observed that the moisture content of red chilli in the solar tunnel dryer was reduced from 2.85 to 0.05 kg/kg on a dry basis within 20 h, whereas open drying was reduced from 0.40 to 0.09 kg/kg on a dry basis within 32 h. It was also observed that the moisture content of green chilli in the solar tunnel dryer was reduced from 7.6 to 0.06 kg/kg on a dry basis within 22 h, whereas open drying was reduced from 0.70 to 0.19 kg/kg on a dry basis within 35 h.

Jangde *et al.* (2021) reviewed different types of solar dryers for chillies, wheat, maize, corn, oil seeds, paddy, pulses, etc. Solar drying of agricultural products has proved that it was economically and technically feasible. It was reported that the forced convective dryer with auxiliary heat was recommended for better control and reliability.

Elavarasan *et al.* (2021) used a solar dryer for ivy gourd drying. It was observed that the proposed drying kinetics model was in good agreement with the experimental result to analysis the drying curve of ivy gourd. It was also observed that the maximum efficiency of exergy of forced and natural convection solar dryers was found to be 70 and 62%. The final desired moisture content under open, natural and forced convection modes were attained in 11, 9, and 7 h, respectively. The moisture diffusivity of dried ivy gourd was reported as 5.85×10^{-8} for forced convection, 4.28×10^{-9} for natural convection and 9.23×10^{-10} m²/s for open sun drying. The activation energy of dried ivy gourd was 24.81 for forced convection, 28.18 for natural convection and 33.34 kJ/mol for open sun drying.

Muazu *et al.* (2012) designed and developed a forced convection vegetable dryer for okra and tomato drying with a thermal energy storehouse. It was observed that the initial moisture content of okra was 72% (6 mm) and 70% (3 mm) decreased to 19% and 21% on a wet basis within 5 and 5.4 h. The mean rate of moisture evaporation of okra was found to be 8.99×10^{-4} kg/s. It was reported that the proximate analysis of okra remains unchanged before and after okra drying.

Sarsavadia (2007) developed a solar-assisted forced convection dryer (SAFCD) for onions drying in different air velocities and drying air temperatures. The moisture content of the onion sample decreased from 86 to 7% on a wet basis. It was found that the energy required per unit of mass of moisture removed was found to be 12.04 to 38.77 MJ/kg with recirculation of drying air, and the energy contribution of a blower, air and electric heater was in the range of 8.6 to 16.3%, 24.5 to 44.5% and 40.2 to 66.9%. It was also found that

the energy required per unit of mass of moisture removed was found to be 23.55 to 62.18 MJ/kg for without recirculation of drying air, and the energy contribution of a blower, air and electric heater was in the range of 11.2 to 37.2%, 33.6 to 62.6%, and 22.4 to 40.9%.

Khan *et al.* (2011) developed a forced convective solar dryer for potato drying, and the dryer plate temperature was recorded as 110 °C, dryer loaded with 12,000 g of blanched potato chips. It was mentioned that the moisture content of dried potato was decreased from 89.75 to 6.95% on a wet basis within 5 h in a solar dryer at the same time open sun drying under shade removed only 33.7% of moisture content.

2.4 Overview on Thermal Energy Storage

Thermal energy storage (TES) is a technology that stores thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation (Sarbu and Sebarchievici, 2018). TES is becoming increasingly important for electricity storage in combination with concentrating solar power (CSP) plants where solar heat can be stored for electricity production when sunlight is scarce. Solar thermal systems, unlike photovoltaic systems with striving efficiencies, are industrially mature and utilize a significant portion of the Sun's thermal energy during the day, but they lack enough (thermal) backup to continue operating during the low or no solar radiation hours.

The design of efficient and cost-effective TES systems has been investigated (Joseph *et al.*, 2016), but few solar thermal plants in the world have employed TES at a large scale. TES not only reduces the discrepancy between the demand and supply by conserving energy, but also improves the performance and thermal reliability of the system. Figure 1 displays the primary forms of thermal energy storage for solar energy.

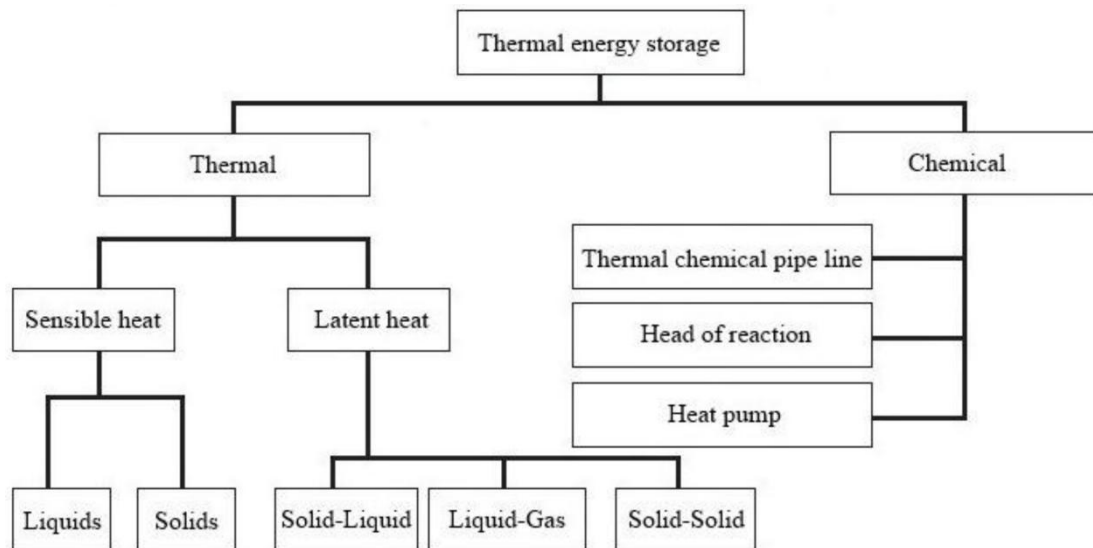


Figure 1: Types of solar thermal energy storage (TES).

(Sarbu and Sebarchievici, 2018)

An energy storage system can be described in terms of the following characteristics (International Renewable Energy Agency (IRENA), International Energy Agency: Paris, France, 2013):

1. **Capacity:** The amount of energy that can be stored inside an energy storage system is referred to as the system's capacity. It relies on elements like the system size, the medium used, and the storage process. How much energy may be saved for subsequent use depends on the capacity.
2. **Power:** Power describes how rapidly the system can charge or discharge the stored energy. It talks about how quickly energy may be put into or taken out of the storage system. The system's capacity to supply electricity at a desired rate is determined by its power rating.
3. **Efficiency:** By contrasting the energy delivered to the user with the energy needed to charge the system, efficiency assesses the performance of the energy storage system. Energy losses that happen during storage time and charging/discharging cycles are

taken into account. Lower energy loss throughout these operations is indicated by higher efficiency.

4. **Storage period:** The amount of time that the system can store energy is referred to as the storage period. It covers a variety of durations, including hours, days, weeks, and even seasonal storage, and spans from hours to months. How long the energy can be held before it needs to be consumed depends on the storage time.
5. **Charge and discharge time:** The amount of time needed to fully charge or discharge an energy storage device is known as the charge and discharge time. It shows how soon the system can refuel or run out of fuel. For applications requiring a quick energy supply or quick rechargeability, the charge and discharge time is a crucial consideration.
6. **Cost:** Energy storage system costs can be analysed from two different angles. The price may depend on the system's power, expressed in euros per kilowatt-hour (kWh), or its capacity, expressed in euros per kilowatt (kW). The cost is determined by the storage device's estimated lifetime in terms of the number of charge/discharge cycles it can withstand, as well as its capital and operating costs.

A thorough evaluation and comparison of various energy storage systems that takes into consideration aspects like their capacity, power rating, efficiency, storage period, charge and discharge time, and cost is possible thanks to an understanding of these features.

2.4.1 Methods of thermal energy storage

Utilising a variety of methods appropriate for various temperature ranges, thermal energy storage (TES) can be accomplished. From 40 °C to over 400 °C, there are three widely used TES approaches that can be utilised: sensible heat, latent heat associated with PCMs,

and thermochemical heat storage associated with chemical reactions (De Garcia and Cabeza, 2015).

1. Sensible heat storage (SHS) : Using this method, thermal energy is stored by increasing or decreasing the temperature of a storage medium, such as molten salts, water, rock, or a storage media made of rock without undergoing a phase change. By taking the heat out of the medium and lowering its temperature, we may release the stored energy.

Water is the most well-liked, cheapest and widely used heat storage medium, and it has many industrial and domestic uses. For typically large-scale applications, underground storage of sensible heat in both liquid and solid mediums is also utilised. SHS has two key benefits: it is inexpensive and doesn't come with the risks that come with using harmful ingredients.

Using solid objects as heat storage media, such as rocks or bricks, is another method of sensible heat storage. Due to their high thermal mass, these substances can easily absorb and store heat. The materials are heated and serve as a thermal reservoir when there is extra heat available. When heat is needed, the accumulated energy is released by returning it to the environment.

When charging and discharging, the SHS system makes use of the heat capacity and temperature variation of the storage medium. The specific heat of the medium, the temperature change, and the quantity of storage material all affect how much heat is stored (Kumar and Shukla, 2015).

$$Q_{hs} = m_{hs}C_{hs}dT = mC_{hs}(t_f - t_i) \text{ ----- (1)}$$

Under the sensible heat storage technique, various materials can be used as storage media to store thermal energy by changing their temperature. Some commonly employed materials for sensible heat storage include:

- **Water:** Water has a high specific heat capacity, making it an efficient medium for storing thermal energy. It is widely used in thermal energy storage systems, such as water tanks or reservoirs. Using water tanks or reservoirs as a means of sensible heat storage is one example. Water can store a substantial quantity of thermal energy due to its high specific heat capacity. For instance, sunlight is captured and used in solar thermal systems to warm water kept in insulated tanks. When solar energy is not available, such as at night or on overcast days, the heated water can be used for household hot water or space heating.

To examine the performance of the compressed-air energy storage (CAES) system with TES, a pilot plant was built that uses water as the working medium for thermal energy storage. An average energy efficiency of 22.6% per round trip was attained. A thorough examination of a specific test was conducted to investigate the key variables influencing the system. The amount of electric energy used by the compressor during the charging process was 1375 kWh, and the air pressure inside the storage tank increased from 3.36 MPa to 9.34 MPa.

A well-known approach for thermal energy storage is the use of hot-water tanks. Hot-water tanks use solar energy and co-generation (i.e., heat and power) energy supply systems to reduce the amount of energy used in water heating systems. Modern experiments have demonstrated that water tank storage is a financially viable choice for storing goods and that it can be made even more efficient by guaranteeing ideal water stratification and strong thermal insulation. Research and development (R&D) activities now concentrate, for instance, on an optimized system integration and an evacuated super-insulation with a thermal conductivity of 0.01 W/(mK) at 90 °C and 0.1 mbar. Figure 2 depicts an instance of a common system that makes use of a water tank.

