BINDURA UNIVERSITY OF SCIENCE EDUCATION
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A PROJECT IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE BSc IN AGRICULTURAL ENGINEERING

INCREASING EFFICIENCY OF A SOLAR DRYER USING PRINCIPLE COMPONENT MATERIAL

By:
Tadiwanashe Mafetuka

SUPERVISOR
Mr O Zingwari

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DECLARATION

I, **Tadiwanashe Mafetuka**, **B201729B**, I declare that, with the exception of what is noted in the acknowledgement and references, all of the research and work for this study was done by me. According to my knowledge NO other university has received this project, in whole or in parts.

Student´s Signature:__________ Date:_20_/__06_/2024_

Academic Supervisor's Name: Eng O. Zingwari Signature: ________ Date: 20 /06/2024

Project Coordinator´s Name: Prof. I. Rodriguez Signature: ________ Date: 01/07/2024

DEDICATION

To the people who made it their goal to see to it that I am where I am today, my parents and everyone that had a hand in helping me.

ACKNOWLEDGEMENTS

To begin with, l would like to thank the Almighty God for making everything possible. Secondly I would like to express my sincere gratitude to my main supervisor Eng O Zingwari who took it upon himself to help me sharpen this project with his input of brilliant ideas and willingness to deliver information and could spare their time for me.

My sincere gratitude also goes to my colleagues for standing with me throughout the project. Last but not least, my profound gratitude and appreciation goes to my parents and my great family at large for their unwavering support and encouragement, financial support and love throughout my life. Without their support, it was impossible for me to be here. Lastly, I would like to acknowledge my fellow classmates for their input throughout my project.

ABSTRACT

Post-harvest losses have appeared to be a persistent problem that haunts smallholder farmers by robbing them of their scarce profits and the troubling effects are observed directly as a community and even governments fear how people are going to survive. Solutions are clear, preservation methods should be put in place. This study expounded such a solution by optimising a conventional solar drying (CS_d) system by designing a solar dryer which uses thermal storage material (ThS_d). The theory on which the ThS_d dryer works is based on energy being stored in the material when solar radiation is high and realised when it is low. The design and fabrication of the dryer was done using Pahl and Beitz (2007) conceptual model for designing processing equipment. Using this model three models were developed and the best of the three was selected using scoring technique devised by Illinois (2017). Evaluation of the dryers' properties and characteristics was done by collecting data showing changes in drying temperature, T in the drying chamber, observing drying time, D_t taken to reach the recommended final moisture content, Φ and observing changes in relative humidity, τ_H. The data was used to find drying rates ( ), drying efficiency ($d_{E,\%}$), energy (Q, MJ) supplied by the dryer, the moisture content removed (M_A) by the dryer and to see if it fits with existing drying curves. Both CS_d and ThS_d dryers were able to remove 92.8 % of the moisture content from the sample. The drying time taken was 8hrs for ThS_d and 20hrs for CS_d. The d_E, d_R, and Q values for ThS_d were 51.9%, 11.7%moisture/hr and 26.0MJ, respectively, and those for CS_d were 20.8%, 3.7%moisture/hr and 24.98MJ respectively. All the data obeyed the underline drying curves; hence, they are in line with expected mathematical behaviours. The results showed optimization of the temperature and drying time of the CS_d by a factor of 2.5, this can improve yield of dried product and possibly quality.

Keywords: solar drying, thermal storage materials, drying rate, drying efficiency, post-harvest preservation

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ABBREVIATION

PHL: Post-harvest loss

SDG: Sustainable Development Goals

SDT: Solar Drying Technology

OSD: Open-Sun Drying

SSA: Sub-Saharan Africa

HTF: Heat Transfer Fluid

WHO: World Health Organisation

FAO: Food Agricultural Organisation

NDS 1: National Development Strategy 1

PHFC: Post-Harvest Food Chain

CHAPTER 1

1.1 Introduction

This chapter introduces and explains the scope of this study

1.2 Background of study

Post-harvest food losses have become one of the major causes of food insecurity in Zimbabwe and the country is losing its food annually. The losses are quiet substantial as these figures are way above the maximum 5% set by the Food and Agriculture Organization (Chigoverah & Mvumi, 2016). For fresh produce the losses are estimated to be more than 50%. Poor postharvest practices and poor handling are attributed to the losses. The effects of post-harvest losses have devastating impacts on food and nutritional security and hunger at household and national level. Vulnerable populations such as women and children are oftentimes disproportionally affected by the impacts of post-harvest losses (World Bank, 2016).

Sheahan (2017) notes that there are many post-harvest management strategies. One of the strategies employed by smallholder farmers is the use of drying techniques. Drying is a component of post-harvest food chain that preserves food by reducing the available moisture or water activity to safe levels. Reduction in water activity levels prevents microbial proliferation, of both spoilage and pathogenic microorganisms. Essential attributes provided by drying include ensuring quality, extending product shelf life, simplifying transport and increasing added value (Omotilewa *et al.,* 2018).

Open- sun drying (OSD) is the most commonly used method of drying practiced by smallholder farmers. It is unhygienic, slow, time consuming, drying efficiency depends on climatic conditions, temperature cannot be controlled, is labour-intensive and there is a high possibility of contamination of the produce (Mkodzongi, 2013). Food quality is also a major issue. Open-sun drying can cause rotting or rewetting of produce as a result of bad weather and often leads to significant nutrient deterioration and color loss due to long exposure to solar radiation. Current drying technologies require critical improvements to enhance food processing sustainability and quality produce (Hodges, 2015).

The intent of this study is to design, fabricate, and evaluate a more improved solar dryer optimized with a sensible heat storage material inorder to ensure a sustsinable drying system that reduces post-harvest losses problems that smallholder farmers incure in Zimbabwe

1.3 Problem Statement

The small scale farmers' reliance on conventional drying methods leaves them vulnerable to food insecurity as it increases post-harvest losses which financially impacts the farmers as there will be reduced available produce for sale thereby affecting market and decreasing income generated from selling the produce. By improving the efficieny of the solar dryer and using cost effective materials and also improving the system by adding a heat storage system for use during off-sun hours it will be possible to provide a more affordable and effective solution for small farmers .

1.4 Objectives of the study

1.4.1 Main objective

- Increasing efficiency of a solar dryer using principle component material

1.4.2 Specific objectives

- To design and develop a solar dryer with a principle component material
- To evaluate the performance of the improved solar dryer
- To determine the efficiency of the improved solar dryer

1.5 Research Questions

- What are the problems associated with the current methods of drying?
- What has been done so far in terms of technology with regard to drying agricultural produce using a solar dryer?
- Are there other solar dryers in Zimbabwe that have been optimized with other sensible heat storage materials?

1.6 Hypothesis

The improved solar dryer will have an impact on the drying rates

The improved dryer will reduce the drying time

The improved dryer will enable continuous operation of the drying process

The improved dryer will improve the livelihoods of smallholder farmers

1.7Justification

The design contributes to dry chain technologies as the agricultural produce will be dried to their recommended final moisture content (Petkova *et al.,* 2013). Inorder to obtain high quality dried products that will not threaten human health, hygienic conditions must be provided during drying process. Besides providing overall hygienic drying conditions, solar dryers have many advantages over open sun drying such as reduced dring time, less spoilage, more uniform drying at low temperatures, texture and taste (Esper and Muhlbauer, 1998).

The use of stones as a sensible heat storage material improves the thermal performance of the dryer and enable continuous operation which improves the keeping qualities of agricultural produce. The dryer has a temperature and humidity control system which improves the consistency in air temperature and increase the efficiency of the dryer (Matavel *et al.,* 2021). The incorporation of stones as a sensible heat storage material and control system on the dryer addresses limiting issues associated with solar drying such as fluctuations in drying temperature, non-uniform drying and reduction in solar dryer's efficiency during off sunshine hours and in times or places of reduced direct solar insolence which leads to solar dryers becoming redundant during non-sunshine hours (Lamidi *et al.,* 2019).

1.8 Limitations

There is limited published documented work about the drying technologies currently used by small scale farmers.

1.9 Delimitations

Design is mostly focusing on the dryer for small scale farmers

1.10Assumptions

-All materials and components required for this project's success will be purchased and be available in time for submission

-the costs of the project will stay within the expected amounts initially budgeted for

1.11 Conclusion

This chapter highlighted on the need for the design of a more efficient solar dryer for small scale farmers. The objectives listed will help maintain the scope and see to it that the project succeeds in solving the problem.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Post-harvest losses are a major threat to food security in developing countries and their reduction is crucial in achieving the sustainable development goals (SDG), particularly, SDG 12 (ensure sustainable consumption and production patterns) and SDG 2 (Zero hunger) (FAO, 2019). Reduction of post-harvest losses can significantly contribute to availability of food. Lack of appropriate preservation technologies and non-renewable energies can lead to huge production losses that can be prevented by implementing solar drying technology (SDT) (Affognon *et al.*, 2015).

2.2 Post-harvest losses and their effects

FAO (2011) defines post-harvest loss as the degradation in both quality and quantity of a food production from harvest to consumption. Quality losses include those that affect the edibility, nutrient/caloric composition and the acceptability of a given product. Post-harvest losses vary greatly among commodities, seasons and production areas. In less developed countries the major reason for increased post-harvest losses is inefficient postharvest agricultural systems that lead to loss of food that people would otherwise sell, eat, or barter to improve their livelihoods (Ghaffari & Mehdipour, 2015).

The main cause of loss is biological spoilage. Fish, livestock products, fruit and vegetables lose value very quickly without refrigeration, while tubers, grain products and roots are less perishable as they have lower moisture contents. A reduction in food losses can have a significant and immediate impact on the livelihoods of smallholder farmers given that the majority of smallholder farmers in developing countries live on the margins of food insecurity (FAO, 2013).

Post-harvest loss reduction interventions are now considered to be a critical component of the efforts of numerous agencies to reduce food insecurity. Post-harvest loss is increasingly recognized as part of an integrated approach to realizing agriculture's full potential to meet the world's increasing energy and food needs (SPORE, 2011).

The first step in identifying an appropriate strategy for reducing post-harvest losses is a systematic analysis of each commodity production and handling system. Strategies to reduce post-harvest losses include harvesting at the proper stage of maturity and at its peak quality, drying, threshers, shellers, winnowers and on-farm storage facilities (Atanda *et al.,* 2011). In rural areas, farmers practice open-sun drying as a method of preserving their produce until the next harvest. Drying is one of the most important factors in reducing post-harvest losses and for maintaining farm produce quality (Parfitt *et al.*, 2010).

2.3 Importance of drying

Drying is a method of preservation which increases the shelf life of the food being dried. It is a complex unit operation that involves the transient transfer of mass and heat along with several rate processes, such as chemical or physical transformations, which, in turn may cause changes in fresh produce quality as well as the mechanisms of mass and heat transfer (Abano *et al.,* 2014). Food drying is a very complex process because of the differential structure of food materials. Physical changes that may occur include puffing, shrinkage, glass transitions and crystallization. Undesirable or desirable biochemical or chemical reactions may occur which may lead to changes in colour, odour, texture and other properties of the solid food material (Ibrahim, 2013).

Before food is dried, it goes through size reduction by being cut into smaller pieces. Size reduction increases the surface area of the food material being dried, thereby increasing the rate of reaction and speeding up the drying process. It is achieved by reducing the moisture in food to a safe level, thus rendering the water in food unavailable for microbial growth (Smith, 2011).

Drying ensures low microbial counts of pathogenic and toxicogenic microorganisms and also slows down the activity of enzymes and the rate at which undesirable chemical changes occur in the food being dried. It also minimizes spoilage, enhances stability and maintains the quality of the dried food (Hoek *et al.*, 2013). Drying reduces the volume and weight of food. These changes in volume and weight can lead to substantial savings in storage and transport costs, as well as costs of packaging (Schmidt, 2015).

Mechanism of drying

During drying of food materials having relatively high initial moisture content the drying rate of the food material is controlled by two basic mechanisms. The dominant mechanism involved in the initial stages of drying is evaporation of moisture from the surface of the food material when it is entirely wet (Gandhi, 2015).

The rate of evaporation stays constant as long as the surface of the food material remains completely wet. This phase of the drying process is called the constant-rate regime. In this phase it is the surface moisture outside individual particles that is being removed (Gummert, 2011).

As the drying process proceeds, part of the surface dries while some parts of the food material remain wet. This is the intermediate phase and the drying rate is governed partially by the rate at which moisture can evaporate from the wet parts and partially by the rate of internal migration of moisture within the food material (IRENA, 2014).

As drying progresses further, the surface dries entirely and the drying rate becomes governed by the internal moisture migration. This phase is called the falling-rate regime. In this phase, the moisture content of the food material falls below a critical value and the drying rate decreases (Lillywhite *et al.*, 2013).

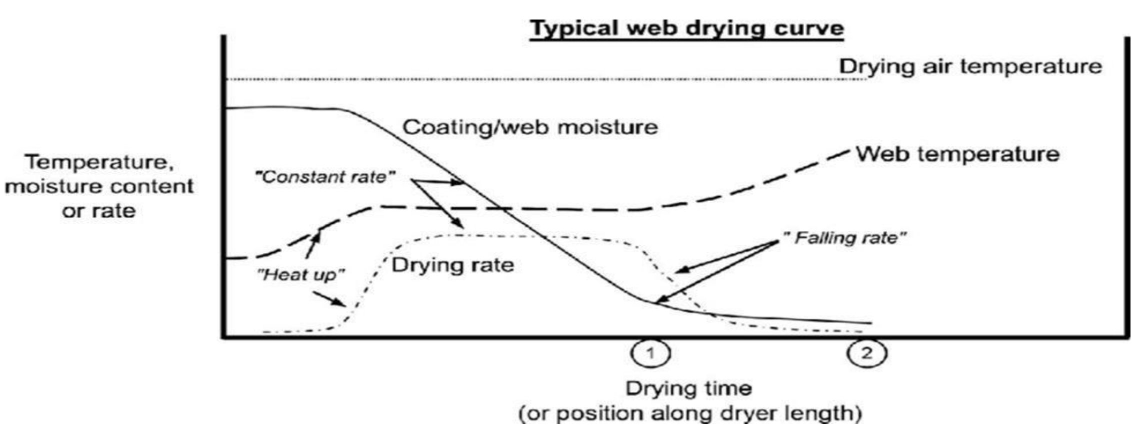


Figure 1. Constant and falling periods (Lillywhite et al.,2013)

Drying curves

There is a representative curve that describes the drying characteristics for each and every food product at specific temperature, velocity and pressure conditions. Such a curve is referred to as the drying curve for a specific material. There may be variations in the curve that may occur principally in rate relative to carrier velocity and temperature (Mekonnen, & Hoekstra, 2011).

The curve is valuable in understanding the idiosyncrasies associated with the drying of each unique product. There are three different phases of the drying process. The first phase, or initial period, involves sensible heat being transferred to the product and the contained moisture (Bhardwaj *et al.*, 2019).

