DEVELOPMENT AND PERFORMANCE EVALUATION OF SOLAR GREENHOUSE DRYER WITH DESICCANT ENERGY STORAGE SYSTEM FOR TOMATOES

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DECLARATION

This thesis is my original work, and has not been presented for award of degree in any other university or institution.

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We confirm that the work reported in this thesis was carried out by the student under our supervision.

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DEDICATION

To all my family

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ABSTRACT

Tomato is one of the most important horticultural crops widely grown in the tropical East Africa countries. It is mostly used as vegetable recipe for food preparation at most homes or consumed raw as a salad. However, during the rainy season, tomato farmers experience widespread post-harvest losses due to insect and molds infestation. Also, during harvesting seasons, most markets in East Africa are flooded with the produce leading to over- supply against low demand resulting to heavy postharvest losses. Therefore, it is necessary to use appropriate drying technologies especially solar drying technology to reduce these losses. The use of solar drying technology is a good alternative solution to the problem of crop drying and especially the perishable tomato crop. Literature review show that most solar crop drying technologies developed for the past 50 years have very small loading capacity and cannot operate during the night. Therefore, in this study, we developed an integrated greenhouse solar dryer with Clay-$CaCl_2$ solid desiccant energy storage system. Solar greenhouse drying systems have an advantage over other solar drying systems because its structural simplicity combined with high loading capacity. In addition, they have relatively good thermal crop drying performance compared to most solar dryers. The system was tested under no-load and load conditions. The experimental study with no-load condition exhibited the mean collector temperature of 41.9 °C giving an average temperature rise of 14.7 °C (35%) above the ambient (27.2 °C) with an average R.H. value of 32.6% at the flow rate of 0.28 m^3/s on the test date. When the desiccant energy storage was used during night an average greenhouse temperature recorded within the drying chamber was 26.5 °C higher than the ambient temperature of 15.9 °C (40 % temperature rise). The results obtained under desiccant energy storage showed that at a 0.07 m^3/s air flow rate with an average rise in temperature of about 13.6 (32.3%) against the average ambient temperature of 28.5°C. The average relative humidity within the system was found to be 36.5% lower than the ambient R.H. (84.1%). The collector efficiencies obtained from no load test was 46.2% and 40.8% for the dryer and desiccant chamber respectively. The performance of the dryer was evaluated with fresh tomato load during the month of September - December 2019 at Kenyatta University field site. The dryer demonstrated capacity to dry fresh tomatoes from 93.9% (wb) to 8.3% (wb) within 27 hours with solar greenhouse drying efficiency of 23% while at night the dryer demonstrated desiccant drying efficient of 19.9%. The drying rate for the two-day solar drying was 0.985 kg/h and 0.875 kg/h respectively and that in night drying using desiccants was 0.34 kg/h. The economic analysis of the drying system shows a payback period of less than a year (0.54 year) with benefit-cost ratio of 8.4 implying that the system is economically viable. On the basis of these results, it was concluded that prototype solar greenhouse dryer with Clay-$CaCl_2$ energy storage system has great potential for tomato drying and other high moisture agricultural products in East African countries.

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Symbols	Description	Units
C_p	Specific heat capacity of the produce	kJ/kg°C
T_d	Temperature of the dryer	°C
T_a	Ambient Temperature	°C
h_g	Enthalpy of water as a vapor	kJ/kg
h_f	Enthalpy of water as a liquid	kJ/kg
Q	Amount of Energy required	kJ/s
L	Latent heat of vaporization, hg – hf	kJ/kg
M_w	Amount of moisture removed	Kg
W_w	Initial total weight of the produce	Kg
M_i	Initial Moisture content in wet basis	%
M_f	Final Moisture content in wet basis	%
MC	Mass fraction of carbohydrate	
MP	Mass fraction of protein	
MF	Mass fraction of fat	
MA	Mass fraction of ash	
MW	Mass fraction of water	
MI	Mass fraction of ice	
F	Future Value	
P	Present Value	
i	Annual Interest Rate	
n	Life Span of the system	
R	Uniform annualized cost	
S	Salvage Value	
P_{atm}	Atmospheric pressure	kPa
V_a	Volume of Air needed for drying	m^3
M_a	Mass of the air	Kg
R	Specific air constant	$kPam^3/kgK$
T_{atm}	Atmospheric temperature in Kelvin	K
FAO	Food and Agriculture Organization	

CHAPTER ONE: INTRODUCTION

1.1 Background Information

According to Food and Agriculture Organization (FAO) and World Bank development indicator (2015), agriculture accounts for 43% of the total Gross Domestic Product (GDP) in the East African region. In Tanzania, Burundi, Rwanda and Uganda, agriculture contributes to 50% of their GDPs. In Kenya, Agriculture contributes less than 30% of the GDP because of structural transformation towards less agricultural-based economy (Salami *et al.,* 2010). The diverse crop mixes across the region includes cereal staples and starchy foods: mainly maize, rice, wheat, millet, beans, potatoes, sorghum, sweet potatoes, cassava, groundnuts, sugarcane and bananas. The major agricultural products under fruits and vegetables category includes mangoes, pineapples, bananas, tomatoes, cucumber, cabbage, onions, carrots, green peppers, spinach, coriander and citrus (Maina & Mwangi, 2008).

About 80% of East Africans population live in the rural areas and derive their livelihood largely from agriculture and pastoralism, and 75 – 80% of this rural communities are poor (Blein, 2013). Greenhouse farming has become popular particularly in Kenya attracting smaller farm holders growing targeted fruits (such as tomatoes) (Birch, 2018 and KHDP, 2009) due to the adverse weather conditions which limit agricultural production under open air. Research conducted by KARI (Kenya Agriculture Research Institute) observed that modern greenhouse farming is smart technology that can be adopted for horticultural farming since it improves the livelihood for the youth. Increasing the agricultural productivity can simultaneously develop the welfare of the agriculturalists as well as the urban poor (Haggblade, 2004). However, boosted agricultural productivity cannot alone ensure a country's food security (a key rural economic indicator). There is need to prevent food loss during the period between harvesting and consumption (Government of Kenya, 2006).

A study on postharvest losses in both industrialized and developing countries showed that farmers lose over 40% of their produce. (Gustavsson *et al*., 2011). Although postharvest losses in developing countries are difficult to estimate, few reports indicate the losses of perishable crops usually amount up to 45%, or half of what is grown

(Kitinoja & Kadar, 2015). This has been attributed mainly to poor road networks which result in mechanical injury of produce or lack of market accessibility. Also, high competition for the same produce from Common Market for Eastern and Southern Africa (COMESA) imports into the nearby market (Songa and Gikonyo, 2005) had contributed to the postharvest losses. Therefore, it is necessary to reduce post-harvest losses using appropriate technology for increased shelf life of agricultural produce (FAO, 2014).

Moreover, lack of energy is among the challenge in processing of Agricultural produce. Solving this challenge could increase agricultural export in developing countries by about 30% (OECD, 2013). Small-scale farmers have a potential to earn generally high income outside of harvest season, but they lack appropriate processing technologies. Furthermore, many smallholders live in isolated, rural areas where power access is low or inaccessible. Solar drying technology is reported to be simplest and least expensive technique for reducing the losses (Stiling *et al.*, 2012).

Drying agricultural produce is one of the oldest approaches used for food preservation. It involves extraction of water or moisture by heat and removal of that moisture by flowing air mass from the food product. Drying of fruits and vegetables requires a right combination of warm temperatures, low humidity and air current. The ideal temperature for drying them is 60°C (Tomar *et al.*, 2017). At higher temperatures, food is cooked instead of drying leading to food spoilage after long storage because of microbial activities (Fellows, 2009).

Farmers harvest tomatoes as developed green, somewhat red and completely red. Most farm produce lose their freshness very quickly after harvest. Their storage life is greatly influenced by respiration and water loss leading to weight reduction and thus a direct marketing loss (Holcroft, 2015; Thanh, 2006). Respiration is measured by the amount of O_2 consumed or the amount CO_2 produced over a given time respectively. During respiration, tomato fruits lose 10-20 mg CO_2/kg-h. This leads to loss of dry matter and hence weight loss. In dry air, the produce may lose 5–10% of weight as water. This makes them wilt or shrivel and they lose the appearance of being “fresh”. The storage life of tomatoes is dependent on temperature and is 2-4 days for red firm, 7-14 days for somewhat red (pink) and 21-28 days for mature green (Boyette *et al.*, 2004). Table 1.1 shows the percentage water loss that makes various produce unsuitable for sale in the market (Holcroft, 2015; Thanh, 2006)

Table 1.1: Percent Water loss at which commodities become unsuitable for sale

Commodities	**% Water loss**
Tomato	4-7
Cabbage	6-11
Carrot	8
Cucumber	5
Lettuce	3-5
Potato	7
Green Peppers	8

1.1.1 Tomato Post-Harvest Handling

The postharvest quality and shelf life of most harvested tomatoes can be maintained through proper physical handling. For instance, during and after harvesting, rough handling can cause mechanical damage thus lowering the quality and shelf life of tomatoes (Arah *et al*., 2015). It is reported that tomatoes under tropical conditions and their state of being perishable as a result of high moisture content has short shelf life of approximately 48 hours particularly when it is fully ripe (Muhammad *et al.,* 2011). Therefore, suitable handling practices and preservation techniques at farm level are needed to preserve the quality and extend shelf life of the product.

1.1.2 Tomato Storage

Farmers in the East African region harvest tomatoes when they are in part and completely red (Arah *et al.,* 2015). Storing tomatoes for short-term and intermediate time is done utilizing evaporative cooling structure made from woven jute sacks. The structures can be fabricated locally utilizing low-cost materials like jute sacks, wooden boards, and bowls. For freshly harvested tomatoes delivered to the market normally fetch good price. However, as time goes their price drops because of loss in freshness accompanied by shrinkage, water loss and rapid deterioration (Njoroge, 2015). Moreover, completely red tomatoes are prone to wounds particularly during harvesting and transportation. Therefore, storage life of tomatoes can be reduced as a result of respiration process and water loss (Pila *et al.,* 2010).

For short-term storage up to one week, tomato natural products can be stored at ambient conditions (Znidacic & Pozrl, 2006) with sufficient ventilation to lower heat accumulation due to respiration. For long-term storage, red tomatoes can be stored at approximately 10 - 14°C and 85 – 95% relative humidity (R.H). At these conditions, ripening and chilling wounds are lessened to the minimum levels. In tropical countries like Kenya and Tanzania it is difficult to obtain these conditions and therefore substantial losses of harvested tomatoes have been reported (Kader, 2005; Pila *et al.,* 2010). However, at higher temperature and humidity the quality of tomato is significantly compromised (Parker & Maalekuu, 2013). At very low temperatures tomato quality and shelf life is detrimentally. For example, refrigerating tomato will reduce its flavor, the quality characteristic that's being determined by dissolvable solids (TSS) and pH of the tomato. Therefore, understanding the proper conditions to manage tomatoes under tropical environment is very important to extend shelf life and maintain the quality of tomatoes.

1.1.3 Tomato Processing

Tomatoes are a very good source of vitamins and minerals and also contain very low calories and high carotenoids, beta-carotene and lycopene (Shi & Maguer, 2000). It should be noted that processing of tomatoes ensures high levels of antioxidants compared to raw tomatoes because of presence of lycopene content. Consuming processed tomato products has been reported with several health benefits such as reduced prostate Cancer and risk of heart disease (Ghadage *et al.,* 2019; Bhowmik *et al.,* 2012). Recent research shows that best source of lycopene come from tomatoes and tomato products, where 80% of lycopene on average diet comes from processed tomatoes (Sharma *et al.,* 2021; Górecka *et al.,* 2020; Lindshield *et al.,* 2007). Tomato can be processed into products such as paste, ketchup and sauces. Literature review shows that solar dried tomatoes have better quality compared to those dried using conventional drying methods (Babarinde *et al.,* 2009). Table 1.1.3 (a) indicates lycopene content and the content of other nutrients in the dried tomato using various drying methods (Grace *et al.,* 2009). The lycopene content of solar dried tomatoes is much higher compared to that in the other oven dried tomato. Research shows that very small amounts of lycopene are found in other fruits including watermelon, guava, and pink grapefruits. Table 1.1.3(b) presents the assessed lycopene substance of few food products (Barnard & Reilly, 2010). Most industries have not invested in the drying process method for drying agricultural produce despite such nutritive value reported on the processed tomato products. Therefore, this research intends to develop a low-cost greenhouse drying system to facilitate the drying process at farm level in East Africa.

Table 1.1.3 (a): Nutrient Content of fresh and dried tomato samples

Sample	Total Solids (%)	Ash (%)	Titratable acidity (%)	pH (%)	Ascorbic Acid (mg/100g)	Total Carotenoids (mg/100g)	Lycopene (mg/100g)
Fresh	12.9c	0.4c	6.3a	2.5e	27.3a	3.5d	1.9c
Sun-dried	89.6b	2.6a	5.8c	2.9b	11.4b	5.2c	3.6a
Solar-dried	89.8b	2.6a	5.8c	3.0a	7.9c	5.3c	3.7a
Oven-dried at 50 °C	90.5a	2.2b	6.2a	2.7d	2.6e	5.4b	3.1b
Oven-dried at 55 °C	90.4a	2.3b	6.3a	2.7d	3.5e	5.5ab	3.2b
Oven-dried at 60 °C	90.4a	2.3b	6.0b	2.8c	5.3d	5.6a	3.2b

Means with similar letters of alphabet in the same column are not significantly different at 5%probability

Table 1.1.3(b): Estimated lycopene content of selected foods (Heinz Institute of Dietary Sciences, www.lycopene.org)

Product	Lycopene (mg/100g)	Serving Size	Lycopene (mg/serving)
Tomato juice	9.5	250 mL (1 cup)	25.0
Tomato ketchup	15.9	15 mL (1 tbsp)	2.7
Spaghetti sauce	21.9	125 mL (1/2 cup)	28.1
Tomato paste	42.2	30 mL (2 tbsp)	13.8
Tomato soup (condensed)	7.2	250 mL prepared	9.7
Tomato sauce	14.1	60 mL (1/4 cup)	8.9
Chili sauce	19.5	30 mL (2 tbsp)	6.7
Seafood Cocktail sauce	17.0	30 mL (2 tbsp)	5.9
Watermelon	4.0	368 g (1 slice: 25 x 2 cm)	14.7
Pink grapefruit	4.0	123 g (1/2)	4.9
Raw tomato	3.0	123 g (1 medium)	3.7

1.2 Problem Statement

Despite high levels of tomato production in East African countries, about 40-45% of the total output goes to waste due to post-harvest losses (Kitinoja & Kadar, 2015; Kamindo, 2015). This loss is attributed mainly to lack of on farm tomato processing industries, poor sun drying methods, poor road networks infrastructure resulting in mechanical injury during transportation to the local market centers. These losses translate to a huge financial loss to the farmers. Therefore, there is a need to preserve tomatoes for local consumption and export market (Kamindo, 2015). Preservation via solar greenhouse drying technology in tropical sunny countries can help reducing the postharvest losses. Therefore, a low-cost integrated greenhouse dryer with solid Clay-$CaCl_2$ desiccant energy storage system was proposed. Solar greenhouse drying technology with desiccant energy storage was chosen for the study because it can easily be commercialized to handle large scale operations. The huge solar energy potential in the East African rural farmlands also motivated this study.

1.3 Justification

Various drying technologies available are expensive in terms of initial capital as well as operational cost due to the nature of their designs and high energy requirements. In rural settings where energy access is a limiting factor, post-harvest and storage losses of crops need to be addressed. Also, the use of depleting fossil fuel has an effect on the environment and agricultural production. Therefore, solar greenhouse drying with the energy storage system was the best option to embrace in this project.

Solar drying technology is the only low-cost technology that is popular with many benefits. Literature review shows that most agricultural produce can be satisfactory dried utilizing sun power. The challenge remains dangers of aflatoxin development due to delay drying (Negash, 2018; Ross *et al.,* 1979). The incorporation of desiccants can facilitate the drying process during night period (Thoruwa *et al.,* 1996), thus, reduced generally the drying time. Therefore, a solar greenhouse drying system with desiccant energy storage capacity for tomato drying was created to empower constant drying operations amid day and night time. A fitting solar greenhouse dryer system with desiccant energy storage structure was finest technology choice for village setting environment within the East African locale.

1.4 Objectives

1.4.1 Main Objective

The main objective of the study was to develop and evaluate the performance of the solar greenhouse dryer with desiccant energy storage system for tomato.

1.4.2 Specific Objectives

The specific objectives of this research were to:

a) Develop Solid Clay Calcium Chloride ($CaCl_2$) based desiccant for solar energy storage;

b) Design and construct a solar greenhouse dryer with desiccant energy storage for tomato drying using locally available materials;

c) Evaluate the performance of solar greenhouse solar dryer with desiccant energy storage for tomato drying;

d) Assess the economic viability of the developed system.

CHAPTER TWO: LITERATURE REVIEW

2.1 Background

Literature review shows that most farmers in developing countries using open sun drying method experience postharvest losses amounting to 30 – 40% of the production (El-Sebaii and Shalaby, 2012). Various methods have been undertaken in preservation of agricultural produce, amongst them being solar drying. It is considered the simplest and least expensive technique for crop preservation (Stiling *et al.,* 2012). Many studies that have dealt with solar drying of food show that there are mainly two categories of solar dryers: active and passive (Kaustav *et al.,* 2017). These dryers are divided into direct, indirect and combined/mixed dryers. Further they are steered by three modes of drying utilizing sun (i) Open sun drying, (ii) Direct sun drying, and (iii) Indirect sun drying. These modes are governed by solar energy collection and conversion into useful thermal energy. Fig. 2.1 shows the classification of the dryers and different drying modes (Leon *et al.,* 2002).

Direct solar dryers are systems where wet crop is directly exposed to solar radiation while covered with a transparent material on its top. The indirect dryers use solar air collectors to generate hot air which is passed through the drying chamber (Simate, 2001). The mixed-mode solar drying systems use both direct and indirect solar heating systems. They are also referred to as hybrid solar systems (Prakash & Kumar, 2013). They are widely used for drying specialized agricultural products. Open air drying is broadly utilized most in developing countries since it may be a basic and cheap drying strategy (Bolaji & Olalusi, 2008). However, it exposes the product to unpredictable weather, dust, potentially damaging UV radiation, and infestation by insects & birds thus poor product quality (Madhlopa *et al.,* 2002).

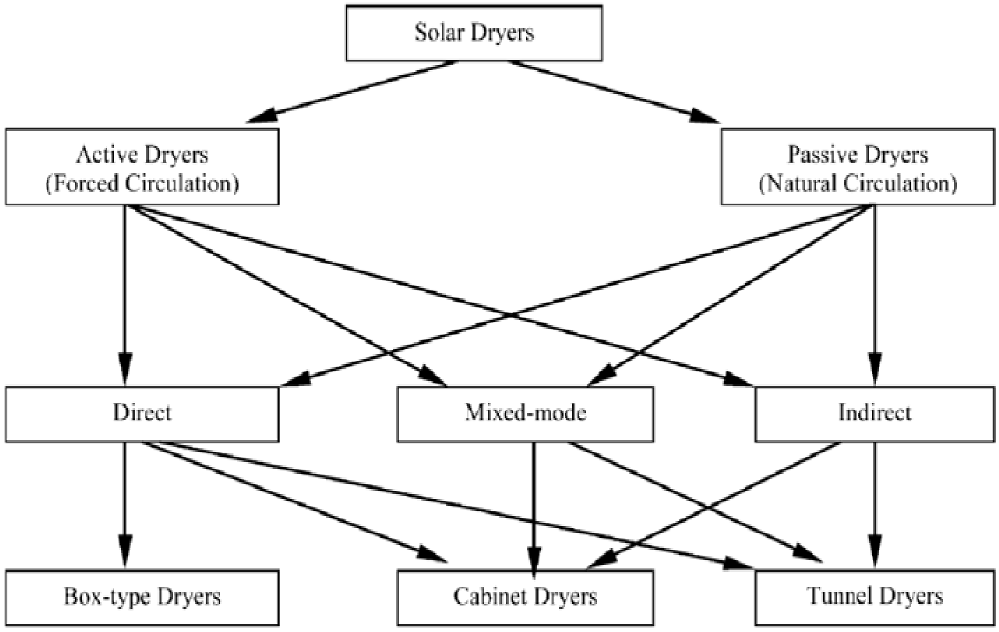

Figure 2.1: Classification of solar dryers and drying modes

2.2 Description of various dryers and drying modes

2.2.1 Active and Passive Mode Solar Drying Systems

Active solar drying systems are designed by consolidating an outside means such as fans and pumps to enable solar energy in the form of heated air to move from the collector area to the drying beds. Sometimes they are called forced convection solar dryers. Most of these dryers are utilized in large scale commercial sun based drying operations. They also incorporate the use of fossil fuels especially during off sunshine hours and rainy weather conditions. These dryers are appropriate for drying high moisture content food crop such as tomatoes, cabbage, kiwi fruits, aubergin and cauliflower slices. The dryers can moreover be classified into direct type, indirect type and hybrid dryers.

Passive solar drying systems employ a mechanism whereby air is warmed and circulated normally by buoyancy force or as a result of wind weight or combination of both. Passive solar drying is broadly utilized in numerous Mediterranean, tropical and subtropical regions particularly in Africa and Asia by small agricultural communities. These are constructed out of locally accessible materials and simple to mount and work particularly in remote areas where sites are off grid. Hughes *et al.* (2011) reported that passive dryers are best for drying little clumps of natural products and vegetables such as mangoes, pineapples, apples, bananas, carrots, tomatoes and other crops.

2.2.2 Direct Mode Solar Dryers

Direct solar dryers expose wet crops direct to the sun light while at the same time protecting the produce from rain and dirt. The collector and the drying chamber are housed within the same walled area. There are two kinds of direct solar dryer systems i.e., passive cabinet and greenhouse solar drying system. Ezekwe, (1981) modified the passive dryer to include a plenum chamber by means of a long plywood chimney to enhance natural circulation. The passive solar cabinet dryer can be developed from locally accessible materials and have an advantage of being cheap. However, their major disadvantage is that drying is taking place only during sunny days unless the system is integrated with another source of energy and also drying process is slow due to its limitation in solar energy collection compared to dryers which use conventional fuels. Fig. 2.2.2a, 2.2.2b and 2.2.2c shows a typical direct solar dryer as well as the working principle of a direct solar dryer (Bhambare, 2020; Vivek *et al.*, 2017; Saleh *et al.*, 2017).

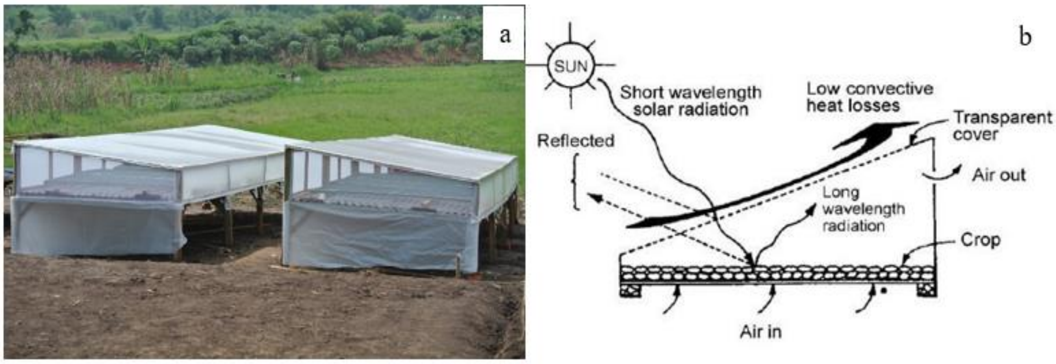

Figure 2.2.2(a) & (b): Typical Direct Solar Dryer and (b) Direct Solar Dryer Working Principle

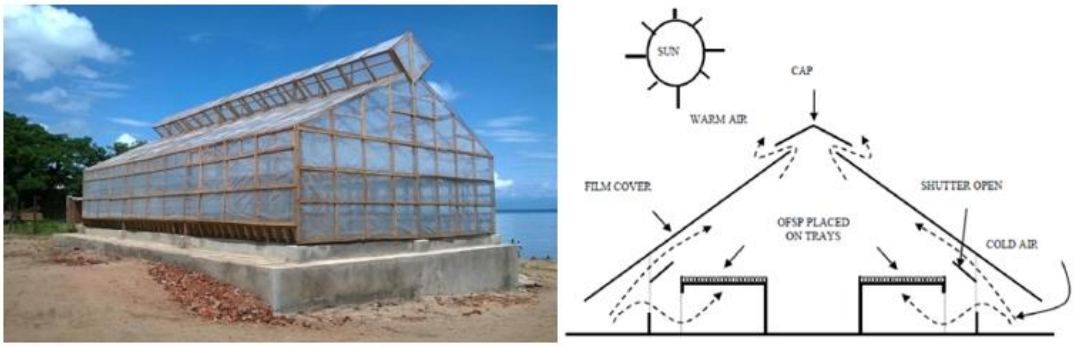

Figure 2.2.2(c): Typical Direct Solar Tent Dryer

2.2.3 Indirect solar drying systems

Indirect mode solar dryers are dryers in which the collector and drying chamber are isolated from each other. Collector warms up air, in this manner warm air rise up through natural convection, driving its way through the racks of drying produce in a drying chamber. In order to extend the capacity of the dryer, the dryer is loaded with more than one layer of trays with crops inside accessible space. Chimneys are used to increase the vertical stream of air as a result of a density difference of the air within the cabinet and atmosphere. (Afriyie & Bart-Plange, 2012). These drying systems are more efficient and allow more control over the drying. Fig. 2.2.3a, 2.2.3b and 2.2.3c show indirect solar dryers (Anand *et al.*, 2021; Mohanraj and Chandraseka, 2008). The disadvantage of indirect solar drying systems is that it allows direct UV radiation that can damage the food and also it is more complex and costly system than the direct solar radiation.