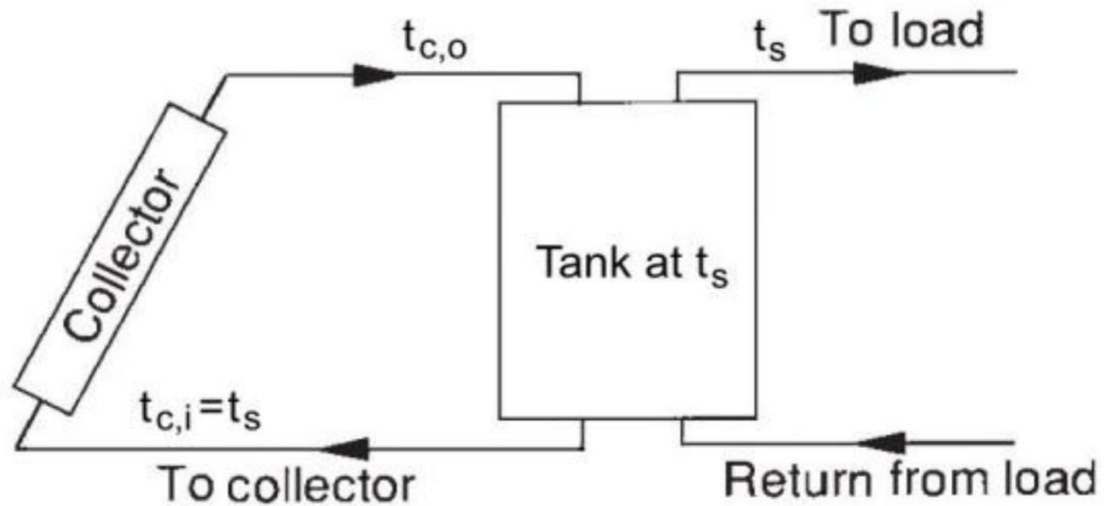


Figure 2: A typical system using water tank storage.

(Sarbu and Sebarchievici, 2018)

- **Rocks and Gravel:** High-density rocks, such as basalt or granite, and gravel are used as storage media in packed bed systems. These materials have good thermal conductivity and can retain heat effectively.

A pebble-bed storage unit is shown in Figure 3 (Sarbu and Sebarchievici, 2018). In operation, flow is maintained through the bed in one direction during addition of heat (usually downward) and in the opposite direction during removal of heat. Note that heat cannot be added and removed at the same time; this is in contrast to water storage systems, where simultaneous addition to and removal from storage is possible.

A packed-bed storage unit's high level of stratification is one of its main advantages. The stones near the entry are heated, while the pebbles near the exit are left at their original temperature, and the air temperature at the exit is still quite close to the temperature of the initial bed. A temperature front moves through the bed as time goes on. The temperature of the bed is constant while it is completely charged.

It is uncommon for a solar heating system with a packed bed to maintain a constant input temperature. A changeable collector outlet temperature is produced during the day by the

fluctuating solar radiation, the ambient temperature, the collector inlet temperature, load needs, and other time-dependent variables.

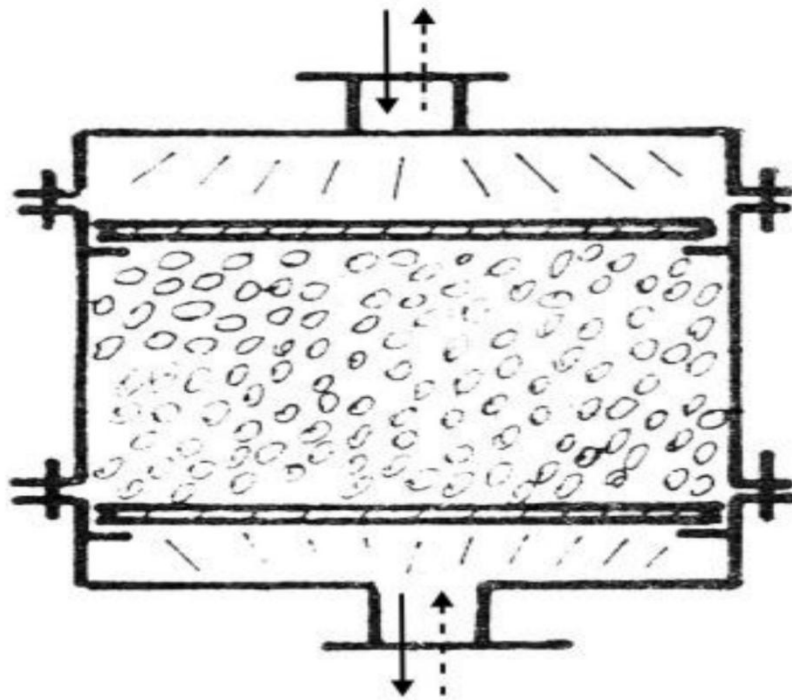


Figure 3: Pebble-bed storage system.

(Sarbu and Sebarchievici, 2018)

- **Concrete:** Concrete has a moderate heat capacity and is commonly used in building structures. It can be integrated into the building envelope or floors to act as a thermal mass for heat storage.
- **Bricks:** Bricks are another material used for sensible heat storage due to their ability to absorb and release heat. They can be incorporated into building walls or as part of heat storage units.
- **Metal Alloys:** Certain metal alloys, such as aluminium alloys, exhibit good thermal conductivity and can be used as heat storage materials. They can be shaped into containers or modules for efficient heat storage and transfer.

2. Latent heat storage (LHS): In this method, thermal energy is stored by transitioning a material from one phase to another, such as from solid to liquid or from liquid to gas. Due to the fact that a large quantity of energy is lost or absorbed during the phase shift, this technique enables a higher energy storage density than sensible heat storage (Cabeza *et al.*, 2017).

Due to their ability to release or absorb energy with a change in physical state, LHS materials are also referred to as PCMs. In the case of LHS, the volume decreases as the energy storage density rises. The heat is primarily retained throughout the phase-change process (at a relatively constant temperature), and it is closely related to the substance's latent heat. With the benefits of high energy storage density and isothermal storage, utilising an LHS system with PCMs is a useful technique to store thermal energy (Sarbu and Sebarchievici, 2018).

The main advantage of using LHS over SHS is their capacity of storing heat at almost similar temperature range. Initially, these materials act like SHS materials in that the temperature rises linearly with the system enthalpy; however, later, heat is absorbed or release at almost constant temperature with a change in physical state.

Properties of Phase Change Materials (PCMs) PCMs have been utilized in thermal applications for several decades. These materials possess specific characteristics and properties that make them suitable for their intended use.

- Thermophysical properties of PCMs include high latent heat of transition and thermal conductivity, as well as high density and minimal volume variations during phase transition, which contribute to minimizing storage volume requirements.
- PCMs should exhibit desirable kinetic and chemical properties. Supercooling, the phenomenon of cooling below the phase transition temperature without undergoing

the transition, should be limited to a few degrees. PCMs should also demonstrate long-term chemical stability, compatibility with construction materials, non-toxicity, and no fire hazards.

In addition to these intrinsic properties, economic advantages play a crucial role. PCMs should be cost-effective and readily available on a large scale to ensure their practical viability.

Latent heat storage (LHS) materials can be broadly classified based on their physical transformation for heat absorption and desorption capabilities. Figure 4 illustrates the wide classification of solid-liquid PCMs, further categorized into organic, inorganic, and eutectic materials. PCMs are grouped based on their nature, such as paraffins, fatty acids, salt hydrates, among others (Liu *et al.*, 2012).

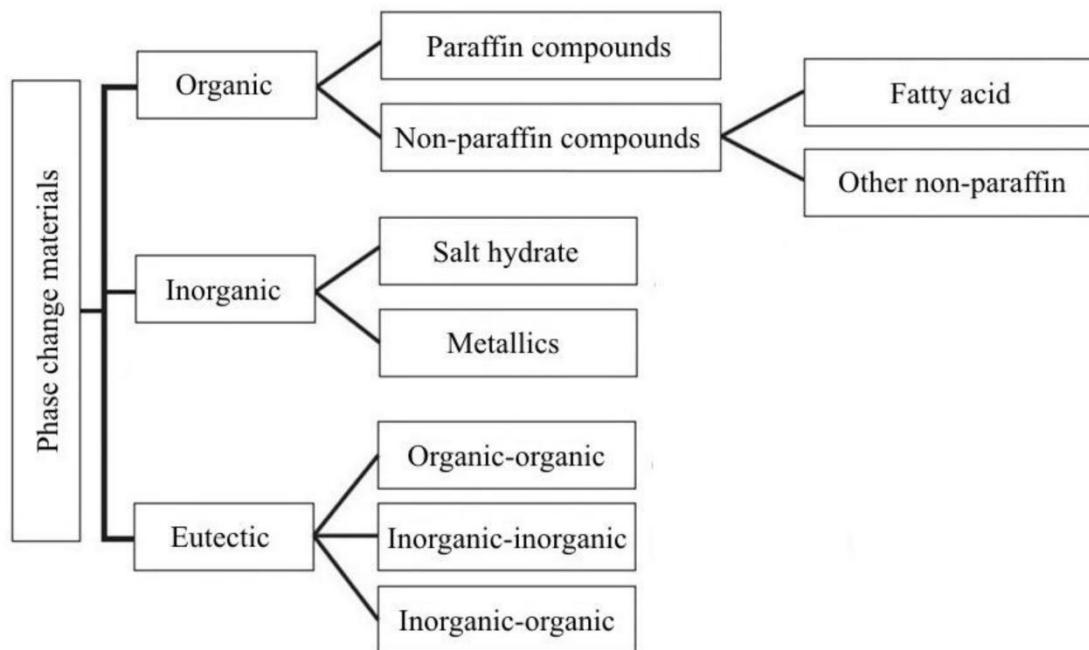


Figure 4: Classification of phase-change materials.

(Sharma et al., 2009)

The thermal performance of a phase change material called graphene reinforced paraffin wax (GrPW-PCM) has been investigated for its suitability in thermal energy storage applications. To ensure the uniform dispersion of graphene within the paraffin wax, a stability test was conducted. Additionally, scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and thermal conductivity measurements were utilized to characterize the microstructure, chemical structure, and thermal properties.

Four different samples of GrPW-NC phase change material (PCM) were prepared, each containing a varying low mass fraction of graphene ranging from 0.0 to 2.0 wt.%. Among these samples, the best thermal conductivity performance was observed in the 2.0 wt.% GrPW-PCM nanocomposites. This particular composition exhibited a remarkable improvement of 66.15% in thermal conductivity when compared to pure paraffin PCM (Krishna *et al.*, 2019).