The food material heats up from the inlet condition to the process conditions, enabling the subsequent processes to take place. In some cases, pre-processing can eliminate or reduce this phase, for example, the inlet condition of the material will already be at a raised temperature if the feed material is coming from a reactor or if the feed is preheated by a source of waste energy (Mohana *et al.*, 2020).

Akhijahani *et al.* (2017) add that during this period the rate of evaporation increases dramatically with mostly free moisture being removed. The second phase, or constant rate period, involves free moisture persisting on the surfaces and the rate of evaporation alters very little as the moisture content reduces. At this stage, drying rates are high and the higher inlet air temperatures than in subsequent drying stages can be used without detrimental effect to the product (Alimohammadi *et al.*, 2020).

There is also a gradual and relatively small increase in the product temperature during this period. The time scale of the constant rate period may determine and affect the rate of drying in the next phase. The third phase, or falling rate period, is the period during which migration of moisture from the inner interstices of each particle to the outer surface becomes the limiting factor that reduces the drying rate (Ananno *et al.*, 2020).

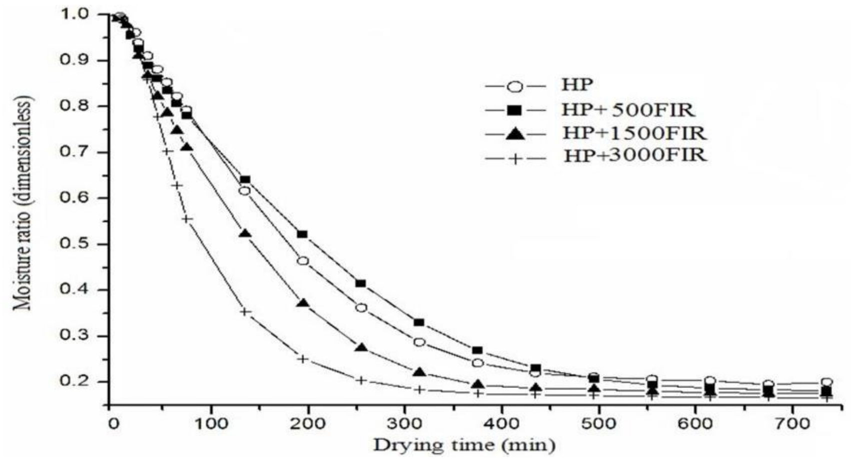


Figure 2 Drying curve of a food product (Alimohammadi et al., 2020)

Drying characteristics of agricultural products

The most commonly used commercial method for drying fruits and vegetables is hot air drying. When hot air drying, convective air flow passes over the surface of the food material and not through the food material (Toure, 2012). Hot air drying is associated with low energy efficiency during the falling rate period and also requires a long drying time. Heat transfer from the surrounding environment to the internal portions of the agricultural products largely rely on the thermal conductivities of the products (Aboltins & Palabinskis. 2016).

In a study, thin-layer drying characteristics of unblanched and blanched slices of eggplant were determined for different sample thickness (0.5 and 1 cm) and by increasing the air temperature from 50°C to 80°C in steps of 10°C. Low sample thickness, high hot air temperature and pre-treatment were effective for shortening the drying time. Fick's diffusion model was used to determine moisture transfer from eggplant slices and various mathematical models were used for predicting drying characteristics. Depending on the experimental condition, effective diffusivity values were varied and Page's model was found to be in good agreement with the experimental drying curves of the eggplant slices (Doymaz & Gol (2011).

Cubes of sweet potato of three different thicknesses were dried under five different velocities and temperatures (Singh and Pandey, 2012). The drying time of the sweet potato cubes increased proportionally with increase in thickness and the decrease in velocity and hot air temperature. Page's model was then used to describe the drying curves of the sweet potato cubes.

Hot air drying characteristics of different fruits, sweet cherry, apple and peach were determined by various researchers (Doymaze & Ismail, 2011; Zlatanovic *et al.*, 2013; Zhu & Shen, 2014) respectively. Hot air temperature and velocity played an important role in deteriorating the quality index such as colour values and decreasing the drying time. For describing the drying characteristics of sweet cherry and peach, Page’s model was considered the best. Among the several models studied, the Henderson and Pabis model fitted the drying curves of apple well.

Open sun drying

Open-sun drying is a traditional drying method for reducing the moisture content of food products. It is the most common method of drying done by spreading food under the sun. Before drying, food undergoes size reduction by cutting it into smaller pieces. This is done to increase the surface area of the food product during drying (Udomkun *et al.,* 2020).

Open-sun drying has limitations, among them include the process being sluggish often leading to significantly huge losses, the products dried under open-sun-drying usually fail to meet international standard quality, nutrients that are sensitive to the sun maybe destroyed, open-sun drying cannot be carried out in dusty or rainy weather, non-uniform and insufficient drying also lead to deterioration of the produce during storage and it is also not possible to sun dry at night or during rain (Mustayen *et al.,* 2014).

Solar drying

Solar drying is a more advanced version of conventional open- sun drying. The objective of a solar drying is to provide sufficient amount of heat that is more than the ambient heat under given humidity. It decreases the relative humidity of the drying air and increases the vapour pressure of the moisture confined within the product, in turn, the moisture carrying capacity of the air is increased (Hii & Ong, 2012).

Natural convection or a fan is used to draw air through the dryer. The air is heated as it passes through the collector and then cooled partially as it catches moisture from the food material.

The material is heated both by the air and sometimes directly by the sun (Umogbai & Iorter, 2013). To maintain relative humidity, warm air holds more moisture than cold air, thus the amount of moisture removed depends on the temperature to which air is heated in the collector. The amount of moisture removed also depends on the absolute humidity of the air when it entered the collector. The moisture absorption capacity of air is influenced by the temperature to which it is subsequently heated and its initial humidity (Hedge *et al.*, 2015).

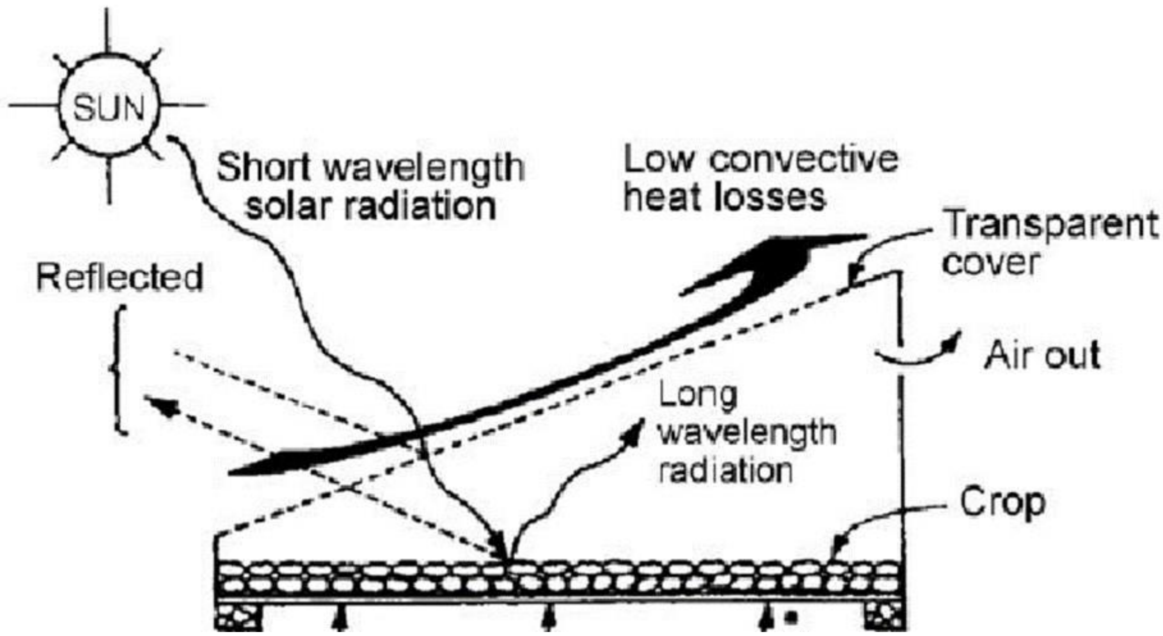


Figure 3Working principle of a direct solar dryer(Isiaka et al.,2012)

It is recommended that solar energy be utilized as the sole energy source for small-scale dryers where there is low risk of spoilage of big quantities of food products due to bad weather. It is strongly recommended that large-scale solar dryers used for commercial purposes be equipped with a back-up heater to bridge periods when there is bad weather (Sevik, 2014). The biggest advantage of solar dryers is that it can dry different types of fruits and vegetables. Sometimes farmers find it difficult to adopt recommended technologies even when there is a demand for technical changes because of labour constraints, economic problems or lack of materials (Komolafe *et al.*, 2014).

Food products dried in this way have excellent quality because of the shorter drying process (up to a one-third of the time as compared to traditional open-sun drying) and also that the food material being dried is not in direct sunlight as it is in a cabinet or in-house dryer (Kumar *et al.*, 2014).

Solar drying involves numerous challenges because of variations in drying conditions, changes in the cellular structure of the agricultural products being dried and the organoleptic properties during the drying process which may causing rejection by the consumer. Solar drying is a low energy consumption, economic and environmentally friendly alternative for smallholder farmers and rural communities that can help reduce post-harvest losses of backyard products (Bvenura & Afolayan, 2015).

Classification of solar dryers

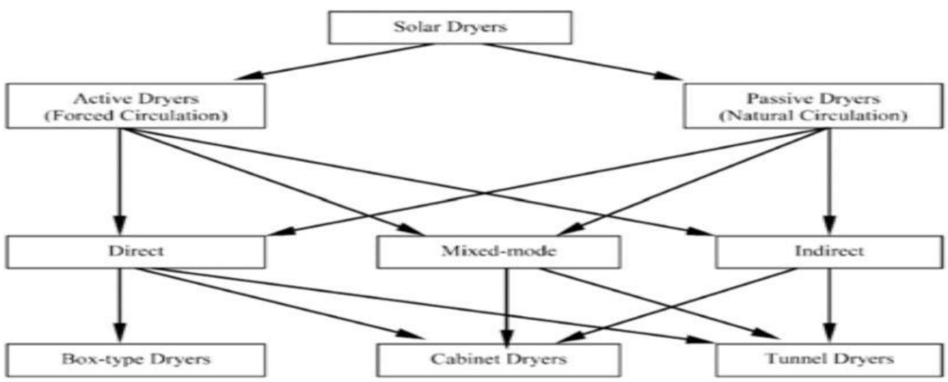


Figure 4Classification of solar dryers drying modes(Hedge et al.,2015)

Mode of exposure of solar radiation

Janjai & Bala (2012) note that there are three groups of solar dryers that are classified under mode of exposure to solar radiation. These are direct dryers, indirect dryers and mixed mode dryers. Direct dryers are those in which crops are directly exposed to solar radiation. They consist of an enclosure with a transparent cover or side panels. The internal surfaces of the closure are painted black so as to further enhance the efficiency. The heat generated from the absorption of the solar radiation within the crops as well as the surfaces of the enclosure causes the removal of moisture (Pahlavan *et al.,* 2011).

Indirect solar dryers are those in which the crops are placed in an enclosed drying cabinet and are protected from direct exposure to solar radiation. They consist of an air heater whose main purpose is to raise the temperature of the drying air and a drying chamber which accommodates the crops as it is the enclosure. In natural convection indirect dryers, a chimney is usually incorporated to increase the airflow through the crop bed (Nkwocha, 2013). Air heated in the collector passes through the drying chamber which contains one or more porous trays where the crop to be dried is placed. The air becomes nearly saturated as it passes through the wet crop bed. As it does so it lowers the temperature to nearly that of the ambient air and then it leaves the dryer via a chimney (Numbing & Maikasuwa, 2015).

A mixed mode dryer is a combination of direct and indirect solar dryer. The dryer usually consists of an indirect dryer with a transparent drying chamber top and/ or sides. They are mainly used for drying crops whose exposure to sunlight is considered essential for achieving the required color or flavor development in the dried produce (Fterich *et al.,* 2018).

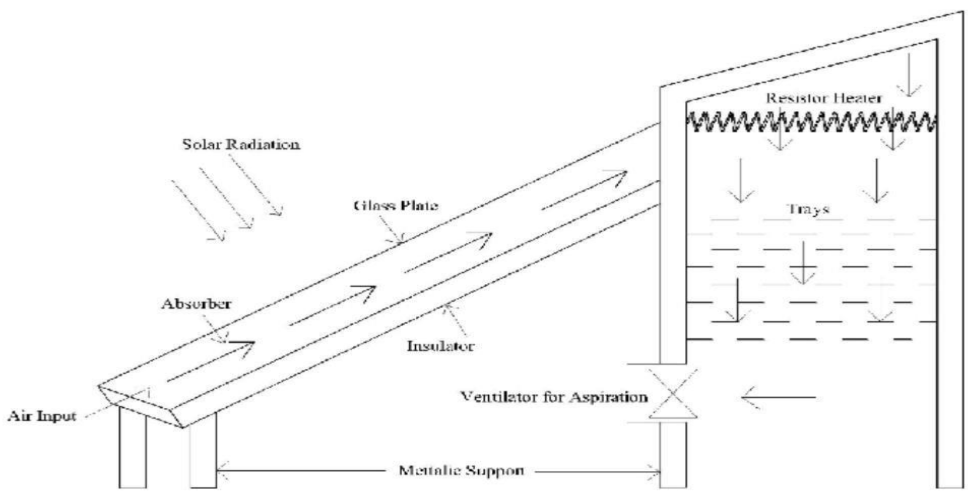


Figure 5Solar drying system with indirect heating(Numbing & Maikasuwa, 2015)

Mode of airflow

Madhava, & Rao (2013) state that solar dryers can be classified according to the mode of airflow that passes through the dryer. A solar dryer can be said to be either a natural or forced convection dryer. Natural or free convection dryers are those which have the flow through the dryer being generated by thermal induced density gradients or flow through the dryer is a result of wind pressure caused by a wind powered fan fitted at the top of the chimney.

Natural convection solar dryers are sometimes called passive dryers. The air circulation of a forced convection dryer depends on the pressure differentials generated by a fan. These types of solar dryers generate much higher air-flow as compared to the air-flow generated by natural convection dryers, thus, making them suitable for drying large loads of crops (Ayua *et al.*, 2017). To overcome pressure drops through the bed crops, high air-flows are required, as well as, through internal thermal energy storage beds, if such thermal storage beds are incorporated in the dryer design. Higher air velocities in the solar collector result in greater collector efficiency. To operate a fan, forced convection dryers require a source of power, which can be electricity or fossil fuel (Mahapatra, & Tripathy, 2019).