Figure 2.2.3a: Indirect Solar Dryer with a wind driven fan

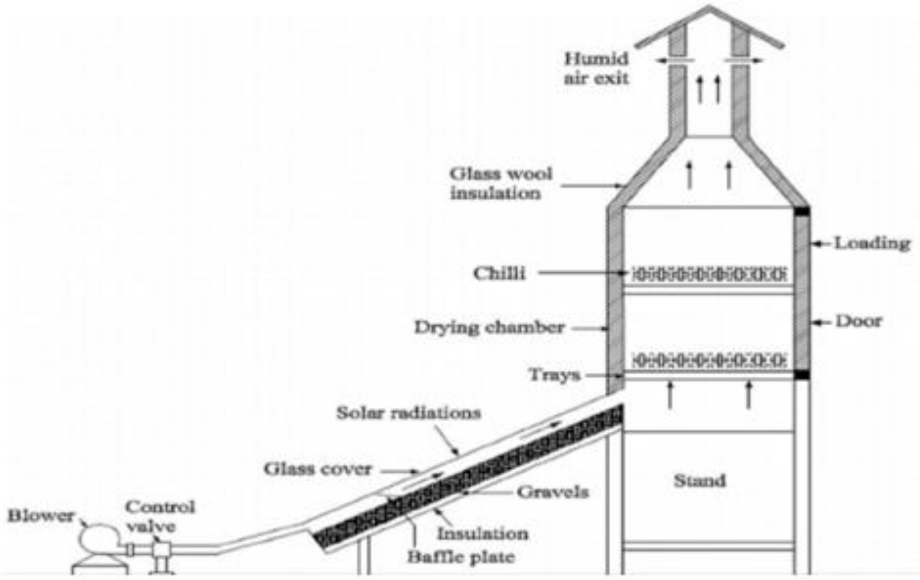

Figure 2.2.3b: Indirect Forced Convection Solar System

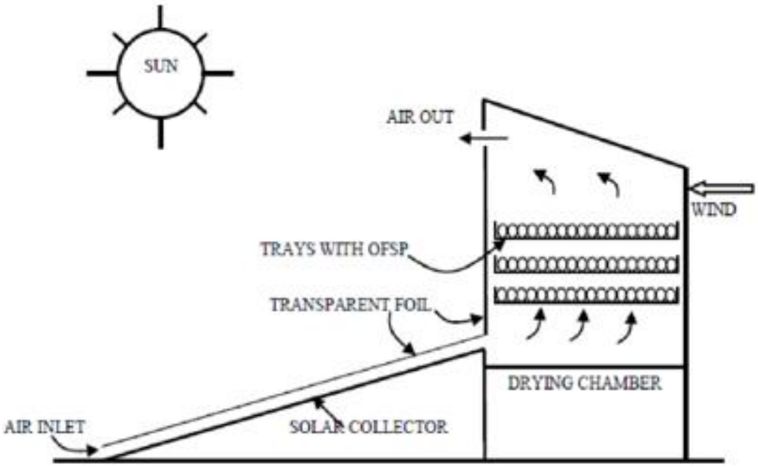

Figure 2.2.3c: Natural Convections Solar System

2.2.4 Mixed Mode Solar Drying Systems

Mixed mode drying system is a normal convection system that comprises solar flat plate air heater, flexible connector, reducer with plenum chamber, drying chamber and chimney. The crop is dried by both direct sun radiation and indirectly heated air. Compared with sun drying, direct and indirect solar dryers, the mixed-mode dryer is the leading drier since it has the highest drying rate. Literature review shows that there are several mixed mode natural convection solar dryers such as the one developed by

Forson *et al.*, (2007). Fig.2.2.4a and 2.2.4b is a typical mixed-mode solar dryer (Singh and Kumar, 2012; Bolaji and Olalusi, 2008).

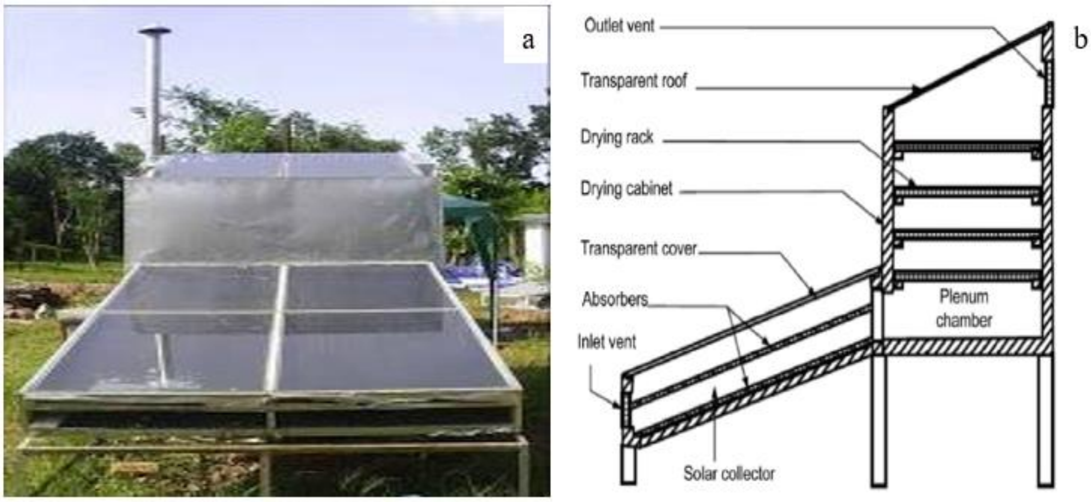

Figure 2.2.4 (a): Mixed-mode solar dryer with Chimney (b) Mixed- mode solar dryer

2.3 Industrial Drying Methods

Commercial dryers are essentially differing in the way solids are moved through the drying zone as well as how heat is exchanged.

A few dryers are continuous and others are batch wise, a few agitate the solids while others are basically un agitated. Some dryers can handle almost any kind of material while others are severely limited to specified types of feed. Different industries including textiles, paper and allied products, chemical, food, herbal, pharmaceutical, dairy, and tea industries respectively use many types of dryers in their production processes. Most of these dryers are highly technical and operate at high temperatures approximately 90 °C (Mujumdar, 2008; Mujumdar, 2001). These temperatures may cause case hardening of the outer shell and impede the drying of the interior part of most agricultural crops including fruits and vegetables. Most agricultural crops tend to suffer from quality losses; losses of color and aroma when dried at high temperatures. Also, the industrial technology is energy and capital intensive and cannot be operated in remote areas where electricity access is limited.

2.4 Greenhouse Solar Drying Technology

The solar greenhouse dryer may be defined as a system that employs the standard greenhouse structure to work as a sun-oriented dryer during the warmer periods of the day in a tropical environment. Examples of such dryers include those developed by Fleming *et al.* (1986) in form of transparent semi-cylindrical chamber with a round and hollow sun-oriented chimney posted vertically at one end and an entryway for air inlet and access to the chamber at another end. Others include semi-cylindrical solar tunnel dryers for drying grapes developed by Rathore *et al*. (2010). Some researchers like Jaijai *et al.,* (2011) have utilized polycarbonate cover for greenhouse solar drying system for construction in order to improve thermal performance and reduce construction costs. Literature review shows that greenhouse solar drying technology is gaining popularity replacing indirect solar drying technologies and improving the quality of the dried products. Greenhouse solar drying technology has found application in orange flesh sweet potato drying in western Kenya (Odhiambo, 2015). Greenhouse drying can be operated under passive or active mode (natural or forced convection modes). The active mode has shown significant results in drying products with high moisture content especially fruits and vegetables. Despite their popularity, greenhouse drying technology has some challenges including poor temperature control, dependency on solar energy alone while others have poor drying performance due to poor airflow control within the system.

2.4.1 Types of Greenhouses drying systems

Greenhouse dryers are classified as presented in Fig. 2.4.1a (Lingayat *et al.*, 2020; Lakshmi *et al.,* 2018; Kannan and Vakeesan, 2016; Kumar *et al.,* 2006). They are categorized into different shapes and sizes based on their requirements (Lingayat *et al.,* 2020; Lakshmi *et al.,* 2018). There are two major classifications based on the structure, roof even span and dome shape type as presented in Fig. 2.4.1b type 1 and type 2 respectively (Kumar *et al.*, 2006; Tiwari and Goyal, 1998). The main purpose of roof even span type greenhouse is to improve air circulation within the dryer whereas dome shape type greenhouse dryers enhance solar radiation utilization (Kumar *et al.,* 2017). Also, greenhouse dryers are classified according to the mode of heating the flowing air, which is active and passive mode of solar greenhouse dryer. Most passive mode solar greenhouse dryers are equipped with a chimney at the outlet to enhance the drying performance. Greenhouse under active mode uses forced convection mode of heat transfer where by the extractive fan is used to force the moist air out.

2.4.1.1 Greenhouse dryer based on the structure

The greenhouse geometry and orientation have an important role in determining the performance of the greenhouse dryer. Shape, sizes and orientation should be considered in order to make a successful design. The choice of shape and orientation of the solar greenhouse dryer is critical to maximize the capturing of the solar radiation. The orientation is normally determined by the latitudes of the place. According to Odesola and Ezekwem (2012) and Orodi (2015) for areas lying in latitudes less than 40° then North-South orientation is recommended because of the greater angle of sun whereas at the higher latitudes (above 40°N) they preferred east-west orientation. The architectural form of the solar greenhouse dryer system on drying agricultural products has an impact on the performance of the system. From the literature different shapes are widely used, namely dome shaped, even span roof, Quonset and Gothic arch shapes. There are other various shapes of greenhouse which are rarely used like modified arch, modified Quonset, gothic arch, dome-like, uneven-span roof, single slope, semi cylindrical roof, sandwich and mansard roof greenhouses. Even span shape and Quonset shape dryers are commonly used throughout the world since their geometry are simple and facilitate the capturing of the solar radiation. Orodi (2015) considered adopting a Quonset shape because it provided much better shape to support the auxiliary ventilator, chimney and axial fan mounting structures with minimum consideration of moisture films. However, even span shape has some advantages over Quonset shape as it has been described by Kassem *et al.,* (2011) as the most convenient shape, that gives the highest water removal, less moisture content, high gain of solar energy, less solar energy loss and highest efficiency (Sahdev *et al.*, 2017). Therefore, this study adopted an even-span roof greenhouse since it is capable of receiving optimum solar radiation at different seasons of the year i.e., winter and summer.

2.4.1.2 Greenhouse dryer based on the mode of heat transfer

The heat transfer mode falls under the two main modes of operation that is natural convection and forced convection. The natural convection mode works under the principle of thermosiphon effect. The humid air is vented via an opening on the roof or through a chimney, whereas in the active mode the humid air is vented by an exhaust fan provided at the ventilator. Commonly, the vent is ordinarily arranged at the upper west wall. For the best dryer performance, the active mode greenhouse was adopted for this study with the position of the extractive fan on the roof top center of the greenhouse.

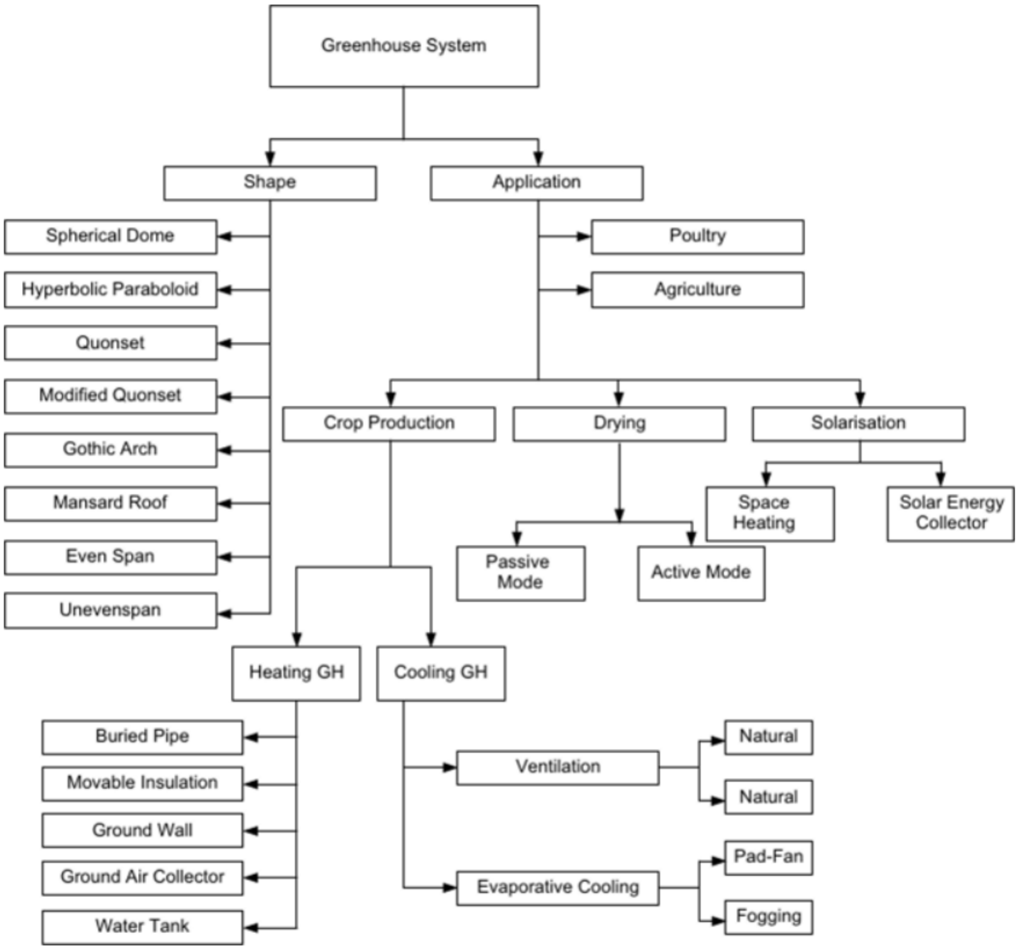

Figure 2.4.1a: Classification of Greenhouses

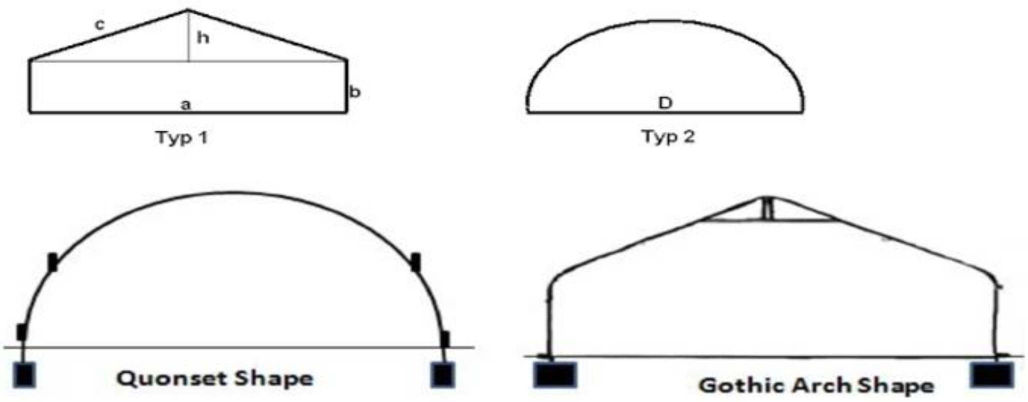

Figure 2.4.1b: Type 1 an even span and Type 2 dome shape, Quonset shape and Gothic arch shape

2.5 Innovation in Greenhouse Dryers

Literature review shows that research to improve greenhouse drying performance over the past few years has focused on minimization of thermal losses to the environment. It is reported that the total solar fraction absorbed by the solar greenhouse dryer is lost mostly through the north wall depending on the orientation of the greenhouse (Gupta *et al.*, 2012). Extensive research in minimizing the thermal losses from the greenhouse dryers has resulted in recommendation to incorporate insulated opaque north wall to reduce losses. Incorporation of insulated opaque north wall has led to temperature rise by 10°C within the greenhouse (Tiwari *et al.*, 2002). Many researchers have noted that the total solar fraction plays an important role as it is required to derive an energy balance equation for both walls and roof of a greenhouse (Gupta *et al.*, 2012; Goal and Tiwari, 2004). Some researchers developed greenhouse dryers with thermal storage on the packed bed in the north wall for drying onions (Jain, 2005) resulting in reduction in temperature fluctuation during off-shine hours. Also, the use of phase change material (PCM) [$CaCl_2 \cdot 6H_2O$] has been applied in greenhouse dryers in the north wall facing east-west orientation (Berrouga *et al.*, 2011) resulting to drying temperature increase of between 6-12°C and 4-5°C cover temperature during off-shine hours with decrease in relative humidity by 10-15%.

Kumar *et al. (*2017) has reported two modifications of the roof even span-type greenhouse dryer that can help in attaining good solar fraction. One is supplanting the north wall (transparent cover) with the reflective mirror and another is by covering the interior floor of the greenhouse dryer with the dark polyvinyl Chloride (PVC) sheet. Two tests were carried out in two continuous days under similar conditions to assess the impact of PVC. The outcome presented higher temperature within the greenhouse with the covered floor compared to bared floor by 14.5% and it was even higher at peak sunshine hours by about 17.6%. When the same was done on the greenhouse dryer under forced convection as presented by Prakash and Kumar, (2014c) the inside temperature was higher (0-5°C) than the uncovered floor (Fig. 2.5a) because of the enforced air flow.

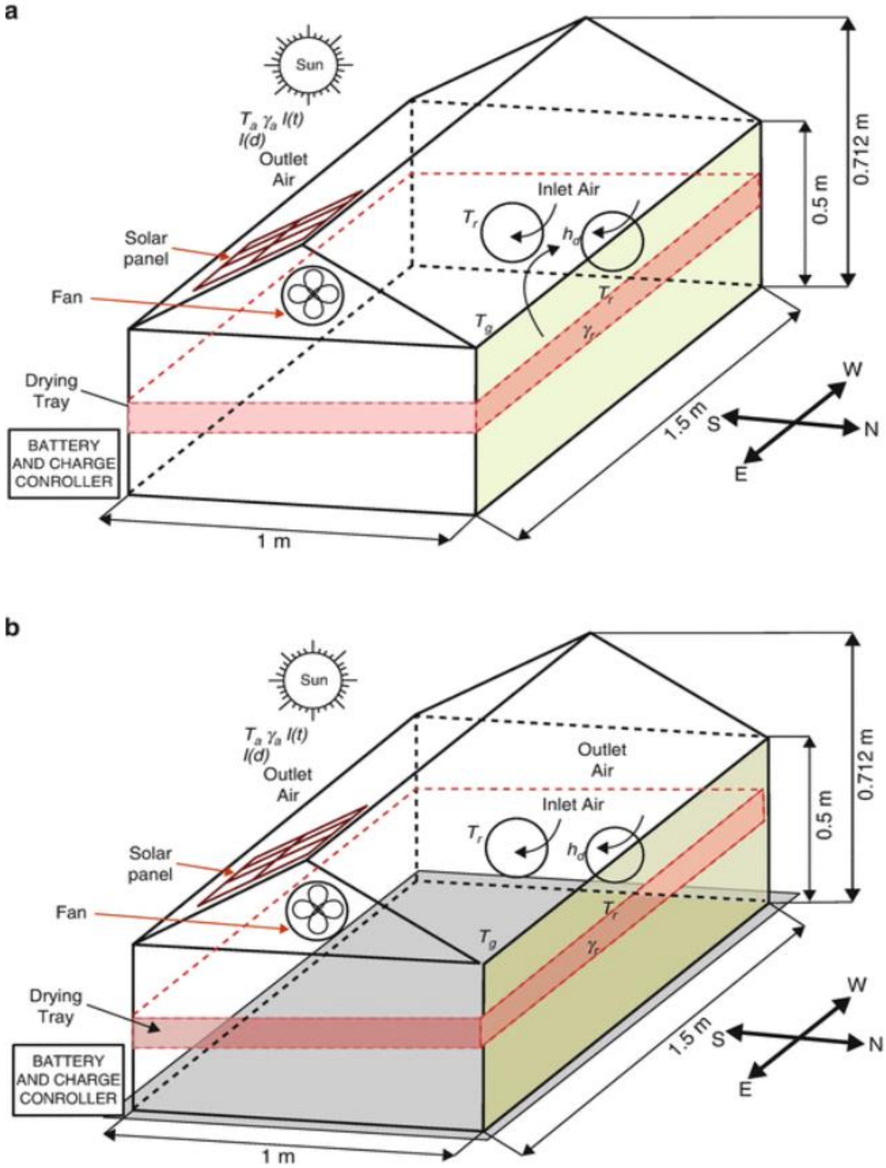

Figure 2.5a: Modified greenhouse dryer (a) Without covered floor and (b) with covered floor

When the reflective mirror was placed on the north wall, the convective heat transfer coefficient with and without a solar collector inside was reported to be high and low respectively (Chauhan and Kumar, 2016a, b). Experiment was conducted in two distinctive floor conditions in similar ambient conditions. A first dryer with covered concrete floor (with collector) and the second dryer with the bared floor (without collector). The modification of this greenhouse dryer to enhance the performance is as shown in Fig. 2.5a and 2.5b (Chauhan and Kumar, 2016a, b). The Convective heat transfer coefficient was 40.3W/m^2°C and 46.6 W/m^2°C for modified greenhouse dryers from the ground to the inside air, and north wall insulated greenhouse dryer respectively. Therefore, the solar greenhouse dryer without a collector was performing poorly compared to the one with solar collector. However, the disadvantage is that the drying can be achieved during the day alone when there is sunshine.

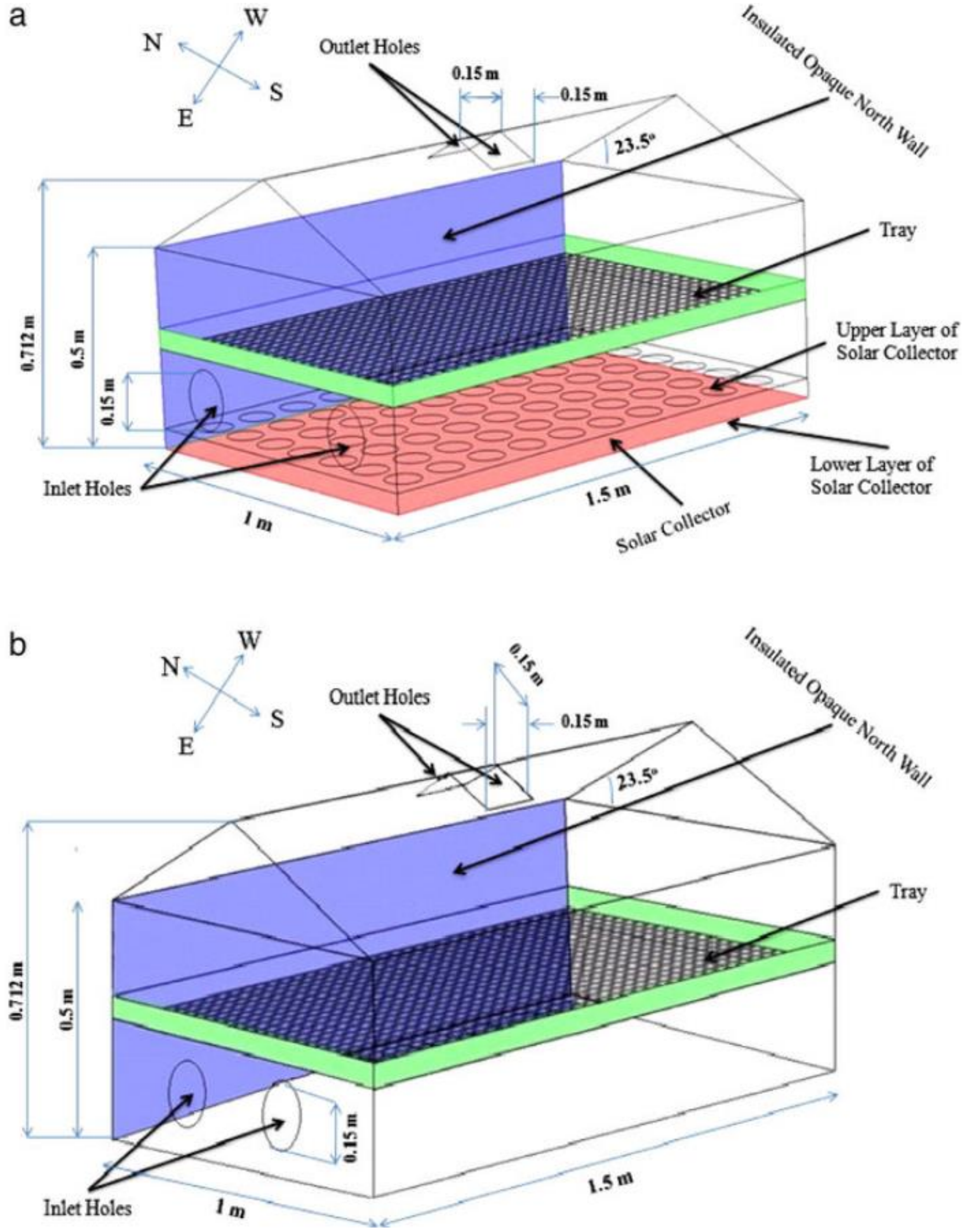

Figure 2.5b: Greenhouse dryer (a) With solar collector and (b) Without solar collector

New invention has been applied in solar greenhouse dryers by Elkhadraoui *et al.*, (2015) as shown in Fig. 2.5c. The idea involved utilizing solar air heater coupled to the greenhouse dryer for supplying additional indirect thermal energy to the greenhouse drying system. It was observed that the moisture removal rate was much higher than the open sun drying method (OSD) reducing the drying time by 7 and 17 h for red pepper and grapes respectively. However, the system performance was limited to day sunshine hours.

In this project, A proposed greenhouse drying with an integrated desiccant energy storage system was developed to enable the drying process to continue uninterrupted until desired final moisture content is achieved. This was to avoid moisture re-absorption from surrounding air as well as mold growth during night time. Literature review shows that most of the solar dryers with energy storage are biomass energy powered (Giwa *et al.*, 2017; Kamindo, 2015; Felix and Gheewala, 2011). The excessive use of biomass energy has led to loss of both biomass resources and biodiversity.

Figure 2.5c: A photo of a Mixed-mode solar greenhouse dryer

2.6 Solar Energy Storage Materials

Literature review shows that there are several solar energy storage methods. These are hot water storage (water), pebble rocks storage (air), Phase Change Materials (PCM) and Chemical energy storage. Again, the technologies that have been developed to overcome the barriers of solar dryer systems are use of desiccant units and thermal energy storage systems to make them work during off-sunshine hours. Thermal storage involves storing heat in the form of latent and sensible heat. Desiccant energy storage has been identified as the means to aid low temperature drying and is in particular suitable for drying heat sensitive food products. Also, desiccant drying systems have been found to have low cost of production hence motivating more researchers to adopt solar drying systems with desiccant energy storage. Desiccant energy storage systems have the ability to dry the agricultural products at low temperature and low humidity ratio. Also, total drying time is reduced by increasing the drying air temperature, flow rate and using less humid air. In view of various desiccant materials developed such as Lithium chloride and Calcium chloride; most of them are found to be very expensive. Therefore, selection of the desiccant material will consider health, cost (low) and local availability of the material as presented by Thoruwa *et al.,* 2000. The selected desiccant material will be incorporated in the solar greenhouse drying to provide dry air during the night.

2.6.1 Performance of desiccant materials

In accord to the reference module in Earth Systems and Environmental Sciences (2016), desiccants have been characterized as materials which have capacity to draw in and hold other gasses or fluids. Precisely desiccant are sorbents that have specific partiality for water. A good sorbent material is characterized by large internal surface area and good thermal conductivity. There are several types of desiccants like Calcium Oxide, Calcium Sulfide and montmorillonite clay, but literature discusses much of the major desiccants materials which are commonly used such as silica gel, clay and molecular sieves (Yaningsih *et al.,* 2020; Singh *et al.,* 2018). The working principle of most desiccants follow the concept of adsorption and absorption, where adsorption is when a substance is held at the surface of the solid or liquid by physical bond and absorption is when the substance is chemically integrated into the other. It should be noted that most desiccants do not combine chemically with water, rather they capture them through adsorption.