There are disadvantages associated with the use of chemical phase change materials (PCMs) in solar dryers. These include the need for careful design of the storage boxes, the degradation of stored food after multiple freeze/melt cycles, low thermal diffusivity, and the potential contamination of food materials due to even minor PCM leakage. However, these limitations can be overcome by utilizing natural energy storage materials in solar dryers (Mugi *et al.*, 2022).

3. Thermochemical storage: In this method, chemical reactions that emit or absorb heat are used to store thermal energy. The method uses two components that may reversibly react with one another, like metal oxides, to either store or release heat. (Fernández *et al.*, 2018).

Figure 5 below explains the various methods of thermal energy storage which includes: sensible heat, latent heat and thermochemical reactions.

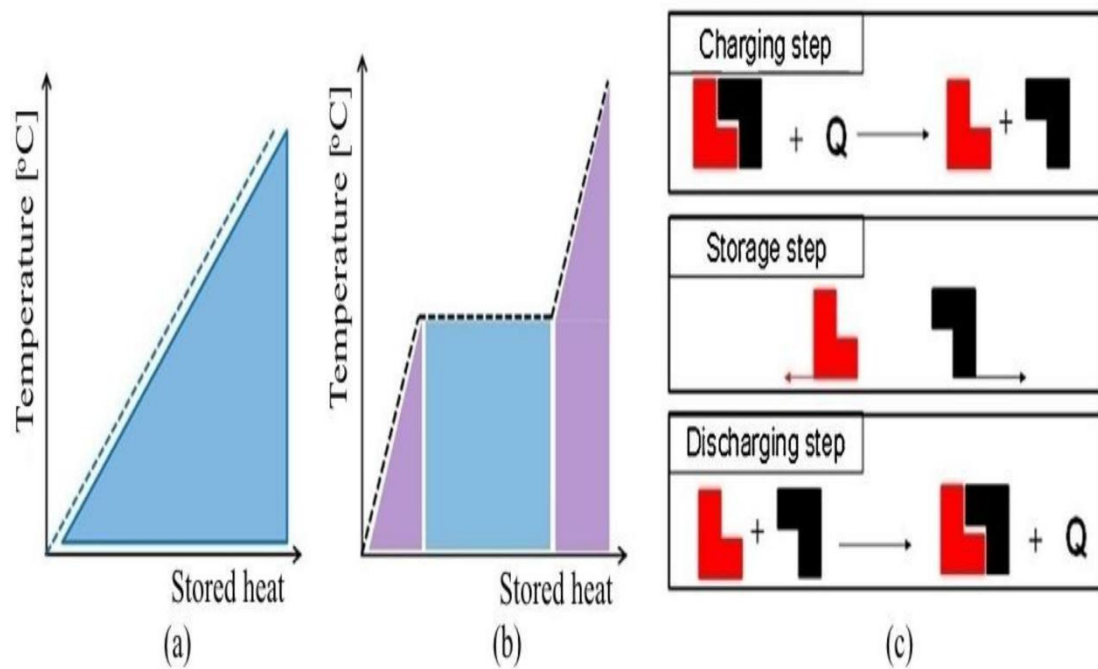


Figure 5: Methods of thermal energy storage: (a) sensible heat; (b) latent heat; (c) thermochemical reactions.

(De Garcia and Cabeza, 2015).

Figure 6 below shows the flow diagram of a drying process.

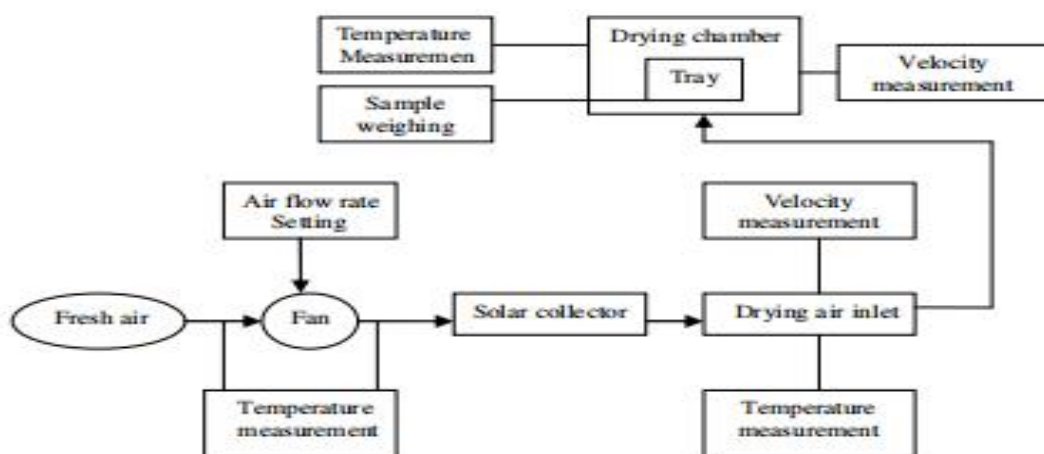


Figure 6: Flow diagram of drying process.

(Gatea, 2010)

Figure 7 below describes the sections of a typical solar drying system.

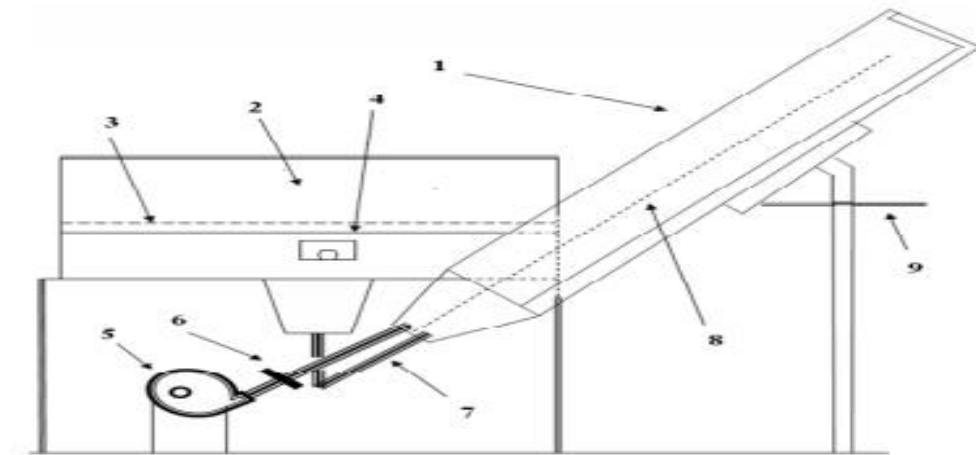


Figure 7: Solar drying system.

Section of the solar drying system: 1. Solar collector. 2. Drying chamber. 3. Drying tray. 4. Thermostat temperature. 5. Air blower. 6. Air valve. 7. Connecting pipes. 8. Absorption plates of two air passes. 9. Slide rule.

(Gatea, 2010)

CHAPTER THREE

3.0 MATERIALS AND METHODOLOGY

3.1 Materials Used for Construction

The following materials were used for the construction of the forced convection solar cabinet dryer:

- Plywood: It is used for the solar thermal collector box.
- Aluminium: it is used as the solar thermal absorber plate.
- Transparent glass: It is used as the solar collector cover and to reduce losses from the topside of the collector.
- Mild steel: It is used in the construction of the solar collector box and its stand frame.
- Fibre lagging material: It is used as insulator in order to minimise heat loss to the surroundings
- Black paint: It is applied to the solar absorber in order to increase solar absorption.
- Granite: it is used as the thermal energy storage material.

3.1.1 Properties of materials to be used for construction

Materials are chosen based on their specific application and inherent properties. The following materials were used for the construction of the forced convection solar dryer.

Table 1 shows some selected properties of some of the materials to be used for construction.

Table 1: Selected material properties

| Material | Modulus Of Elasticity E, GPa | Relative Density | Ultimate Strength MPa |
|-----------------|---|-------------------------|----------------------------------|
| Aluminium | 70 | 2.7 | 250 |
| Mild Steel | 210 | 7.8 | 400 |
| Glass | 50 – 90 | 2 – 2.6 | 50(Compression) |
| Plywood | 7 - 8.6 | 0.4 - 0.6 | 31.0 - 41.4 |

3.2 Methods

3.2.1 Basic theory

The dryer's dimensions were established by assessing the amount of heat needed to eliminate the moisture from a specific quantity of damp produce, ensuring it reaches the optimal moisture content for the safe preservation of the produce. The **mass of water** (M_w) to be extracted during the drying process is calculated using the expression provided by Pardhi et Bhagoria (2013) and Akoy et al. (2012).

$$M_w = \frac{M_c (m_i - m_f)}{(100 - m_f)} \quad \text{---- (2)}$$

where M_c , mass of the produce to be dried (kg), and m_i and m_f , the initial and desired final moisture content (wb).

Drying efficiency is a measure of the overall effectiveness of the drying system. It generally depends on the mass of water evaporated, latent heat of evaporation, the surface area of the collector, and Instantaneous flux incident on a tilted surface. It is defined as the ratio of energy required to evaporate moisture from food products by supplementing heated air.

$$\eta_{thermal} = \frac{m_{WT} \times L}{A_c \times I} \quad \text{----- (3)}$$

where m_{WT} = mass of water evaporated

L = latent heat of evaporation

A_c = area of the solar collector

I = instantaneous flux incident on the tilted collector surface (Chauhan *et al.*, 2017)

The **amount of useful heat that can be harnessed from solar collectors** can be calculated using heat removal factor (F_R) and incident solar radiation (I_t). Q_u value is dependent on the material of construction used for collector, as well as the surface area, as suggested by Baradey *et al.* (2016)

$$Q_u = F_R A_c [I_t (\tau \alpha) - U_L (T_t - T_a)] \quad \text{----- (4).}$$

where A_c is the solar collector area (m^2)

I_t = incident insolation (W/m^2)

U_L = overall heat loss by the collector (W/K)

α = solar absorptance

τ = transmittance of absorber plate

T_c = collector temperature (K)

T_a = ambient air temperature (K)

The **heat gained by air (Q_g)** (Bolaji, 2011; Sevik, 2014) is given by:

$$Q_g = \dot{m}_a C_{pa} (T_c - T_a) \quad \text{-----}(5)$$

where \dot{m}_a is mass flow rate of air though the dryer per unit time (kg/s) and C_{pa} the specific heat capacity of air (kJ/kg K)

The **collector heat removal factor (F_R)** is (Bolaji, 2011; Alta *et al.*, 2010)

$$F_R = \frac{Q_g}{Q_U} = \frac{\dot{m}_a C_{pa} (T_c - T_a)}{I_c A_c} \quad \text{-----}(6)$$

The **heat energy (Q_m) required to evaporate moisture from the product** was obtained though the relation (Karlekar, 1982)

$$Q_m = M_p C_p dT + M_w L \quad \text{-----}(7)$$

where M_p is the mass of the product to be dried (kg)

C_p is its specific heat

M_w , mass of water removed (kg)

dT , change in temperature in °C

$L = 2256$ kJ/kg, the latent heat of vaporisation of water (Liley, 1997)

Drying rate (DR) should be proportional to the difference in moisture content between the material to be dried and equilibrium moisture content (M_e) and calculated as

$$DR = \frac{dM}{dt} = -k(M_t - M_e) \quad (\text{Hegazy, 1999}) \text{ -----}(8)$$

The quantity of heat stored (kJ), Q_{hs} , by the heat storage media can be calculated by using the relation (Bal *et al.*, 2011)

$$Q_{hs} = M_{hs}C_{hs}dT \text{ ----- (9)}$$

where M_{hs} is mass of heat storage medium (kg)

C_{hs} , specific heat of the heat storage medium (kJ/kgK)

dT the difference in temperature level between which the storage operates.