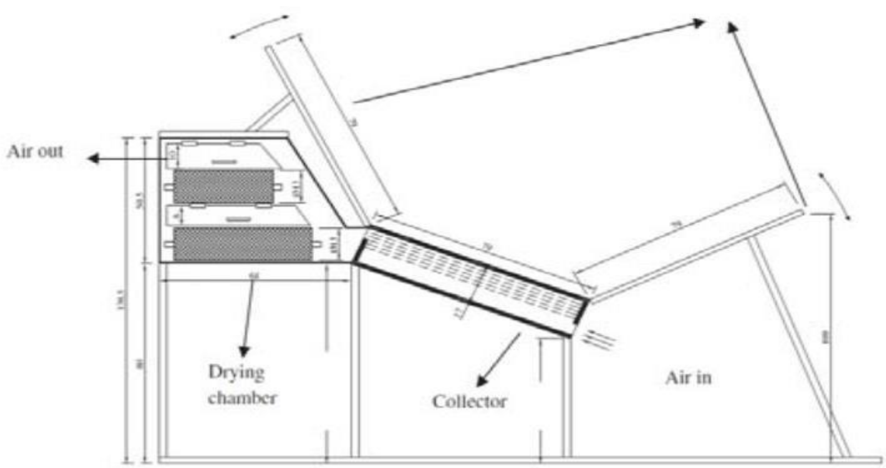


Figure 6 Schematic view of the constructed indirect natural convection solar dryer (Madhavha, & Rao, 2013)

Circulated air temperature mode

The air entering the drying chamber of a solar dryer can either be at higher temperatures or at the ambient temperature. The rise in air temperature is achieved by the passage of air through a solar collector prior to the drying chamber (Nimrotham *et al.*, 2017). If the drying chamber and the solar collector are combined, the dryer is called an integral ducting dryer. Dryers that employ a separate drying chamber and solar collector are called separate ducting dryers. These dryers tend to be more efficient as both the drying chamber and the collector can be designed for the optimum efficiency of their respective functions (Wang *et al.*, 2018).

Design considerations of a solar dryer

There are no uniform design standards applied to all models as far as designing a solar dryer is concerned. This is mainly due to the fact that drying parameters are variable from one product to another (Castillo-Tellez *et al.*, 2017). Knowledge of mass and heat transfer combined with material properties is essential for the designing of a solar dryer as all the processes involved are highly non-linear. Scaling is generally complicated because of this. Field-level familiarity and design experience of pilot scale are helpful for the development of a new solar dryer (Gatea, 2011).

An advanced design will lead to considerable reduction in drying duration and hygienic production of high-quality product. The temperature required for a particular product is also an important aspect for the design of a solar dryer (Yahya *et al.*, 2016). Many commercial designs are evolved out with the market, with the course of time, even though market penetration of solar dryers is very poor. Lack of good designs to perform a suitable requirement and nonawareness about the technicalities can be considered as barriers to large-scale deployment of solar dryers (Baniasadi *et al.*, 2017).

Thermodynamic aspects

The quantity of air needed for drying a specified mass of the food material is based on the thermodynamical aspects. Two methods can be used for such calculations, the energy balance equation for drying and the psychrometric chart (Shiga *et al.*, 2015). The energy balance is an equation that expresses the following idea mathematically, that is, the energy needed to evaporate the amount of water to be removed from the food material should be equal to the energy available from the air going through the food inside the dryer (Dasin *et al.*, 2015).

The removal of water from a surface by evaporation requires a current of air moving over the surface to carry away the water vapour produced plus an amount of heat equal to the latent heat of evaporation of water. The task in solar dryer is to calculate and then achieve optimum temperature, Tf and air flow, ma to remove the specified amount of water, mw (Mitchell, 2018).

It follows that mwL = (Tf−Ti)maCp, where mw = mass of water evaporated; L = latent heat of evaporation and ma = mass of air circulated; Cp = specific heat of air; Tf, Ti = final and initial temperatures. The volume of air can be determined after these by using the gas laws, that is, where mw, the amount of water evaporated can be read from moisture ratio scale or can be calculated from the energy balance equation (Yadav *et al.*, 2018).

The effect of bound water is also to be taken into account because the vapour pressure of bound water in hygroscopic material is less than saturation and the latent heat value should be chosen to correspond to a very low vapour pressure. Various parameters can be evaluated using the equations. The equations are made use of in calculating the quantity of air needed for drying (ma) for various materials to be dried (Sallam *et al.,* 2015).

The amount of air needed for drying a particular quantity of product can be calculated using a psychrometric chart. The capacity of air for moisture removal depends on its temperature and humidity. Psychrometry is the study of the relationship between air and its associated water (Azaizia *et al.,* 2017).

Various thermodynamic properties of moist air such as vapour pressure, relative humidity, humidity ratio, dry bulb temperature, wet bulb temperature, dew point temperature, enthalpy and specific volume can be estimated on the psychrometric chart. All other properties can be determined from the psychrometric chart when any two of the three temperatures are known, that is, dry bulb, wet bulb or dew point (Reyes *et al.,* 2013).

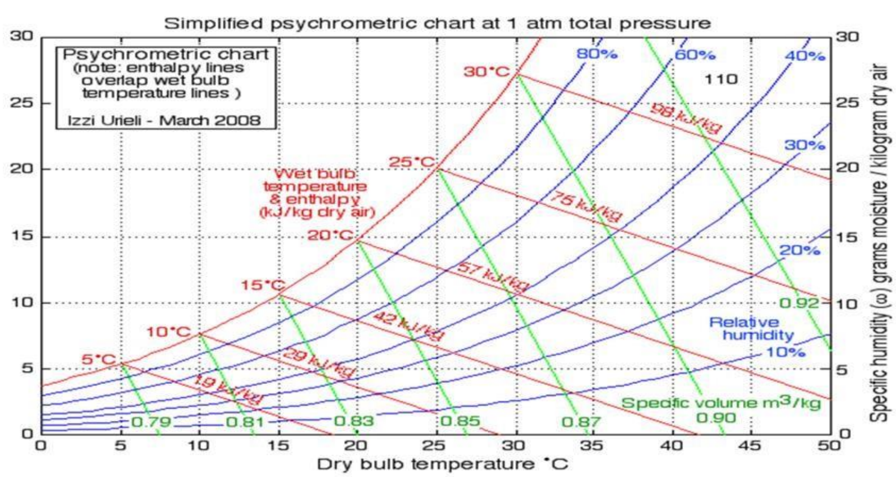


Figure 7Drying Process on Psychometric Chart (Azaizia et al., 2017)

2.4 Design considerations of a solar collector

Air is heated when a solar air collector is irradiated by the sun. The basic components of a solar collector are cover, absorber, insulation and air passage. The absorber is heated by solar radiation transmitted through the cover, which in turn heats the air in the air passage (Qiu *et l.*, 2016).

Advancements in solar drying

In an effort to combat the limiting issues associated with solar drying such as the intermittent effects and weather dependency nature of solar dryers, which have been significant barriers to the effective and efficient use of solar energy, various advancements in solar drying system have been proposed, for example, solar drying system using the V-groove solar collector, double pass solar collector with fins, indirect active hybrid solar–electrical dryer system, solar drying system with chemical heat pump, solar dryer with dehumidification system and solar drying system integrated with thermal heat storage materials (Markowski & Zielinska, 2013).

Thermal energy storage materials

Thermal energy storage (TES) is a technology that involves stocking thermal energy by cooling or heating a storage medium and the stored energy is used at a later time for power generation, heating and cooling applications. Energy storage has become a crucial part of renewable energy technology systems. Advantages of using thermal energy storage in an energy system include reduction in running costs and investment, increased overall efficiency and improved reliability, can lead to better economics, and less pollution of the environment, that is, fewer carbon dioxide (CO2) emissions (Sarbu & Sebarchievici, 2016).

Abedin & Rosen (2011) add that thermal energy storage important technology that can bridge the period between periods when the energy is harvested and periods when it is needed. It is helpful for maintaining the balance between the supply and demand of energy, thus, playing a critical role in increasing the contribution of various types of renewable energy in the energy mix of countries and regions

2.5 Classification and characteristics of storage systems

Thermal energy storage has found its place in thermodynamic systems because of constant variation in solar radiation and intermittency in its availability. It enhances the performance and thermal reliability of a system and reduces the discrepancy between demand and supply by conserving energy, as such, designing an economical and efficient thermal energy is of great importance. A few solar thermal plants around the world have employed thermal energy storage at a large scale (Dincer & Rosen, 2011).

The main types of thermal energy storage materials are sensible, latent and thermochemical. Sensible thermal energy storage systems store energy by changing the temperature of the storage medium and these include water, rock and soil. Latent thermal energy storage systems store energy through phase change, for example, water/ice is used for cold storage applications and paraffin waxes have found their use in heat storage systems (Pavlov & Olesen, 2011). Thermochemical thermal energy storage is more flexible and more complex as compared to other thermal energy storage materials. Storage depending on chemical reactions has much higher thermal capacity than sensible thermal energy storage. The systems are not yet commercially viable. Research and development is still required to better understand and design the technologies and to solve other important practical aspects before commercial implementation can occur (Navarro *et al.,* 2011).

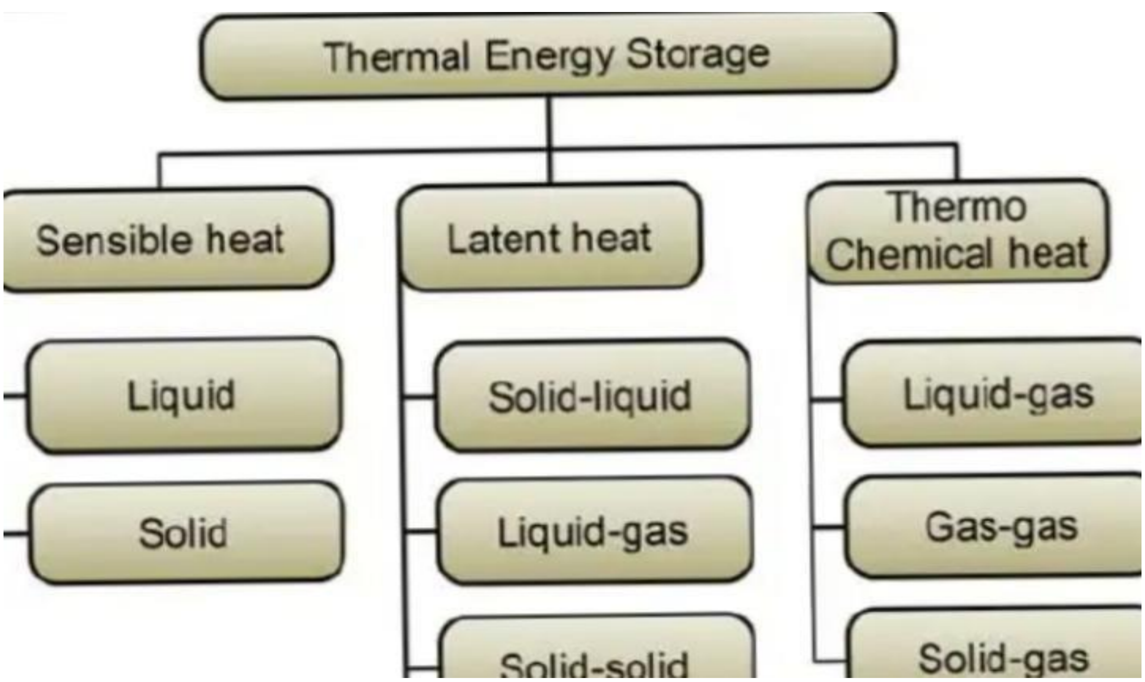


Figure 8Classification of thermal energy storage materials(Pavlov&Olesen,2011)

Sensible heat storage

Sensible heat storage (SHS) systems utilize the change in temperature of the material and the heat capacity during the process of charging or discharging. When the energy is absorbed, the temperature of the storage material rises when energy is absorbed and drops when energy is withdrawn. One of the advantages of sensible heat storage systems is that for an unlimited number of cycles, charging and discharging operations can be completely reversible, that is, over the life-span of the storage (Tian & Zhao, 2013). Other advantages of sensible heat storage materials are that they are cheap and without risks associated with the use of toxic materials. The amount of heat stored depends on the temperature change, specific heat of the medium and the amount of storage material (Sarbu & Sebarchievici, 2018).

There are other parameters which affect the performance of the system which include thermal conductivity, the temperature of operation, thermal diffusivity, compatibility between the storage material and the container, vapour pressure, the cost of the system and stability of the material at the highest temperature of cyclic operation (Lefebvre & Tezel, 2017). The sensible heat Q gained or lost by a material in changing temperature from T_1 to T_2 is

$$Q = m \int_{T1}^{T2} C_p \quad dT$$

$$= V \int_{T1}^{T2} {}_0 C_p \quad dT$$

where m is the mass, C_p is the specific heat, p is the density and V is the volume of the material. From the equation above it can be noted that the higher the specific heat and density of the material, the more the energy that can be stored in a given volume of the material (Sarbu & Sebarchievici, 2016).

There are two types of sensible heat storage, liquid media storage and solid media storage. Liquid media storage can be used for heating or cooling purposes with thermal oil and water being the most popular liquid sensible heat storage materials. Other liquid media storage includes oil-based fluid, ethanol, propanol, glycerine, engine oil and molten salts (Ayyappan *et al.*, 2012).

Solid media storage makes use of solid materials such as copper, rock piles, metals, bricks, sand, wood, concrete, wet and dry earth, aluminum, granite and limestone are the most commonly used storage materials because of their availability and low cost. Generally solid storage materials can store more energy than liquids, are chemically inert and have low vapour pressure hence, can operate under no pressure containing vessel (Bauer *et al.,* 2012).

Solid storage is commonly utilized in low-temperature applications and they generally have a low energy density. Limitations associated with solid media storage is that they cannot be circulated easily as a result they can only be used for passive storage, with a fluid, usually air, being used to transfer heat in and out of a storage tank loosely packed with the solid sensible medium (Alva *et al.,* 2016).

Storage in rocks

Rocks generally take the form of a pebble bed or loosely packed rock pile. Hot air is circulated through the gaps between the rocks during the charging period, while during discharging, cold air is gets heated when it circulates. The large surface area over which the air comes into contact with the rocks enables heat transfer to be efficient. Advantages of using rocks as a sensible storage material are that they have a very low cost, their easy availability, lack of toxicity and are non-flammability (Sarı & Bicer, 2012). Challenges with using rocks include elevated air mass flow rates and increased pressure drops. The quantity of energy that can be stored in rocks depends on its packing density, the thermophysical properties of the solid media, the heat transfer fluid used and the shape and size of particles. For a temperature difference of 50 ℃, rocks and concrete will store approximately 36 kJ/kg (Fan & Khodadadi, 2011).