It is reported that desiccant materials adsorb moisture at the rate that is pleasing thus in drying they tend to shorten the drying time (Amarakoon and Navaratne, 2017; Abasi *et al.,* 2017; Aviara, 2020; Yang *et al.,* 2017). Most studies on the performance of desiccants were either done experimentally or numerically. On the other hand, the focus was on cost benefit ratio for their respective applications. Therefore, understanding the properties and capacities of desiccants will inform the decision on the selection of desiccant for a particular application. For comparison purposes see Table 2.6.1 and Fig. 2.6.1 on the properties and capacity of each desiccant product (Yaningsih *et al.*, 2020; Singh *et al.*, 2018; Zahari *et al.*, 2020; https://www.sorbentsystems.com/desiccants charts.html). Silica gel, Molecular sieve and CaO have shown very high adsorption capabilities of water. In particular silica gel is reported to be a Non-Toxic desiccant thus can be used as a drying agent in food stuff. However, with the potential found in all types of desiccants still is expensive to use them in drying (Shahadat and Isamil, 2018). Therefore, this research used a clay-based desiccant to support the drying process of tomato during the night-time because can be obtained locally and its capacity to adsorb moisture at lower temperatures is high.

Table 2.6.1: Properties of Adsorbents

Characteristics	**Molecular Sieve**	**Silica Gel**	**Clay**	**CaO**	**$CaSO_4$**
Capacity of adsorption in low concentrations of H_2O	Excellent	Low	Average	Excellent	Good
Rate of adsorption	Excellent	Good	Good	Low	Good
Water Capacity @ 77°F (25°C), 40% RH	High	High	Medium	High	Medium
Separation by molecular sizes	Yes	No	No	No	No
Capacity of adsorption @ high temperatures	Excellent	Low	Low	Good	Low
Toxicity (Health)	No	No	No	Yes	No
Cost	Medium	High	Low	High	Medium
Availability	Somewhat Yes	Somewhat Yes	Yes	Yes	Somewhat Yes
Regeneration Temperature	High	High	Low	Low	High

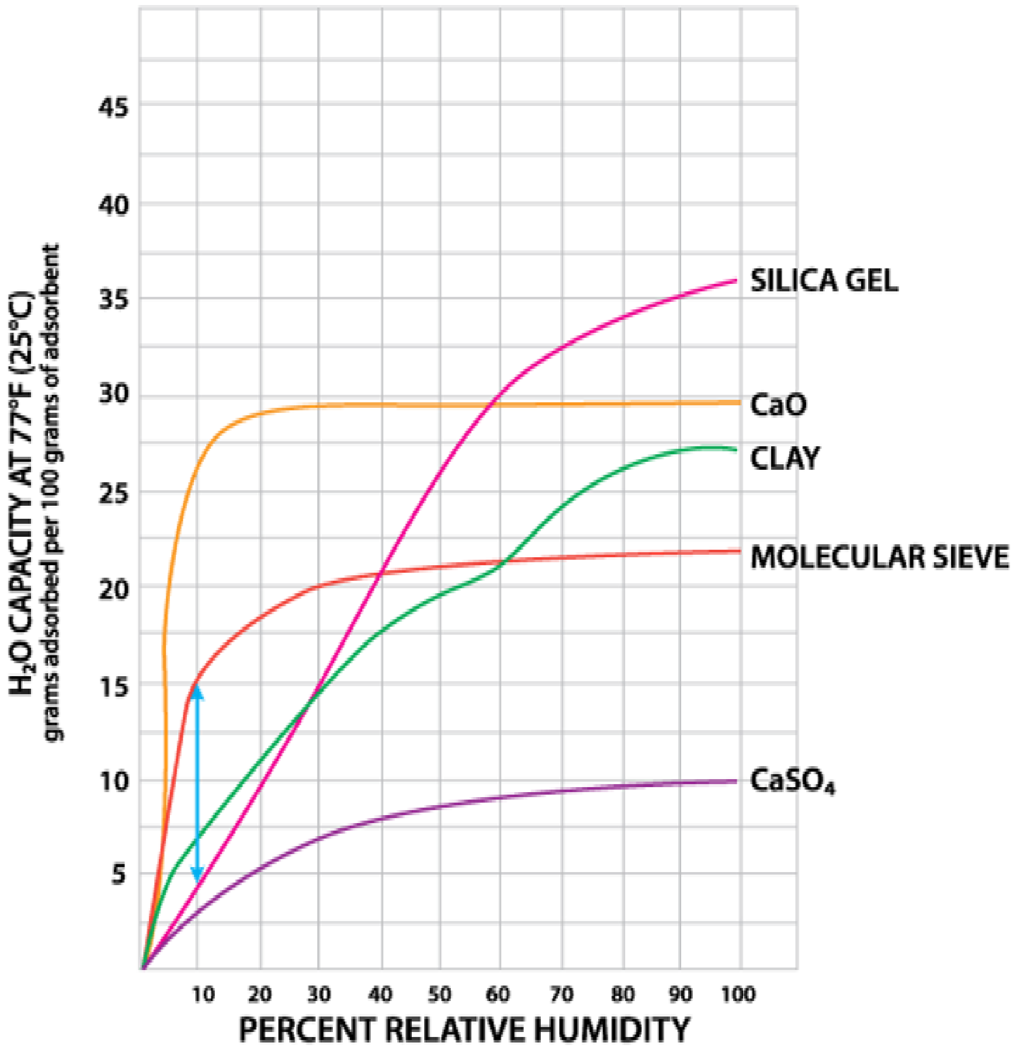

Figure 2.6.1: Adsorption rate (H_2O) of various adsorbents

2.6.2 Composite clay based desiccant production

There are recommended ratios to develop clay-based desiccants as suggested in patent work (U.S. Pat. No. 6652775 B2) by Payne *et al.*, 2003.The work has quantified the ideal adsorbent compositions by considering size of the particles and amount by weight which were preferred for individual component in the mix i.e., Clay, Calcium Chloride and Vermiculite.

2.6.3 Desiccant Solar drying systems

Drying systems incorporated with energy storage systems have proved to work efficiently particularly in drying high moisture content produce. Desiccant solar drying system is gaining popularity particularly in drying herbs and flowers because it produces high quality products in terms of colour, texture and durability. Some desiccants which are suitable for flowers and herbs include borax, silica gel, cornmeal or alum (Chua and Chou, 2003).

Furthermore, low-cost desiccant materials have been developed by Thoruwa *et al.*, (2000); and used by Shanmugam and Natarajani, (2006) to dry various agricultural products particularly cereal grains but none have been tested for fruits and vegetables drying. Low cost solid $CaCl_2$ – based desiccant is proved to work very well under hot, humid air conditions. It is reported that a 75kg solid $CaCl_2$-based desiccant comprised a mixing ratio of 6:1:2:1; bentonite, $CaCl_2$, vermiculite and cement respectively was involved in an experiment for preservation of the green peas at different airflow rates. The pickup efficiency was 63% and the system was found satisfactory for uniform desiccant drying. Also, equilibrium moisture content was achieved between 14 to 22 hours depending on the airflow rate.

Thoruwa *et al.*, (1996) established a desiccant solar cabinet dryer to dry maize grains. The dryer was capable of holding 32.5kg of bentonite-$CaCl_2$ desiccant materials enclosed in 250g bags (Fig. 2.6.2). The desiccant materials adsorbed a maximum of 14.6kg of water and dehumidified air by 40% and increased drier temperature by 4°C. The desiccant was regenerated at an average solar radiation of 567.7W/m^2. The average regeneration obtained was 5 % (dwb) moisture drop from 16.5% (dwb) to 11.5 (dwb) during day time.

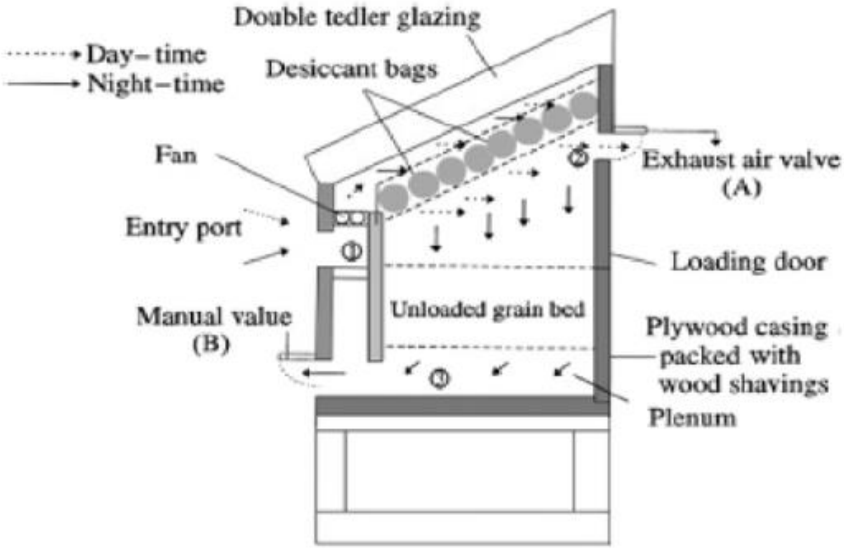

Figure 2.6.2: Integrated desiccant/collector dehumidifier

2.6.4 Selection of Desiccant Materials for Tomato Drying

There is significance difference in the properties and prices of desiccants materials which are commonly used namely montmorillonite clay, silica gel, molecular sieve, Calcium Oxide (CaO), and Calcium Sulfate ($CaSO_4$). For example, montmorillonite clay occurs as natural porous adsorbent and is being activated for use as a desiccant through careful drying. Therefore, it is least expensive and falls inside ordinary temperature and relative humidity ranges. On the other hand, silica gel is very efficiency at temperatures below 25 °C but loses its adsorbing capacity when the temperature rises. Its popularity is due to its non-toxic nature, non-corrosive and the approval for use in food and drug packaging by Food and Drug Administration (FDA), U.S. federal government agency. Silica gel is quite expensive and requires very high regeneration temperatures of 120 °C for 1 – 2 hours.

Another material is molecular sieve/synthetic zeolite which absorbs moisture very well and does not give back moisture into the container once there is temperature rise as compared to silica gel or clay. They are most economic desiccant if used where low relative humidity is required due to their high moisture adsorption capacity at low relative humidity. CaO has a high capacity to absorb high amount of water at low relative humidity compare to any other material and it’s effective in retaining moisture at high temperatures. However, CaO is very costly as compared to other desiccants.

Calcium Sulphate ($CaSO_4$) is commercially known as Drierite, chemically stable, non-disintegrating, non-toxic, non-corrosive and does not discharge absorbed water when exposed to higher ambient temperatures. Its higher regeneration temperature characteristics limit its useful life and despite its low cost yet it is mostly used in the laboratory works.

It is evident that most commercial desiccants especially silica gel are quite expensive and require high temperatures to regenerate, and again some of them cannot be suitable for drying food. Therefore, the use of low-cost clay desiccant materials in a developed greenhouse dryer system is economically viable. The study has evaluated the use of composite desiccant material in drying tomatoes under a greenhouse solar dryer.

2.7 Performance Evaluation of the Solar Greenhouse Dryers

Depending on the climatic conditions the thermal performance of the solar greenhouse can be achieved via thermal balance/heat energy balance which combines the useful energy gained as a result of incident solar radiation and the thermal losses as described by various researchers (Abdellatif *et al.,* 2010; Hossain & Bala, 2007; Shanmugan & Natarajn, 2006; Bargash *et al.*, 2000; Duffie & Beckman, 1991). To attain the performance of the greenhouse dryer then one has to treat the system as an air heating solar collector. Almuhanna, (2011) developed the thermal balance by mathematical model and used it to foresee the solar energy accessible inside the solar greenhouse by summing the heat gained and the total heat losses from the system. Among the factors that appeared to influence the thermal balance of the solar greenhouse dryer was accessibility of solar radiation inside the greenhouse, the forced convection heat transfer coefficient, variation in the air temperatures within the solar greenhouse and the ambient air temperature surrounding the greenhouse dryer. Therefore, it is important to see whether there is a distinction between the real heat energy gained and lost as well as to determine the heat energy required to obtain the required drying air temperature within the solar greenhouse dryer.

2.7.1 Solar Energy Collector Efficiency

Thermal performance can be measured by collector efficiency. This is the heat gained by air with respect to the actual solar energy received. There will also be heat losses by convection and radiation within the drying system. This can be expressed by equation 2.7.1:

$$Solar\ Energy\ Collector\ Efficiency, \eta c = \frac{\dot{m}Cp(To-Ti)}{IcAc} \times 100\% \qquad 2.7.1$$

Where; $\dot{m}$ – air mass flow rate kg/s

Cp – Specific heat capacity of air, kJ/kg°C

Ic – Insolation radiation on the collector surface, W/m^2

Ac – Collector Area, m^2

2.7.2 Drying Efficiency

Drying efficiency, ηd is the proportion of the energy required to evaporate moisture from the wet product to the heat provided to the dryer. This will be used to measure the thermal efficiencies of the drying system (Dhanushkodi *et al.*, 2014). It is calculated with respect to the factors affecting the drying process of the product such as the materials to be dried, air temperature within the dryer and air flow of the dryer. It is expressed by the following equation:

$$Drying\ efficiency, \eta d = \frac{MwL}{IcAct} \times 100\% \qquad 2.7.2(i)$$

Mw – Weight of water to be removed, kg

L – Latent heat of vaporization of water at a drying temperature, kJ/kg

Ic – Solar radiation of the collector, W/m^2

Ac – Area of the collector, m^2

t – Drying time, s

For the dryer assisted by the exhaust fan then the expression becomes:

$$Drying\ efficiency, \eta d = \frac{MwL}{IcAct+Pf} \times 100\% \qquad 2.7.2(ii)$$

P_f – Power of the fan, Watt

2.7.3 Drying Rate

Drying rate is the amount of evaporated moisture over time (Dhanushkodi *et al.*, 2014). It is expressed by equation 2.7.3(i):

$$D.R = \frac{mi-md}{t}\ kg/s \qquad 2.7.3(i)$$

m_i – Mass of sample before drying, kg

m_d – Mass of sample after drying, kg

t – Drying duration time, s

The moisture removal rate/moisture loss is expressed by equation 2.7.3(ii) (Rajesh & Karuppasamya, 2016):

$$M.R.R\ \% = \frac{mi - md}{md}\ kg/s \qquad 2.7.3(ii)$$

2.7.4 Moisture Content

One of the important parameters in assessing the performance of the dryer is moisture content (M.C) of the material to be dried. This is the amount of moisture in the given sample's weight expressed in percentage. It can be determined on wet basis (w.b) or dry basis (d.b). Fudholi *et al.*, (2011) gave the expression of moisture content as follows:

$$M.C.(w.b)\% = \frac{w - d}{w} \times 100 \qquad 2.7.4(i)$$

w – Weight of wet sample material, kg

d – Weight of dry sample material, kg

Moisture Content on the dry basis has been given by Mercer, (2008),

$$M.C(d.b)\% = \frac{w - d}{d} \times 100 \qquad 2.7.4(ii)$$

This research obtained its moisture content based on the wet basis.

If the system is going to work over night, then there will be either night time moisture loss or moisture reabsorption, Rn. This is the ratio of moisture content during night duration to the moisture content value at sunset time. For the positive Rn value moisture is reabsorbed while for the negative value indicates moisture loss (Medugu, 2010). It is being expressed as follows:

$$Rn = \frac{Msr - Mss}{Mss} \times 100 \qquad 2.7.4(iii)$$

Msr – Moisture content at sunrise, %

Mss – Moisture content at sunset, %

2.8 Economic Analysis of the System

In this project, economic analysis of the dryer system was carried out using various economic indicators including Discounted Cash Flow Method, Net Present worth Value (NPV), Benefit-Cost Ratio (BCR), Payback period and Rate of Return (RR). It was very important to conduct the economic analysis of this project in order to see its viability.

2.8.1 Discount Cash Flow Method

The discount cash flow method was utilized because it recognizes the changing value of money and it takes into consideration the reality that the same amount of money received today is more valuable than the one received after a year and so on. Investing in this system for several years, then one should take into consideration the cash flows anticipated from the system over the future year and discount them back to the present to determine the net present worth of the investment capital. Therefore, this method will reflect the ability of this project to generate cash in future. The expression that was utilized to decide the discounted cash flow is shown on Equation 2.8.1 (Dhanushkodi *et al.*, 2015).

$$F = P\left(\frac{1+i}{100}\right)^{n} \qquad 2.8.1$$

Where; P – Initial Investment Cost

i - discount rate

n - expected life of the dryer in years

Discount Cash Flow (DCF) analysis finds the present value of anticipated future cash flows employing a discount rate. A present value estimate is then utilized to evaluate the potential investment. If the calculated value through DCF is higher than the current cost of the investment, then the opportunity should be considered, otherwise an alternative has to be sourced out.

2.8.2 Net Present worth Value

The method under discounted cash flow attempts to compare the present value of the future benefits with the present value of the investment. The advantage of this strategy is that it permits one to compare the systems having different service lives, even when in case the life span of the system varies. In order to find the total present value of all cash flows generated out of the investment then equation 2.8.2 was the formula involved (Fudholi et al., 2011).

$$NPV = \sum_{t=1}^{n} \frac{Rt+S}{(1+i)^{t}} \qquad 2.8.2$$

Where; $R\ sub\ t$ – Annualized uniform cost

n - Expected life of the dryer in years

S - Salvage value

i - discount rate

2.8.3 Benefit-Cost ratio analysis

This is an orderly progression for calculating and comparing benefits and costs of the system. The major aims for using this analysis were to decide in case it could be a sound investment/decision (justification/feasibility) and to provide a basis for comparing systems. It was involved in comparing the total expected cost of each alternative against the overall anticipated benefits to see whether they exceed the costs and by how much. This is given by Equation 2.8.3 (Blumberga *et al.*, 2015).

$$Benefit - Cost\ ratio = \frac{Total\ Benefits}{Annualized\ Uniform\ Cost} \qquad 2.8.3$$

Total Benefit = CF – (R – R')

CF – Annual Cash flow.

R = Annualized uniform cost, $P_{NPV} \times CRF$

$$R = P_{NPV} \times \frac{i(1+i)^n}{(1-i)^n - 1}$$

CRF = Capital recovery factor

P_{NPV} = Net present value of the dryer

R' = Annualized salvage value,

$$R' = \frac{S}{(1+i)^n - 1}$$

2.8.4 Life Cycle Cost Analysis

This is the systematic analytical process of evaluating alternative courses of action early within the system, with the objective of choosing the best alternative to utilize scarce resources. The expression is given as follows (Repele and Bazbauers, 2015);

Annual Cash Flow (CF) = Savings from the Renewable Energy based dryer or Cost of electricity in conventional dryer

Annualized cost of dried tomato = R – R'

Cost of drying Fresh tomato Ct = Kshs/dried product per year

2.8.5 Simple Payback Period

This is calculated by dividing the initial investment by the annual cash flow. The formula is as shown on equation 2.8.4 (Nayak *et al.,* 2012; Dhanushkodi *et al.,* 2015);

$$Payback\ period = \frac{Initial\ Investment}{Annual\ Cash\ Benefits} \qquad 2.8.4$$

2.8.6 Rate of Return

Profitability of the investment into the system was measured on the basis of bookkeeping data derived from the financial statement. This is known as the Accounting Rate of Return Method (ARR). It was calculated by dividing the average income after taxes by the average investment or average book value after depreciation. The expression used is as shown on equation 2.8.5 (Dhanushkodi et al., 2015);

$$Average\ Rate\ of\ Return = \frac{AverageNet\ Income\ after\ Taxes}{Average\ Investment\ Over\ the\ life\ of\ the\ system} \qquad 2.8.5$$

2.9 Research Gaps and Lessons

Solar drying technology is one of the most effective methods for preserving food by lowering water content to slow down food spoilage through microbial activities. About 20% of all worlds' perishable crops are dried to extend shelf-life and promote food security (Mulet, 2011).

Literature review on solar greenhouse dryers revealed that Solar Greenhouse Dryer systems are widely used in fruit and vegetable drying. It is an enclosed structure which has a transparent walls and roofs made up of polyethylene films, polyvinyl fluoride, fiber glass reinforced plastic among others (Purusothaman & Valarmathi, 2017). The systems are reported to be two to five times more effective than other types of dryers (Chauhan & Kumar, 2016). Greenhouse solar dryer covered with polycarbonate sheet working under forced convection attained higher temperatures compared to all the others (Purusothaman & Valarmathi, 2017). Greenhouse dryers with PCM have shown significant results in enhancing temperatures within the system but the costs were so high. Most greenhouse dryer's performance has been tested and documented by various researchers but none have done on the use of desiccant materials under greenhouse dryers. Therefore, this study involved developing of the greenhouse dryer with the desiccant unit and evaluating its performance. Most researchers have dealt with composite desiccant material in drying; this is due to the low cost of production as compared to commercial desiccants. Therefore, this study had employed the use of low-cost clay based desiccant materials in drying fresh tomatoes under a greenhouse dryer. Photovoltaic integrated solar greenhouse dryers are most suitable for large scale commercial drying since the production rate increases with the increase in flow rate of air.

On the basis of these findings, design of a prototype solar greenhouse photovoltaic powered dryer with desiccant energy storage system for tomato was proposed. The drying performance of the system was tested against the use of desiccant units.

CHAPTER THREE: METHODOLOGY

An autonomous solar greenhouse dryer integrated with desiccant energy storage system both powered by photovoltaic (PV) system was designed, constructed and tested for performance in tomato drying under typical weather conditions at Kenyatta University (K.U.). The system operated during the day using solar drying mode while at night it used solid clay-$CaCl_2$ desiccant drying system. The research was undertaken in the following sequence:

a) It started with the production of solid kaolin clay–$CaCl_2$ based desiccant materials through hand-rolling of one-centimeter desiccant balls;
b) The desiccants were then dried at 50^{o}C using drying oven model OVB-300-010N (UK) for 24 hours followed by firing at 200^{o}C and tested in constant humidity salt solutions of Sodium Chloride ($NaCl_2$) (Shanmugam and Natarajan, 2006; Quincot *et al.*, 2011).
c) The dried desiccants were then loaded into porous bags weighing 2000 grams each totaling 96 kg weight.
d) This was followed by design and construction of the solar greenhouse dryer integrated with clay based $CaCl_2$ desiccant energy storage.
e) Lastly the system was tested for its drying performance in terms of drying rate using solar energy and desiccant drying during night time.
f) Finally, economic analysis of the developed system was carried out in terms of Net Present Value (NPV) and Internal Rate of Return (IRR). Also, other economic indicators evaluated included Cost Benefit Ratio (CBR) and payback period.

In carrying the experimental tests to evaluate the performance of the solar greenhouse dryer with desiccant energy system, the flow chart was used to describe the experimental design employed under the test conditions as presented under Fig. 3.0.

Experimental Design Flowchart

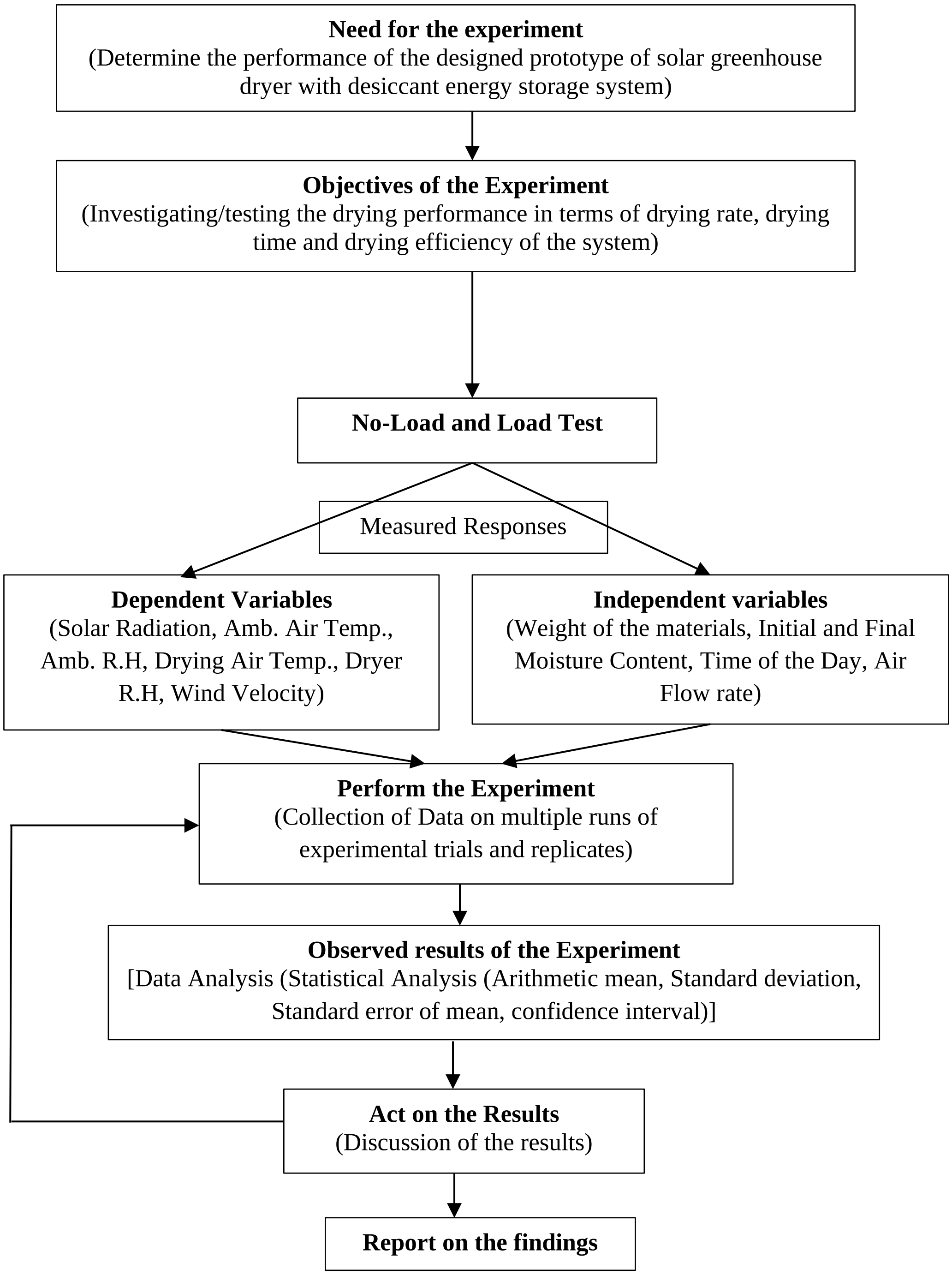

Figure 3.0: Experimental Design Flowchart

3.1 Research Site

The study was carried out at Kenyatta University (KU), Nairobi County (Kenya) with geographical coordinates 1°10′50.0″S, 36°55′41.0″E (Latitude: -1.180568; Longitude: 36.928042). It is located 18 km North of Nairobi City Centre and lies at an altitude of

1500m above sea level. It experiences temperature range between 15 - 30°C. The annual average solar energy potential of the area is about 850 kWh/m^2 per year (Muchiria *et al.*, 2019). The area experiences high solar insolation from December to February (6.5 kWh/m^2 per day) and the insolation decreases between June and September (3.5kWh/m^2 per day) (Tigabu, 2016).