3.2.2 Design calculations

The following assumptions were made in the design of the forced convection solar cabinet dryer:

- i. The system is assumed to operate under steady-state conditions
- ii. The ambient temperature is assumed to remain constant during the drying process
- iii. The dryer's thermal energy storage system is assumed to have no heat losses, ensuring all stored heat is available for drying
- iv. The airflow inside the drying chamber is assumed to be uniform

The heat energy (Q_m) required to evaporate moisture from the product

The dryer is designed to be able to dry food crops such as plantain and pepper.

The heat available to the dryer is used to dry the products. Actually the heat is used for two purposes.

i. To raise the temperature of the products.

ii. To remove the moisture.

i. Heat required to raise the temperature of the product

$$Q_1 = M_p C_p dT \text{ -----(10)}$$

where M_p = mass of the product

C_p = specific heat capacity

dT = temperature change

ii. Heat required to remove the moisture

$$Q_2 = M_w L \text{ -----(11)}$$

where M_w = amount of moisture to be removed

L = latent heat of vaporisation

In carrying out calculations, the ambient temperature was assumed to be 30°C, while the specific heat capacity values, C_p , and the optimal drying temperature values, T_2 , were obtained from appropriate literature.

For pepper

Heat required to raise the temperature

Let mass of the product = 1 kg

C_p for pepper = 3.8 kJ/kg.K

T_1 = 30°C

$T_2 = 50^\circ\text{C}$ (Getahun *et al.*, 2021).

Hence heat required for 1kg of pepper is

$$Q_1 = 1 \times 3.8 \times (50 - 30) = 76 \text{ kJ}$$

Heat required to remove moisture

Mass of water removed, $M_w = M(m_i - m_f)/(100 - m_f)$

m_i = Initial moisture content = 90% (Refrigerating, 2006)

m_f = Final moisture content = 12% (Getahun *et al.*, 2021)

Mass of water removed (M_w) = $(90 - 12) / (100 - 12) \times 1 = 0.89 \text{ kg}$

Therefore,

$$Q_2 = M_w L$$

L = latent heat of vaporisation (water) = $2.26 \times 10^3 \text{ kJ/kg}$ (Datt, 2011)

$$Q_2 = 0.89 \times 2.26 \times 10^3 \text{ kJ}$$

$$= 2011.4 \text{ kJ}$$

Total heat required = $Q_1 + Q_2 = 76 + 2011.4$

$$= 2087.4 \text{ kJ}$$

For Plantain

Heat required to raise the temperature

Let mass of the product = 1 kg

C_p of plantain = 2.61 kJ/kg.K (Essien, 2016)

$T_1 = 30^\circ\text{C}$

$T_2 = 70^\circ\text{C}$ (Oforkansi & Oduola, 2016).

Hence heat required for 1kg of plantain is

$$Q_1 = 1 \times 2.61 \times (70 - 30) = 104.4 \text{ kJ}$$

Heat required to remove moisture

mass of water removed, $M_w = M(m_i - m_f)/(100 - m_f)$

m_i = Initial moisture content = 60% (Muritala *et al.*, 2022)

m_f = Final moisture content = 15% (Muritala *et al.*, 2022)

Mass of water removed (M_w) = $(60 - 15) / (100 - 15) \times 1 = 0.53 \text{ kg}$

Therefore,

$$Q_2 = M_w L$$

L = latent heat of vaporisation (water) = $2.26 \times 10^3 \text{ kJ/kg}$ (Datt, 2011)

$$Q_2 = 0.53 \times 2.26 \times 10^3 \text{ kJ}$$

$$= 1197.4 \text{ kJ}$$

$$\text{Total heat required} = Q_1 + Q_2 = 104.4 + 1197.4$$

$$= 1301.8 \text{ kJ}$$

For Okra

Heat required to raise the temperature

Let mass of the product = 1 kg

C_p of okra = 1.77 kJ/kg.K (Obomeghei *et al.*, 2022)

$$T_1 = 30^\circ\text{C}$$

$$T_2 = 65^\circ\text{C} \text{ (Pendre } et al., 2011).$$

Hence heat required for 1kg of okra is

$$Q_1 = 1 \times 1.77 \times (60 - 30) = 53.1 \text{ kJ}$$

Heat required to remove moisture

$$\text{mass of water removed, } M_w = M(m_i - m_f)/(100 - m_f)$$

$$m_i = \text{Initial moisture content} = 90\% \text{ (Nandi *et al.*, 2020)}$$

$$m_f = \text{Final moisture content} = 10\%$$

$$\text{Mass of water removed (} M_w \text{)} = (90 - 10) / (100 - 10) \times 1 = 0.89 \text{ kg}$$

Therefore,

$$Q_2 = M_w L$$

$$L = \text{latent heat of vaporisation (water)} = 2.26 \times 10^3 \text{ kJ/kg} \quad (\text{Datt, 2011})$$

$$Q_2 = 0.89 \times 2.26 \times 10^3 \text{ kJ}$$

$$= 2011.4 \text{ kJ}$$

$$\text{Total heat required} = Q_1 + Q_2 = 53.1 + 2011.4$$

$$= 2064.5 \text{ kJ}$$

For Cassava

Heat required to raise the temperature

Let mass of the product = 1 kg

$$C_p \text{ of cassava} = 3.90 \text{ kJ/kg.K} \text{ (Sanni *et al.*, 2016)}$$

$$T_1 = 30^\circ\text{C}$$

$$T_2 = 65^\circ\text{C}.$$

Hence heat required for 1kg of cassava is

$$Q_1 = 1 \times 3.90 \times (65 - 30) = 136.5 \text{ kJ}$$

Heat required to remove moisture

$$\text{mass of water removed, } M_w = M(m_i - m_f)/(100 - m_f)$$

$$m_i = \text{Initial moisture content} = 70\%$$

$$m_f = \text{Final moisture content} = 12\% \quad (\text{Alonso } et \text{ al.}, 2012)$$

$$\text{Mass of water removed } (M_w) = (70 - 12) / (100 - 12) \times 1 = 0.66 \text{ kg}$$

Therefore,

$$Q_2 = M_w L$$

$$L = \text{latent heat of vaporisation (water)} = 2.26 \times 10^3 \text{ kJ/kg} \quad (\text{Datt, 2011})$$

$$Q_2 = 0.66 \times 2.26 \times 10^3 \text{ kJ}$$

$$= 1491.6 \text{ kJ}$$

$$\text{Total heat required} = Q_1 + Q_2 = 136.5 + 1491.6$$

$$= 1628.1 \text{ kJ}$$

$$\approx 1628 \text{ KJ}$$

Table 2 below shows the values for the crops including the total heat required to dry them.

Table 2: Heat required to dry the crops

| Crop | C_p (kJ/kg.K) | Optimal drying temp ($^{\circ}\text{C}$) | Initial moisture content, m_i (%) | Final moisture content, m_f (%) | Q_1 (kJ) | Q_2 (kJ) | Total Q (kJ) |
|----------|--------------------|--|--|--|---------------|------------|-----------------|
| Plantain | 2.61 | 70 | 60 | 15 | 104.4 | 1197.4 | 1301.8 |
| Pepper | 3.80 | 50 | 90 | 12 | 76 | 2011.4 | 2087.4 |
| Okra | 1.77 | 60 | 90 | 10 | 53.1 | 2011.4 | 2064.5 |
| Cassava | 3.90 | 65 | 70 | 12 | 136.5 | 1491.6 | 1628.1 |

Since pepper requires the most heat for drying, this design would be based on this value to ensure the other food crop is covered.

Dryer Capacity

Length, width and thickness of trays = 0.5 m, 0.4 m and 1×10^{-3} m respectively:

Distance between subsequent trays = 0.1 m

Bed thickness = 5 cm = 5×10^{-3} m (Hegde *et al.*, 2015)

$$\text{Volume of food crop per tray} = 5 \times 10^{-3} \times 0.5 \times 0.4 = 1 \times 10^{-3} \text{ m}^3$$

$$\text{Total volume of food crop} = \text{Number of trays} \times \text{volume per tray}$$

$$= 3 \times 1 \times 10^{-3} = 3 \times 10^{-3} \text{ m}^3$$

Using pepper as an example, bulk density of pepper = 400 kg m^{-3} (Woldemariam *et al.*, 2021)

$$\text{Total mass of pepper} = \text{bulk density} \times \text{total volume}$$

$$= 400 \times 3 \times 10^{-3}$$

$$= 1.2 \text{ kg}$$

Calculation for TES Using Granite

The granite is stored in a top-open box inside the dryer cabinet beneath the food trays. Based on the dimensions of the box, the quantity of granite stored is known. Further from the quantity of granite stored, the energy stored in it is calculated.

Length, width and height of granite box = 0.5 m, 0.4 m and 0.1 m respectively:

$$\text{Volume of granite box} = 0.5 \times 0.4 \times 0.1 = 0.02 \text{ m}^3$$

Assuming the granite takes up 50% volume, therefore the volume of granite

$$= 0.5 \times 0.02 = 0.01 \text{ m}^3$$

Density of granite = 2750 kg/m^3 (*Properties and Types of Granite - a Material That Is Taking Homes by Storm - Cosentino, 9/10/23*)

Therefore, mass of granite stored = Volume \times Density

$$= 0.01 \times 2750 = 27.5 \text{ kg.}$$

The quantity of heat stored by granite can be calculated using eq (9):

$$Q_{hs} = M_{hs} C_{hs} dT$$

$$= 27.5 \times 790 \times (65 - 30) = 760.4 \text{ kJ}$$

Assuming efficiency of TES = 80%, actual energy stored by granite

$$= 0.8 \times 760.4 \text{ kJ} = 608.3 \text{ kJ}$$

Determination of Collector Area

Total energy required for drying pepper = 2087.4 kJ

Total energy stored by granite = 608.3 kJ

So the energy to be supplied by collector = 2087.4 + 608.3

Here, the drying time is assumed to be 12 h, so TES system is to used for 1 day

Therefore, total energy demand = 2087.4 + 608.3 = 2695.7 kJ

Assuming the efficiency of the collector (η) = 30%

Average monthly solar insolation for Abeokuta, $I_s = 5.1 \text{ kWh/m}^2/\text{day}$ (*Solar Insolation Calculator | Fabhabs, 9/10/23*)

$$= (5.1 \times 3600) \text{ kJ/day} = 18360 \text{ kJ/day}$$

Assuming the area of the flat-plate solar collector to be 0.5 m^2

Energy retracted from collector per day, $Q_c = \eta I_s A_c$ -----(12) (Big Ladder Software LLC, 9/10/23)

$$= 0.3 \times 18360 \times 0.5 = 2754 \text{ kJ/day}$$

Therefore for one day, total energy supplied = 2754 kJ/day \times 1 day = 2754 kJ

The flat-plate collector area required for supplying the essential heat energy is 0.5 m^2 .