Concrete

Concrete is very easy to implement as a solid SHS because of its high mechanical strength and also there is no need for a container. The heat exchange can be attained between concrete and a heat transfer fluid (HTF) by circulating the HTF through pipes installed within a concrete block (Sole *et al.,* 2014). The tendency of concrete to crack under repeated cycles of thermal expansion and contraction are a disadvantage in high temperature applications, presently work is being carried out to develop the optimal mixing method so as to enhance its chemical and physical properties and durability at higher temperatures. In terms of energy density, 400 kWh of energy can be stored in 20 m^3 of concrete (Tripathy, 2015).

Sand

Fine-grained materials such as gravel and silica sand have a good capacity for thermal energy storage. This is commonly achieved in beds of 0.2–0.5 mm diameter sand grains and using air as an HTF. Beds such as these have been shown to have storage potential up to 550 ℃ (Song *et al.,* 2011). The finer the sand, the greater the packing density. Gravels have larger grains, c.a. 0.4 mm in diameter. Basalt gravel grains can be directly used to collect solar thermal energy in a solar receiver. The gravel grains drop under gravity from the top of the receiver tower and absorb heat from concentrated solar rays as they fall. The sand can reach temperatures of 700– 1000 ℃, is then collected at the bottom and employed to produce steam to drive a Rankine cycle power plant (Saffa *et al.*, 2013).

Bricks

Bricks can be used to store thermal energy and thereby reducing electricity costs for space heating. They are heated using cheaper off-peak electricity at night and the stored heat is then extracted during the day through natural radiation and convection or with an electric fan used to force convection. This minimizes the cost of heating during the hours when peak electricity prices are in effect (Babagana *et al.*, 2012).

Factors to consider when selecting a sensible heat storage material

Khare et al. (2012) note that there are many factors to consider when selecting a sensible heat storage material. Some of the factors to consider include:

- Power defines how fast the energy stored in the system can be discharged and charged
- Efficiency is the ratio of the energy provided to the user to the energy needed to charge the storage system. It accounts for the energy loss during the storage period and the charging/discharging cycle
- Capacity defines the energy stored in the system and depends on the storage process, the medium and the size of the system
- Cost refers to either capacity (USD/kWh) or power (USD/kW) of the storage system and depends on the capital and operation costs of the storage equipment and its lifetime (the number of cycles)

- Charge and discharge time defines how much time is needed to charge/discharge the system
- Storage period defines how long the energy is stored and lasts hours to months (number of hours, days, weeks, and months for seasonal storage

Insight from literature

Ayyappan *et al.* (2015) conducted an experiment to improve the thermal performance of a natural convection solar greenhouse dryer using concrete, sand and rock as sensible heat storage materials. Various experimental trials were run for different materials and they found that for both sand and rock a 4-inch thickness layer was the optimum solution to provide better drying during the day and night. Coconut was used as the drying product during the experiment. When concrete was used to store heat energy, the dryer system was able to lower the moisture content of coconut from 52 % (wet basis) to 7 % (wet basis) in 78 hours in comparison to open sun drying which takes 174 hours. This indicated a saving of drying time by about 55 %. When heat energy was stored using sand, the drying time of coconut was reduced to 66 hours with a saving of 62 % of drying time as compared to open sun drying. If rock was used, the drying time was further reduced to 53 hours, saving the drying time by about 69 %. According to their results, rock provided the highest thermal efficiency of 11.65 % while sand yielded the least thermal efficiency of 9.5 %.

Halil (2017) designed an indirect solar dryer for apple slice drying. Dryer is attached with packed bed thermal energy storage. To recover the waste heat from the dryer used a recuperator. It used for mixing the fresh air with waste heat to improve more moisture diffusion. So the drying rate increase up to 60%. Initial moisture in apple slice is 20% but to prevent it from spoiling it should be reduced to 10%. Size of the apple slice was maintained 2 to 5mm. for the 8Kg of capacity total 12 experiments performed to take all readings. Mathematical model analysis also done to measure the moisture removal rate and solar collector efficiency. Furthermore, packed bed energy storage system can provide more energy if required for drying after the sun shine hours.

Control systems components

Temperature controlling devices

Temperature is a critical parameter in solar drying since it greatly influences drying time of agricultural produce. A temperature deviation by a couple of degrees can result in an under dried or over-dried product. The drying temperature is generally monitored with accuracy not less than ± 0.5°C. Stainless steel Pt100 sensors are normally used for temperature measurements (Sharma, 2020)**.**

2.6PID control systems

The process parameters which are measured using probes may be controlled using control loops. A control loop consists of four components; a measuring element, a controller, a final control element and the process to be controlled. A simple type of control is feedback control in which the measuring element senses a process property and generates a corresponding output signal (Tchaya, 2018). The controller compares the measurement signal with a predetermined desired value (set point) and produces an output signal to counteract any differences between the two. The final control element receives the control signal and adjusts the process by changing a valve opening or pump speed and causing the controlled process property to return to the set point. In Manual control system a plant operative is instructed to monitor the data throughout the time and will take appropriate action in case change from the set point (Reyes *et al.*, 2014).

PID

A proportional-integral-derivative controller (PID controller), is a generic control loop feedback mechanism widely used in industrial control systems. A PID controller attempts to correct the error between a measured process variable and a desired set point by calculating and then outputting a corrective action that can adjust the process accordingly. The PID controller calculation (algorithm) involves three separate parameters, which are, the Proportional, the Integral and Derivative values (Tullberg, 2014).

The Proportional value determines the reaction to the current error, the Integral determines the reaction based on the sum of recent errors and the Derivative determines the reaction to the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve or the power supply of a heating element (Wang, 2014).

By "tuning" the three constants in the PID controller algorithm the PID can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation (Sarrouy & Lillywhite, 2012). The use of the PID algorithm for control does not guarantee optimal control the system. Some applications may require using only one or two modes to provide the appropriate system control. This is achieved by setting the gain of undesired control outputs to zero (Salam, 2015). A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions. PI controllers are particularly common, since derivative action is very sensitive to measurement noise, and the absence of an integral value prevents the system from reaching its target value due to the control action (Abakarov, 2012).

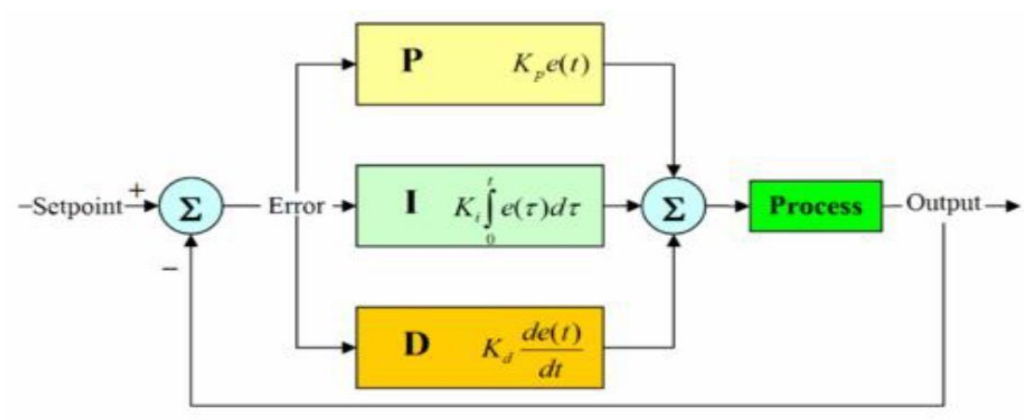


Figure 9A block diagram of a PID controller(Abakarov,2012)

The PID control scheme is named after its three correcting terms, whose sum constitutes the manipulated variable (MV). Hence:

$MV(t) = Pout + Iout + Dout$

Controllers

Sims *et al.* (2011) suggest that to accurately control temperature without extensive operator involvement, a temperature control system relies upon a controller, which accepts a signal from temperature sensor such as thermocouple as input. It compares the actual temperature to the desired control temperature, or set point, and provides an output to a control system and the whole system should be analyzed in selecting the proper controller. The following items should be considered when selecting a controller:

- Type of input sensor and temperature range
- Type of output required (electromechanical relay, solid state relay, analogue output)
- Control algorithm needed (on/off,).
- Number and type of outputs (heat, cool, humidity).

These controllers reduce the common problem of over-ventilation and have often been shown to significantly reduce fuel consumption (Nkwocha, 2013).

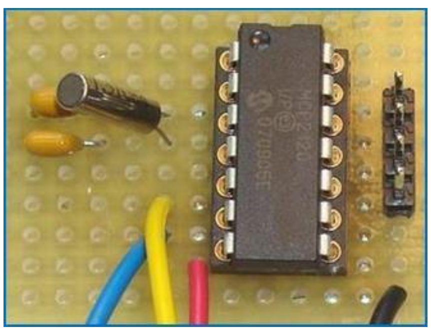


Figure 10Microcontroller(Source:www.st.com)

2.7 Types of temperature sensors

LM35 Sensor

LM35 sensors find application in humid environments since the sensor circuitry is sealed and not subjective to oxidation. The LM35 is an integrated circuit sensor that can be used to measure temperature with an electrical output proportional to the temperature (in degrees Celsius). It does not require any external calibration or trimming and maintains an accuracy of +/-0.4 degrees at room temperature and +/-0.8degrees over a range of 0 to 100 degrees Celsius (Zoukit *et al.*, 2016).

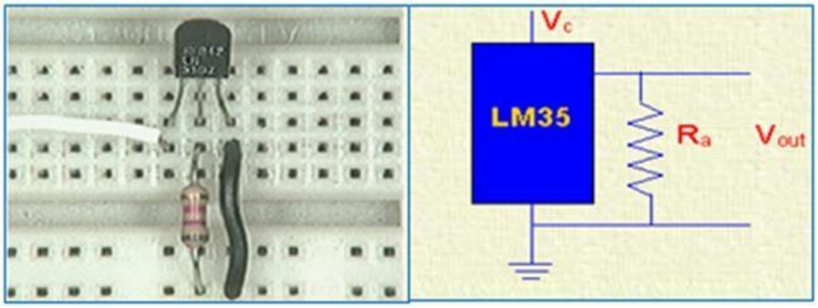


Figure 11LM35 Sensor (Source:www.facstaff.bucknell.edu,image by unknown)

The LM35 comes in many different packages, including the following:

- TO-92 plastic transistor-like package.
- TO-46 metal can transistor-like package.
- 8-lead surface mount SO-8 small outline package.
- TO-202 package

Thermocouples

A thermocouple is a device made of two different wires called a junction end. The junction is immersed in the environment whose temperature T2 is measured, which can be for instance the temperature of the incubator at 22°C, while the tail end is held at a different temperature T1 at ambient temperature. Because of the temperature difference between junction end and tail end, a voltage difference can be measured between the two thermo elements at the tail end. The thermocouple is a temperature-voltage transducer (Nkwocha, 2013).

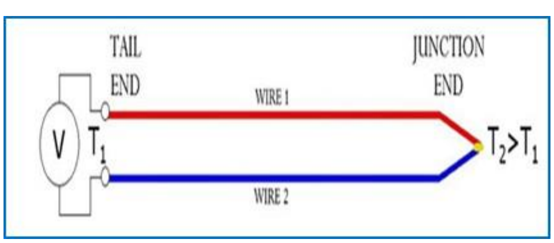


Figure 12Thermocouple sensor(University of Cambridge)

The electromagnetic force produced is directly proportional to the temperature differences. The temperature-voltage relationship is given by:

$$\text{Emf} = \int_{T1}^{T2} S_{12} dT$$

$$= \int_{T1}^{T2} S_1 - S_2 dT$$

S12 is called See beck coefficient of the thermocouple and S1 and S2 are the See beck coefficient of the two thermos elements. The See beck coefficient depends on the material the thermo element is made of (Salam, 2015).

2.8 Humidity sensors

Humidity sensors, also known as hygrometers, are used to measure humidity levels in the atmosphere. There are different types of humidity sensors. They are used to detect the level of moisture in the air. Humidity sensors measure humidity through electrical capacitance (Sims, 2011). They control humidity levels by measuring moisture and air temperature, and reporting the relative humidity (RH) in the air. Their purpose is to ensure that a constant temperature is maintained. Humidity sensors contain a sensor mechanism that enables them to become aware of electrostatic changes in the air. The change is detected and transformed into a digital reading, which displays the level of moisture in the air (Wang, 2014).

2.9 Application and the use of solar dryers in Zimbabwe and around the world

Greenhouse solar drying of red chillies in Burma

The dryers consist of a forced ventilation system and a greenhouse type tunnel drying unit. The ventilation system ensures that the circulation of air inside the greenhouse solar dryer and moisture removal is entirely powered by solar panels (Madhava & Rao, 2013).

Figure 13Greenhouse solar drying of red chillies (Madhavha & Rao,2013)

Drying of Mangoes in Uganda using solar dryer

The solar dryer in Uganda that is used to dry mangoes is designed from basic materials locally available and is constructed by local crafts-men. The solar dryer measures about 4 m long, 1.5 m wide and 0.5 m high and is covered in plastic sheet (Hoang *et al.,* 2021). The cabinet has steel legs which are placed above the ground. The frame is covered in plastic which is standard UV-stabilized agricultural polythene (Ndukwu *et al.,* 2018).

Figure 14Solar drying of mangoes in Uganda (Ndukwa et al.,2018)

Zimbabwe Solar Dryers (ZSD)

The Zimbabwe Solar Dryers (ZSD) is an organization that manufactures solar dryers for small and large scale producers, entrepreneurs, and households looking to preserve and add value to their crops and fresh produce. The dryers have been successful in drying various fresh fruit and vegetables including mangoes, bananas, tomatoes, apples and leafy vegetables, all of which are grown and eaten within Zimbabwe. The dryers have over 2 square meters of drying space in each section of the dryer and the smaller dryers can dry upward of 10 kilograms of heavier fruits such as mangoes in less than 2 days, with leafy vegetables emerging ready for packaging after just a few hours (Mandisvika *et al.,* 2015).

Figure 15Cabinet solar dryer for green leafy vegetables (Mandisvika et al., 2015)

Conceptual Framework

Solar drying is one of the most cost-effective, efficient, renewable and sustainable technologies used to preserve agricultural products in sub-Saharan African (SSA) countries. It is conceptualized that the use of an improved solar dryer optimized with a sensible heat storage material will improve the thermal performance of the dryer and also address the limiting factors associated with conventional drying (Lingayat *et al.*, 2020). The dryer will improve the livelihoods of farmers, increase their income, enhance food security and also improve households' nutritional statuses (Ssemwanga *et al.,* 2020).

The variables in the research are drying efficiency, drying rate, temperature, relative humidity, solar irradiation and the dynamics of moisture content of agricultural products with time.