3.2 Preparation of Solid Clay based $CaCl_2$ desiccants

Solid Clay based $CaCl_2$ desiccants were prepared by mixing kaolin clay, vermiculite, $CaCl_2$ and distilled water and rolled into 1 cm balls as recommended by Thoruwa *et al*., (2000). Four types of desiccants were made. Type 1 was mixed at ratios of 13:1:4:2 by mass of Kaolin Clay: Calcium Chloride: Vermiculite: Cement. It was then dried at 50°C for 24 hours followed by firing at 200°C based on research work by Thoruwa *at al.*, (2000). Type 2 desiccant was the same ratio as Type 1 and applied conditions but it was transferred to a furnace and then heated for 1hr at 500°C for activation as recommended by Castrillo *et al.*, (2018). Type 3 desiccant was mixed at ratios of 6:1:2:1 by mass for Kaolin Clay: Calcium Chloride: Vermiculite: Cement to increase the concentration of Calcium chloride for more moisture adsorption capacity based on the study curried out by Kumar & Yadav, (2017). Lastly, Type 4 desiccant was mixed at the ratios of 3.8:1:3.3:0 by mass of Kaolin Clay: Calcium Chloride: Vermiculite: Cement as recommended by patented work (U.S. Pat. No.6652775B2) (Payne *et al.*, 2003).

All the desiccants were then oven dried at 50°C for 24 hrs after which they were fired at 200^{o}C for 24 hours using a Gallenkamp Hotbox Bench Top Laboratory drying oven model OVB-300-010N (UK). The four desiccant types were then exposed in a controlled environment by use of Sodium Chloride (NaCl) salt solutions at conditions ranging from 73.6 – 75.6% RH and 24.6 - 25°C for 168 hrs for moisture adsorption. Silica Gel desiccant balls were used as a control during testing the developed desiccant materials.

3.3 Determination of Moisture Sorption Characteristics of Solid Clay-$CaCl_2$ desiccants

Determination of the moisture sorption performance of desiccants was carried out in constant humidity solutions of sodium chloride (NaCl) salt generated in glass beakers (Quincot *et al.,* 2011). Desiccants were loaded onto the perforated petri dishes suspended just above the NaCl salt solution which provided a constant humidity environment of about 75.6% RH within the beaker at room temperature. The beakers were carefully sealed using a para-film and monitored every 24 hrs. Weight of empty petri dishes and desiccant loaded in the perforated petri dishes were obtained using a balance (model JA1003B, RS-232C series (China)) for 168 hrs as shown in Figure 3.3. The weight of the desiccant was obtained by subtracting weight of petri dish loaded with desiccant from empty petri dish. The physical properties observed were wetting, colour changes and stickiness. Six runs for the four desiccants were tested and their weight were recorded. The best desiccant with the highest adsorption capacity and low processing temperature was selected for solar–desiccant drying field experiments (Payne and Powers, 2003, Thoruwa *et al.,* 2000).

Figure 3.3: Suspended solid clay-$CaCl_2$ desiccant in Constant Humidity Environment

3.4 Design of Solar Greenhouse Dryer Integrated with Desiccant Energy Storage

The design of the integrated solar greenhouse – desiccant drying system took into consideration scientific design criteria and all parameters were derived from literature review whereas a few were determined using a sequence of numerical calculations. The design parameters included climate parameters of the field-testing area, drying temperature, amount of moisture to be removed, heat energy requirement and airflow requirement.

3.4.1 Design Parameters for Greenhouse Solar Drying System

3.4.1.1 Drying Temperature

Correia *et al.,* (2015) recommended optimal drying temperatures of 52 – 67 °C within 35 – 44 hrs for tomato sliced between 15 mm and 27 mm thickness. Scanlin, (1997) suggests drying temperature between 37.7 °C – 54.4 °C for fruits and vegetables drying while Papade *et al.,* (2014) recommends averaged drying temperature of 45°C. Therefore, when the temperature is adjusted at 40°C - 60°C, a much thinner tomato slices can be used to reduce the processing time. In this project, the average drying temperature, Td, of 60°C was assumed.

3.4.1.2 Moisture Drying Load

The equation to determine the total amount of moisture to be removed (Mw) from fresh tomatoes is given by Bassey and Schmidt (1987) as:

$$Mw = \frac{Ww(Mi - Mf)}{1 - Mf} \qquad [3.4.1.2]$$

Where: Ww – Weight of Wet tomato sample, kg

Mi – Initial Moisture Content, %

Mf – Final Moisture Content, %

On the basis of assumptions made, the total water removal from fresh load of 50kg tomatoes with initial moisture content 95% (dwb) and final moisture content 6% (dwb) was calculated as follows:

$$\mathrm{Mw} = \frac{\mathrm{Ww(Mi - Mf)}}{1 - \mathrm{Mf}} = 47.34 \text{ kg}$$

3.4.1.3 Energy Required to Remove Water

The energy requirement to remove moisture from fresh tomato load was calculated using the formula provided by Mercer (2008) via two stage drying process (sensible heating and latent heating). The sensible heating involves raising the temperature of the wet tomatoes to a desired drying temperature in which the moisture would be removed. Usually given by:

$$Q1 = Ww \times Cp \times \Delta T = 8948.9903\ k \qquad [3.4.1.3]$$

Where: $Cp = 1.424Mc + 1.549Mp + 1.675Mf + 0.837Ma + 4.187Mw + 2.0505Mi = 3.977329\,\frac{kJ}{kg}\,°C$

$\Delta T = T_d - T_a$, is temperature change (◦C). The chemical composition i.e., M_c, M_p, M_f, M_a, M_w and M_i *are* as given in Appendix A under Table A-1.

Where: Q1 – Sensible heat; Ww – Weight of Wet tomato sample, kg; Cp – Specific heat capacity of the crop; ΔT – Temperature change, ◦C; Mc – Carbohydrate Content, %; Mp – Protein Content, %; Mf – Fat Content, %; Ma – Ash Content, %; Mi – Ice Content, %

3.4.1.4 Energy Requirements during Latent Heating Process

The second stage is latent heating process in which moisture evaporates from the wet tomatoes. Assuming that the water is pure, the enthalpy values were obtained at the boiling temperature of water under standard atmosphere since water starts to evaporate at 100°C; from steam table, h_g = 2676.1kJ/kg; h_f = 419.04kJ/kg. The energy required to evaporate this moisture is given by:

$$Q2 = Mw \times L = 106849.2204\ kJ \qquad [3.4.1.4]$$

Where: Q2 – Latent Heat, kJ; Mw – Amount of water removed, kg; L – Latent heat of vaporization, kJ/kg

3.4.1.5 Total Energy Requirements for Tomato Drying

Total energy requirements to dry 50 kg of fresh sliced tomatoes was $Q_1 + Q_2$ = 115798.2107 kJ which is equivalent to 32.17 kWh. This theoretical value obtained does not take into account the heat loss from the drying system because it was assumed negligible.

3.4.1.6 Air Flow Requirement for Tomato Drying

The system was working under all times (day and night) therefore the ambient temperature and relative humidity (R.H) was assumed to be 15°C and 90% respectively on day time. Using Psychrometric chart in Appendix A on Chart A_2, the kilogram of moisture per kilogram of dry air (R.H ratio/mixing ratio) was 0.0096 kg of water/kg of dry air. The assumption was that during the day the temperature within the greenhouse was increasing and the R.H was decreasing to 50% though the amount of water remained constant. For this case the air entering the drying chamber would have a temperature of 15°C and 50% R.H. Therefore, from the psychrometric chart the humidity ratio becomes 0.0054 kg of water/ kg of dry air. The temperature within the greenhouse varies from 30 – 45 °C in sunshine hours (Bouadila *et al.*, 2015). Assume the temperature within the dryer to be 45°C and the humidity ratio is remaining constant at 0.0054 kg of water/kg of dry air. From the psychrometric chart the R.H would be 9.1%. If we assume the R.H of air leaving the greenhouse drying chamber to be 75% then the dry bulb temperature and humidity ratio corresponding to this would be 30°C and 0.008 kg of water/kg of dry air. It should be noted that the dry bulb temperature was taken as an average of the air entering and leaving the dryer [(15+45)/2]. Thus, change in humidity ratio of the drying air would be; 0.008-0.0054=0.0026 kg of water/kg of dry air. Consequently, the volume of the air needed for drying was calculated with the ideal gas equation formula (Brown *et al.*, 2005) on equation 3.4.1.6;

$$PatmVa = MaRTatm \qquad [3.4.1.6]$$

Where: P_{atm} – Atmospheric pressure; V_a – Volume of the air; M_a – Mass of the dry air; R – Ideal Gas Constant; T_{atm} – Atmospheric Temperature

Therefore, the Volume of the air was calculated since we have the values of P*atm* =101.3kPa; R=0.287kPam^3/kg K; T*atm* = 303K. For humidity ratio increase of 0.0026 kg of water/kg of dry air, this means; 1 kg of water requires 1/0.0026 kg of dry air = 384.62 kg of dry air.

Mass of dry air required to remove 47.34 kg of water was 384.62*47.34 = 18207.91 kg of air. The volume of the dry air required was equal to (18207.91*0.287*303)/101.3 = 15630.58m^3.

3.4.1.7 Fan Sizing

Assume the drying time to be 24 hours, there would be 24*3600 = 86400seconds. Therefore, the air flow rate was 15630.58/86400 = 0.18091m^3/s. If the pressure drop through the drying tray was assumed equal to the atmospheric then the minimum size of the fan size would be 0.18091*2118.9 (conversion factor to CFM) = 383.33 CFM (ft^3/min). With the locally available exhaust fans there were two categories identified under Appendix B Table B-1 with their specification.

3.5 Sizing the Greenhouse Drying System with Desiccant Energy Storage

One of the criteria considered for the design of the drying system is its ability to operate in two drying modes i.e., solar drying mode during day-time and at night mode using desiccant drying to remove designed moisture load continuously within 24 hours as presented on Figure 3.5. The maximum designed drying load was approximately 50 kg of fresh tomatoes corresponding to the general demand for a small-scale tomato farmer in East Africa. In addition, it was assumed that the system would be operated during sunny conditions making it self-sufficient in terms of solar drying and solar-desiccant regeneration process.

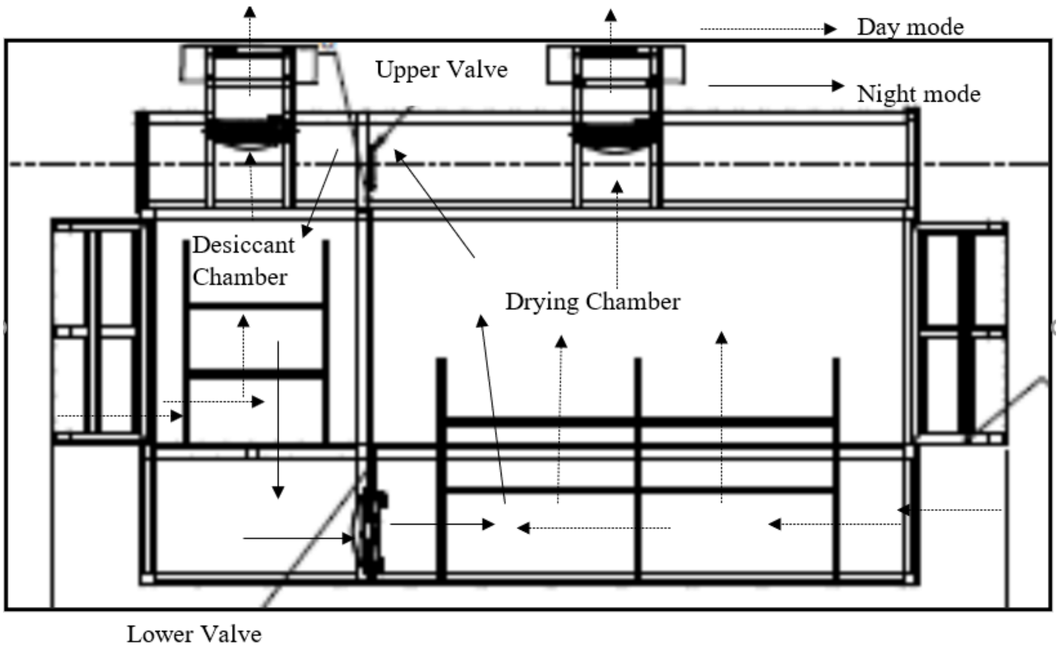

Figure 3.5: Principle of Operation of Solar Greenhouse-Desiccant Drying System (Day and Night Mode)

3.5.1 Determining Greenhouse Drying System size on the basis of Energy Requirements

The overall area of the solar greenhouse dryer for collecting the solar energy radiation was related by the overall drying efficiency of the system η_d, as given by equation 3.5.1

$$\eta d = \frac{MwL}{IAt}, \quad [3.5.1]$$

From the previous research an average solar radiation received by solar greenhouse dryer that ranged from 300 – 500W/m^2 had the effective drying time of 24 – 48 h (Sahu *et al.,* 2016; Intawee & Janjai, 2012; Janjai *et al.,* 2009). The overall drying efficiencies of the solar greenhouse dryers have been varying depending on the load densities and weather conditions. Distinctive values reported for a PV – ventilated solar greenhouse dryers ranged from 8% - 30%. (Patil & Gawande, 2016, Elsamila & Dyah, 2014). To achieve an optimal design, maximum value of greenhouse energy collection efficiency of 30% was assumed as a design parameter. Substituting M_w = 47.34kg, L = 2257.06kJ/kg. t =172,800s (i.e., 48h), I = 400W/m^2, into equation (3.5.1), and assuming a mean overall efficiency of 30%. As a result, Collection area for solar greenhouse dryer required for drying was calculated and yielded A = 5.15m^2. An even span shaped solar greenhouse dryer was chosen as recommended by Barnwal and Tiwari (2008) to maximize capturing of the solar radiation. Therefore, based on the standard size of polyethylene paper (200µm thickness) and structural materials the dimensions of the solar greenhouse dryer collection area were selected to be 2m by 2.5m floor area, 1.5 m central height and 1.1 m side walls.

3.5.2 Area of the Drying Bed

The drying bed area was calculated by using equation 3.5.2 (Forson *et al.,* 2007) by relating the solid density of the wet tomato produce to its mass and corresponding volume.

$$Adb = \frac{Mw}{\rho hL\xi\,(1-\varepsilon v)} \quad [3.5.2]$$

Where Mw mass of the crop to be dried, ρ bulk density of the crop on wet basis, hL layer drying bed thickness, ξ crop porosity, εv loading bed void fraction. Substituting M_W = 50kg, ρ = 565kg/m^3 (Ilori &Raji 2018; Ilori &Raji, 2013), h_L = 0.2m (Forson *et al.*, 2007) a maximum value recommended for a thin layer drying, ξ = 0.47 (Kaymak *et al.,* 2010), and εv = 0.82, the drying bed area is given as 5.23m^2. Loading density corresponding to this is 9.6kg/m^2. Following the available tray size of 0.97 m by 0.65 m i.e., 0.6305m^2, thus the number of trays required was 8.

3.5.3 Drying Bed Arrangement

The drying chamber floor area needs to have a corridor to allow loading and unloading of the crop product easily. According to Forson *et al.*, 2007, 60 – 80% of the drying chamber floor area is utilized as the drying surface area. Therefore, a two-layer drying bed is recommended by Forson (1999). A passage way of 0.7m was provided along the length of the drying chamber from main entrance door, between the drying racks. Therefore, 33% of the chamber floor area provided access to the drying chamber. The trays were arranged in two layers viz. the upper and lower layers comprising of 4 trays respectively. It was recommended that the lower layer to be placed 90 cm above the ground floor within the drying tomato chamber and 30 cm below the upper layer to capture air inflow through the vent into the system.

3.6 Determination of Desiccant Drying System size on the Basis of Energy Requirements

The sizing of the desiccant chamber unit considered the following; Amount of water to be absorbed by the desiccant bed which was assumed to be 50% of the total moisture to be removed, that is 23.67kg of moisture was to be removed over night by the desiccant balls on the bed. The amount of desiccant required was estimated by the regression correlation equation 3.6 as suggested by Thoruwa (1999).

$$M = 1.16002+1.93263\Delta t-0.03805(\Delta t)^2+0.0038(\Delta t)^3 \text{ with correlation } R^2=99.3\% \quad [3.6]$$

Where by M = Moisture Content per unit desiccant dry weight, % (dwb) and Δt is the time interval in hours. Since the testing conditions of the bentonite-$CaCl_2$ desiccant were at 85% relative humidity and 25 ^oC. The same was applied under Kaolin – $CaCl_2$ Clay based desiccant to describe its performance. Therefore, for Δt = 16 hours the amount acquired by the desiccant was 37.91% (dwb) (Thoruwa *et al.*, 1999).

3.6.1 Sizing of the Desiccant Energy Storage System

The solar greenhouse dryer with the forced convection photovoltaic fan was designed to dry 50 kg of fresh tomatoes from a moisture content of 95% (dwb) or 80% (dwb) to 6% (dwb) or 10% (dwb). This is equivalent to removing 47.34 kg of water within 8 hrs of sunshine. Therefore, the assumption that under tropical conditions only 50% of the total moisture was removed during the day time. Therefore, 23.67 kg of moisture is to be removed during the 16 hours at night time.

From literature data solar regeneration of silica gel can start at 40°C and at an R.H. value between 50% and 80% is suitable as a solid desiccant for air conditioning. Therefore, on average using solar energy is about 65% of its operating moisture capacity (Pramuang and Exell, 2007). Since moisture sorption acquired by Kaolin-$CaCl_2$ desiccant after 16h is 37.91% (dwb), therefore 65% of the operating moisture sorption capacity was 24.64% (dwb). This has to absorb a water load of 23.67 kg. Therefore, the amount of desiccant was calculated from equation 3.6.1;

$$M_D = \left(\frac{Mw}{24.64}\right) * 100 = 96.06\,kg \quad [3.6.1]$$

Therefore, the amount of desiccant used is 96.06 kg.

Sizing of the desiccant energy storage system considered the shape of the mold, the amount of desiccant to be used during drying as well as its bulk density. The system was designed as an air tight chamber attached to the drying chamber with a plenum to enable air exchange with the tomato chamber. Therefore, the volume of the desiccant bed was derived by considering a rectangular packed boxlike bed due to the design features of the photovoltaic solar greenhouse dryer. The volume of the desiccant bed was calculated by the equation 3.6.2 which relates mass and volume to density,

$$V_D = M_D/\rho_D \quad [3.6.2]$$

Where, the ρ_D is the bulk density of the Kaolin-$CaCl_2$ desiccant. From the test carried out on this desiccant its bulk density was recorded as 594.70 kg/m^3.

$$V_D = \frac{96.06kg}{\frac{594.70kg}{m^3}} = 0.16152682 \approx 0.1615\,m^3$$

3.6.2 Sizing Desiccant Chamber based on Energy Requirement

Considering the Energy requirement Desiccant size was derived using equation 3.5.1. The assumption was that the solar radiation received by desiccant chamber was 400 W/m^2 with the estimated drying time of 48 hrs. The overall efficiency was assumed to be 30%. Therefore, substitute the same L = 2257.06 kJ/kg and the amount of water to be removed from the desiccant energy storage be 23.67 kg. Then the collection area of the desiccant chamber required for drying was calculated as 2.3 m^2. With the breadth of the tomato drying chamber being 2m then the length of the desiccant chamber was determined to be 1.14 m.

3.6.3 Sizing Desiccant Drying Bed Area

Desiccant drying bed area was calculated by using equation 3.5.2. Given the amount of desiccant to be used into the system being 96 kg, the bulk density being 594.7 kg/m^3, the layer drying bed thickness of 0.2 m, the porosity of the desiccant as 0.68 as presented by Thoruwa *et al.,* 1999 together with void ratio of 0.7, the desiccant drying bed area is given as 3.96 m^2. Using the same available tray size of 0.97 m by 0.65 m i.e., 0.6305 m^2, therefore the number of trays required will be 6. With the length of the drying rack of 0.97 m we expect the desiccant chamber length to be slightly higher. It was decided a 1.1 m length desiccant chamber will be enough to be able to be covered by the greenhouse paper breadth. Therefore, desiccant balls were packed in a porous bag about 2 kg weight. Each tray accommodated a total of 8 porous bags. And the trays were arranged in three layers within the desiccant chamber.

3.6.4 Determining Airflow Requirements for Desiccant Solar Regeneration

Using a psychrometric chart as shown in Appendix A-2 the amount of airflow required by the desiccant regeneration process was calculated. Ambient air temperature was assumed to be, T_a = 15°C and ambient relative humidity, R.Ha = 90% which was heated to T_p = 50°C, then the R.Ha was reduced to R.Hp = 40%. The heated air was utilized to remove moisture from the thin layer of desiccant on drying trays ($\leq$0.1m) as the dry bulb temperature dropped then moisture was absorbed by the desiccant and this continued along the line of constant wet bulb temperature till there was an intersection with the saturation curve of $R.H_c$ = 100% was reached, and drying air temperature was reduced to 24.8°C. This decrease in temperature from 50°C to 24.8°C represents the maximum amount of heat available for evaporation of water per kg of dry air circulated. The variation in humidity ratios W_1 = 0.009667$kg_w/kg_{d.a}$ to W_2 = 0.019833$kg_w/kg_{d.a}$. The mass of water that was evaporated M_W from the desiccant bed and absorbed by a mass flow rate of drying air was related by equation 3.6.5 (Sawardsuk *et al.*, 2018).

$$MwHfg = \dot{m}aCpa(Tp - Tc) \qquad [3.6.5]$$

Latent heat of vaporization of water at T_c = 24.8 °C is given as H_{fg} = 2442.172 kJ/kg_w and specific capacity of air C_{pa} = 1.02 kJ/kg_a°C.

Therefore, the mass of air required was 2248.918894 $kg_{d.a}$

Since the specific volume of air at 24.8°C was 0.871$m^3/kg_{d.a}$ then the Volume of air was determined as;

V_a = m_a*Specific volume of air

V_a = 1958.808356 m^3

Air flow during generation was;

$$Air\ flow\ rate\ = \frac{Total\ volume\ of\ air\ to\ evaporate\ the\ amount\ of\ water\ in\ m3}{Total\ generation\ time\ in\ hours\ (8hrs)}$$

= 1958.808356 m^3/ 8 hrs = 244.85 m^3/h = 0.06801 m^3/s = 144.106 CFM

Using Categories of fans in Appendix B then category 1 was selected and two fans of each 113.11 CFM were used.

3.7 Design of the Photovoltaic electrical system

3.7.1 Sizing Photovoltaic Module and Battery Storage System to Power Fans

The PV modules have to produce adequate energy to power the fans. Sizing and configuration of the solar panels has to consider the energy produced and consumed by the system. Estimation was made to size the panel and battery utilizing the design processes as presented by Salah *et al.*, 2015 and Jägern *et al.*, 2016.

3.7.2 Power Consumption Determination

The power requirement considered an operating voltage of 12V to be used for the PV system. The power rating of the dryer was approximately 64.8W (12V 2.7A) and the operating drying period was assumed 24hours.

$$Daily\ energy\ requirement\ (Wh) = \ 64.8W\ \times 24h = 1{,}555.2Wh$$

In order to add up to the system losses from the components of the PV system, charge regulator and battery use energy, a battery efficiency of 80% and compensating factor of 1.11 (This figure is available from battery manufacturer) was used. Therefore, total energy requirement by loads was calculated as follows;

$$Total\ energy\ requirement = \left(\frac{1555.2}{0.8}\right) \times 1.11 = 2157.84Wh$$

3.7.3 Sizing of the PV modules

The PV module differs in the amount of power it produces. The solar panels available were with the following specification; Peak Power P_{max} = 50 Wp, Peak Voltage V_{max} = 12 V, Peak Current I_{max} = 16.5 A, Open circuit voltage V_{oc} = 16.5 V and Short circuit current I_{sc} =5.4 A. Therefore, the ampere hour required per day was 1555.2Wh/12V = 129.6 Ah. If the average daily sunshine hours were assumed to be 8hours then the solar panel charging current was 129.6 Ah/8 hrs = 16.2 A. Therefore. the photovoltaic panel rating was,

$$PV\ panel\ rating(W) = Charging\ V\ \times Charging\ A = 12V \times 16.2A = 194.4W$$

Panel rated 50W peak power then the number of PV panel needed was 194.4 W/50 W = 3.888 panels. Therefore, the PV system design was powered by 4 panels of $50W_p$ PV modules connected in parallel.

3.7.4 Sizing of the Battery

Battery sizing was attained by considering operational load at night and in both times the PV modules was receiving limited sunlight. As a rule of thumb for PV system to operate safely to all anticipated conditions with cloudy weather then the number of autonomy days (number of days the system can continue to operate while receiving little or no charge) was taken to be 3. Therefore, the required battery Bank Ampere hour was 1555.2 Wh/12V = 129.6 Ah. The total battery capacity for the system was given by;

$$Battery\ capacity\ required = Total\ DC\ energyrequired\ by\ load\ \times Days\ of\ Autonomy$$

The Total Ampere hour required was 129.6 × 3 = 388.8 Ah. The battery used was rated 12V 200Ah and two of these were connected in series.

3.7.5 Sizing of the Charger Controller

Charger controller size was determined based on the recommendation from the National Renewable Energy Laboratory (NREL) – USA in which the solar charger controller was calculated on the short circuit current of the panel rated as 5.4A. Solar charge controller = number of panels connected in series × short circuit current × factor to take care of losses which is 1.3. Charge controller rating = 4×5.4×1.3 = 28.08A. In this study a 30A 12Vrated charge controller was selected and adopted.

3.7.6 Solar PV system component arrangement

The Photovoltaic (PV) module rated 50W, 12V a make from China, powered both drying chamber and desiccant chamber fans are as shown on figure 3.7.6 (a) showing all the component arrangement of the PV electrical system and Figure 3.7.6(b) showing the circuit diagram for the fans. Fan 1 and 2 were rated as 12V 4.1A whereas fan 3 and 4 were 12V 2.7A and 12V 4.5A respectively.