Power Required by the Blower

Power required by the dryer = Quantity of heat / time (sec)

Intended drying time = 12 hours = $12 \times 60 \times 60$

= 43200 sec

Power = $2754/43200$

$P_{\text{dryer}} = 0.06375 \text{ kW} = 63.75 \text{ W}$

Work done by solar collector = Work done on air

Power of solar collector = 63.75 W

Work done on air per sec = Mass flow rate of air \times Specific heat capacity of air \times Temperature difference

Therefore mass flow rate of air = $\frac{\text{Work done on air per sec}}{\text{Specific heat capacity of air} \times \text{Temperature difference}}$

$$= \frac{63.75}{1005 \times (65 - 30)} = 1.81 \times 10^{-3} \text{ kg/s}$$

Density of air at 65°C = 1.067 kg/m^3 (from deduction)

Therefore, discharge = $\frac{\text{mass flow rate}}{\text{density}}$

$$= \frac{0.00181 \text{ kg/s}}{1.067 \text{ kg/m}^3} = 1.7 \times 10^{-3} \text{ m}^3/\text{s}$$

The power requirement of the blower, P, in kW can be calculated using the formula

$$P = \frac{Q \times SP}{7.068 \times \eta} \text{ -----(14)} \quad (\text{CheCalc - Blower and Fan Calculations, 2/10/23})$$

where

P is the power in kilowatts (kW)

Q is the air flow rate in cubic metres per second (m^3/s)

SP is the static pressure in pascals (Pa)

η is the efficiency of the blower

Assuming $SP = 15 \text{ Pa}$ and an efficiency of 85%,

$$P = \frac{0.0017 \times 15}{7.068 \times 0.85} = 4.24 \times 10^{-3} \text{ kW} = 4.24 \text{ W}.$$

3.2.3 Experimental setup

The designed forced convection solar dryer consists majorly of three units namely; the drying chamber, the solar collector box and solar PV system (which also consists of a solar panel or cell, charge controller and battery). All contacts between these units were firmly closed to minimise infiltration losses.

Dryer Cabinet:

The structural frame for the cabinet is made up of mild steel with a fibre lagging material used to line the inner walls of the cabinet. The fibre lagging material serves as insulation to enhance the thermal efficiency of the drying process. A rectangular hole of (38 x 76) mm is cut at bottom left corner on one side of the cabinet for hot air inlet.

Tray slots is provided to accommodate and securely hold the trays used for drying the food crops. The cabinet has room for only 3 trays and granite box.

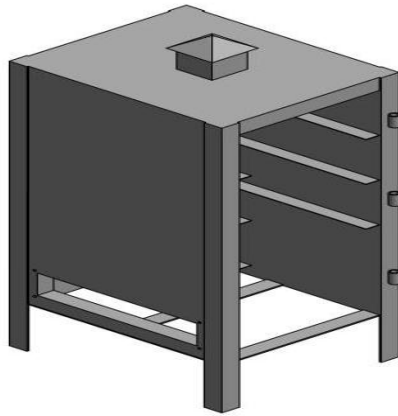
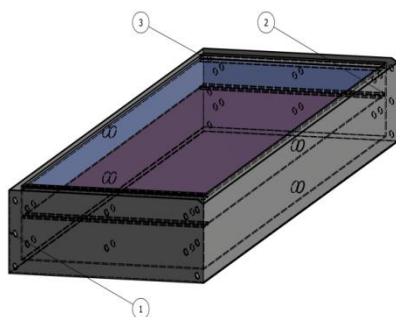


Figure 8: The solar dryer cabinet.

Solar Thermal Collector Box:

The solar collector is a plywood box of size 1000 mm × 500 mm × 175 mm made from plywood. The box covered with 5 mm thick glass is inclined at about 17° to the horizontal. A 1000 mm × 500 mm black-painted flat aluminium sheet is placed below, a gap of 50mm is placed between the aluminium plate and plywood. An air gap of 20 mm is then placed between the plywood and another plywood which serves as the bottom of the box. This design helps to ensure minimal heat loss in the box.



| PARTS LIST | | |
|------------|-----|--------------------------|
| ITEM | QTY | PART NUMBER |
| 1 | 1 | Solar box collector |
| 2 | 1 | Aluminium absorber plate |
| 3 | 1 | Glass |



Figure 9: The solar thermal collector box.

Granite Box:

The granite box is designed to accommodate granite, serving as a heat storage material. The container features a top-opening configuration and is constructed from mild steel with a thickness of 1.5 mm, measuring 500 mm in length, 400 mm in width, and 100 mm in height. This specialized mild steel box is strategically positioned within the lower compartment of the solar cabinet.

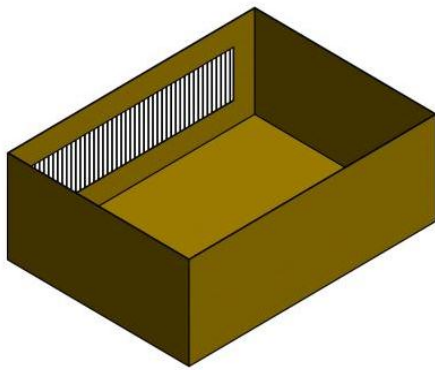


Figure 10: Granite box.

Solar Pv System and Blower:

The solar photovoltaic (PV) system comprises essential components, including a 50 W solar panel, a charge controller, and a 12 AH battery. The primary purpose of this PV system is to power a DC 10 W blower situated at the inlet of the solar thermal collector box.

The 50 W solar panel serves as the energy generation source, converting sunlight into electrical power. The charge controller ensures efficient charging and protection of the battery from overcharging or discharging. The battery acts as an energy storage unit,

allowing the system to supply power even when there is no sunlight. The 10 W blower is an integral part of the system, responsible for facilitating airflow and heat transfer from the solar thermal collector box to the dryer cabinet.

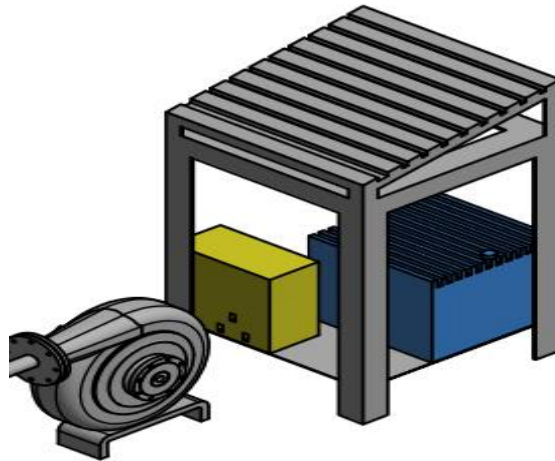


Figure 11: Solar PV system.

3.3 Principle of Operation of the Dryer (Drying Procedure)

The forced convection solar cabinet dryer with granite as thermal energy storage represents a highly sophisticated and energy-efficient drying system specifically designed to utilise solar energy for the purpose of drying agricultural products and food items. In contrast to direct solar dryers that directly expose the drying surfaces to solar radiation, this ingenious dryer operates through an indirect approach, employing a solar collector strategically positioned beside the drying chamber.

The solar collector, crafted from aluminium which is painted black, serves as an exceptionally efficient solar absorber. As it basks in sunlight, the solar collector adeptly captures and converts solar radiation into thermal energy, substantially raising the temperature of the air passing through it. The heated air is then propelled into the drying

cabinet with the assistance of the blower, setting the stage for the drying process to commence.

Within the drying chamber, the agricultural produce or food items intended for drying are thoughtfully arranged on the trays. As the heated air from the solar collector circulates within the chamber, it comes into contact with the products, initiating the process of moisture evaporation. Consequently, the hot and humid air exits the drying chamber, facilitating the drying process and ensuring a continuous exchange of heat between the air and the products.

To optimise the overall drying efficiency and ensure a consistent drying process regardless of solar radiation availability, the incorporation of granite as a thermal energy storage material within the drying cabinet is of paramount importance. Renowned for its superior heat storage capabilities, granite acts as an exemplary heat sink, efficiently absorbing and storing excess heat generated during periods of intense sunlight. This surplus thermal energy is cleverly directed and stored in the granite, forming a valuable reserve of thermal energy.

The stored thermal energy in the granite proves to be particularly advantageous during periods of limited solar radiation, such as cloudy days or night-time. When the solar collector is not actively producing heat, the stored thermal energy in the granite is gradually and steadily released. This controlled and sustained release of stored heat maintains the temperature inside the drying cabinet at a sufficiently elevated level, enabling the drying process to persist even in the absence of direct solar radiation.

Further enhancing the overall efficiency of the forced convection solar cabinet dryer is the utilisation of insulation materials, which are strategically applied to line the walls and bottom of the drying chamber. These insulation materials act as an effective thermal

barrier, minimising heat dissipation and optimizing the retention of higher temperatures within the drying cabinet. By reducing heat loss and promoting a stable internal environment, the insulation materials play a pivotal role in accelerating the drying rate and maintaining a consistent and conducive drying atmosphere. The full assembly design of the forced convection solar dryer with thermal energy storage is shown in figure 12.