Assuming that other factors remain constant during the study's performance, it will be possible to relate the variables and confirm that the improved dryer optimized with a sensible heat storage material will increase the drying temperature, lower the relative humidity, decrease the drying time of agricultural products and effectively reduce the moisture content of agricultural products to their final recommended safe moisture levels (Matavel *et al.*, 2021; Veremachi *et*

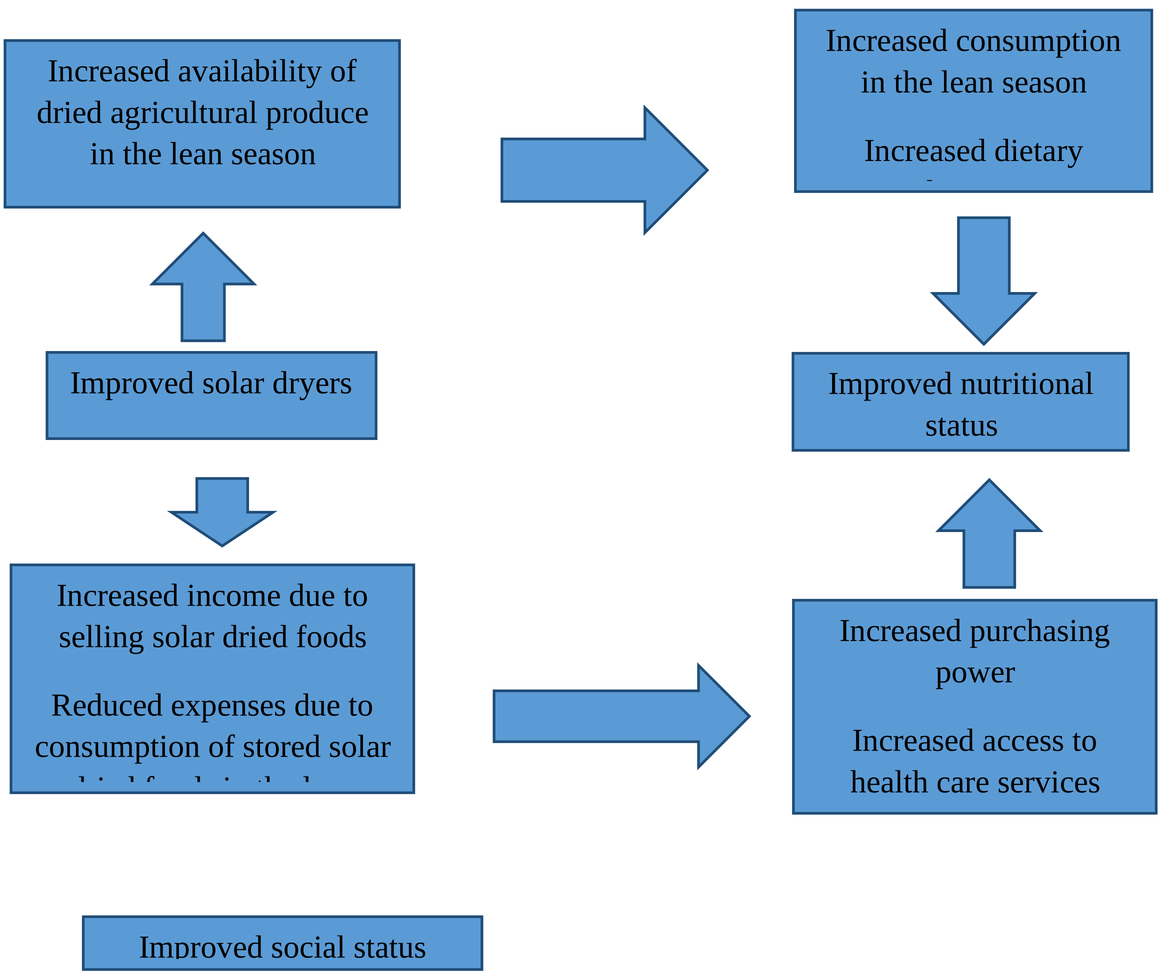


Figure 16 Conceptual framework (Source: Author)

Summary of literature review

The chapter devoted to literature review. It began with the introduction, fresh produce production trends in Zimbabwe, theories of drying, drying curves, mechanisms of drying and mathematical models. The chapter also dwelt on traditional methods of drying, solar drying, their advantages and disadvantages, factors to consider when designing a solar dryer, advancements in solar drying, control systems components, different types of thermal heat storage materials and factors to consider when selecting a thermal heat storage material for use. Insights from literature were also looked at. The chapter highlighted the application of solar dryers in Zimbabwe and around the world and closed with the conceptual framework.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter focuses on the description of the methods employed in the study. It focuses on the research design, the description of the study area and the methods of data presentation used in the research.

3.2 Description of study area

The town is located in Makoni District in the Manicaland Province. Rusape is a midsized town with a population of approximately 29292 people .It is located approximately 75km away from Mutare and about 138km from Zimbabwes capital Harare.It is in natural region 1.

3.3 Research design

The research design includes the methods and considerations made to come up with possible options and parameters that will help in producing the best solar dryer design that is more efficient and economically feasible. The design-focused models below focused strongly on the technical aspects of solving the design problems, prescribing or describing the steps considered to be necessary to advance from problem to solution. The research design followed the Pahl and Beitz (2007) model.

3.3.1 Research Model

Pahl and Beitz (2007) divided their model into four phases which are:

- Product planning and clarifying the task
- Conceptual design
- Embodiment design
- Detailed design

The approach acknowledges that due to the use of complex nature of modern technology it is now rarely possible for a single person to undertake the design and development of a major project on their own.

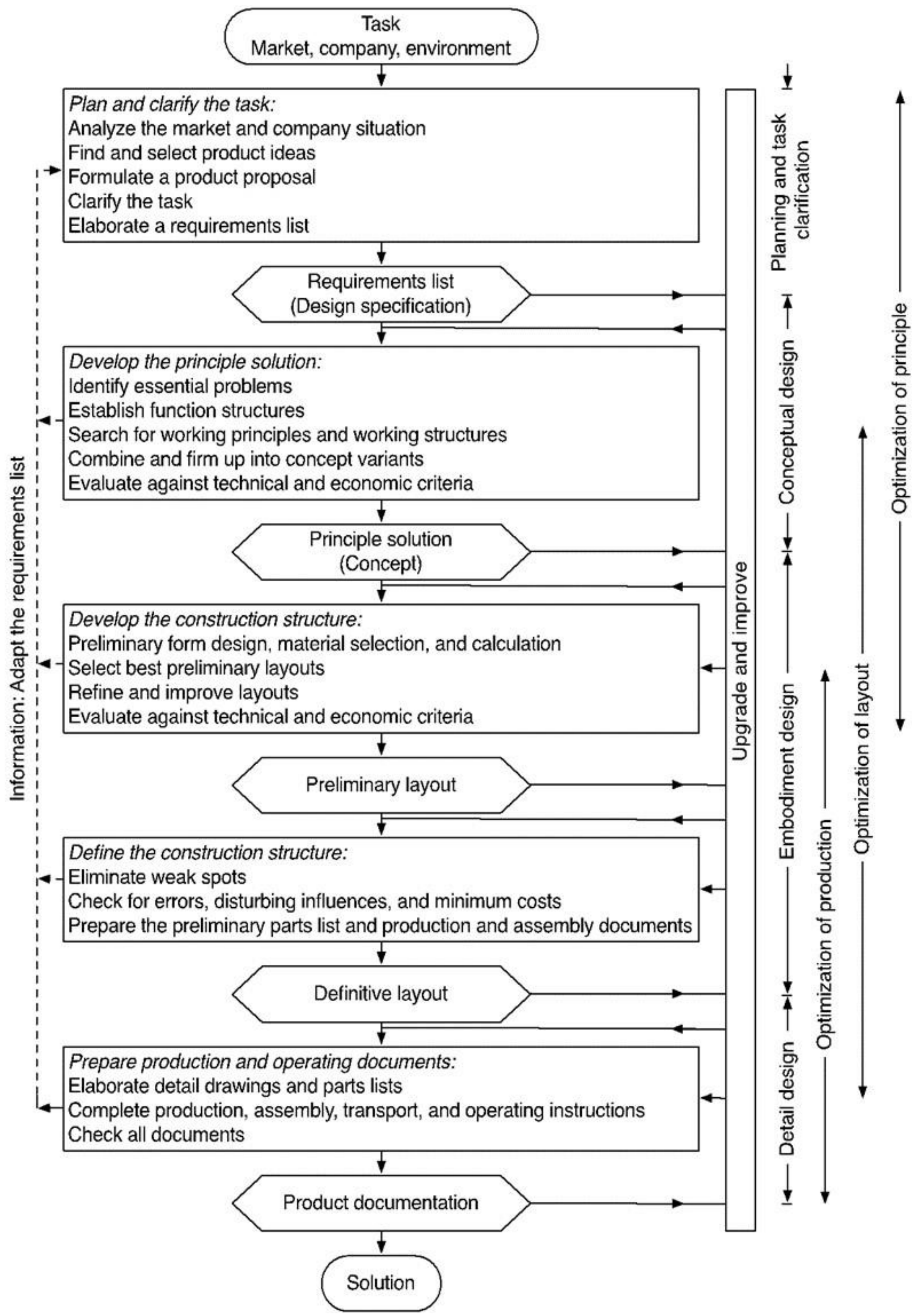


Figure 17The design process as proposed by Pahl and Beits(2007)

3.3.2 Planning and clarification of Task

The task of this research study was to design and fabricate an improved solar dryer optimized with a sensible heat storage material for drying agricultural produce for smallholder farmers in Rusape.

3.3.3 Conceptual Design

The solar dryer consisted of a solar collector, drying chamber, air flow system and a sensible heat storage material compartment to enable continuous processing of fresh produce. A temperature and humidity control and monitoring system was incorporated to maintain a constant temperature (below 60℃) and to measure humidity throughout the drying process.

Essential problems

Moisture content was a parameter that affects the shelf life of fresh produce. Inadequate drying results in high moisture content in fresh produce which leads to rapid spoilage and deterioration which, in turn, decreases the fresh produce market value, diminishes income and increases food insecurity.

Function structures

The design of the solar dryer consisted of the following components:

- Dying chamber
- Solar collector
- Air flow system
- Thermal energy storage material compartment
- Temperature and humidity control and monitoring system

3.3.4 Conceptual Solutions

A concept is an approximate description of the working principle, technology and form of the product. According to Lamidi *et al.* (2019) the best solution is regarded as one that would offer the greatest benefits and advantages. A distinction such as this can be made between alternatives subject to the problem of making value measurements. Three alternative concepts were generated. The three alternative concepts were drafted and designed using Autodesk AutoCAD 2007. The best concept was chosen as the detailed design.

Concept one

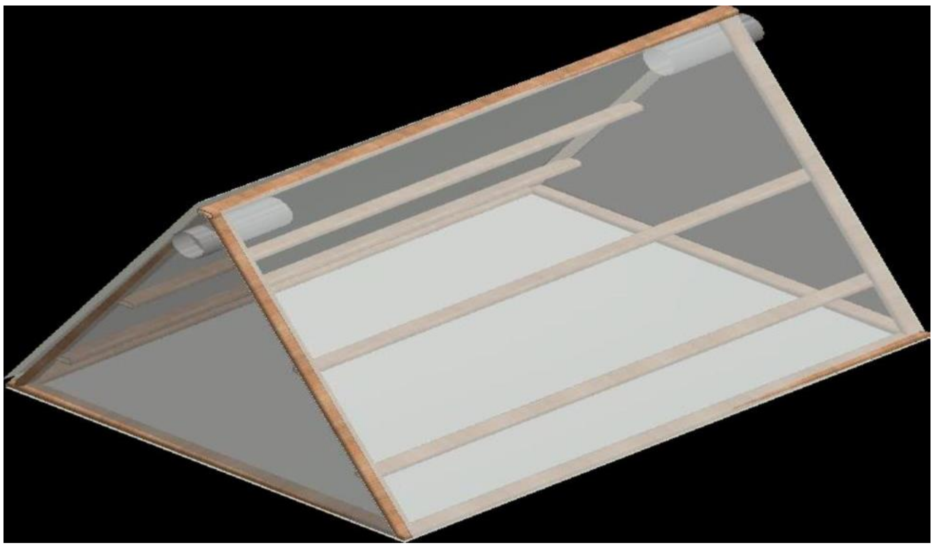


Figure 18Concept drawing for alternative design one(Source: Author)

Operating principle

The tent dryer is a natural convection solar dryer. The concept is based on the 'single front pass' principle. A black inner tent polyethylene or cardboard converts the solar radiation into heat. Openings are left at the bottom and top sides (Bala & Janjai, 2012). The heat is contained by an outer roof of two layers of clear polyethylene sheet that are large enough to enclose the entire tent. The air between outer and inner tent heats up and rises to the top. It enters the tent and mixes with the cooler air. The cool air at the bottom is drawn into the air layer (Dasin *et al.,* 2015). The air warms up and rises. White vertical stripes form a pattern on the black surface. This improves the circulation by differential absorption (Musembi *et al.,* 2016).

To avoid heat loss by conduction, the tent is placed on an insulated black floorboard. The frame of the tent is placed on black stones or bricks. The black floorboard converts additional incident solar radiation into heat which provides extra heat at the bottom of the tent (Aboltins & Palabinskis, 2016). The blocks also function as heat storage by slowing down the cooling of the tent overnight. Fresh produce is placed on trays which are raised above the floor of the tent so as to allow heating from all sides. It is possible, with this design, to create temperatures inside the dryer that range from 75°C in the top, 66°C in the middle, to 55°C at the floor (Mohana *et al.*, 2020).

Design evaluation

The tent solar dryer is cheap and easy to fabricate. It protects fresh produce from dust, dirt, rain, wind and predators. It can also be taken down and stored when not in use. Loading and unloading of fresh produce is very simple. It requires one operator; hence it involves low labour costs (Abdullahi *et al.,* 2013). The design is integrated with rocks which are sensible heat storage materials that can increase the efficiency of the dryer. Drying period of fresh produce is shorter as compared to open-sun drying. On the flip-side, there is a tendency to over-dry fresh produce at the upper trays and the dryer can be easily damaged by strong winds (Hii & Ong, 2012).