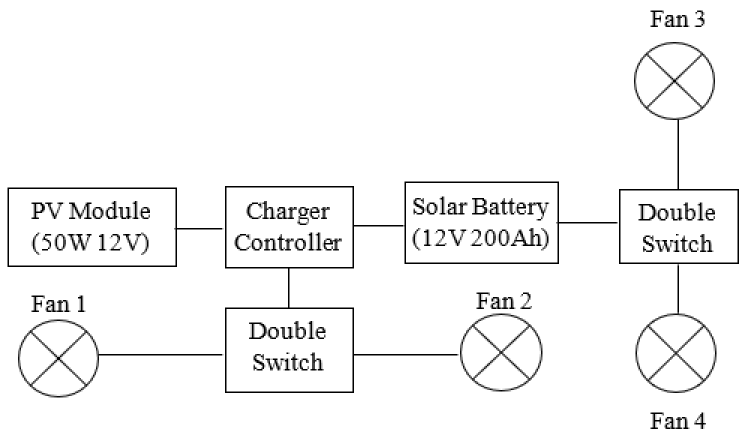

Figure 3.7.6(a): Schematic diagram of the Solar PV electrical System

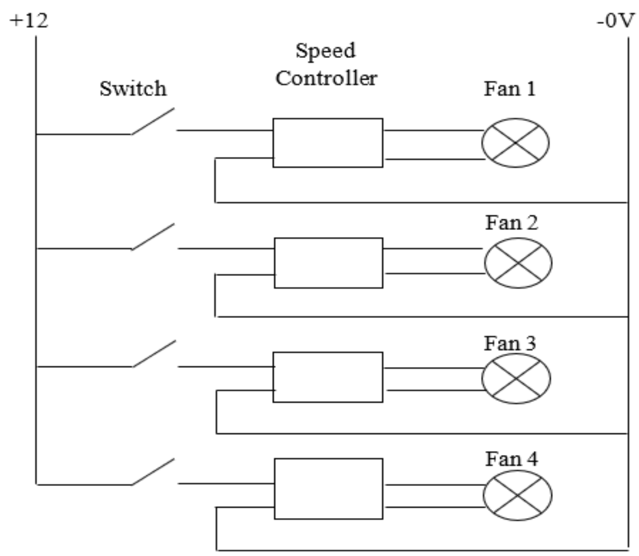

Figure 3.7.6 (b): Circuit diagram of the fans

Two solar batteries of a 200Ah, solar charger controller of 30A, 2.5 mm electrical cable and two double switches were included in main components. The solar panel was charging the solar battery via a charger controller to protect the battery from overcharging, and it was placed on top of the roof of the workshop building. Both solar battery and the charger controller were placed inside the workshop.

3.8 Construction of the Solar Greenhouse Dryer with desiccant energy storage system

The system construction considered appropriate selection of the materials that were locally available, easy to handle during fabrication, low cost and ability to withstand environmental and operating conditions (Serviceability life). The solar greenhouse dryer incorporated with desiccant dryer chamber orientation was facing N-S direction and tilt angle, were derived from the test site/location; therefore, manufacturing of the system at village setting have to follow the same rule of thumb considering latitude of the site as described in section 3.1. Plenum chamber was considered to enhance the exchange of dry air between the drying chamber and desiccant chamber during night as shown on figure 3.8(a). Both floors on each chamber were covered with the black sheet materials for better heat collection during the day. A photo of constructed solar greenhouse dryer incorporated with desiccant energy storage is as shown on figure 3.8(b). The working Drawings with dimensions are given under Appendix E

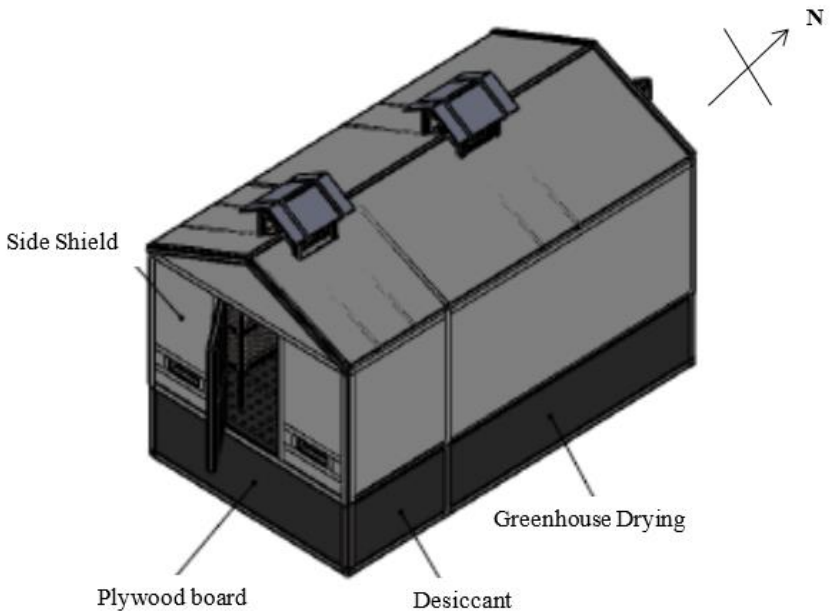

Figure 3.8(a): Isometric View of the SGH with desiccant Energy Storage system

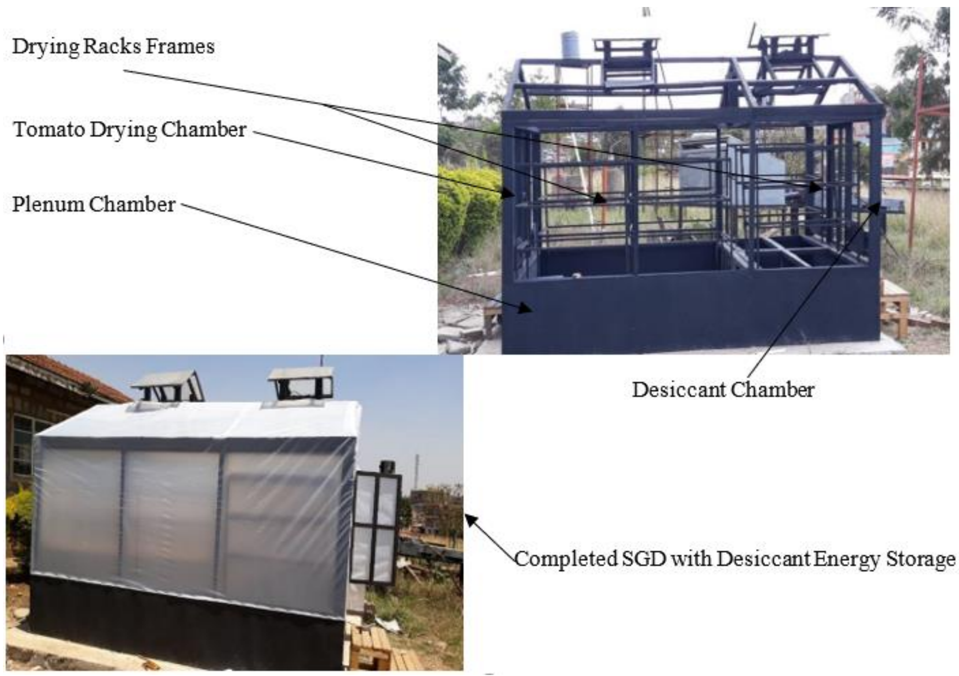

Figure 3.8(b): Constructed Solar Greenhouse Dryer (SGD) with Solid Clay-Cl_2 Desiccant energy storage system Photo

The solar greenhouse dryer with its desiccant chamber main frame is as shown in figure 3.8(c). The system was constructed on top of a concrete floor for the experiments; wooden poles of size 76.2 mm x 50.8 mm were used to create the side walls, plenum chamber and the gable with the main frame made by 101.6 mm x 50.8

mm timber. The partitions were done by 50.8x50.8 mm square shape timber. The drying racks frames were made by using square bar, angle iron and flat bar both 19.05 mm. The drying trays were made from wooden bars size 0.65 m x 0.97 m.

Figure 3.8(c): Solar Greenhouse Dryer with desiccant Energy Storage System Framework

3.9 Experimental Procedures and Solar Greenhouse Drying System Evaluation

The experiments were carried out during months of August 2019, October 2019, November, 2019, December 2019 and January 2020. During this time the weather ranged from sunny to cloudy weather conditions. The solar greenhouse drying system (SGDS) was set with its longest side facing North-South direction to capture maximum solar radiation. Four 25W DC fans with speed regulator were installed in the system to control the speed of the fan to provide the required flow rate. Each chamber had one extractive fan at the roof top to extract moist air out and one fan to exchange moist air from the SGD and one to exchange dry air during the night time when using desiccant energy storage system. The fans were powered by a solar charged battery of 200Ah.

3.9.1 Tomato Preparation for Drying Tests

Tomatoes were purchased from the Githurai market located 8km from Kenyatta University, Kiambu County along Thika Road superhighway. Tomatoes were sorted and only firm, ripe and unstained tomatoes were selected, then washed and dried with clean cloth, and sliced into 5mm thick round pieces because drying rate increases with increasing temperature and reduced thickness (Sadin *et al.*, 2014). Using a digital platform balance Model No. 14191-461F (UK) with an accuracy of ±0.01g, the weight of the sliced tomatoes for different trays on their respective layers was determined. The sliced tomatoes were spread on the drying trays with a spacing distance less than 1cm and placed in double layers within the system. Slicing the tomatoes into small sizes aimed at lessening drying time and keeping up the quality of the dried tomatoes. Figure 3.9.1(a) shows the tomato samples before and after being sorted and Figure 3.9.1(b) shows the sliced tomatoes uniformly spread on the trays and loaded in the drying chamber.

Figure 3.9.1(a): Tomatoes samples used in the tests

Figure 3.9.1(b): Sliced and tray loaded with uniformly spread tomatoes

3.10 Solar Greenhouse Drying with Desiccant Energy Storage System Performance and Data Collection

Evaluation of the solar greenhouse dryer incorporated with desiccant energy storage system was done using several test runs. The first performance tests were conducted with no drying load test, where the temperature of the solar greenhouse drying system was measured without drying load. The temperature variation from the system inlet through the drying bed and ambient temperatures were monitored and recorded at every 15 minutes interval via a data logger (model RIGOL's M300 Series, China).

Carrying out the no load test helped to establish the maximum possible temperature rise attained within the drying and desiccant chamber respectively when compared to the corresponding ambient temperature. Under load test, parameters measured included temperature, solar radiation, air velocity and moisture content. The data recorded during this test were used to determine the solar drying efficiency of the drying system. All test runs conducted are summarized in Table 4.1.

3.11 Preliminary Drying Experiments

Preliminary experiments were undertaken to examine the thermal behavior of the system with and without load. The tests began by all open vents of the SGD with DES system during the day and closed during the night times. During the day, natural airflow was allowed to flow through the vents and hot air was extracted on the rooftop using extractive fans system as shown in Figure 3.5. During night time, all the extractive fans were switched OFF and inlet vents covered while fans placed between the drying chamber and the desiccant chamber were switched ON. Solar radiation and temperature measurements were recorded at 15 minutes time interval via a data logger (model RIGOL's M300 Series, China).

A total of 10 test runs were conducted without and with load conditions. The first 3 test runs were conducted with no-load conditions tested at low, medium and high air flow rates. The other tests were under load and the test was done under an optimal airflow rate of 0.28 m^3/s and 0.07m^3/s for drying and desiccant chamber respectively. Air speed entering the system was also recorded at one-hour time interval and averaged. The pressure drops within the solar greenhouse dryer with desiccant energy storage and through the drying trays was assumed to be equivalent to the atmospheric pressure.

3.12 Calibration and Measurements

To ensure collected data was accurate, calibration of measuring equipment was carried out. Calibration of temperature measuring equipment was carried out via thermocouple type K hooked onto a data logger (Model RIGOL's M300 Series, China) and was compared with standard mercury bulb thermometer readings. The readings were obtained at ice point and during heating of water to about 82°C testing temperature range carried out during test experiments. Figure 3.12 represents a linear calibration curve obtained when the thermocouple temperature and mercury bulb thermometer readings were compared simultaneously. The results were shown in Table C_1 in Appendix C.

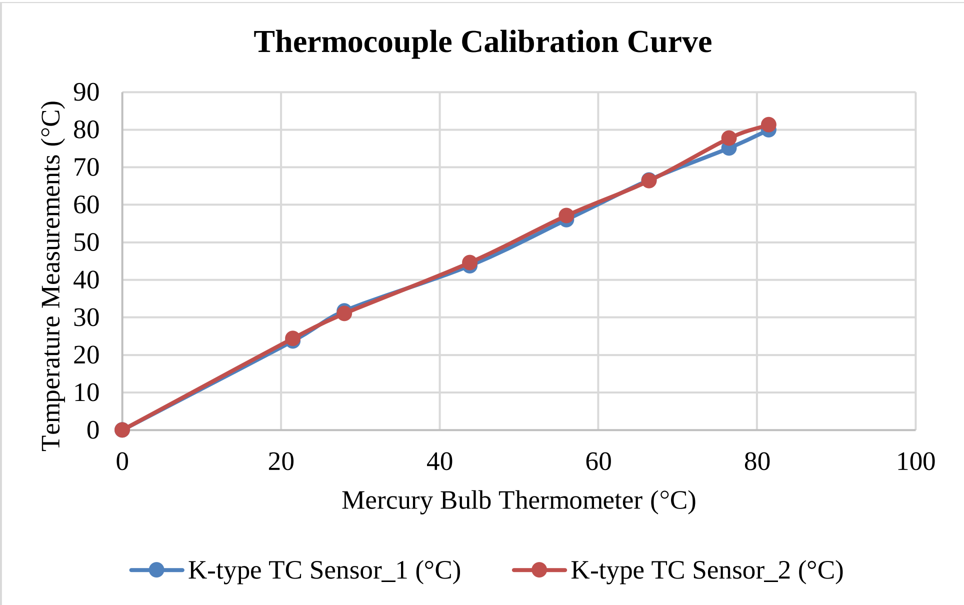

Figure 3.12: Thermocouple calibration curve

3.13 Experimental Data Collection

Ambient temperature, greenhouse dryer air temperature, relative humidity of the inlet and outlet air conditions and solar radiation were recorded. Airflow rate were set at 0.19m^3/s, 0.28m^3/s, and 0.45m^3/s for tomato dryer chamber and 0.07 m^3/s, 0,19 m^3/s, and 0.36 m^3/s for desiccant chamber as independent variables termed as low, medium, and high flow rate respectively. The experiments were conducted at different flow rate corresponding to a new testing day to make comparison because of the weather changes at all time.

Moisture content of the dried tomatoes was recorded as dependent variable. The greenhouse shield facilitated the heating of air within the system to create hot air to dry sliced tomatoes as well as regeneration of the desiccant. The sliced tomatoes were distributed in eight trays in two layers to measure the performance of the individual trays. The drying process was observed until the product weight was constant under the greenhouse dryer. Lastly under each tray the weight loss of the product was measured and the overall drying performance of the system was estimated.

3.14 Experimental Measurements of Variables

Evaluation of the solar greenhouse dryer with desiccant energy storage system; with and without load was conducted using several different test runs. Temperatures and solar radiation measurements were recorded via a data logger at 15 minutes intervals while airflow and moisture content measurement were made on hourly basis.

3.14.1 Solar Radiation Measurements

The solar irradiance was measured by Kipp and Zenon pyranometer (CN27-277), Australian with sensitivity of 91.68 W/m^2 per mV which was mounted on the rooftop adjacent to the solar greenhouse dryer and connected on the data logger.

3.14.2 Temperature Measurements

The temperature measurements were made in various positions as shown on Figure 3.14.2. The measurements were recorded via data logger (Model RIGOL’s M300 Series, China) at 15 minutes time interval using Thermocouple type K (with an optimum range of -270 °C to 1372°C and temperature coefficient of ± (0.015% +1mV)/°C). Description of measurements made is presented in Table 3.14.2.

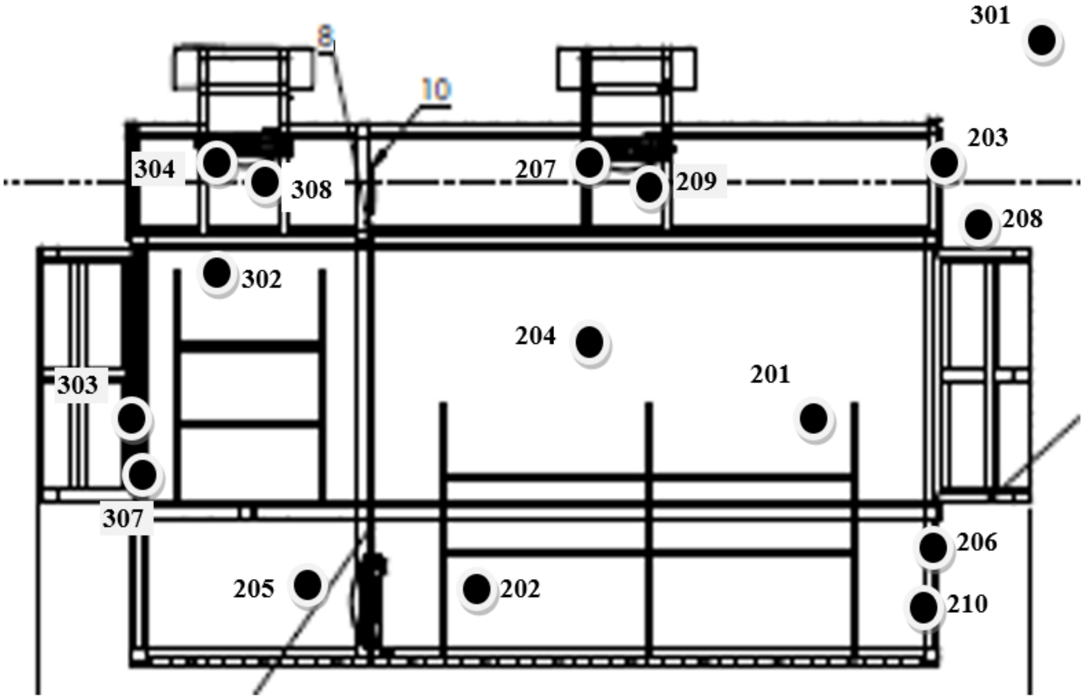

Figure 3.14.2: Experimental Setup and Data Measurement Positions

Table 3.14.2: Data Collection Measurements Locations

Location	Description of Measurements
Point 201	Temperature within the greenhouse just slightly above the upper layers of trays
Point 202	Temperature on lower layers of trays in the greenhouse
Point 203	Ambient Temperature (dry bulb temperature)
Point 204	Temperature at the middle of the greenhouse
Point 205	Temperature within the desiccant chamber
Point 206	Temperature of the air entering the greenhouse drying chamber at the right-hand vent
Point 207	Temperature of the air leaving the greenhouse at the rooftop (dry bulb temperature)
Point 208	Ambient Temperature (wet bulb temperature)
Point 209	Temperature of the air leaving the greenhouse at the rooftop (wet bulb temperature)
Point 210	Temperature of the air entering the greenhouse chamber left hand vent
Point 301	Solar Irradiance
Point 302	Temperature in the Desiccant chamber
Point 303	Temperature of the air entering the desiccant chamber on the right-side vent of the wall
Point 304	Temperature of the air leaving the desiccant chamber (wet bulb temperature)
Point 307	Temperature of the air entering the desiccant chamber on the left side vent of the wall
Point 308	Temperature of the air leaving the desiccant chamber (dry bulb temperature)

3.14.3 Relative Humidity measurement

Ambient relative humidity and exit conditions of the greenhouse drying system with desiccant energy storage were calculated using equation 3.14.3 as presented by Australian Government Bureau of Meteorology and the other researchers (Huang *et al.*, 2013). The equation considered dry bulb temperature, wet bulb temperature and the atmospheric pressure of the field-testing site. The atmospheric pressure was taken at an altitude of Nairobi which is 1500m as shown on Table 3.14.3 (Huang *et al.*, 2013).

$$R.H \;= \frac{100\left[expexp\left[1.8096+\left(\frac{17.2694Tw}{237.3+Tw}\right)\right]-7.866*10^{-4}*P(T-Tw)\left(1+\frac{Tw}{610}\right)\right]}{expexp\left[1.8096+\left(\frac{17.2694T}{237.3+T}\right)\right]} \qquad [3.14.3]$$

Where: R.H – Relative humidity (%), T – Dry bulb temperature (°C), T_W – Wet bulb temperature (°C), P – Station level pressure (kPa).

Table 3.14.3: Standard Pressures if the pressure is not known

Station Altitudes (m)	0 – 250	251 – 500	501 – 750	1001 - 1250	1251 - 1500
Pressure (kPa)	998.3	969.0	940.4	912.5	885.2

The equation was applicable because the air temperature was greater than or equal to 0°C (Zelin *et al.*, 2010). The inside relative humidity for both greenhouse chamber and desiccant chamber was obtained on hourly basis by using a digital psychrometer (model 5105, UK) and humidity meter (model 5070, UK) with range 20% - 90% R.H and temperature range 0 - 60°C.

3.14.4 Measurement of other Variables

Air flow rate (m^3/s), air velocity (m/s) and weight (kg) of the wet and dried tomatoes were measured manually at an hour interval. Wind speed and air flow rate were measured using VELOCICALC portable air flow meter (model 8357, TSI, USA). The weight (kg) of the wet and dried tomatoes was measured by the digital platform balance (model 14191 – 461F, China).

3.14.5 Moisture Content Measurements

Moisture content of tomato samples were monitored on hourly basis via manual weighing via a digital platform balance (model 14191 – 461F, China). The scale was placed within the tomato and desiccant chamber. The gravimetric method was a technique used. The samples were weighed, then oven dried (for one hour at 105 °C under enclosed chamber) and weighed again. The moisture content of tomato samples was determined using equation 3.14.5 (Zambrano *et al.*, 2019). Initial moisture content was calculated based on initial and final weight of the sample and the assumption made was that the weight loss was due to water removal and other losses of volatiles were ignored. An electric air convection oven (200 ± 1°C) was used for drying samples (Zambrano *et al.*, 2019, AOAC, 2000).

Moisture content was calculated on dry bases as follows:

Initial moisture content $Mo = \frac{Wo-Wd}{Wd}$

Final moisture content $Mf = \frac{Wwet-Wd}{Wd}$

Where: Wo – Original weight of the sample before drying, kg; Wd – Weight of the dried sample, kg; $Wwet$ – Weight of wet sample, kg

At time interval t, the moisture content 'M_t' of tomato slices on wet bases was expressed as:

$$Mt = \frac{Wt-Wd}{Wt} \quad [3.14.5]$$

Where: Wt – Weight of the dried sample at time t, kg

3.15 Experimental Data Analysis

The experimental observation data of the solar greenhouse dryer with desiccant energy storage for different observed thermal energy was presented in Table 4.2. The analysis of the results used a descriptive statistical analysis where by arithmetic mean and standard deviation were calculated as suggested by Holman, 2003. A series of mathematical equations to calculate thermal efficiency, drying efficiency as well as drying rate were used as present under literature review of this study.

3.16 Economic Analysis

Economic analysis of the solar greenhouse dryer with desiccant energy storage was carried out as shown on Appendix B on Table B_2. The economic analysis of this study considered costs of construction materials and labor charges as well as the output of the solar greenhouse drying system with desiccant energy storage together with other assumptions as shown on Table B_3. Also selling price of sun-dried tomatoes was considered as sourced at Naivas Supermarket along Moi Avenue in the Central Business District (CBD) Nairobi with sell price at Ksh 575/= for a 280g dried tomato slices by weight.

3.17 Economic Analysis Evaluation

In this study the following economic indicators were used to assess the investment cost of the solar greenhouse dryer with desiccant energy storage system for tomato drying operation.

The Discounted Cash Flow method was used as shown in Appendix B_7 to estimate the value of an investment based on the future cash flows (Dhanushkodi *et al.,* 2015). Simple payback period with Rate of Return Investment (RRI) method was used as shown in Appendix B_8 and B_9 (Dhanushkodi *et al.,* 2015). Annualized Cost method (AC) was used as shown in Appendix B_6 (Kalbande and Jadhev, 2007; Sreekumar *et al.,* 2008) and Life cycle cost analysis was used [as shown in Appendix B_10 (Repele and Bazbauers, 2015)

Assumptions made while carrying out economic evaluation of the system is shown under Appendix B_3 and also the calculations were done as described under section 2.8 of this thesis.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

In order achieve more efficient energy use, the experimental solar greenhouse dryer with energy storage was designed and constructed to have two components namely solar greenhouse dryer for drying fresh tomatoes during the day using solar energy and solar greenhouse desiccant energy storage to facilitate night drying operation using solar regenerated solid Clay-$CaCl_2$ desiccants as shown in Figure 3.5. The desiccant bed was regenerated during day time to enable desiccant materials to adsorb moisture during the night. In view of the comprehensive nature of the research project, the results of the study project are presented in the following sequence:

a) Performance evaluation results for solid Clay-$CaCl_2$ desiccants in moisture sorption and regeneration
b) Thermal performance evaluation results for solar greenhouse dryer and solar greenhouse desiccant dryer without drying load
c) Thermal performance evaluation results for solar greenhouse loaded with Clay-$CaCl_2$ desiccants
d) Performance evaluation results for solar greenhouse dryer loaded with fresh tomatoes coupled to desiccant energy storage system
e) Economic viability results for the experimental solar greenhouse dryer with desiccant energy storage for widespread technology dissemination and commercialization

The overall performance of the system was assessed in terms of drying rate and thermal drying efficiency as well as economic practicability for the experimental dryer portrayed. The summary of the results obtained during the sorption study test of the desiccants is as shown on table C_2 in Appendix C. The raw information collected during all trials and tests are as shown in Appendix D.

4.1 Solid Clay-$CaCl_2$ Desiccant Moisture Sorption Performance

Table 4.1 shows performance results of solid Clay based $CaCl_2$ Desiccant Moisture Performance under constant humidity conditions of 75% RH, 25^oC. The results show that solid Clay-$CaCl_2$ desiccant developed at varying composition by mass of Kaolin Clay, Calcium Chloride, Vermiculite and Cement and rolled into one cm balls and processed at 50^oC for 24 hours and fired at 200^oC/500^oC and then tested in constant humidity bottle at 75% RH and 25^{o}C exhibited varying moisture sorption performance. Table 4.1 and Figure 4.1 shows the moisture sorption performance contrast.