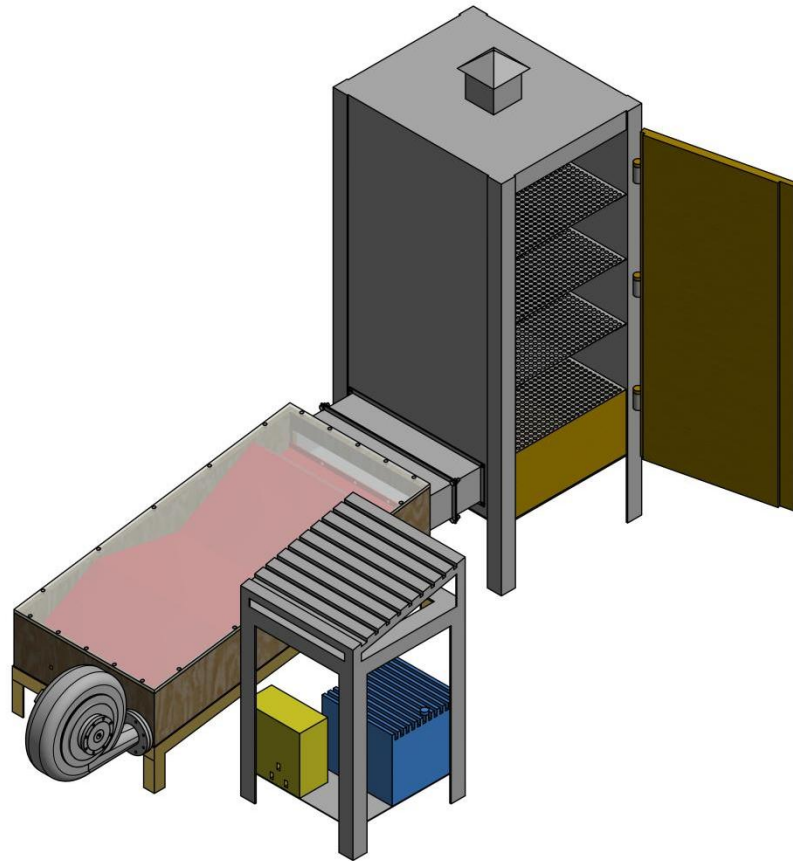


Figure 12: Forced convection solar cabinet dryer
with thermal energy storage.

3.4 Instrumentation and Experimentation

3.4.1 Instruments used for the experiment

Temperatures of the ambient and drying chamber were measured using TC thermocouple temp/RH data loggers with the accuracy of $\pm 0.5^{\circ}\text{C}$. The temperature readings were recorded on an hourly basis starting from 8:00 am. Three TC-4 data loggers were fixed at the specific points in the drying cabinet and one in open air outside the cabinet to measure the average inner temperature of the cabinet (T_{average}) and the ambient temperature (T_{amb}) respectively. Weight of granite used during the experiment was estimated using an electronic weighing balance (GALLENKOMP DT - 5000, linearity $\pm 0.1\text{g}$) of 5000 g capacity.



Plate 1: Gallenkomp Electric Balance.

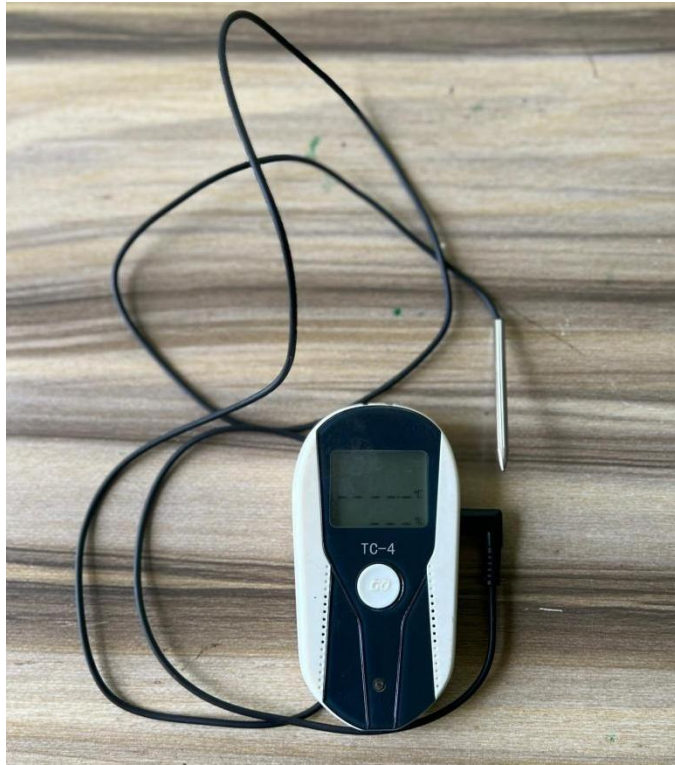


Plate 2: TC-4 Data Logger.

3.4.2 Data measurement

Temperatures were measured and at different locations using NTC thermal resistor temperature sensing probes capable of measuring temperatures ranging from -55 to $+125^{\circ}\text{C}$ ($\pm 0.5^{\circ}\text{C}$ accuracy). These sensing probes were connected to the TC-4 thermocouple data loggers each powered by a 3V Li-ion battery. The data loggers recorded the data at hourly intervals.

The following procedures were followed in carrying out the measurements:

- THC-4 temperature and humidity data logger management software was installed on a computer to calibrate and obtain recorded data information.
- The TC-4 data loggers were connected to a computer via USB and each of them was calibrated via the software.

- The required parameters were set and saved and the data loggers were disconnected from the computer.
- To start recording, the button on the data logger is pressed and held for about two seconds. The same is done to stop recording.
- After recording, the THC-4 data logger are connected to the computer and the recorded data is extracted.
- Exit from THC-4 temperature and humidity data logger management software

3.4.3 Experimentation

Experiments were conducted to study the performance of the forced convection solar dryer with granite as the thermal energy storage material. The dryer was tested without any produce to determine its no-load operating conditions.

There were four days of experimentation was carried out between November 28th and December 2nd, 2023. Experimentation involved varying the presence of the blower and thermal energy storage (TES) as follows:

- Day 1 (Nov 28): Testing without the blower and without TES. Data was recorded from 8:00 a.m. till 6:00 p.m.
- Day 2 (Nov 29): Testing with the blower and without TES. Data was recorded from 8:00 a.m. till 6:00 p.m.
- Day 3 (Nov 30): Testing without the blower and with TES. Data was recorded from 8:00 a.m. till 8:00 a.m. of December 1.
- Day 4 (Dec 1): Testing with blower and with TES. Data was recorded from 9:00 a.m. till 9:00 a.m. of December 2.



Plate 3: Experimental setup.

Three trays were placed inside the drying chamber. The door of the dryer was closed properly. While performing the experiment, the solar dryer was tested by measuring temperature for 1-hour intervals of time using the TC-4 thermocouple data loggers.

On days one and two (testing without TES), the collector outlet temperature, ambient temperature, top tray and bottom tray temperatures were recorded hourly by placing the TC-4 thermocouples at those points.

On days three and four (testing with TES), the collector outlet temperature, ambient temperature, top tray and granite temperatures were recorded hourly by placing the TC-4 thermocouples at those points.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

The results of the drying tests carried out during the performance evaluation of the solar dryer are presented in this chapter. The temperatures inside the dryer and the solar collector were much higher than the ambient temperature during most hours of the daylight.

Appendix 1 shows the hourly temperature readings at different points of the solar dryer which was gotten on 2023-11-28.

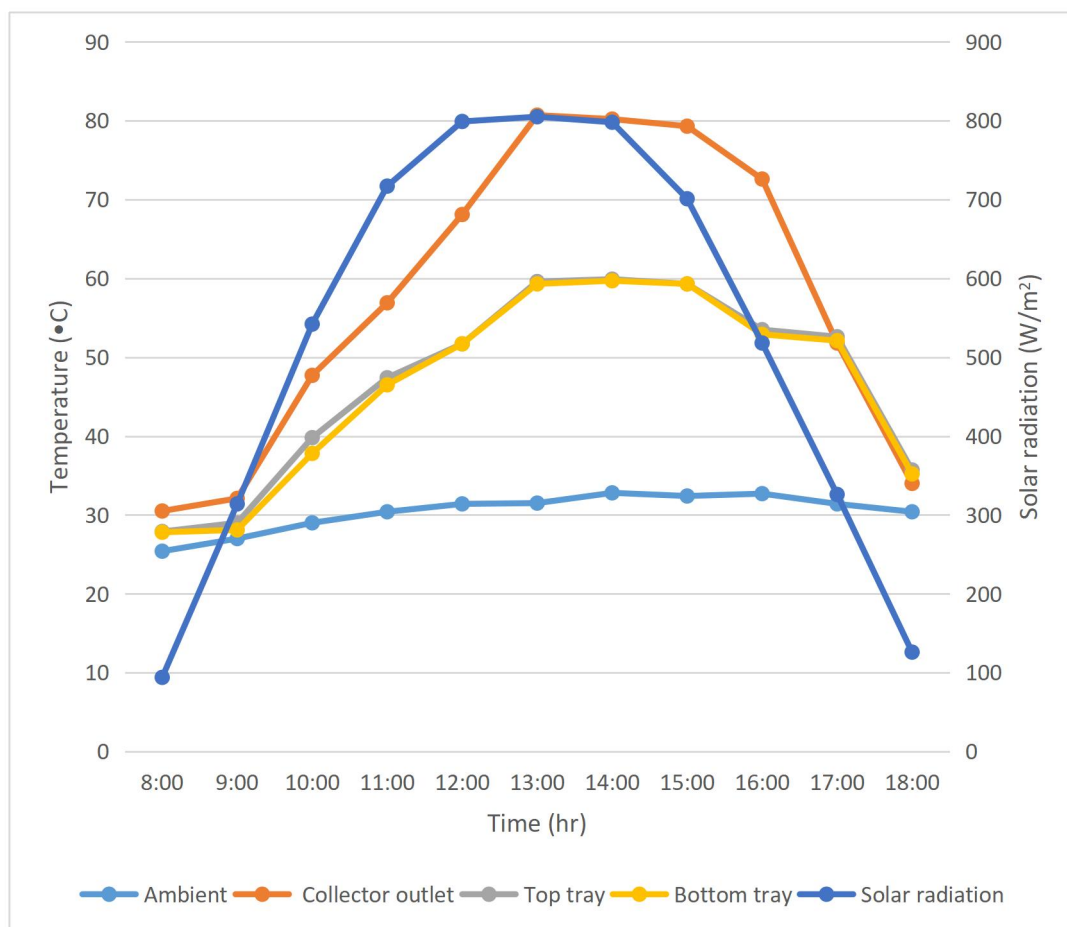


Figure 13: Chart of solar radiation and the solar dryer temperature readings without blower and no TES.

The average ambient temperature was observed to be 30.4 °C. The maximum collector outlet air temperature was observed to be 80.7 °C which occurred at 13:00, while the maximum temperatures at the top and bottom trays were 59.9 °C and 59.7 °C respectively. Higher temperatures are observed across board in the absence of the blower but there is a huge disparity between the collector outlet air temperature and the temperature at the trays.

Appendix 2 shows the hourly temperature readings at different points of the solar dryer which was gotten on 2023-11-29 .