Concept Two

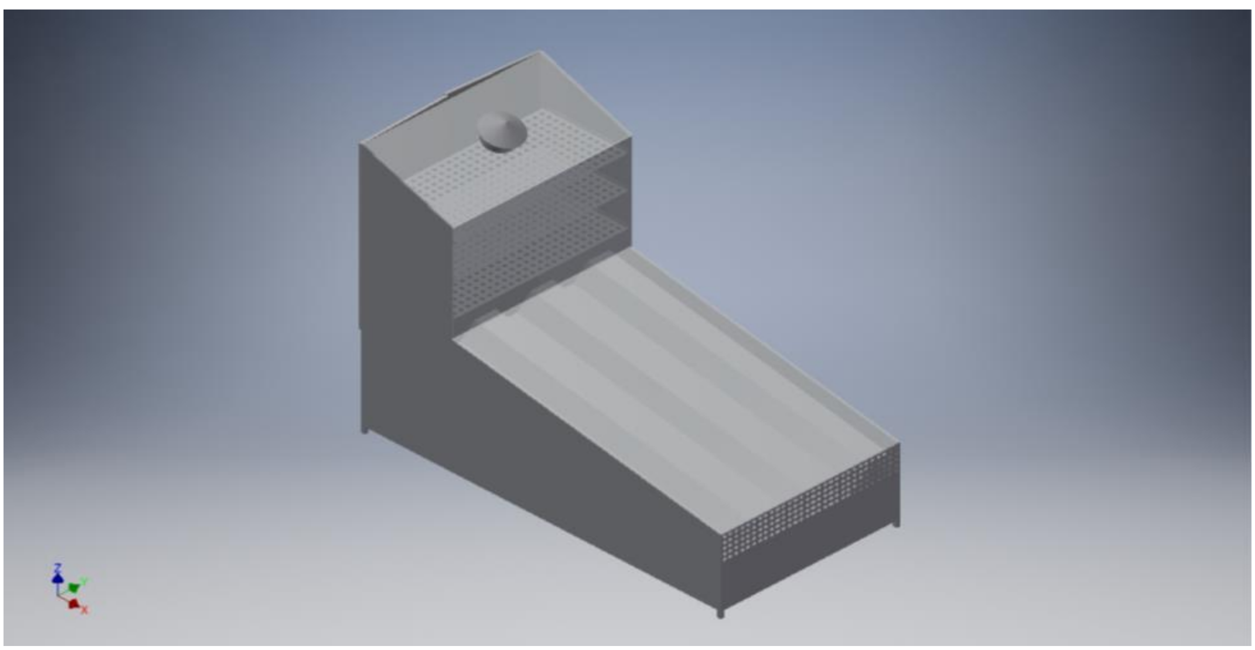


Figure 19Concept drawing for alternative design two(Source:Author)

Operating principle

The design operates in natural convection and in a discontinuous way. It consists of a solar collector, drying chamber and a thermal energy storage material compartment in the drying chamber below the trays where fresh produce is placed. The solar collector consists of a black surface which is the absorbent of the incident solar energy, a glazing cover, which is a transparent layer that transmits radiation to the absorber, but prevents radiative and convective heat loss from the surface (Ibrahim, (2013). It also consists of a support structure that protects the components and holds them in place. The sides and the bottom of the collector are insulated to reduce heat loss (Lakshmi *et al.*, 2018).

The solar collector absorbs the incoming solar irradiance, converts the solar irradiance into heat, and transfers the heat to a fluid, which is air. The air flows between the absorber and bottom of the collector. Fresh produce is laid out on trays in the drying chamber allowing the passage of the air (Olimat, 2017). The heated air enters the drying chamber and then passes over the fresh produce. It exits upwards through the chimney. As it does so, it takes the moisture released from fresh produce with it. The thermal performance of the dryer is improved by the sensible heat storage material (Numbing & Maikasuwa, 2015).

Design evaluation

The advantage that this design has is that heated air moves from the solar collector into the drying chamber where textured vegetable protein is placed on trays. This ensures heat transfer to the fresh produce as heat travels by convection (Tian & Zhao, 2013). It also consists of thermal energy storage material which improves the thermal performance of the dryer as continuous processing is enabled. The design makes use of one operator and is convenient in cases where personnel are less skilled (Zoukit *et al.*, 2016).

The materials required for the construction of the design are affordable and readily available. It is also easy to fabricate (Umogbai & Iorter, 2013). On the flip-side the design of the door does not give provision of display to which the operator can view the fresh produce through it. The door is opened each time the operator wants to view the products inside. Opening the door during drying affects the temperature inside the drying chamber (Salim *et al.*, 2016).

Concept three

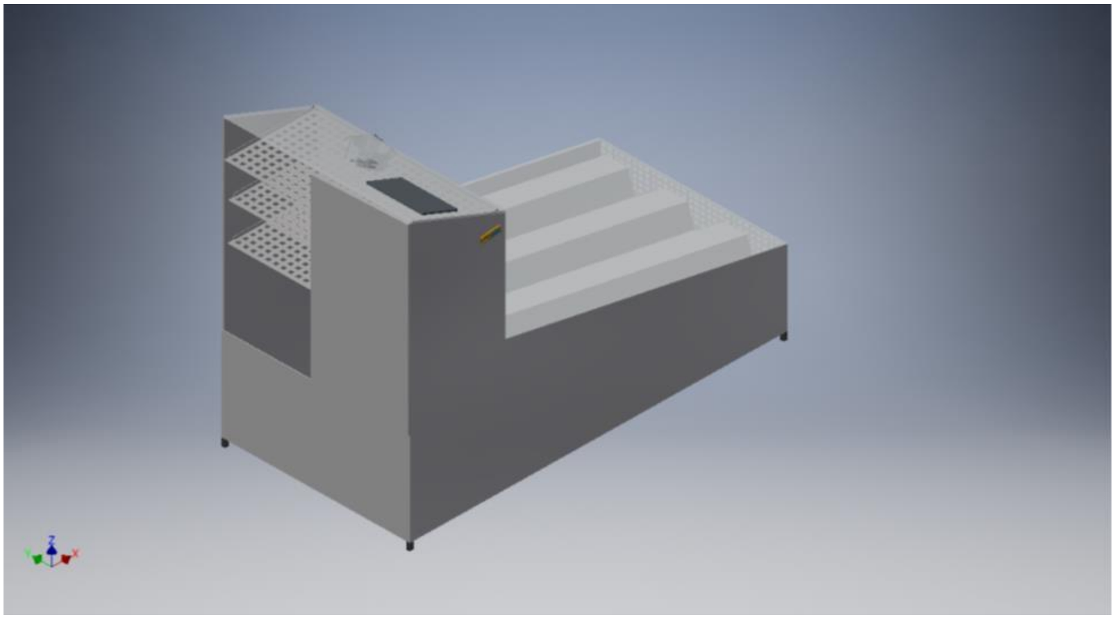


Figure 20Concept drawing for alternative design three (Source: Author)

Operating principle

The design is an indirect forced convection solar dryer. It consists of a solar collector, a drying chamber with a chimney, a fan, a compartment with sensible heat storage material in the drying chamber below the tray where fresh produce is to be placed and dried, a solar panel, a battery, an insulator and a temperature and humidity control and monitoring system (Salim *et al.*, 2016). The solar collector consists of a black surface which is the absorbent of the incident solar energy, a glazing cover, which is a transparent layer that transmits radiation to the absorber. It also consists of a support structure that protects the components and holds them in place. The sides and the bottom of the collector are insulated to reduce heat loss (Mitchell, 2018). The solar collector absorbs the incoming solar irradiance, converts the solar irradiance into heat, and transfers the heat to a fluid, which is air. The air flows between the absorber and bottom of the collector (Mustayen *et al.*, 2014).

Fresh produce is placed on trays in the drying chamber allowing the passage of the air. The heated air enters the drying chamber and then passes over fresh produce. It exits upwards through the chimney. As it does so, it takes the moisture released from fresh produce with it. The solar panel charges the battery which the source of power for the control system (Kusum & Wadhawan (2018). The purpose of the control system is to control and monitor temperature and humidity. The fan maintains the desired air flow rate to the drying chamber. The sensible heat storage material absorbs and stores excess heat energy during sun peak hours and releases thermal energy during off sun peak hours, thus maintaining a regulated temperature, improving the drying process and promoting continuous processing (Mghazli *et al.*, 2017).

Design evaluation

The design has a temperature and humidity control and monitoring system. Solar drying under controlled conditions of temperature, humidity and moisture removing rate promotes perfect drying and desirable fresh produce quality. The fan quickly sucks out hot air when the temperature rises from the set point, thus maintaining required drying temperatures. The sensible heat storage material improves the thermal performance of the dryer. To enable on the operator to view the product, a transparent material is incorporated in the design (Gatea, 2011).

The design of the door is such that it is locked during the drying process. When fresh produce has dried to their required recommended moisture content the dryer signals are sent to the controller and the result is that light will flicker and a ringing sound is heard. This is so as to alert the operator that fresh produce has dried. There is scaling up of material and utilities required to this design as compared to alternative design 2. The materials required are affordable and available locally (Desisa & Shekata, 2020).

Concept selection

The solution that offers the greatest advantages and benefits is the best solution. Each alternative is to have some rating that result from a value judgment. The set of ratings will be tabulated in the form of a matrix. The alternative with the most favourable subset of ratings will be selected as the successful contender in the list (Illinois, 2017).

selection Criterion

The study made use of a two-stage concept selection methodology which gave a detailed comparison between the proposed concepts. It also gave a quantitative evaluation using scoring matrix and screening as a guide. Effectiveness and feasibility were the key evaluative criteria for concept screening in selecting the best possible solution. A thorough analysis of the three solutions was done. A comparison of the analysis was made in order to find the most suitable solution for the problem at hand. A rating scale was developed which was based on the researcher's judgment in exactly the same way. The study made use of the Concept Selection Criteria which is applied in Product development. A reference scale (+ - 0) was used. The positive rating was used to refer to good features of a concept. A negative rating indicated bad features regarding a concept. The concept with the least ranking was rejected.

Table 3.1: Concept screening

Criteria	**Reference**	**Concept 1**	**Concept 2**	**Concept 3**
Drying efficiency	0	0	0	+
Performance	0	0		+
Product safety	0	-	+	+
Pluses		0	2	3
Same		0	0	0
Minuses		1	0	0
Net		-1	2	3
Rank		3	2	1
Contain		NO	YES	YES

Table 3.2: Concept scoring

		Concept 2		**Concept 3**	
Criteria	**Weight**	**Rating**	**Weighted score**	**Rating**	**Weighted score**
1. Drying efficiency	0.4	3	1.2	4	1.6
2. Performance	0.5	4	2	5	2.5
3. Product safety	0.3	3	0.3	3	0.3
Total score			**3.5**		**4.4**

Rank	**2**	**1**
Decision	**Reject**	**Develop**

Selected Solution

Concept three proved to be best solution for the desired application as demonstrated by the magnitude of its total points shown in the Table above. There are no complicated manufacturing processes that are required for the design. The design possesses all the essential features for the effective functionality of the solar dryer.

Tomato (*Solanum lycopersium*), was the vegetable to be dried in this research study. It is perennial and also the second-largest cultivated vegetable (after potato). It is cultivated throughout the world and is one of the most popular vegetables due to its numerous health benefits and the range of products available in the market. Tomato consumption is linked to reduced risk of cardiovascular and chronic diseases and cancer (Adenike, 2012). Recent studies have also reported the relation between tomato consumption and tomato products with brain health, improved skin and bone health.

Tomato has a high moisture content with an average initial moisture content of around 90% or more (Davis variety). Such a high moisture content makes the tomato susceptible to postharvest deterioration, nevertheless, drying of tomatoes has been useful to increase the shelf life of this perishable commodity since ages (Eze & Ojike, 2012). Tomatoes should be solar dried to a final moisture content of 10% with temperatures between 45-60℃ (Karaaslan *et al.*, 2019).

Stones was the selected sensible heat storage material to be used in this study. Stones was chosen due to its abundance, availability and cost.

3.4 Detailed design

3.4.1 Material selection for the fabrication of the solar dryer

The material for the construction of the solar dryer was selected on the basis that it was chemically inert such that it did not leach elements into the medium or chelate elements (principally metal ions) from the medium. The requirement for the material of construction to be chemically inert is a regulation that guides in the selection of materials for equipment, as laid down by the (FDA, 2013).

The design of the solar dryer used stainless steel. This is because stainless steel is corrosion resistant and more durable as compared to other materials. Stainless steel is the preferred surface for food equipment and is specified in many industry and regulatory design and construction standards (Lervada & Budaciu, 2012). Sanitary Standards specify AISI 300 series, that is, 304 and 316 stainless steel, however, not all grades are recommended for food contact surfaces. Soft metals such as aluminium, brass, copper or mild steel can also be used for food contact surfaces and care should be taken in their cleaning as some cleaning agents can attack their surfaces (Schmidt, 2015).

3.4.2 Cost benefit analysis of the chosen solution

Table 3: **3** Cost benefit analysis of the chosen solution.

Item	**Quantity**	**Cost($)**
Stainless steel sheet	1250×2400	90
Stainless steel hinges	4	12
Solar panel	1	55
Battery	1	50
Perspex	1.2×0.6m	40
Tempered glass	1.6×0.8m	95
Mash wire	0.90×0.8m	30
Foam	1.8×0.8×1.0m	10
Fan	1	30
Reverts	50units	25
Black paint	1	10
Microcontroller	1	15
Buzzer	1	4
Pic holder (40 pin)	1	4

LCD	1	15
Electrical appliances	Array of materials	90
Angle iron	3	21
Total		596

To design the solar dryer, a total amount of $596 was required

3.4.3 Cost benefit analysis of the solar dryer

Generally, solar dryers are capital intensive and for that reason financial feasibility is key to compete with any of the other commercial dryers. The financial analysis commonly includes the cost of dryer (fixed cost), cost of drying (operating cost) and payback (Magdalena *et al.*, 2018). Solar dryers can be viable only if the yearly cost of extra investment on the solar dryer could be balanced against fuel savings, or if the equipment cost could be reduced. The dryer design optimizes cost, energy efficiency, quality, and price of the final product (Malaisamy *et al.*, 2012). Payback is the measure of time, that is, number of days, months or years it takes to regain the total investment of the dryer rather than seasonal use which will decrease the drying cost and payback. Economic analysis on a solar dryer should also incorporate the cost benefits due to enhanced quality, higher yields, reduced floor area and more rapid drying (Pavlov & Olesen, 2011).

Production costs = $596×1 phase in a year

= $596

Labour cost = 2 operators needed each paid $300/month

= (2×12×300)

= $7200

Depreciation =10% per month calculated using straight line method on value of the dryer

= (0.1×12×596)

=$715.20

Maintenance costs = 8% on the value of the dryer

= (0.08×12×596)

= $572.16

Overhead expenses

Rent $200 per month =$2400

Insurance $70 per month =$840

Others $150 per month =$1800

Total costs per year =$14 123.36

Benefits

Total sales of dried tomato slices per month = ($1150×12)

= $13800

Payback time = total costs÷ total benefits

= $(14 123.36÷13 800)

= 1.023

= 1 year

The payback period is 1year which indicates that the design is worth investing.

3.4.4 Design features and function analysis of the solar dryer

The design consists of the following:

3.4.4.1 The drying chamber

The drying chamber houses the sliced tomatoes during drying. It consists of three aluminum perforated trays. The trays hold the sliced tomatoes during the drying process (Qiu *et al.*, 2016). The trays were evenly spaced to allow maximum heat flow. The fan is fixed in the chimney of the drying chamber and forces the ambient air to pass through the collector and rise up through the sliced tomatoes being dried. A sensible heat storage material compartment with stones, raised to a height of 10mm, was placed at the base of the drying chamber below the trays holding the tomato slices being dried (Singh & Gaur, 2020).