Table 4.1: Solid Clay based $CaCl_2$ Desiccant Moisture Performance

Desiccant Type	Mixing Ratio Kaolin Clay: $CaCl_2$: Vermiculite: Cement	Processing Conditions	Testing Average Conditions RH%, Temperature (^{o}C)	Maximum Moisture Sorption % (dwb) after 168 hrs
1	13:1:4:2	Drying 50°C for 24hrs, Fired at 200^{o}C for 1 hour	75% RH, 25^{o}C	16.0
2	13:1:4:2	Drying 50°C for 24hrs, Fired at 500^{o}C for 1 hour	75% RH, 25^{o}C	27.6
3	6:1:2:1	Drying 50°C for 24hrs, Fired at 200^{o}C for 1 hour	75% RH, 25^{o}C	16.0
4	3.8:1:3.3:0	Drying 50°C for 24hrs, Fired at 200^{o}C for 1 hour	75% RH, 25^{o}C	30.2
Control Sample	Silica Gel Desiccant	-	75% RH, 25^{o}C	37.8

Type 1 & 3 of desiccants gave the lowest moisture adsorption of 16% dry weight basis (dwb) as shown in figure 4.1 because of the low vermiculite exfoliation upon heat application (Miner, 1934 & Miner, 1933). Other researchers showed that vermiculite undergoes exfoliation at 500°C and above (Muiambo *et al.*, 2010). The exfoliated vermiculite is very efficient in retaining moisture and can serve as a heat insulation material. Results of the current study showed that increase in Calcium Chloride content in type 3 desiccants, did not show any significant difference in moisture sorption performance. Compare with the silica gel desiccant it is evident that from this test, the mixing ratios did not affect adsorption rate.

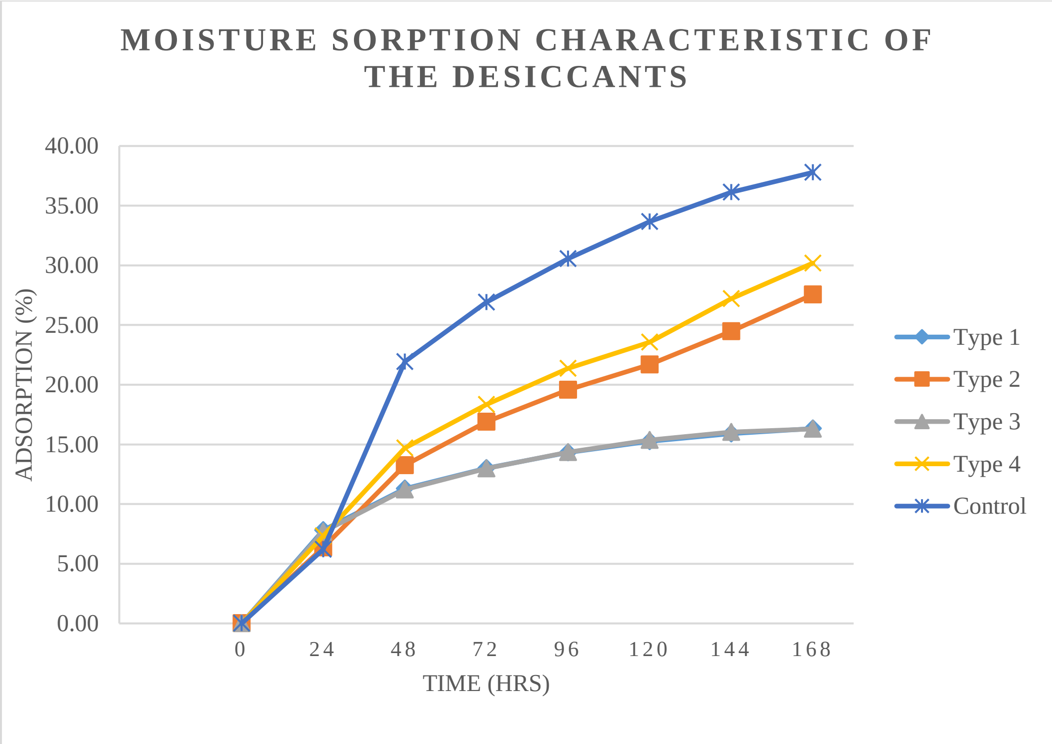

Figure 4.1: Moisture Sorption characteristic of solid clay-$CaCl_2$ desiccants

Type 2 & 4 clay-$CaCl_2$ solid desiccants exhibited 27.6% and 30.2% (dwb) moisture adsorption respectively. Figure 4.1 represent the moisture adsorption capacity of the desiccant types. The result conforms to the sorption of composite desiccant (clay-$CaCl_2$) developed by Thoruwa *et al.*, (2000) as well as commercial desiccants (ASHRAE, 2002 and ASHRAE, 2007). The results were compared with the silica gel and it showed that there was slightly higher moisture uptake of 7.6% for the same time because of the increased surface area of the silica gel. From these tests it was observed that processing type 2 desiccants at higher temperatures brought a significant change in the moisture uptake by 11.6% (42% increment) as compared to type 1 as shown on table 4.1.

On the basis of these results type 4 clay-$CaCl_2$ solid desiccant was selected as the best composition for mass production and for use as energy storage material extending the tomato drying process during night time. Despite the fact that, silica Gel showed good results compared to type 4 yet type 4 was selected because it is low-cost. Other authors have previously reported that clay-type desiccants performed better at lower temperature and have an advantage of being regenerated at lower temperature compared to other commercial desiccants (Singh *et al.,* 2018; Payne *et al.,* 2003). Therefore, type 4 desiccant exhibited the highest moisture sorption performance and required the lowest processing temperatures.

4.2 Thermal Performance of the Solar Greenhouse Dryer with Desiccant Clay - $CaCl_2$ desiccant results without load and loading Conditions

Thermal performance evaluation of the solar greenhouse dryer with desiccant energy storage system; with and without load was conducted. A total of ten test runs were carried out and results obtained are summarized on Table 4.2a. It can be seen that for all experimental test runs the average solar energy radiation that is being recorded was ranging from 342.8 W/m^2 to 559.2 W/m^2 as maximum and minimum values respectively. This is a substantial energy amount that can generate heat within the system for drying. It is indicated on test run no. 5 and 6 that has equally average solar radiation was able to carry out almost equally amount of moisture content from fresh sliced tomatoes during day time one within the tomato chamber. The inlet air temperatures of the system were approximately equal to ambient temperatures and the values were high by 50% when the air was heated under greenhouse hence higher temperatures within the system. The humidity values recorded were low within the system.

Table 4.2(a): Greenhouse Drying System with Energy Storage Summarized Performance Results

Test Run Number	Mode of Operation (Day/Night), Load/No Load	Average Ambient Temp. (ºC)	Average Greenhouse Temp. (°C)	Airflow Drying, Desiccant (m^3/s)	Average Solar Rad. (W/m^2)	Average Ambient R.H%	Average R.H % Greenhouse/ leaving drying chamber at night	Average Inlet Drying, Des. Chambers Temp.(°C)	Average R.H% Desiccant/ from the Desiccant Chamber	Average Desiccant Temp. (°C)	Average Wind Speed (m/s)	Moisture removed from tomatoes (kg_w)	Average Moisture Adsorbed by Desiccants (kg_w)
1	Day, No Load	28.5	43.1	0.19, 0.07	554.7	84.1	38.6	24.4, 24.4	36.5	42.1	1.2	-	-
2	Day, No Load	27.2	41.9	0.28, 0.17	397.2	83.3	36.2	25.8, 24.2	40.6	40.6	1.3	-	-
3	Day, No Load	27.1	41.0	0.45, 0.36	510.8	84.4	38.9	23.9, 24.0	40.4	39.3	1.5	-	-
4 16/10/2019	Day 1, Load	28.5	42.2	0.28, 0.07	559.2	71.7	35.4	27.9	-	-	1.1	8.49	-
	Night, Load	18.0	24.2	0.28, 0.07	-	94.4	82.9	-	61.4	24.7	-	5.20	5.35
	Day 2, Load	27.3	39.7	0.28, 0.07	389.0	74.5	38.9	25.8	-	-	1.0	2.01	-
5 28/10/2019	Day 1, Load	29.0	44.0	0.28, 0.07	550.8	61.3	33.1	29.4	32.2	40.6	1.0	7.59	-
	Night, Load	16.5	22.7	0.28, 0.07	-	90.5	96.5	-	41.6	23.8	-	5.40	5.45
	Day 2, Load	27.3	40.0	0.28, 0.07	473.1	57.1	35.6	24.4	35.4	40.1	1.6	1.56	-
6 7/11/2019	Day 1, Load	24.9	42.1	0.28, 0.07	510.4	82.4	34.8	26.3	23.9	41.9	1.4	7.88	-
	Night, Load	15.9	28.9	0.28, 0.07	-	77.9	87.5	-	45.2	26.5	-	5.42	5.44
	Day 2, Load	26.4	40.8	0.28, 0.07	463.6	79.7	30.1	20.8	27.5	41.3	1.3	1.75	-
7 12/11/2019	Day 1, Load	27.7	40.9	0.28, 0.07	462.8	81.5	41.8	26	28.9	41.7	1.1	6.95	-
	Night, Load	16.4	28.9	0.28, 0.07	-	91.1	94.9	-	49.2	30.1	-	4.55	4.55
	Day 2, Load	25.0	38.8	0.28, 0.07	437.8	82.5	40.8	24.4	28.7	40.4	1.7	3.49	-
8 14/11/2019	Day 1, Load	29.3	42.2	0.28, 0.07	552.2	79.2	29.6	25.0	22.8	42.5	1.8	7.66	-
	Night, Load	16.2	30.4	0.28, 0.07	-	87.7	91.5	-	48.6	33.2	-	3.98	4.00
	Day 2, Load	26.3	39.4	0.28, 0.07	342.8	82.9	40.6	24.8	28.2	40.3	1.9	4.10	-
9 16/11/2019	Day 1, Load	29.3	40.5	0.28, 0.07	500.9	79.7	32.1	25.2	22.8	40.5	1.4	7.40	-
	Night, Load	16.1	30.6	0.28, 0.07	-	90.5	94.5	-	49.1	39.6	-	3.25	3.30
	Day 2, Load	29.1	39.8	0.28, 0.07	469	79.7	34.3	25.3	25.3	40.5	1.3	3.45	-
10 18/11/2019	Day 1, Load	28.5	39.9	0.28, 0.07	428.1	81.4	35.5	25.6	26.1	40.7	1.7	5.45	-
	Night, Load	16.1	28.8	0.28, 0.07	-	90.2	93.8	-	49.0	39.8	-	5.10	5.15
	Day 2, Load	29.8	40.0	0.28, 0.07	521.9	81.4	31.8	25.8	24.0	40.8	1.3	3.95	-

Table 4.2(b): Relative Humidity and Temperature Results of the Greenhouse Drying with Desiccant Energy Storage under No Load Condition for test run number 1 to 3

Parameter	**Solar Greenhouse Dryer**			**Desiccant Energy Storage System**		
Air Flow Rate m^3/s (Test Number)	**0.19 (1)**	**0.28 (2)**	**0.45 (3)**	**0.07 (1)**	**0.17 (2)**	**0.36 (3)**
Average chamber R.H%	38.6	36.2	38.9	36.5	40.6	40.4
Maximum chamber R.H%	47.1	49.4	49.2	49.9	45.0	49.3
Minimum chamber R.H%	22.5	22.2	22.1	20.6	37.7	27.8
Average Ambient R.H%	84.1	83.3	84.4	84.1	83.3	84.4
Maximum ambient R.H%	87.4	98.7	87.4	87.4	98.7	87.4
Minimum ambient R.H%	76.4	66.4	75.1	76.4	66.4	75.1
Average chamber Temp. °C	43.1	41.9	41.0	42.1	40.6	39.3
Maximum chamber Temp. °C	54.8	45.9	43.9	54.9	45.0	41.5
Minimum chamber Temp. °C	35.3	35.8	37.5	37.1	37.7	37.8
Average ambient Temp.°C	28.5	27.2	27.0	28.5	27.2	27.0
Maximum ambient Temp.°C	34.9	36.8	35.1	34.9	36.8	35.1
Minimum ambient Temp.°C	20.7	16.4	17.8	20.7	16.4	17.8

4.2.1 Performance of the Solar Greenhouse Drying System without drying load

The test of the solar greenhouse drying system under no-load with various flow rates are shown on figure 4.2.1 and Table 4.2(b). The significance of carrying out this test was to find out the effect of flow rate on temperature, relative humidity profiles within the solar greenhouse dryer. Also, it was important to study the performance of solar greenhouse dryer considering various ambient conditions (temperature and solar radiation), relative humidity and velocity of air in order to understand the behaviour of the system at different dates of testing. With the test run 2 conducted under typical weather conditions average solar insolation of 397.2W/m² and average ambient temperature of 27.2˚C, average temperature of 41.9 °C was observed within the tomato chamber system. The results showed that temperatures within the chamber was approximately twice ambient temperature.

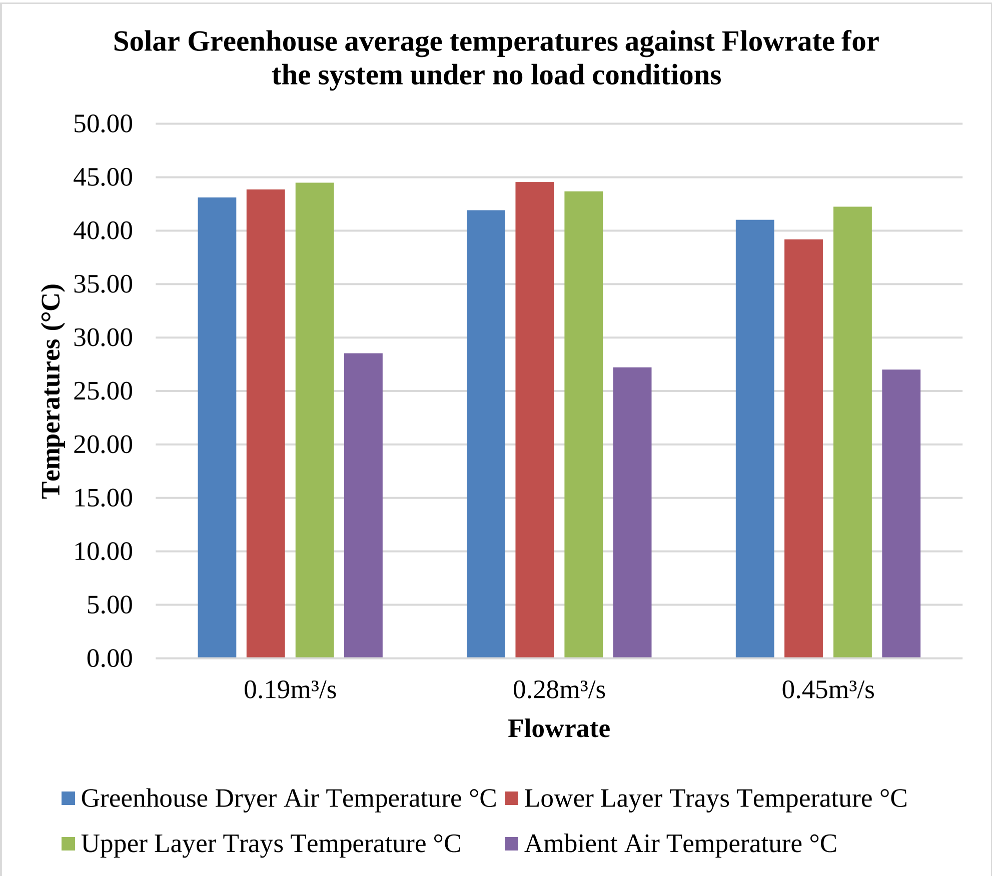

Figure 4.2.1 Flow rate against average temperatures of the system under no load conditions

The maximum greenhouse drying temperature attained was 45.9 °C as shown under Table 4.2(b). The average drying temperature attained was 41.9°C giving an average temperature rise of 14.7 °C (35.1%) above the ambient. The average relative humidity obtained within the system was 32.6% lower than the ambient relative humidity on the test date. Therefore, these conditions indicated that the solar greenhouse dryer is capable of drying fruits and vegetables which required moderate drying temperature of 30 – 40 °C (Bouadila *et al.*, 2015). The experimental study of the solar greenhouse drying system with no-load condition revealed that the flow rate of 0.28m^3/s was more favorable in maintaining drying temperatures. Researchers, have reported on the heat convection phenomenon, whereas higher airflow rates lower heat transfer and for this reason it tends to reduce the drying temperatures within the system during the day (Tham *et al.*, 2017). Therefore, such temperature trend with different flow rates is observed under figure 4.2.1 for the individual experiments as obtained in the field on the test dates. The details of effects of airflow on the system with individual solar radiation profile and temperatures is as shown on Figures 4.2.2 a; b; and c.

4.2.2 The Effect of Airflow on Greenhouse solar Drying Temperature without Drying Load

Figure 4.2.2 (a) shows the effect of low flow rate of 0.19m^3/s on the variation of greenhouse air temperature for lower- and upper-layer trays, ambient temperature and solar radiation profiles. It was observed that the greenhouse air temperature varied from 35.3 °C to 54.8 °C whereas lower and upper layers of trays temperatures varied from 37.2 °C – 53.5 °C and 38.5 °C – 54 °C respectively. Temperatures on the upper layer were greater than the lower layer trays despite the variation range being small; this could be due to the fact that the greenhouse floor dryer was covered with a black high-density polyethylene sheet which gave rise in temperature of the lower layer. Therefore, there is difference in temperatures across the layers within the dryer. The ambient temperature increased from 20.7 °C - 34.9 °C during day time because of the weather changes which was controlled by solar heating. Both greenhouse air temperature and ambient air increased up to 13:15 hrs then later decreased at 18:00 hrs. An average greenhouse air temperature rise was 14.6 °C (33.8%) above the average ambient temperature during the test date. Similar trend results have been reported by Anil *et al.*, (2013); Dulawat and Rathore, (2012); Seveda, (2012); Rathore and Panwar, (2011) and Singh et al., (2007) for developed forced convection solar greenhouse dryers. For this study, the solar radiation varied from 33.83 W/m^2 to 921.24 W/m^2 with an average value of 554.7 W/m^2.

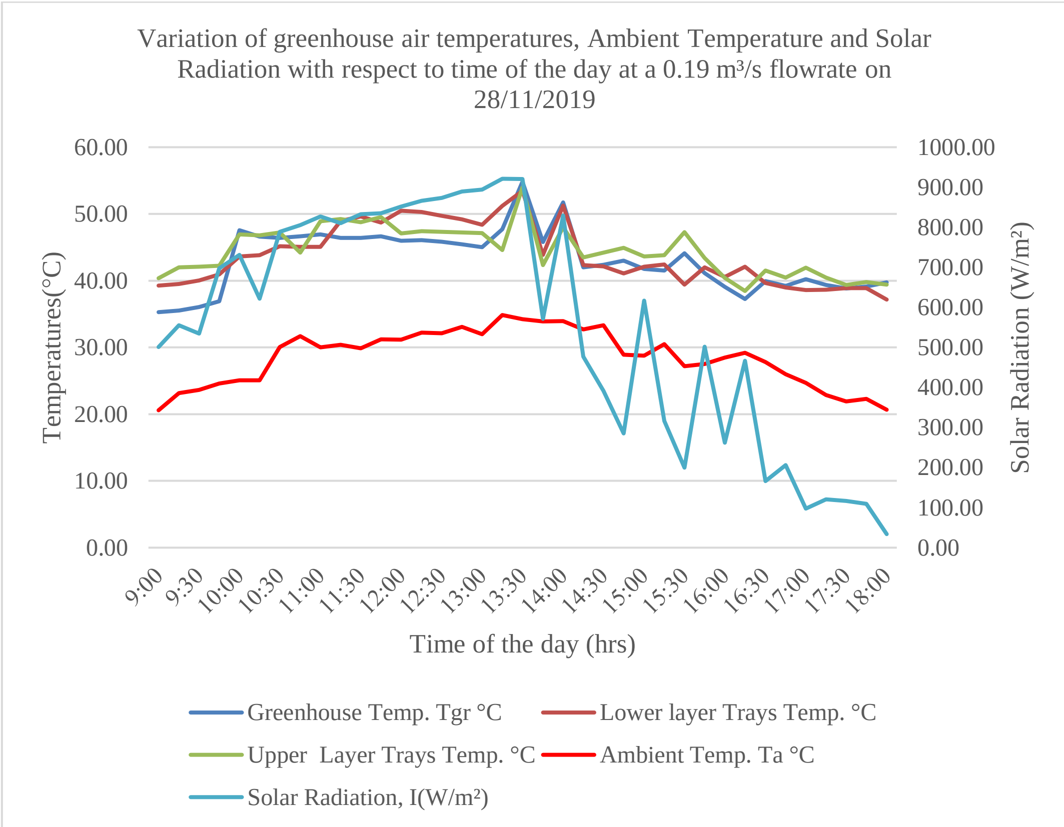

Figure 4.2.2(a): Variation of greenhouse temperature, ambient and solar radiation with respect to time of the day at 0.19m^3/s flow rate

Figure 4.2.2 (b) shows the effect of medium flow rate (0.28 m^3/s) on greenhouse temperature and solar radiation profiles with time. It was observed that ambient temperature increased to a maximum value of 36.8 °C at 12:31 hours and then decreased to 16.4 °C at 18:01 hours. There was an average temperature rise within the greenhouse system of 14.7 °C (35.1%) compared to ambient temperature. Also, it was observed that there is variation of greenhouse temperature profile for lower- and upper- layers of trays. The temperatures at different locations varied considerably with the ambient temperature. However, temperatures on the upper layer of trays were higher than lower tray layers because of the effect of direct sun light on the polythene sheet as reported by other researchers (Madhava & Smith, 2017). In this experiment the maximum solar radiation recorded was 871.2W/s^2.

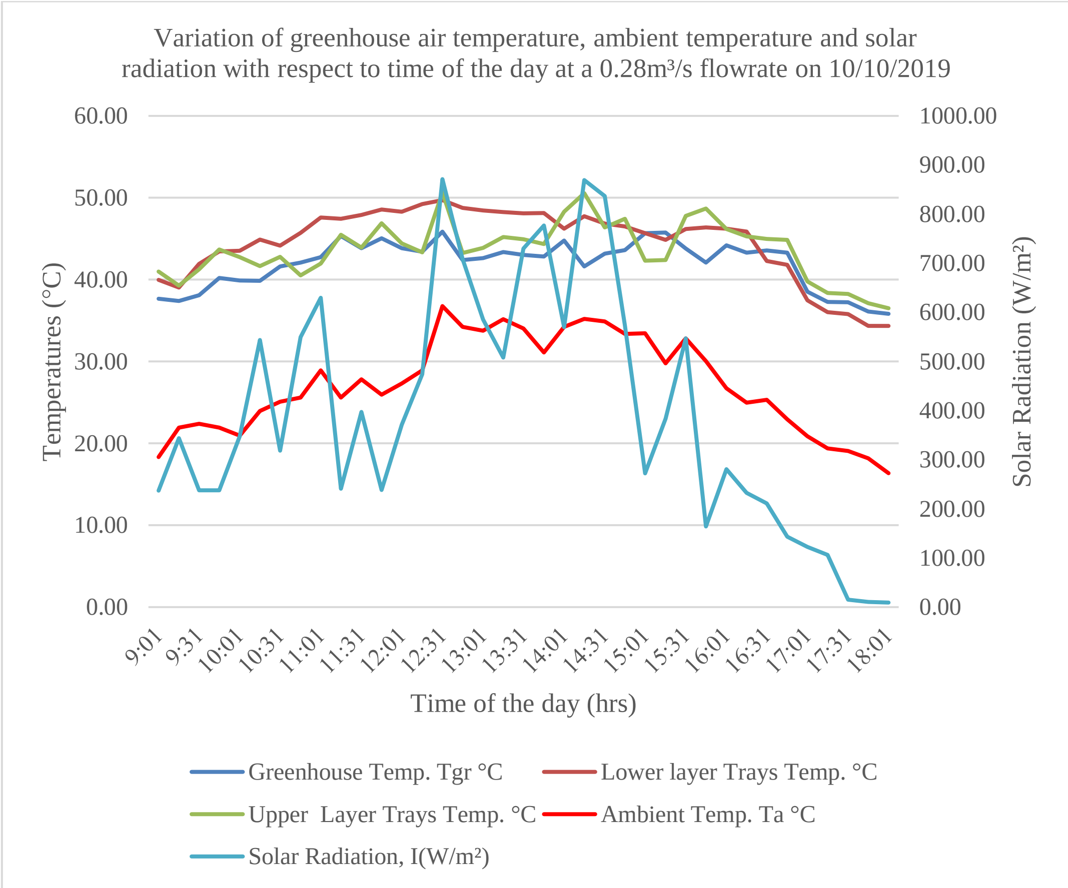

Figure 4.2.2(b): Variation of greenhouse temperature, ambient and solar radiation with respect to time of the day at 0.28 m^3/s flow rate

Figure 4.2.2.(c) shows the effect of higher flow rate on greenhouse temperature variation for lower- and upper-layers with varying ambient air temperature and solar radiation. With the 0.45m^3/s flow rate the greenhouse drying temperatures were observed to be much lower compared to other flow rates. The average temperature rise in the solar greenhouse against ambient air was 14 °C (34.2%). This was the lowest temperature rise recorded for the three flow rates tested. For 0.19 m^3/s and 0.28 m^3/s, the average greenhouse drying temperature rose by 14.6 °C (33.8%) and 14.7 °C (35.1%) above ambient temperature respectively. Therefore, this shows that high flow rate lowered drying greenhouse temperatures a finding that agrees with the report of other researchers (Madhava and Smith, 2017; Hanif *et al.*, 2013). Therefore, with this

observation drying process will not be supported by this flow rate rather delaying it hence affecting the quality of product.