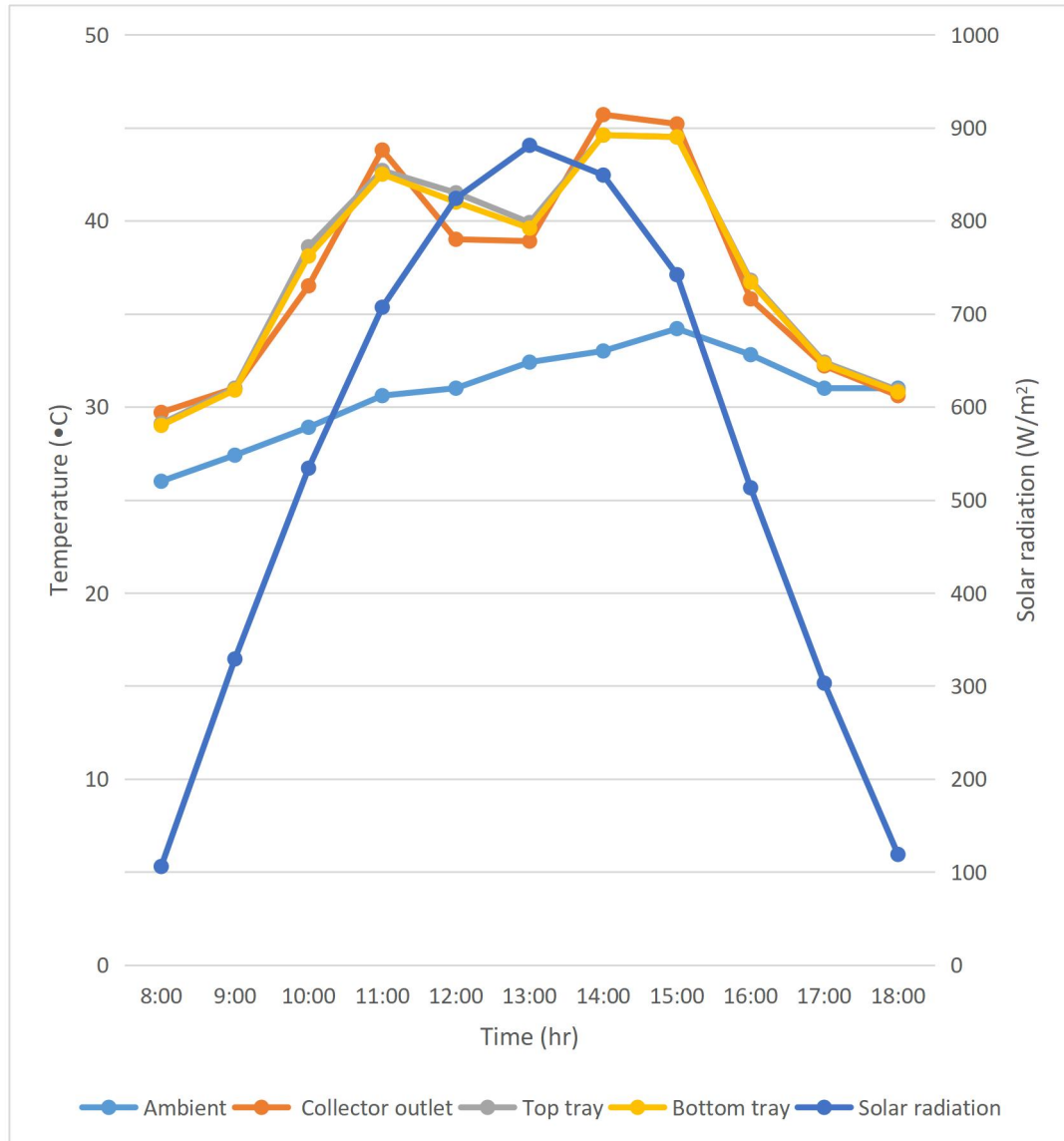


Figure 14: Chart of solar radiation and the solar dryer temperature readings with blower and no TES.

The average ambient temperature was systematically monitored and found to be 30.8 °C. The maximum collector outlet air temperature, reaching 45.7 °C at 14:00, was duly recorded. Simultaneously, the top and bottom tray temperatures registered at a maximum

of 44.6 °C each. The parity between these temperatures underscores the efficacy of the blower system in fostering uniform thermal distribution throughout the chamber via enhanced air circulation.

Appendix 3 shows the hourly temperature readings at different points of the solar dryer which was gotten from 2023-11-30 to 2023-12-01, due to the presence of granite as the TES we took overnight readings.

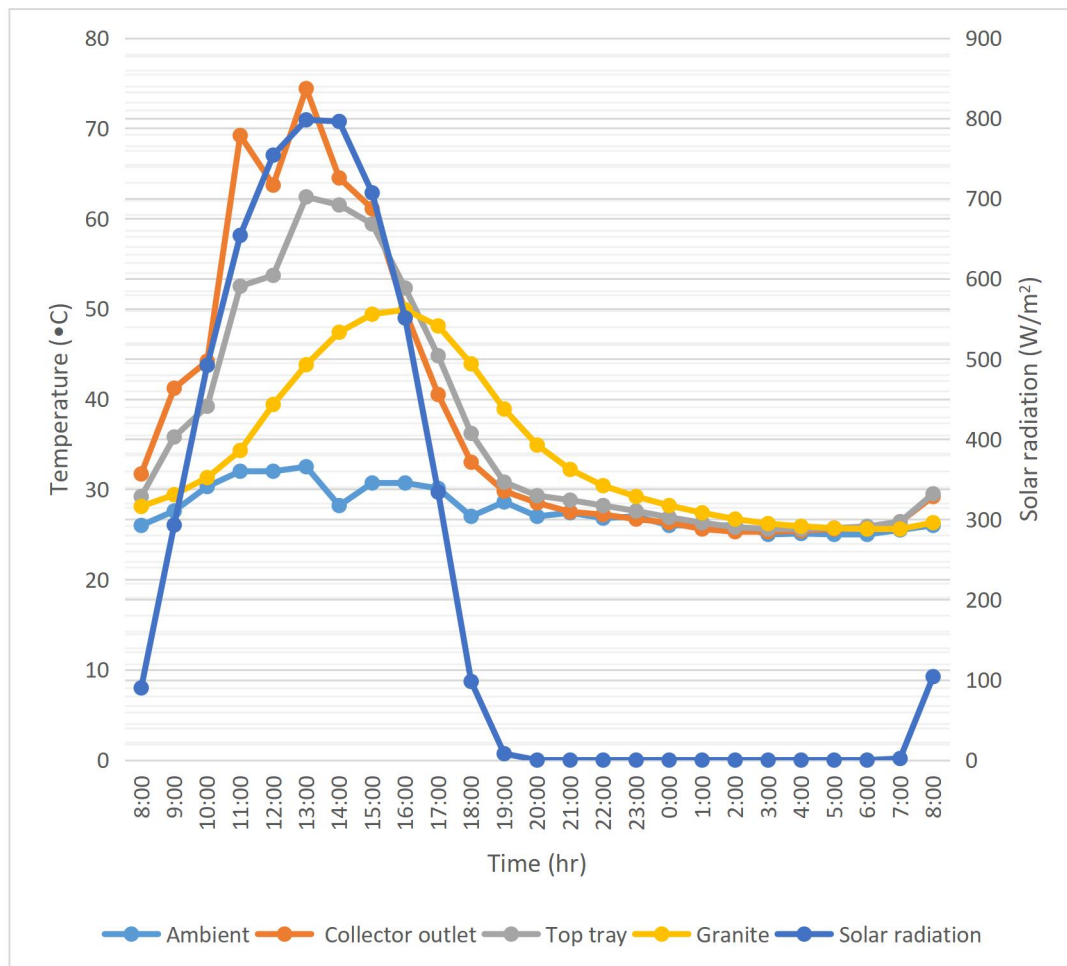


Figure 15: Chart of solar radiation and the solar dryer temperature readings without blower and with TES.

The average ambient temperature was observed to be 27.7 °C. The maximum collector outlet air temperature was observed to be 74.4 °C which occurred at 13:00, while the maximum temperature at the top tray was 62.4 °C. The granite reached a maximum temperature of 49.9 °C at 16:00. Comparison of the results from figure 13 and 15 showed that the temperature of the top tray was higher in the presence of granite than it was without.

Appendix 4 illustrates the hourly temperature readings recorded at various locations within the solar dryer from 2023-12-01 to 2023-12-02. Overnight readings were specifically acquired to account for the influence of granite as the Thermal Energy Storage (TES) material.

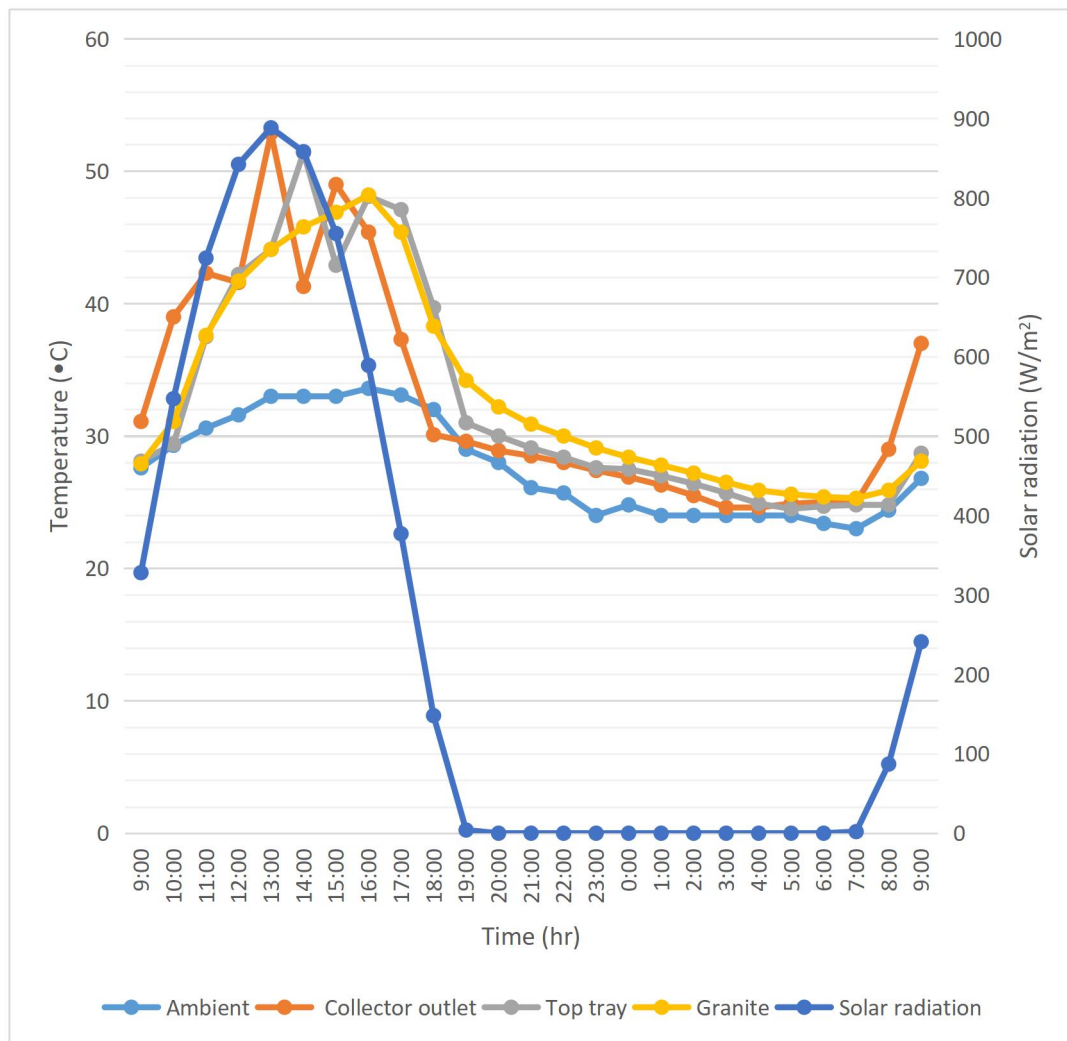


Figure 16: Chart of solar radiation and the solar dryer temperature readings with blower and TES.