3.4.4.2 The solar collector

The solar collector is attached to the drying chamber and the tilt angle for the collector is 16.8º. Zenera & Mtetwa (2018) note that the collector tilt for maximum collection of solar radiation should be taken as the latitude of the area. It acts as an auxiliary heat recovery unit. The solar collector consists of a flat plate collector placed about 5cm above matt black painted metal absorber sheet (Weiss, 2012). It is painted black so as to absorb solar radiation transmitted by the cover plate thereby heating the air between it and the cover. The plate is transparent and made of tempered glass which is glass that has been toughened to increase its strength so as to enhance its durability. All collector walls except the transparent glass cover are insulated by foam to 8cm thickness to minimize heat loss (Zhu & Shen, 2014).

3.4.4.3 The control system

The programming language used to design the system was Embedded C programming and the Dynamic programming algorithm was the type of algorithm used in designing the control system. The system works in such a way that the measuring element senses a process property and generates a corresponding output signal. The controller compares the measurement signal with a predetermined desired value (set point) and produces an output signal to counteract any differences between the two (Reyes *et al.,* 2014).

The final control element receives the control signal and adjusts the process by changing an auxiliary speed and causing the controlled process property to return to the set point. In the event that there is temperature exceeds the set point which is the drying temperature in the range 45-60°C the system will send signals to the fan which in turn is switched on and blows air into the drying chamber thereby adjusting the temperature. When the set value has been attained, the fan switches off (Sarbu & Sebarchievici, 2016).

The control system also functions in such a way that when the required final moisture content of sliced tomatoes of 10% has been achieved, the system will turn on the light and sound such that the light will flicker and a ringing sound will be heard. The sound and flickering of the light will go on for about five minutes. This is so as to alert the operators that sliced tomatoes have dried (Thirugnanasambandham & Sivakumar, 2016).

The sound and light can be switched off manually within the five-minute time frame from the time the light starts flickering and the sound is heard. The time interval of five minutes is so as to alert the operators in the event that they will not be in close proximity they will still be alerted if they happen to be close by within the five-minute frame (Tulek, 2011).

3.4.4.4 Air flow system

In forced convection air is forced through the drying chamber with artificial means like fans. The use of forced convection can reduce drying time by three times and decrease the required collector area by 50%. A dryer using fan may achieve the same throughput as a natural convection dryer with a collector six times as large (Kusum & Wadhawan, 2018). It is necessary to have a fan in the drying system in order to maximize the drying quality and to minimize drying time. The airflow should be variable, so that an optimal drying temperature may be reached. The fan should be of low power consumption which may be driven by a solar cell panel or a small generator driven by a motor (Heller, 2012).

3.5 Methods of joining

Two methods of joining were used in coming up with the design. These are welding and reverting.

3.5.1 Welding

Welding is a permanent method of joining components with or without the application of pressure and a filler material. The assembly of the design was carried out by welding (butt and fillet welding). The following design parameters were considered:

3.5.1.1 Butt welds

Tensile strength (P) = $tl\sigma_t$

The stresses in a welded joint are difficult to determine because of the changeable and irregular parameters such as homogeneity of the weld metal, thermal stresses and changes in physical properties due to high rate cooling (Savanya, 2012).

3.5.1.2 Fillet welds

Shear stress ($\tau) = \frac{3T}{tl^2}$ and Maximum shear stress ($\tau_{max}) = \frac{4.242\,T}{s\,l^2}$

Where: T – Torque acting on the vertical plane

$l-$ Length of the weld

$s = t -$ Throat thickness

3.5.1.3 Rivets

A rivet is a structure that has a hemispherical head on one side and a cylindrical shaft on the other. It is made from aluminium alloys, steel and other special metals like titanium and nickel. The riveted joints have a broad range of applications ranging from aircraft bodies to high pressure boilers. Riveted joints are strong and can handle high stress (especially in shear (Hall, 2012).

3.6 Technical requirements

Design considerations used in selecting a suitable design.

3.6.1 Ergonomics

Consideration of ergonomics in the design was crucial in reducing exposure to physical risk due to immediate or long term use of the machine. Ergonomics elements to consider in the design included that all dryer user interfaces be positioned so as to provide easy access to the dryer controls, loading and unloading ports be within the reach of the average tall person, ease of physical operation, all dryer controls must be marked clearly and positioned so as to provide easy operation (Atanda *et al.,* 2011).

3.6.2 Product safety

The design must allow for protection of sliced tomatoes and it should not have dead ends or void spaces that can allow for growth and accumulation of microbial cells which leads to contamination ((Schimdt, 2015). Source of contamination can be from either outside or inside the dryer.

3.6.3 Aesthetics and appearance

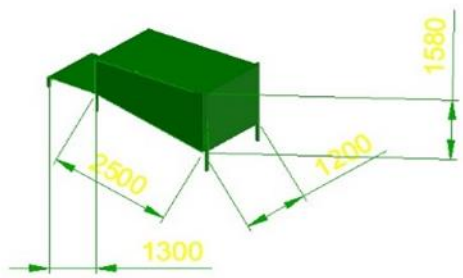
Body parts must be blended into one another as much as possible to give the most appealing appearance. Components must be hidden from sight and the operator must only be presented with the necessary input ports and output ports. Paint can be used to enhance the appearance of the dryer. Food contact surface should not be rough or have cracks and crevices but should have a smooth finish (Bvenura & Afolayan, 2015).

3.6.4 Maintenance and logistics

The dryer should be easy to maintain even by the operators or persons with minimum technical knowledge. All parts requiring frequent maintenance to be easily accessible. Equipment that is difficult to maintain or that does not perform as expected could cause major microbiological problems. All necessary repairs should be done on site (Jacxsens *et al.,* 2019).

3.6.5 Service life

The dryer should have an expected service life of at least 5 years without a major breakdown.



	Date	Name	Signature	BINDURA UNIVERSITY OF SCIENCE EDUCATION
Draw	01/06/24	Tadiwanashe	Mafetuka	
Checked by				

Scale	ACTUAL SOLAR DRYERS	Number:
		Replace to:
		Replaced by:

Figure 21Design of the solar dryer

3.7 Experimentation and data analysis

To evaluate the characteristics of the dryer several calculations were performed and evaluated to see if the dryer was working in line with the intended functionalities. The evaluation of the solar dryer with thermal storage material (ThS_d) was done parallel to a control experiment. The control involved using a dryer without stones, that is, the conventional solar dryer (CS_d).

3.7.1 Sample preparation and instrumentation

Experiments were conducted in the month of April in Rusape, Zimbabwe from 8am to 4am. The drying process was done on 5 days, roughly from the 8th to the 22nd of April. The parameters used to monitor the drying process were moisture content (Φ, %) of the product, temperature, (T, °C) of the drying chamber, relative humidity (τ_H, %) in the drying chamber and drying time (D_t, hr). Temperature and relative humidity were determined using temperature sensor (DS18B20, Thermik Corp. Germany) that measures temperature from -55 to +125°C (±0.5°C accuracy) and relative humidity sensor (DHT22, TE Connectivity, Japan) measuring relative humidity from 0-100% (3% accuracy) respectively. A Pyranometer (TBQ2-B, measurement range 0~2000W/m² accuracy ±2%) was used for measuring the solar radiation intensity. All readings were recorded at every 2-hour interval until the moisture content of the product reached the final recommended moisture content of 10%, as denoted by (Karaaslan *et al.*, 2019).

To determine the moisture content of the product, approximately, 10 kg of firm and ripened tomatoes were used for each ThS_d and CS_d dryer. Fresh tomatoes were purchased from a local farmer in Mupfumati village, Ward 6 in Mt Darwin. 100g of fresh tomato slices were removed from a sample of 10.1kg and placed on a moisture analyzer so as to determine its initial moisture content. The initial moisture content for each 10.1kg sample were determined using a moisture analyzer (OHAUS MB27, USA) set at 160°C for 8.2 minutes and recorded.

In order to reduce errors caused by drying raw materials, the tomatoes used in this experiment were selected according to the same species and purchase batches. The tomatoes were almost the same size and harvested in the sixth and final stage of maturity when over 90% of the surface is red according to the standard tomato ripening chart as shown in Figure 3.8 below.

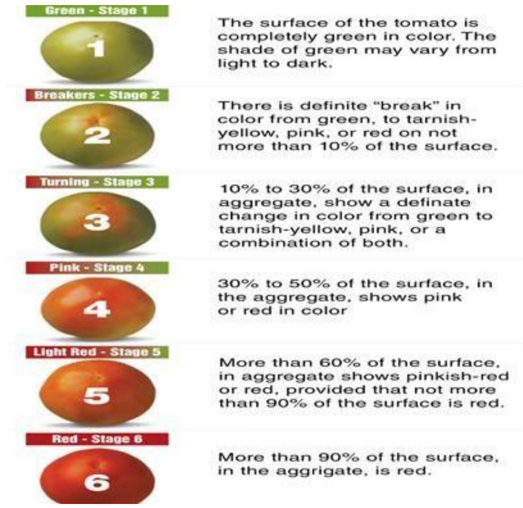


Figure 22Standard tomato ripening chart(USDA, 2012)

The fresh tomatoes without pre-treatment were sliced with the similar size . The tomato slices were placed evenly on trays in the drying chamber. For each of the tests, the sample weights of an experimental group and a contrast group were selected without replacement from 100~200g using a digital compact weighing scale (ATOM-126 Digital Compact Weighing Scale, Sunrise Technologies, China), for studying drying characteristics of tomatoes. Tomato slices were sampled randomly from the trays and slices were taken from various positions of the trays.


Figure 23Sliced tomatoes placed on a tray

Figure 24Bowl of tomatoes


Figure 25Dried tomatoes

Figure 26Sliced tomatoes in drying chamber

Figure 27Thermal storage material

3.7.2 Determination of thermal and physical characteristics of the dryer

Several calculations were conducted to determine the thermal and physical characteristics, that is, the drying properties or characteristics of the dryers. Included are the calculations of the thermal storage materials (stones) with reference to ThS_d.

ASSUMPTIONS

Table 3.4: Assumptions made in calculations

	Attribute	Assumed Value	Reference
1	General heat loss of the dryer	10% (0.1)	Husainy & Kulkarni (2015)
2	Average solar radiation	547W/m^2	Kadebe (2022)
3	Latent heat of storage of stones(C_p, kJ/kg)	0.79kJ/kg	Engineering ToolBox (2003)

3.7.2.1 Design analysis of the dryers

The amount of moisture content (M_a, kg) which can be removed by the dryer can be expressed as follows (Husainy & Kulkarni, 2015; Kilanko, *et al.*, 2019; Missan *et al.*, 2020 and Iglesias *et al.*, 2017):

$$M_A = \left[\frac{M_p(M_i - M_f)}{(100 - M_f)}\right] \qquad (1)$$

Where:

M_f – final moisture (approx. 10%)

M_i- initial moisture

M_p- mass of product (total mass of product that can be placed in the dryer).

The amount of energy (heat) required (Q, MJ/kg) to evaporate water from the product was calculated as given below (Husainy & Kulkami, 2015; Kilanko *et al.*, 2019):

$$Q = M_A \times h_{fg} \qquad (2)$$

Where: M_A is the amount of moisture removed in kg.

h_{fg} is the heat of vaporization of water. $h_{fg} = 4186(5.97 - 0.56T_p)$. T_p is the initial temperature of the product (23°C)

The drying efficiency of the dryer was calculated as shown in Eq. 3 below (Iglesias *et al.*, 2017; Zendera & Mutetwa, 2018)

$$d_E = \frac{M_A \cdot h_{fg} \cdot 100}{A_c \cdot I_c \cdot D_t} (\%) \quad \ldots\ldots\ldots\ldots (3)$$

Where:

A_c is the surface area of the collector (m^2)

I_c is the average solar radiation of the area (Wm^{-2})

The drying rate was calculated as the change in moisture content (Φ, %) per unit of the drying time (D_t), Eq. 4.

$$d_R = \frac{m_i - m_f}{D_t} (\%\Phi. hr^{-1}) \quad \ldots\ldots\ldots\ldots (4)$$

3.7.3.2 THERMAL ENERGY STORAGE CALCULATION OF STONES (GRANITE)

Calculations for the thermal energy stored by stones was adopted from Husainy & Kulkarni (2015). The calculation requires that the quantity of stones be known, so as its thermal properties and dimension of the storage facility.

Table 3.5: Factors used to calculate thermal storage properties of stones

	Equation	**Equation No.**
Volume of thermal storage compartment (v_c, m^3)	$v_c = L \cdot W \cdot H$	(5)
Weight of stones(granite)(w_s, kg)	$w_S = v_c \cdot \rho_s$	(6)
Amount of energy that can be stored by TES (Q_T, kJ)	$Q_T = C_p \cdot w_s$	(7)
Actual energy that can be stored (Q_A, kJ)	$Q_A = S_E \cdot Q_T$	(8)
Energy to be supplied by the collector (Q_c, MJ)	$Q_c = Q - Q_A$	(9)

3.7.3 Mathematical modelling

3.7.3.1 MOISTURE RATIO, $\boldsymbol{\Lambda}$

Moisture ratio, Λ is a dimensionless parameter that can used to express changes in the final moisture content with reference to the initial moisture content (Missana *et al.*, 2020; Hssaini *et al.*, 2021; Hao *et al.*, 2020). Λ can be calculated as below (Eq. 10).

$$\Lambda = \frac{M_t - M_e}{M_i - M_e} = \frac{M_t}{M_i} \quad (10)$$

Where:

M_t is the moisture content at any time t; M_e is the equilibrium moisture content (is much far less than M_i and is usually removed from calculations) and M_i is the initial moisture content.

Figure 28The actual solar dryer

3.8 Summary

The chapter explained the methodologies carried out in this study. It looked at the study area, research model used to come up with the best concept design, material selection for the construction of the dryer, cost benefit analysis for the solar dryer, design features and function analysis of the dryer and the technical requirements of the solar dryer. The last section of this chapter looked at experimentation and data analysis.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The results and discussion includes observations of the conventional solar dryer, CS_d and thermal storage solar dryer, ThS_d, used for drying tomatoes. More emphasis was given on the comparison of the conventional drying and thermal storage solar drying system. Principle parameters which were used for such comparisons include, temperature variations for both dryers (T, ℃), drying time (D_t, hr), relative humidity (τ_H, %), and moisture content (Φ, %).

4.2 Overview of the design parameters of the dryers

The list of parameters considered in the design on the dryer are given in Table 4.1 below. Most of the parameters for both dryers were the same, the only difference was on attributes which are needed for the storage of thermal storage material (stones), that is, the amount of stones and dimensions of the storage unit.

Table 4.1: A summary of the design properties of the CS_d and ThS_d dryers.