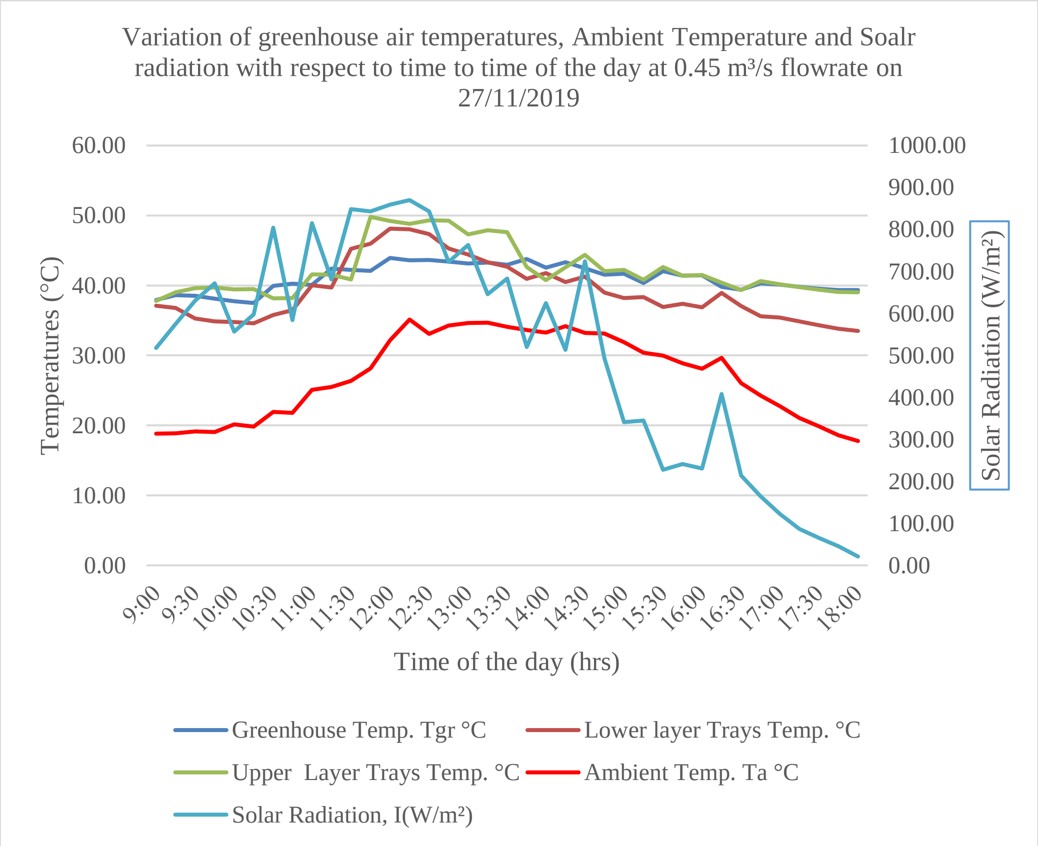

Figure 4.2.2(c): Variation of greenhouse temperature, ambient and solar radiation with respect to time of the day at $0.45 m^3/s$ flow rate

Overall experimental results reflect high temperature variation at different layers within the greenhouse dryer. This study used an experimental forced convection solar greenhouse dryer whose temperatures were not regulated and 4 sets of potentiometers were used to vary speed of the exhaustive fan hence varying flowrate from $0.19 m^3/s$ to $0.45 m^3/s$. Nevertheless, the percentage average temperature rises across the upper- and lower- layer for $0.19m^3/s$ flow rate was 35.8% and 34.9%; for $0.28m^3/s$ flow rate was 37.7% and 38.9%; and for $0.45m^3/s$ flow rate was 36.1% and 31.1% respectively. In this study, it was noted that the flow rate was very important factor affecting the drying air temperature and that a flow rate of $0.28m^3/s$ gave higher percentage rise in temperature compare to the other flow rates. A small range in flow rates of 1% to 5% is observed as reported by other researchers (Seveda & Jhajharia, 2012). There was a significant difference between the greenhouse temperature and the ambient temperature. It was also observed that the temperature on the upper layer was always higher than the lower layer due to the effect of shade by the upper layer on the parallel lower layer trays as reported by Madhava & Smith, 2017. All these results can play a significant role in drying the tomato slices. Details of the recorded temperature values with the flow rates set at different test dates is shown in Table C-6 under Appendix C.

4.2.3 Performance of Desiccant Energy System with No Desiccant Load

The Desiccant Energy Storage system was tested under no load condition and the results are presented on figure 4.2.3 and Table 4.2(b). The test no. 1 conducted at an average solar radiation and ambient temperature of 554.7 W/m^2 and 28.5 °C respectively. Three different airflow rates (0.07m^3/s, 0.17m^3/s, and 0.36m^3/s) were simultaneously investigated for desiccant energy storage system. The results showed that at low air flow rates of 0.07 m^3/s, there was a temperature rise by 13.6 ^{o}C (32.3%) above average ambient temperature while the average relative humidity within the system was lower by 36.5% compared to ambient relative humidity. These results agree with those of Ye Yao *et al.* (2014) on low-cost solar regenerative solid clay-$CaCl_2$-based desiccant with the lowest regeneration temperature of 33°C. Details of Solar radiation and temperature profiles in as indicated on Fig. (a, b & c)

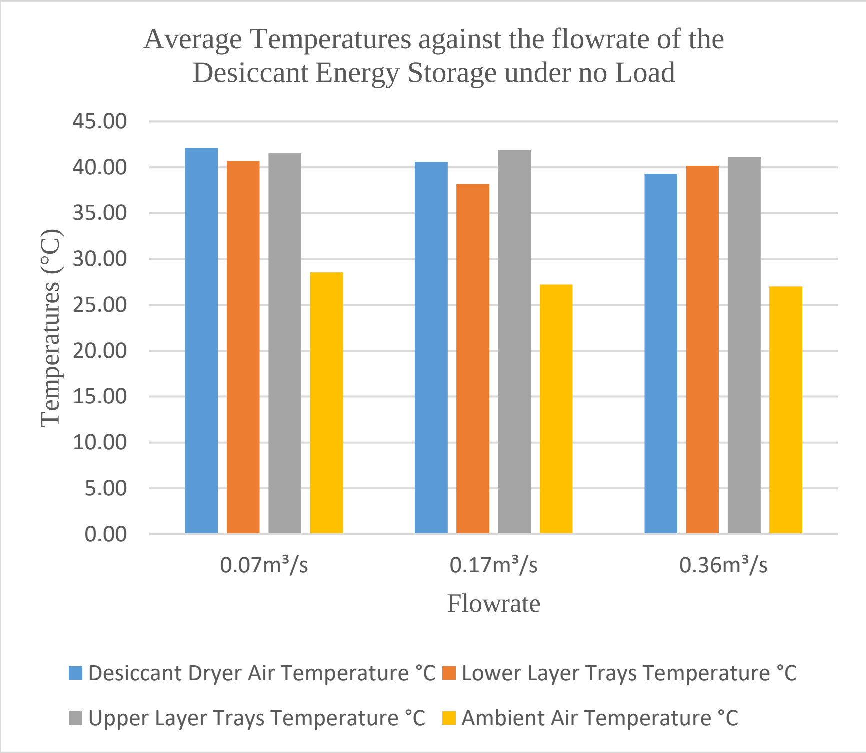

Figure 4.2.3: Variation of Average temperatures against flowrate of the desiccant energy storage system under no load conditions

4.2.4 Effect of Airflow on Desiccant Energy Storage System without Load

Figure 4.2.4(a) shows temperature and solar radiation profiles of a test conducted at an average ambient temperature and solar radiation of 28.5 °C and 554.7 W/m^2respectively. The test was conducted at a flow rate of 0.07 m^3/s. The trend shows that desiccant energy storage system attained relatively high temperatures of 53.3 °C at 13:30 hrs when solar radiation reached 920.8 W/m^2. The average temperature rise was 13.6 (32.3%) above the ambient. The lowest temperature recorded within the system was 37.1°C. The highest and lowest relative humidity attained was 49.9% and 20.6% respectively with an average R.H. of 36.5% below ambient RH as shown on Table 4.2(b). These results showed that minimum drying time can be attained under typical field test conditions in Kenya.

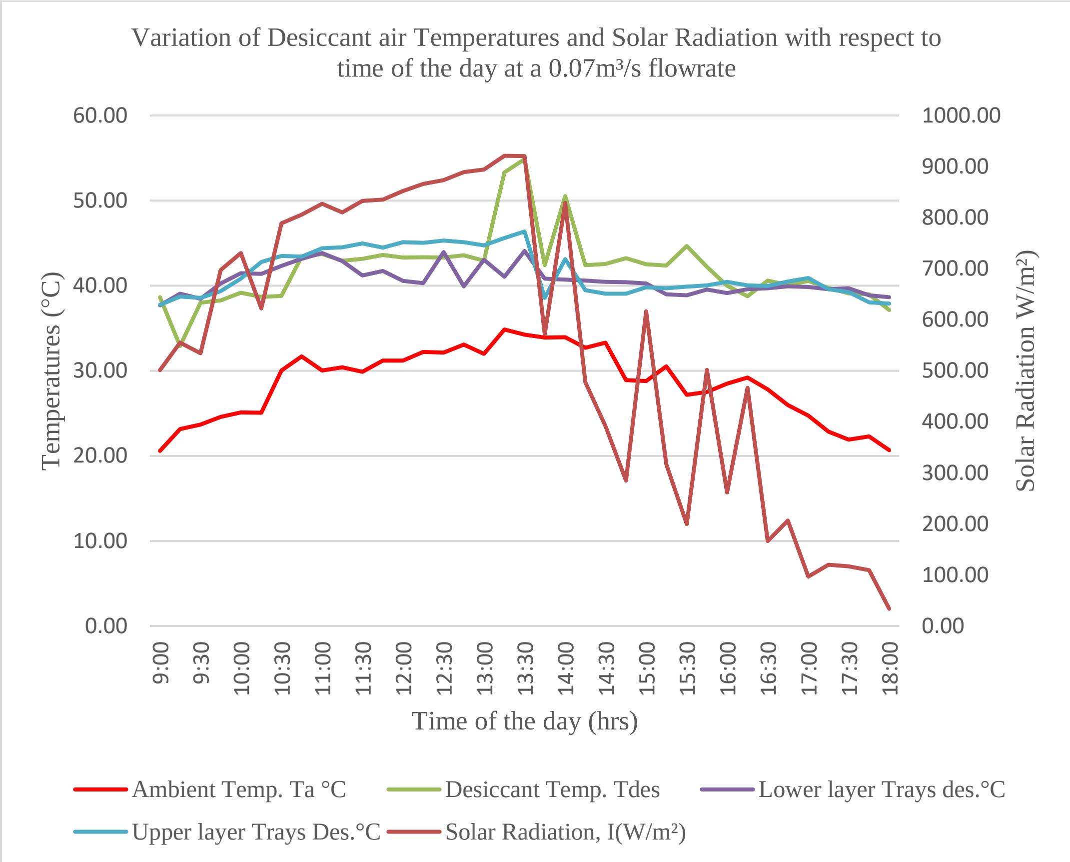

Figure 4.2.4(a): Typical Temperatures and Solar Radiation Profiles with Time at $0.07m^3/s$ airflow within desiccant chamber

Figure 4.2.4(b) shows that ambient temperature increased with solar radiation and vice versa. The average desiccant energy storage system temperature reached was at 40.6 °C, a value that was 13.4 °C (33%) above the ambient air temperature of 27.2 °C. An average solar radiation of $397.2W/m^2$ was obtained. The average relative humidity of the desiccant energy system was 40.6%. This drop in average temperature when a flow rate of $0.17m^3/s$ was used showed change in flow rate has an effect on temperatures within the system hence will affect the drying rate, drying time and efficiency of the system (Hanif *et al.*, 2013). In Literature, Tiwari, (2016) stated that an optimal airflow can be obtained over the drying process in the manner to control temperature and moisture over a wide range independent of weather conditions. Therefore, this study has clearly portrayed that. Hence air flowrate can be controlled independent of the dryer capacity and its reliability.

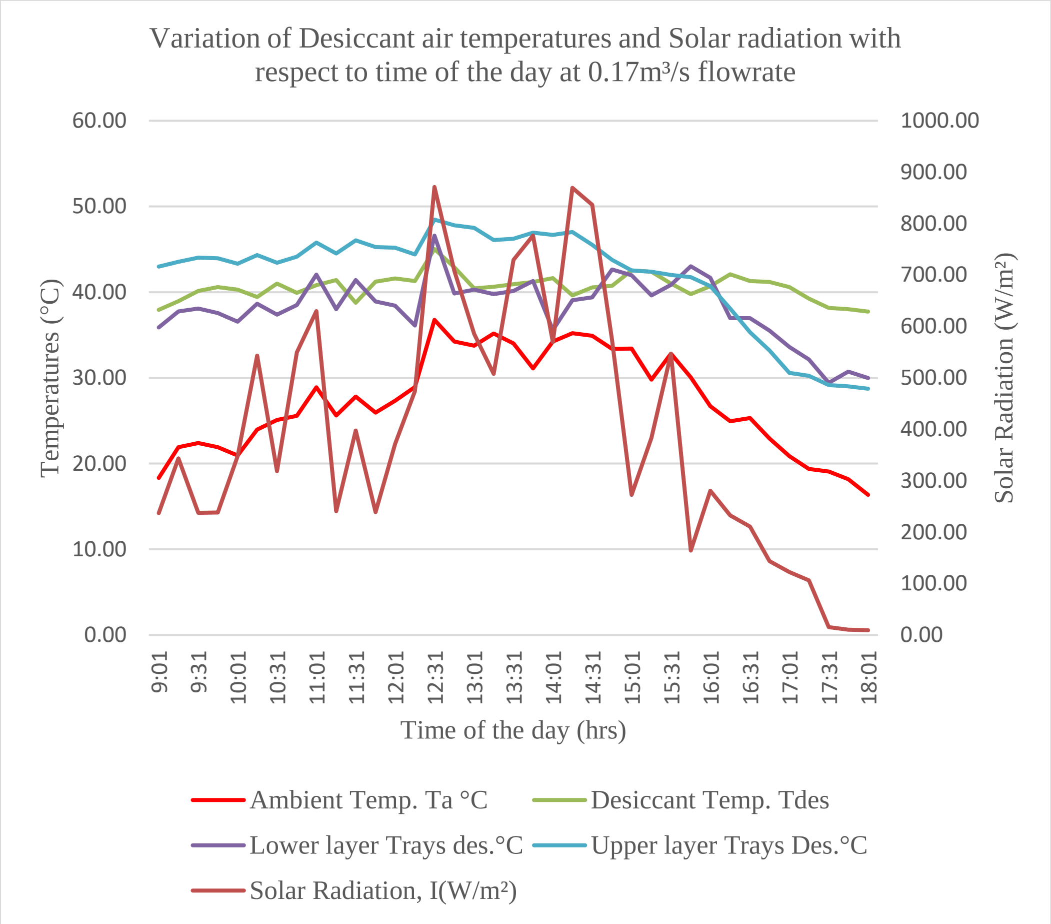

Figure 4.2.4 (b): Unloaded Desiccant Energy Storage Temperatures and Solar Radiation Profiles at a flow rate of 0.17m^3/s

Figure 4.2.4(c) shows the variation of the desiccant energy storage dryer temperature, lower - upper temperature and solar radiation profiles with time. The results showed that, the average temperatures attained were 39.3 °C, 40.2 °C and 41.2 °C, and 27 °C for Desiccant Dryer chamber, Lower- and Upper-layer Trays, and Ambient temperatures respectively at an average solar radiation of 510.8 W/m^2 and flow rate of 0.36 m^3/s. The study shows that higher air flow rates lowered the desiccant energy storage temperatures within the system. The same trend has been reported by other researchers (Madhava & Smith, 2017). The average temperature rose by 12.3 °C (31.3%) above ambient temperature. The average relative humidity attained was 40.4%. However, much lower temperatures were recorded within the system for the stated flow rate as expected.

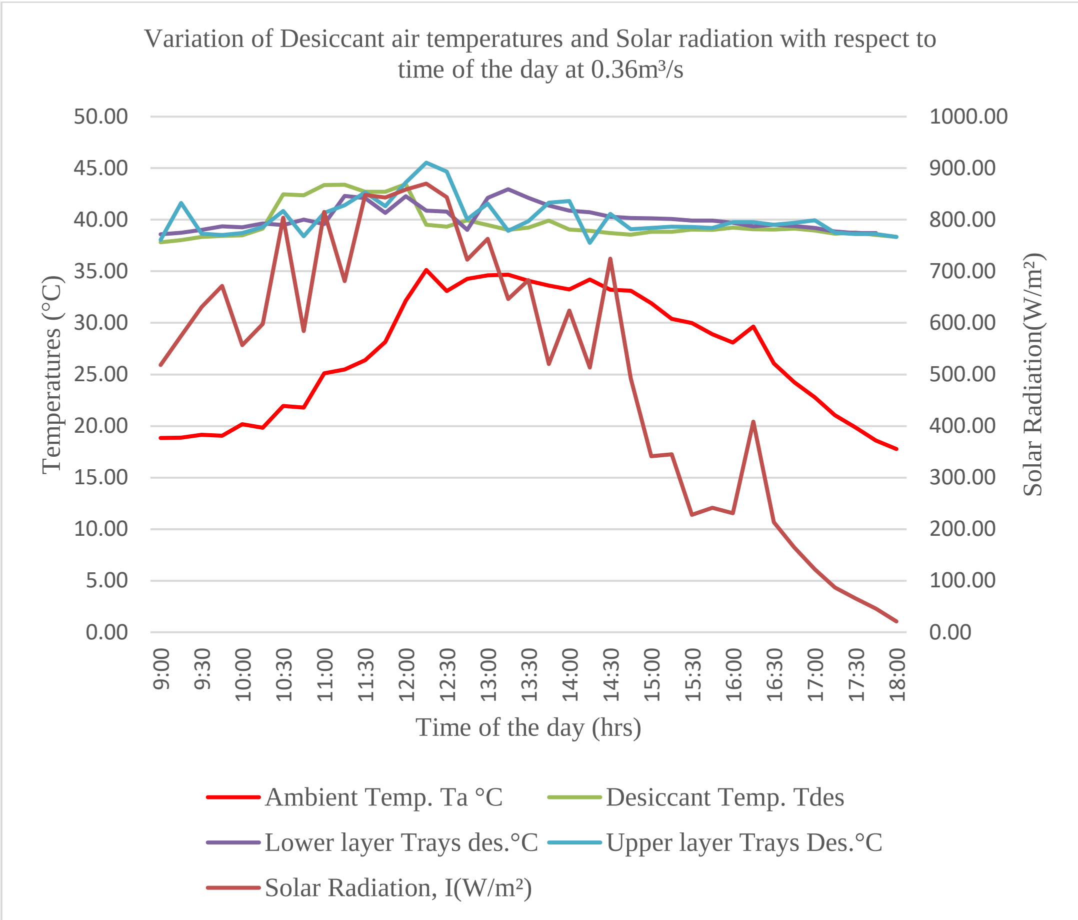

Figure 4.2.4 (c): Unloaded Desiccant Energy Storage Temperatures and Solar Radiation Profiles at a flow rate of 0.36 m^3/s

Consequently, the results obtained from the desiccant energy storage chamber indicated that there was disparity in temperatures within the system when different flow rates were used. However, the average rise in temperature against the ambient within the system was found to be 13.6 °C (32.3%), 13.4 °C (33%) and 12.3 °C (31.3%) for different flow rates i.e., 0.07m^3/s, 0.19m^3/s, and 0.36m^3/s respectively at different times of the day. From the graphs, we see both flow rates indicated that temperature on the upper layer was higher compared with the lower layers and varying with the ambient air at 31.3% and 29.9%; 35.1% and 28.7%; and 34.3% and 32.7%; for the upper- and lower- layer respectively. Similar trend has been observed and reported by Madhava & Smith (2017). On the basis of no-load test results, the subsequent performance tests were conducted based on 0.07m^3/s air flow rate within the desiccant unit system since it gave much higher temperature rise hence higher desiccant regeneration temperature can be achieved at lowest time possible.

4.3 Performance of a Loaded Greenhouse Solar Dryer under Field Test Conditions

4.3.1 Drying with Solar Energy During Daytime 1 Conditions

Figure 4.3.1(a) shows typical variation of greenhouse temperature and solar radiation profiles of loaded system with time during the month October 2019. The graph trends depicted are actual measurements recorded during the experiment. It can be seen that the solar radiation increased from morning time and reached a maximum of 940.7 W/m^2 at 13:15 hours and decreased in the afternoon. The ambient temperature increased with solar radiation intensity up to 15:30 hours and decreased slowly towards the end of the day. The average greenhouse temperature attained was 42.2 °C at a flow rate of 0.28 m^3/s. It was observed that the maximum and minimum temperature, inside and outside the greenhouse dryer were 45.3 °C and 33.8 °C, and 31.7 °C and 21.3°C, respectively. The average solar radiation on the testing date was 559.2 W/m^2 while the minimum was 18.2 W/m^2 at 18:00 hours, end of the day. The drying temperatures of 33.8 – 45.3 °C observed in the present study are close to the range of those reported by Yokeshwaraperumal *et al.*,2019 of 40.7 °C – 62.6 °C. However, the results of this study did not have any effect on the performance because of different testing dates conditions prevailed.

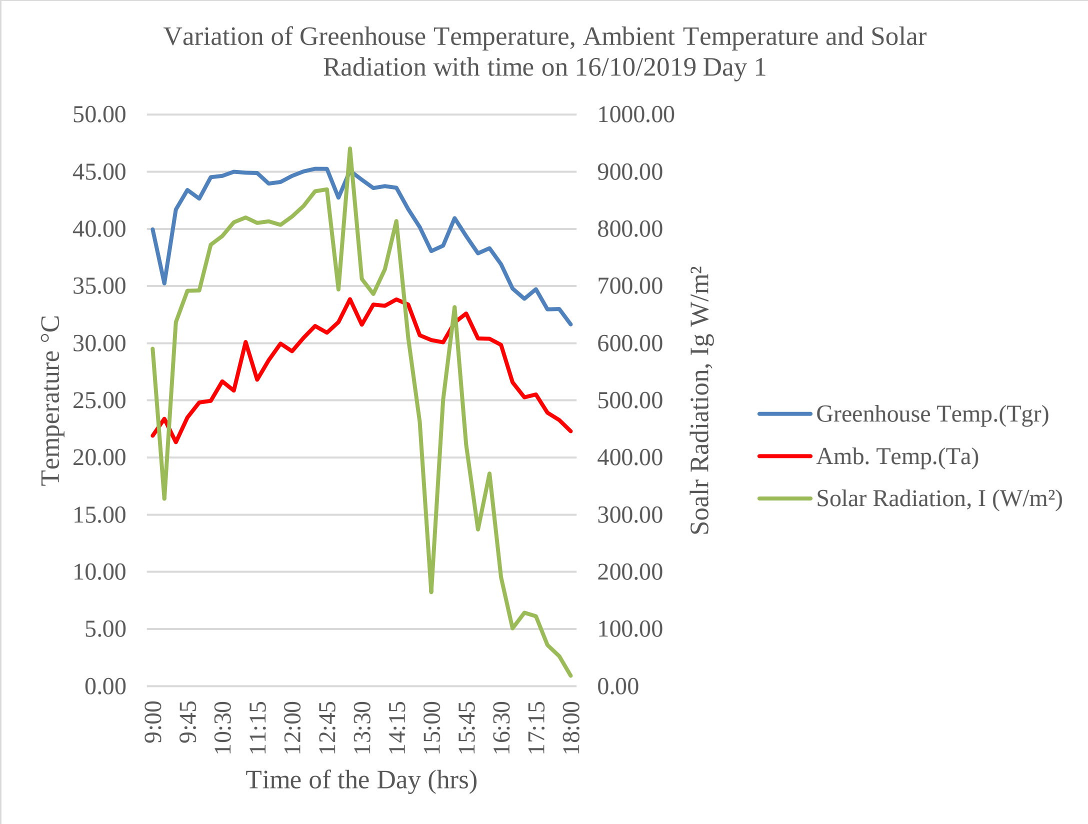

Figure 4.3.1(a): Typical Temperature and Solar radiation profiles for the Loaded System

Figure 4.3.1(b) shows relative humidity profiles of the loaded solar greenhouse drying system. An ambient air with 72.2% relative humidity (R.H). entered the system and heated to an average temperature of 42.2 °C. Its R.H. was lowered to 38.4% but left the drying chamber with higher R.H. by 6% compared to the ambient R.H. of 72.2%. It is seen that the R.H. within the greenhouse is comparatively low compared to the ambient air, and the air leaving the chamber. The air leaving the drying chamber is highly humid due to addition of moisture from drying fresh sliced tomatoes. Thus, the lower the relative humidity the high chance to keep the favorable temperatures within the system for moisture uptake. Water holding capacity of the greenhouse air increases with low relative humidity within the system hence more moisture uptake as it has been described by Ahmad and Prakash (2020) and Madhava and Smith (2017). Therefore, from figure 4.3.1(a) and (b) we can see that temperatures within the greenhouse chamber rises as relative humidity falls and conforms to findings of Prakash *et al*. (2016). The fact that hot air has the capacity to hold more water than cool air, therefore as the temperature rises there is always moisture added to the air. Therefore, this makes temperature inversely promotional to the R.H.

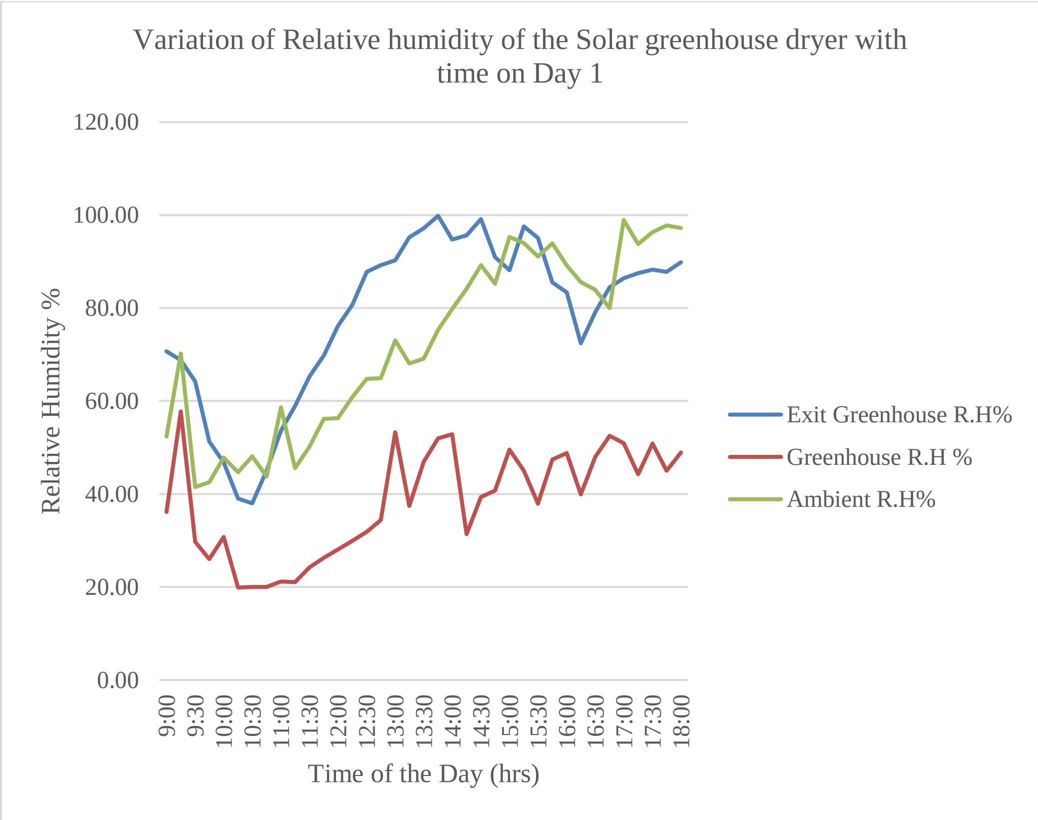

Figure 4.3.1(b): Typical Relative Humidity profiles of the loaded system

4.3.2 Drying with Desiccant Energy Storage during Night Conditions

Night drying of tomato slices was achieved via desiccant energy storage system through circulation of the dehumidified air using an axial fan placed between the desiccant energy storage system and tomato drying chamber. Two air flow rates were investigated viz.: low and high flow air rate of 0.07 m^3/s and 0.28 m^3/s for greenhouse desiccant and tomato dryer chamber respectively. The operating environment was at an average ambient temperature and relative humidity of 18.2 °C and 94.4% respectively. Figure 4.3.2(c) and (d) shows typical temperature and relative humidity profiles of the tomato drying chamber and desiccant energy system with time. It was observed that the desiccant energy storage exits air temperature varied from 22.5 °C to 29.5 °C giving an average temperature of 26.6 °C temperature while maintaining an average R.H. of 59.9 % during the off-shine duration between 18:15 hours to 08:45

hours. The values were in good agreement with the data presented by other researchers (Fumo & Goswami, 2002; Gurtas & Evranuz, 2000). The moisture adsorption rate was driven mainly by dehumidified air from the desiccant energy storage which had a higher temperature by 8.4 °C above ambient and 34.5% relative humidity below ambient R.H. respectively. These conditions favored energy transfer for moisture uptake from the fresh sliced tomatoes during night period.