The average ambient temperature was observed to be 27.7 °C. The maximum collector outlet air temperature was observed to be 52.9 °C which occurred at 13:00, while the

maximum temperature at the top tray was 51.4 °C. The granite reached a maximum temperature of 48.2 °C at 16:00. It is observed that despite a sharp decrease in the surrounding ambient temperature, the temperature in the cabinet declined in a fairly steady manner due to the TES material present.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This undergraduate project report was on the design, fabrication, and performance evaluation of a forced convection solar cabinet dryer with granite as the Thermal Energy Storage (TES) material. The experimental results with the dryer show that the temperatures of the drying air at different locations within the drying system were much higher than the ambient temperature during the day time period operation, while the temperatures are almost the same in the night time.

The recorded maximum temperatures in the collector outlet and the top tray of the drying chamber during four distinct experiments under no-load conditions are as follows: 45.7 and 44.6 °C (with blower and no thermal energy storage material), 52.9 and 51.4 °C (with blower and thermal energy storage material), 80.7 and 59.9°C (without blower and no thermal energy storage material), and 74.4 and 62.4°C (without blower and with thermal energy storage material), respectively. These values obtained showed that the dryer is suitable for drying agriculture products like pepper, okra, cassava and plantain within a reasonable period to safe moisture content. The dryer is simple and required semi-skilled labourer to be fabricated and can be used both in the urban and rural areas.

5.2 Recommendations

Building upon the findings of this study, the following recommendations are proposed to enhance the application of forced convection solar dryer and foster further research in the realm of renewable energy integration:

Based on the challenges we had while sourcing for the necessary measuring equipment, it is recommended that the university establish a dedicated fund or resource centre for lending specialised equipment to students

Integrate automation and real-time monitoring systems into the solar dryer design. This would enable remote control, data collection, and analysis, facilitating a deeper understanding of system performance.

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APPENDICES

Appendix 1 : Solar dryer temperature readings without blower and no TES

| Time | Ambient Temp. (°C) | Temp. at the solar collector outlet (°C) | Temp. at the top tray (°C) | Temp. at the bottom tray (°C) | Solar radiation (W/m ²) |
|-------|-----------------------|--|-------------------------------|-------------------------------------|---|
| 08:00 | 25.4 | 30.5 | 27.9 | 27.8 | 94 |
| 09:00 | 27.0 | 32.1 | 29.0 | 28.1 | 314 |
| 10:00 | 29.0 | 47.7 | 39.8 | 37.8 | 542 |
| 11:00 | 30.4 | 56.9 | 47.4 | 46.5 | 717 |
| 12:00 | 31.4 | 68.1 | 51.7 | 51.7 | 799 |
| 13:00 | 31.5 | 80.7 | 59.6 | 59.3 | 805 |
| 14:00 | 32.8 | 80.2 | 59.9 | 59.7 | 798 |
| 15:00 | 32.4 | 79.3 | 59.3 | 59.3 | 701 |
| 16:00 | 32.7 | 72.6 | 53.5 | 52.9 | 518 |
| 17:00 | 31.4 | 51.8 | 52.6 | 52.1 | 326 |
| 18:00 | 30.4 | 34.0 | 35.7 | 35.2 | 126 |

Appendix 2 : Solar dryer temperature reading with blower and no TES

| Time | Ambient Temp. (°C) | Temp. at the solar collector outlet (°C) | Temp. at the top tray (°C) | Temp. at the bottom tray (°C) | Solar radiation (W/m ²) |
|-------|--------------------|--|----------------------------|-------------------------------|-------------------------------------|
| 08:00 | 26.0 | 29.7 | 29.3 | 29.0 | 106 |
| 09:00 | 27.4 | 31.0 | 31.0 | 30.9 | 329 |
| 10:00 | 28.9 | 36.5 | 38.6 | 38.1 | 534 |
| 11:00 | 30.6 | 43.8 | 42.7 | 42.5 | 707 |
| 12:00 | 31.0 | 39.0 | 41.5 | 41.0 | 824 |
| 13:00 | 32.4 | 38.9 | 39.9 | 39.6 | 881 |
| 14:00 | 33.0 | 45.7 | 44.6 | 44.6 | 849 |
| 15:00 | 34.2 | 45.2 | 44.5 | 44.5 | 742 |
| 16:00 | 32.8 | 35.8 | 36.8 | 36.7 | 513 |
| 17:00 | 31.0 | 32.2 | 32.4 | 32.3 | 303 |
| 18:00 | 31.0 | 30.6 | 30.9 | 30.8 | 119 |

Appendix 3 : Solar dryer temperature readings without blower and with TES

| Time | Ambient Temp. (°C) | Temp. at the solar collector outlet (°C) | Temp. at the top tray (°C) | Temp. of granite (°C) | Solar radiation (W/m ²) |
|-------|-----------------------|--|-------------------------------|--------------------------|---|
| 08:00 | 26.0 | 31.7 | 29.2 | 28.1 | 90 |
| 09:00 | 27.6 | 41.2 | 35.8 | 29.4 | 293 |
| 10:00 | 30.3 | 44.2 | 39.2 | 31.3 | 492 |
| 11:00 | 32.0 | 69.2 | 52.5 | 34.3 | 654 |
| 12:00 | 32.0 | 63.7 | 53.7 | 39.4 | 754 |
| 13:00 | 32.5 | 74.4 | 62.4 | 43.8 | 798 |
| 14:00 | 28.2 | 64.5 | 61.5 | 47.4 | 796 |
| 15:00 | 30.7 | 61.1 | 59.4 | 49.4 | 707 |
| 16:00 | 30.7 | 49.7 | 52.3 | 49.9 | 551 |
| 17:00 | 30.1 | 40.5 | 44.8 | 48.1 | 334 |
| 18:00 | 27.0 | 33.0 | 36.2 | 43.9 | 98 |
| 19:00 | 28.6 | 29.8 | 30.8 | 38.9 | 8 |
| 20:00 | 27.0 | 28.5 | 29.3 | 34.9 | 0 |
| 21:00 | 27.4 | 27.5 | 28.8 | 32.2 | 0 |
| 22:00 | 26.8 | 27.2 | 28.2 | 30.4 | 0 |
| 23:00 | 27.0 | 26.7 | 27.6 | 29.2 | 0 |

| | | | | | |
|-------|------|------|------|------|-----|
| 00:00 | 26.0 | 26.3 | 26.9 | 28.2 | 0 |
| 01:00 | 26.0 | 25.6 | 26.3 | 27.4 | 0 |
| 02:00 | 26.0 | 25.3 | 25.8 | 26.7 | 0 |
| 03:00 | 25.0 | 25.3 | 25.6 | 26.2 | 0 |
| 04:00 | 25.1 | 25.4 | 25.6 | 25.9 | 0 |
| 05:00 | 25.0 | 25.6 | 25.7 | 25.7 | 0 |
| 06:00 | 25.0 | 25.7 | 25.9 | 25.6 | 0 |
| 07:00 | 25.5 | 26.4 | 26.4 | 25.6 | 2 |
| 08:00 | 26.0 | 29.2 | 29.5 | 26.3 | 104 |

Appendix 4 : Solar dryer temperature readings with blower and TES

| Time | Ambient Temp. (°C) | Temp. at the solar collector outlet (°C) | Temp. at the top tray (°C) | Temp. of granite (°C) | Solar radiation (W/m ²) |
|-------|-----------------------|--|-------------------------------|--------------------------|---|
| 09:00 | 27.6 | 31.1 | 28.1 | 27.9 | 328 |
| 10:00 | 29.3 | 39.0 | 29.4 | 31.1 | 547 |
| 11:00 | 30.6 | 42.3 | 37.5 | 37.6 | 724 |
| 12:00 | 31.6 | 41.6 | 42.2 | 41.7 | 842 |
| 13:00 | 33.0 | 52.9 | 44.1 | 44.1 | 888 |
| 14:00 | 33.0 | 41.3 | 51.4 | 45.8 | 858 |
| 15:00 | 33.0 | 49.0 | 42.9 | 46.9 | 755 |
| 16:00 | 33.6 | 45.4 | 48.1 | 48.2 | 589 |
| 17:00 | 33.1 | 37.3 | 47.1 | 45.4 | 377 |
| 18:00 | 32.0 | 30.1 | 39.7 | 38.3 | 148 |
| 19:00 | 29.0 | 29.6 | 31.0 | 34.2 | 4 |
| 20:00 | 28.0 | 28.9 | 30.0 | 32.2 | 0 |
| 21:00 | 26.1 | 28.5 | 29.1 | 30.9 | 0 |
| 22:00 | 25.7 | 28.0 | 28.4 | 30.0 | 0 |
| 23:00 | 24.0 | 27.4 | 27.6 | 29.1 | 0 |
| 00:00 | 24.8 | 26.9 | 27.5 | 28.4 | 0 |

| | | | | | |
|-------|------|------|------|------|-----|
| 01:00 | 24.0 | 26.3 | 27.0 | 27.8 | 0 |
| 02:00 | 24.0 | 25.5 | 26.4 | 27.2 | 0 |
| 03:00 | 24.0 | 24.6 | 25.7 | 26.5 | 0 |
| 04:00 | 24.0 | 24.6 | 24.9 | 25.9 | 0 |
| 05:00 | 24.0 | 24.9 | 24.5 | 25.6 | 0 |
| 06:00 | 23.4 | 25.0 | 24.7 | 25.4 | 0 |
| 07:00 | 23.0 | 25.0 | 24.8 | 25.3 | 2 |
| 08:00 | 24.4 | 29.0 | 24.8 | 25.9 | 87 |
| 09:00 | 26.8 | 37.0 | 28.7 | 28.1 | 241 |