Parameter	CS_d	ThS_d
Product capacity	10kg	10kg
Declination	15.8^o	15.8^o
Collector slope (β)	16.8^o	16.8^o
Average solar radiation	547 W/m^2	547 W/m^2
Amount of thermal storage material (stones)	-	28.8kg
Thermal storage compartment elevation height	-	15mm

Dimensions		
Overall length	4.01m	4.01m
Overall height	1.58m	1.58m
Drying chamber (L, W, H)	(1453, 853, 1344) mm	(1453, 853, 1344) mm
Solar collector (L, W, H)	(2200, 1200, 220) mm	(2200, 1200, 220) mm

Both dryers had a capacity of 10kg of the product and the thermal storage unit was found to hold 28.8 kg of stones. The amount of storage material was obtained from the fact that 1m^3 of stones weighs about 2500kg. Using the dimensions in Table 4.1, the volume of thermal storage material chamber was 0.0124m^3 and using Eq. 6 the amount of stones was obtained.

Table 4.2: Characteristics of solar dryers

Parameter	**Eq.**	$\boldsymbol{CS_D}$	$\boldsymbol{ThS_D}$
$M_p(kg)$	-	10	10
$M_A(kg)$	$M_A = [M_p(M_i - M_f)/(100 - M_f)]$	9.28	9.28
Q (MJ)	$Q = M_A \cdot h_{fg}$	24.98	24.98
d_E (%)	$d_E = (M_A \cdot h_{fg} \cdot 100)/(A_c \cdot I_c \cdot D_t)$	20.76	51.89
d_R ($\%moisture.\ hr^{-1}$)	$d_R = (M_i - M_f)/D_t$	3.69	11.69

Table 4.3

	Eq.	Value
Volume	$v_c = L \cdot W \cdot H$	0.012
Weight of stones (w_s, kg)	$w_S = v_c \cdot \rho_s$	28.8
Latent heat of storage of stones (C_p, kJ/kg)	-	0.79
Estimate storage efficiency (S_E, %)	-	90.00
Amount of energy that can be stored by TES (Q_T, kJ)	$Q_T = C_p \cdot w_S$	22.75
Actual energy that can be stored (Q_A, kJ)	$Q_A = S_E \cdot Q_T$	20.47
Energy to be supplied by the collector (Q_c, MJ)	$Q_c = Q - Q_A$	24.79

*Q is the energy required for removing water (24.98 MJ, see Table 4.2 above)

The characteristics of the CS_d and ThS_d are shown in Table 4.2. The mass of moisture which was removed from the product M_p was 9.28 kg and the relative thermal energy Q needed to remove this water was 24.98MJ. This value of Q is the minimum value required to reduce moisture content from 93.5% to 10.0%. Mathematically speaking, 0.65kg of the product which consist of 0.07kg of water, giving a mass total of 0.72kg was the yield of dried product. Since, both drying systems were supposed to give product with same properties when it comes to moisture, results for M_A and Q should also be the same here because the equations (Eq. 1 & 2) used do not answer to what rate the water was removed but rather to what extent.

The drying efficiency (d_E, %) was high in solar dryer with stones (ThS_d) as compared to the conventional solar dryer (CS_d), that is., 55.89% versus 20.76% respectively (Table 4.2). Using Eq. 3 the only parameter which is different for the 2 drying system is the drying time, that is, it took 8hrs for ThS_d and 20hrs for CS_d to dry tomato slices to the final recommended moisture content of 10%. This shows that ThS_d reduced the drying time for drying the tomato slices as compared to CS_d. The same can be seen in the drying rate (d_R) where the differences between the moisture content ($M_i - M_f$) is fairly the same, yet the large differences come from drying time D_t (Eq. 4). This results in d_R values of 3.69 and 11.69 for CS_d and ThS_d respectively. These differences in the d_E and d_R, caused by some variations in the drying time, unveils the importance of the thermal storage material-stones in optimizing the drying rate and efficiency of the conventional solar dryer (CS_d).

The results for the thermal storage material-stones are provided in the next part. Stones, 28.8kg can store up to 22.75kJ or 20.47kJ when we assume 90.0% storage efficiency (Missana *et al.*, 2020). Considering 24.98MJ of thermal energy (Q) needed to remove 9.28kg of water from tomatoes it seems a lot of energy has to be extracted from solar radiation (24.79MJ) rather than from the stones itself. However, that small input of energy can thermodynamically improve the drying performance of the dryer given that the system is intact and proven to have low energy losses.

4.3 Distribution of temperature, humidity and moisture content as drying time changes

Below is an analysis on the changes of moisture content with time. The final recommended moisture content is shown at 10.0%. Solar dryer thermal storage (ThS_d) achieved its final moisture at A within 8 hours whilst conventional solar dryer achieved the moisture content after 20 hours at B. Thus, if we draw straight line from the initial moisture content to connect points A and B the differences in the rate of removing moisture can be represented by the area D.

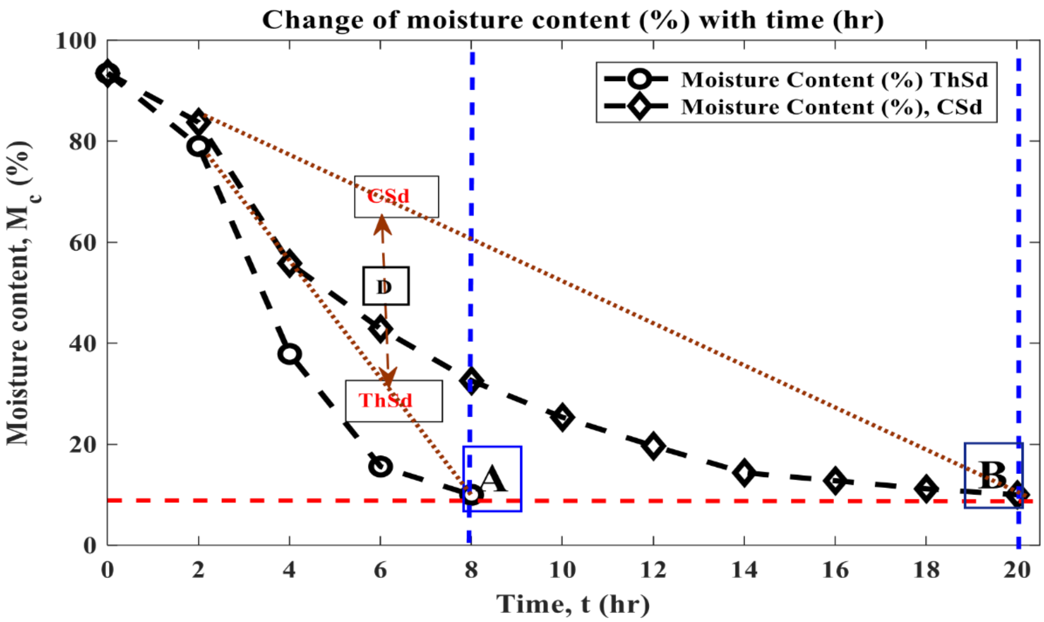


Figure 29Change of moisture content with drying time

For a system of two dryers ($D_t(A)$ and $D_t(B)$), with relative the same initial and final moisture content values, M_i and M_f respectively, the difference in the rate of moisture removal (Φ_{diff}) can be expressed by:

$$\Phi_{diff} = \left[\frac{(M_i - M_f)\cdot(D_t(A) - D_t(B))}{D_t(A)\cdot D_t(B)}\right] \qquad (24)$$

Using M_i = 93.5%, M_f = 10.0%, and final drying time for CS_d, ((A) = 20hr) and

(B) = 8hr for ThS_d. Thus, Φ_{diff} = 6.3%$moisture/hr$. It can be deduced that this value is close to the difference between the drying rate of the solar dryers.

Fig 4.5 below shows changes in relative humidity with drying time. The graph shows a drop in relative humidity which reaches a minimum value at the 10th hour (6pm) and turn to rise-up as the night progresses (6pm-4am). However, such increases were small enough such that less moisture was re-absorbed in the product, otherwise a huge increase in the moisture content would have resulted. In general, ThS_d relative humidity was lower at all instances as compared to those CS_d.

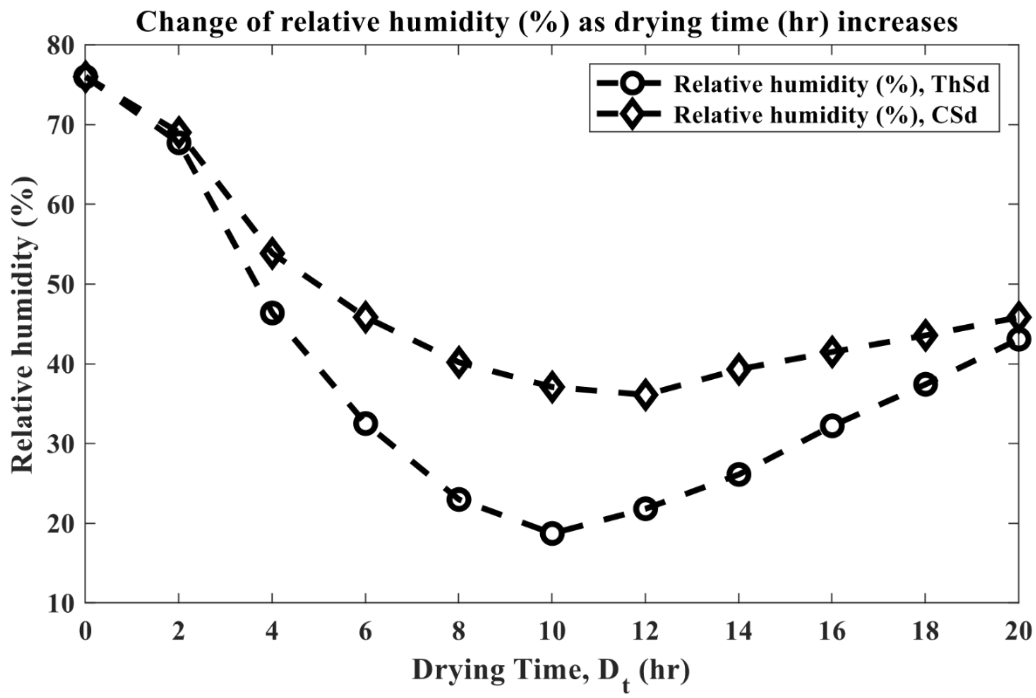


Figure 30Change of relative humidity with drying time

Change in the temperature values in the drying chamber as time increases are shown in Fig.

31

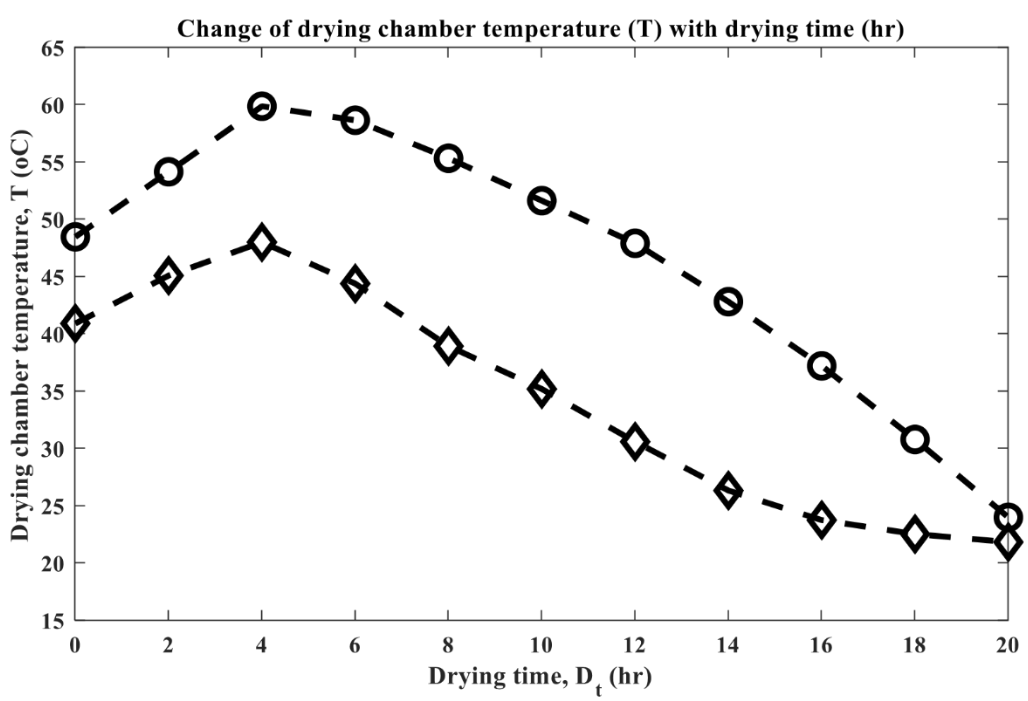


Figure 31Changes of temperature with drying time

Temperature initially increases with drying time until it reaches the highest value after 4-6 hours, that is, during midday, before embarking on a constant decrease. Temperatures below 20-25^{o}C (room temperature) were observed around the 18th-20th hour for the CS_d, however, temperatures for ThS_d were relatively high up to the 20th hour, that is, close to 30^{o}C.

4.5 Summary

This chapter focused on the conventional solar dryer, CSd and thermal storage solar dryer, $ThSd$, used for drying tomatoes. Comparisons of the two solar drying systems were made. The parameters used for the comparisons included temperature variations for both dryers (T, ℃), drying time (Dt, hr), relative humidity (τH, %), and moisture content (Φ, %). Various mathematical models (which are based on the above parameters) were employed to make inferences of the dryers' characteristics like thermal energies which can be stored and generated by the dryers, performance of the dryers and drying properties.

CHAPTER 5

SUMMARY, RECOMMENDATIONS AND CONCLUSION

5.1 Research summary

In summary, the main objective of this study was to design a solar dryer suitable for small scale farmers with a heat storage system to reduce drying time of the normal dryers. In this respect, the research looked at various characteristics of the dryer which include drying rates, drying efficiency, the amount of thermal energy the solar dryer supplied to sustain the drying process, testing of the dryer to see if it obeyed mathematical concepts which are aligned to drying properties and to find the relationship between drying parameters through mathematical modelling.

Calculations were also done to determine the amount of stones(thermal storage material) needed for a dryer with a 10kg drying product capacity and the amount of thermal energy it stores and releases. A pseudo set of experiments were also done for a similar solar dryer without heat storage material- the control experiment. The study clearly proves that sensible heat storage materials indeed improves drying properties of conventional dryers.

5.2 Recommendations

The study depicted that there is a high possibility of optimizing the capacity of the dryer and still get positive results. The study recommends further research in this area.

Research on the impact on quality properties of the product still need to be established though the thermal storage solar dryer has been improved.

5.3 Conclusion

Post-harvest losses vary greatly among commodities, seasons and production areas. In less developed countries the major reason for increased post-harvest losses is inefficient postharvest agricultural systems that lead to loss of food that people would otherwise sell, eat, or barter to improve their livelihoods. A clear method for reducing the losses is drying which has been found to be economically favourable to use. The research optimized the conventional solar drying method which is in common use, by including a sensible heat storage material-stones, in its drying system. The results indicate a successful improvement in increasing drying temperature and substantially shortening the drying time

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