Figure 4.3.2(d) illustrates the moisture air out of the dryer was at an average R.H. of 91.9%. The highest humidity of the air leaving the dryer was 94.3% and the lowest was 89.1% respectively. This shows that there is moisture transfer from tomatoes being dried during night process. During this time desiccant material were able to absorb 5.44 kg (37.3% of the total moisture to be removed from 16 kg of fresh sliced tomatoes) of water, from 8.92 kg of the fresh sliced tomatoes left during solar drying of on the day time. The study confirms that with $CaCl_2$ salt impregnated in composite desiccant can be used to retain water uptake during night period to extend the drying process as reported by Anish *et al.*, 2017.

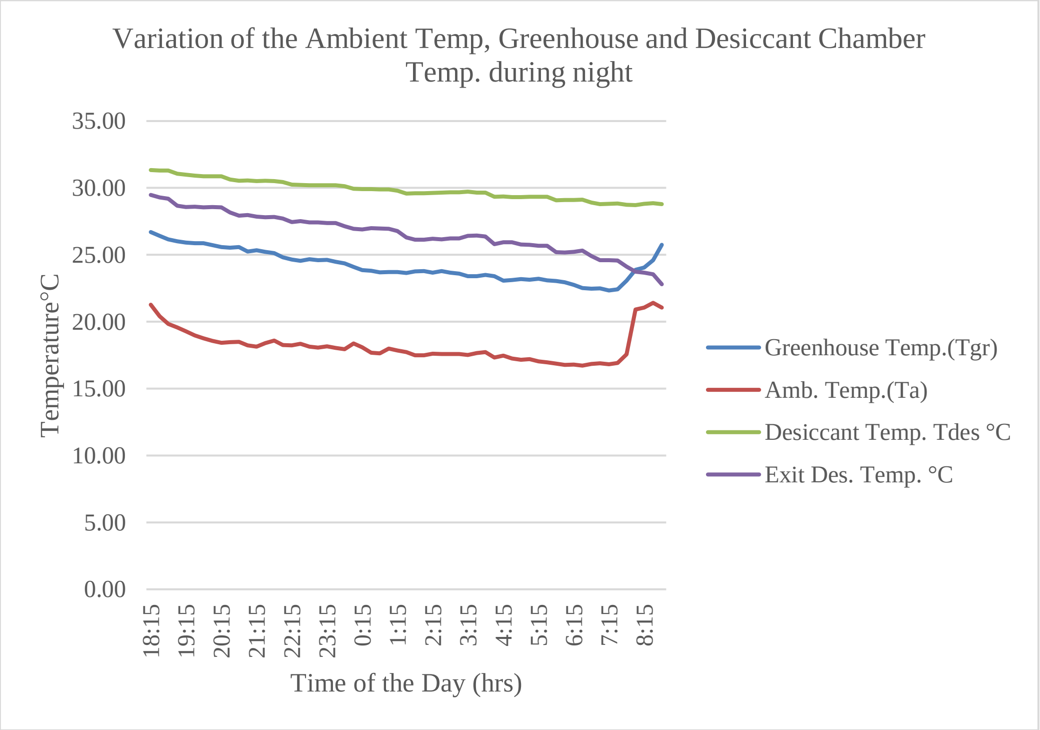

Figure 4.3.2 (c): Greenhouse and Desiccant Chamber Typical Temperature profile during night time

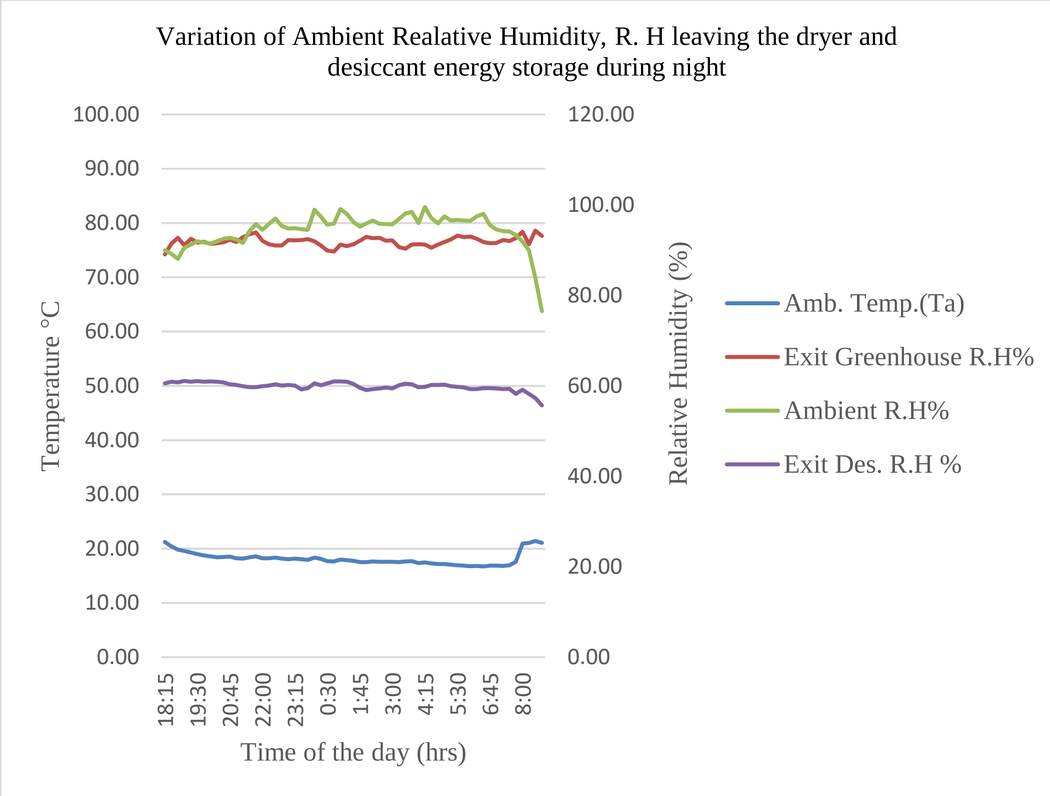

Figure 4.3.2(d): Greenhouse and Desiccant chamber Typical Relative Humidity Profile during night time

4.3.3 Tomato Drying Performance using Solar Energy during Daytime in day 2

Figures 4.3.3 (e) & (f) illustrate the real trend of the greenhouse dryer temperature and relative humidity on day 2 drying condition. The drying processes continue on the second day after desiccant drying during the night. Drying conditions achieved were under an average ambient temperature and solar radiation of 27.8 °C and 389W/m² respectively. From the trend it was observed that the temperatures of the system were high when the relative humidity were low at most points in time. The average greenhouse temperature and relative humidity obtained were 41.2 °C and 31.9% respectively. Similar values have been reported by Odhiambo, (2015) and Janjai, (2012) closer temperature increase of about 20 °C within the solar greenhouse dryer system. This reflects that more moisture content can be absorbed from fresh sliced tomatoes. The drying process started maintaining the same value of 1.75 kg at 11:00hrs of this day drying under Table C_3 in Appendix C.

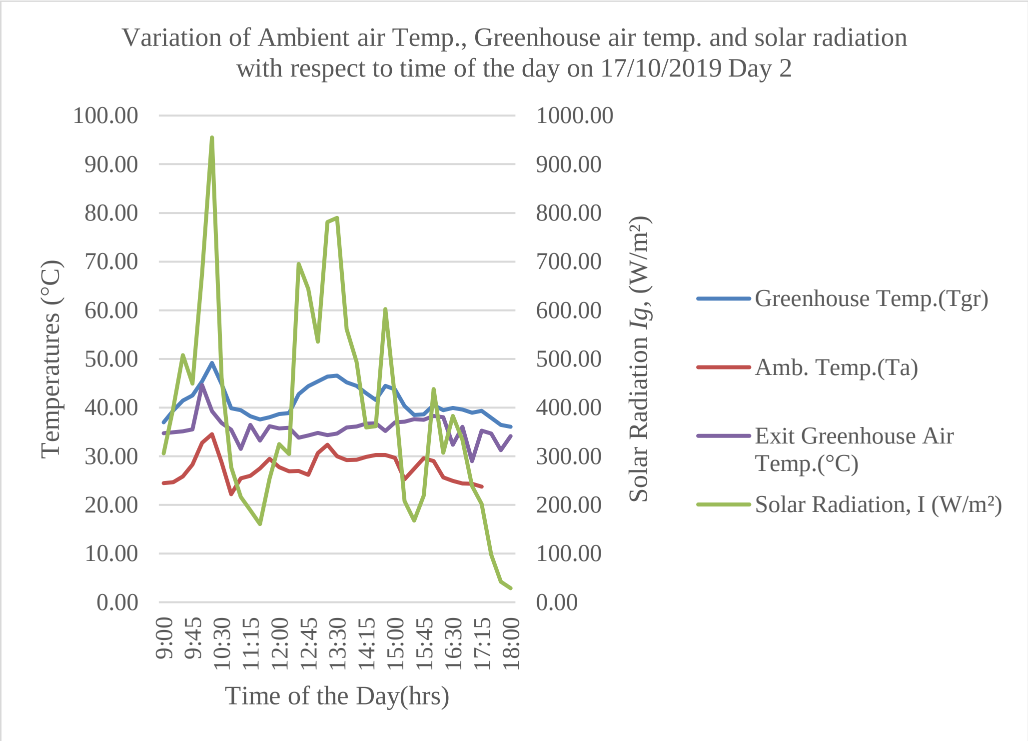

Figure 4.3.3(e): Greenhouse Chamber Typical Temperature and Solar Radiation profile with time During Day 2

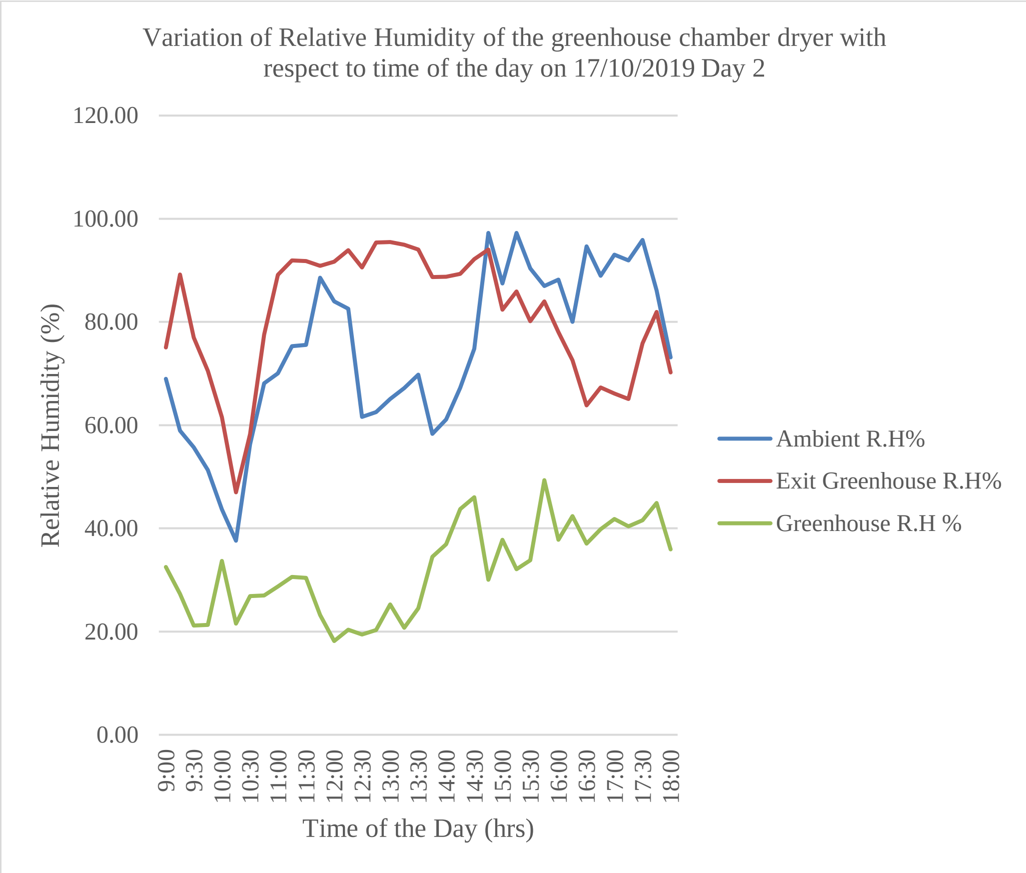

Figure 4.3.3(f): Greenhouse Drying and Desiccant Chambers Relative Humidity Profiles of with time During Day 2

4.4 Determination of Initial Moisture Content of fresh sliced tomatoes

In this study, moisture content of the tomato sample was determined using the standard oven drying method at 105°C until there was no further change in dry weight (AOAC, 2000). Table 4.4 shows the average initial moisture content of the fresh sliced tomatoes to be 93.9% (dwb) and varied along the layers of trays from 92.9% to 94.8% (dwb). This is compatible with other researcher's findings which showed that fresh tomatoes moisture content varied from 92% to 95% (dwb) (Lopez-Quiroga *et al.*, 2019; Correia *et al.*, 2015).

Table 4.4 Average Initial Moisture content of fresh sliced tomatoes

Layers	Tray Labels	Initial weight of tomatoes in kg	Final weight of Oven dried tomatoes in kg	Initial Moisture Content (%)
Lower Layer Trays	H1	2.1	0.14	93.3
	H3	2.1	0.15	92.9
	H5	2.1	0.14	93.3
	H7	2.1	0.13	93.8
Upper Layer Trays	H2	2.1	0.11	94.8
	H4	2.1	0.12	94.3
	H6	2.1	0.11	94.8
	H8	2.1	0.12	94.3
		16.8	**1.02**	**93.9**

4.5 Tomatoes Drying Rate During Solar Drying and Desiccant Phase

In this experiment, tomatoes were dried in the first day light using solar energy followed by desiccant drying phase during night and lastly by second day light using solar energy. Figure 4.5(a) shows the evolution in moisture content of the dried tomatoes with respect to drying time within the solar greenhouse dryer incorporated with desiccant energy storage. With the initial moisture content of 94.3% (dwb) to the final moisture content of 25.5% (dwb) in day one solar drying, after 9 hours it gave a loss of water mass approximately to 10.5 kg. The falling rate of the curve reflects the loss of water mass during drying process. At the end of the first day drying a total of 5.51 kg of the tomato remained. The product was left within the dryer and kept drying using desiccant energy storage materials overnight and the moisture content dropped to 16.4% (dwb). The second day drying process ended after 3 hours and the moisture content reached was 8.3% (dwb). Figure 4.5 (b) shows weight reduction of the fresh sliced tomatoes during the drying process in the solar greenhouse dryer with desiccant energy storage. The final weight of the dried tomato after 27 hours of drying rested at 1.31 kg from initial weight of 16 kg. The graph shows that weight of tomato remained constant after 25 hours, meaning that there was no further moisture removal. The trend of the mass loss curve obtained by Kam *et al.*, (2017), Cakmak and Yildiz, (2011) and

Hawlader *et al.*, (1991) is in agreement with the observed in the current study despite the fact that their product took three-day light solar drying. Therefore, the drying process of the tomato sample under the system was fast with forced convection system together with the use of desiccant.

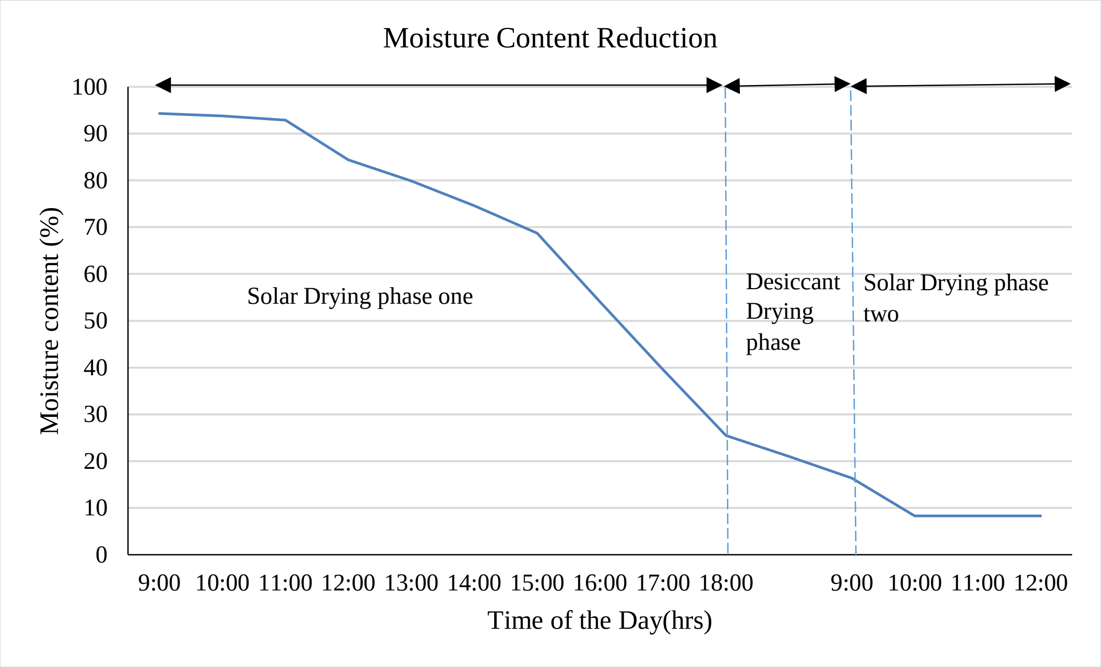

Figure 4.5 (a): Moisture Content Profile of tomato samples with respect to time during Solar Drying and Desiccant Drying Processes

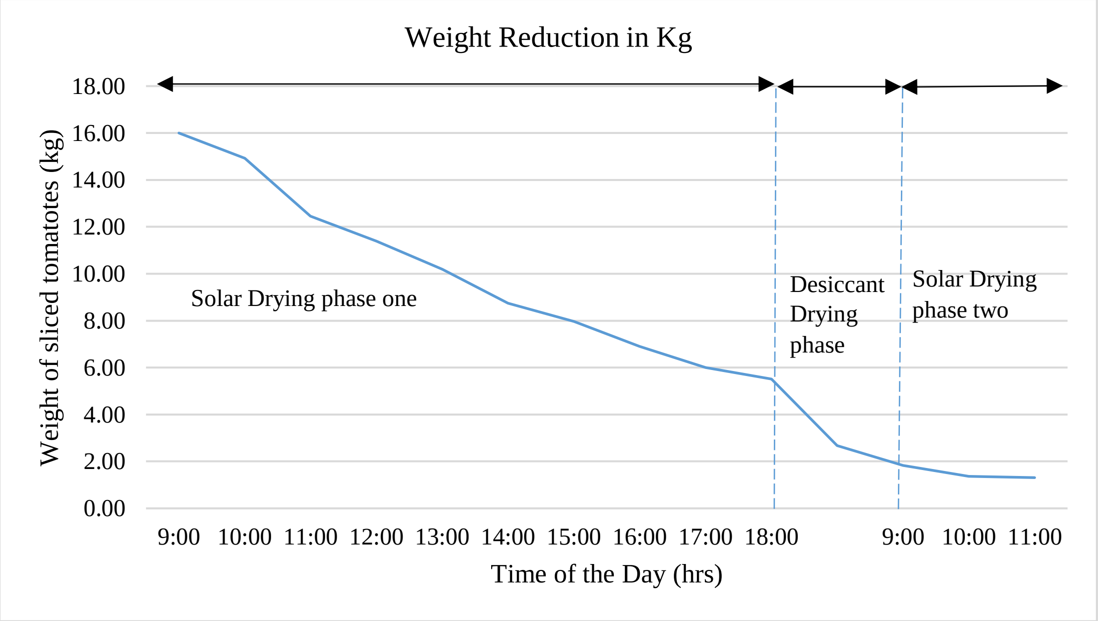

Figure 4.5(b): Weight Loss of the tomato samples with respect to drying time

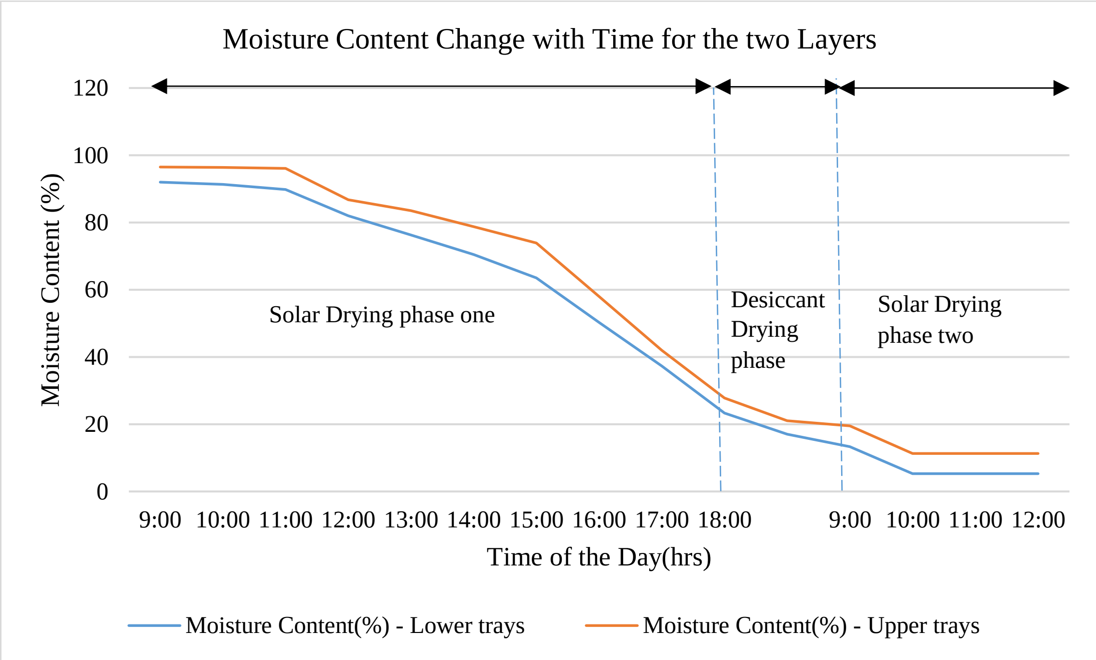

Figure 4.5(c): Moisture Content Change of the dried tomato samples with respect to time for the two-tire layers

The system demonstrated a uniform drying with respect to lower and upper layers of trays whereas, both layers showed moisture content reduction with respect to time as seen on figure 4.5(c). This means that the temperature within the solar greenhouse is uniformly distributed and thus experiencing small change on both layers.

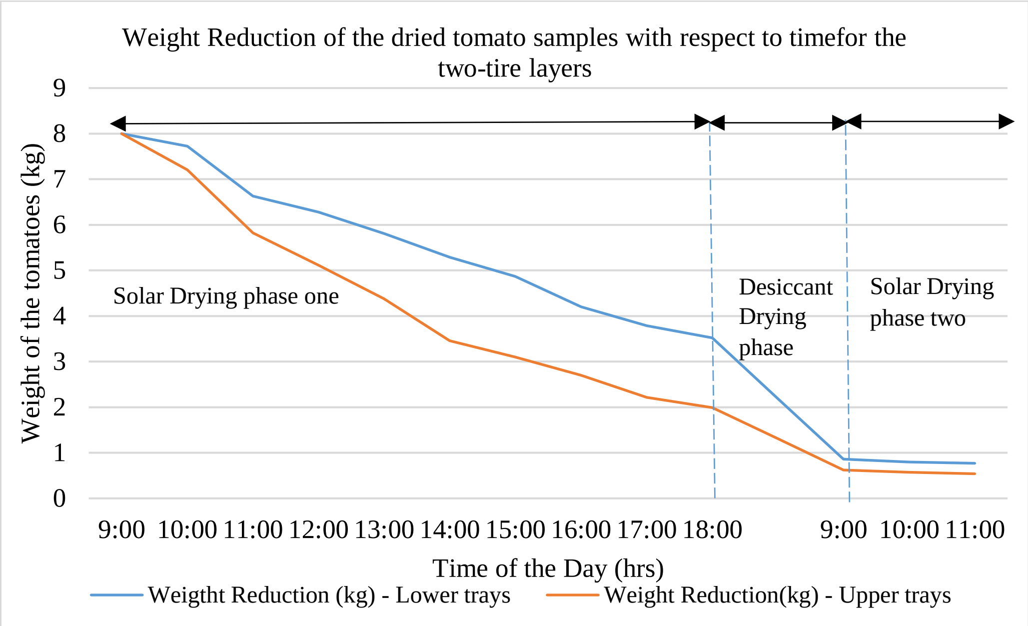

Figure 4.5(d): Change of weight with respect to time for the two layers during drying on day time and night time

Moisture Content and weight reduction of the tomato samples on both lower and upper layers are presented on Figures 4.5 (c) and 4.5 (d) respectively. It is observed from figure 4.5 (d) that the trend of the upper layer trays indicated a sharp drop in weight of tomato samples compared to lower layer trays and it is shown by their difference in nature of their slopes. A similar trend of declining in weight of the fresh sliced tomatoes within the system with respect to time has been reported by Abou *et al.*, (2019). Equally, Figure 4.5(c) shows decreased in moisture content with respect to drying time.

4.6 Performance of Desiccant Energy System with Desiccant Load

Desiccant drying chamber temperature and relative humidity (R.H.) profiles are presented in Figures 4.6 (a) and 4.6 (b). The temperature within the desiccant chamber was higher most of the time during drying of the desiccant energy materials. The highest recorded temperature within the system was 43.3 °C at 10:15 hours when the average desiccant temperature was 38.3 °C. The average ambient temperature and solar radiation was 27.8 °C and 389.0 W/m^2 respectively during drying the desiccant materials. The trend of the R.H. within the desiccant system was observed low compared to ambient R. H. and R.H. leaving the desiccant chamber. From figure

4.6(b) the R.H. of the air exiting the system was high because moisture was being driven out of the desiccant during solar regeneration of the desiccant bed. Therefore, this is an indication that desiccant materials were dried during regeneration process. Thoruwa *et al.*, 2000 recommended 50 °C and 20% (R.H.) for 8 hrs regeneration. Therefore, this study depicted closer value conditions that favored desiccant regeneration process.

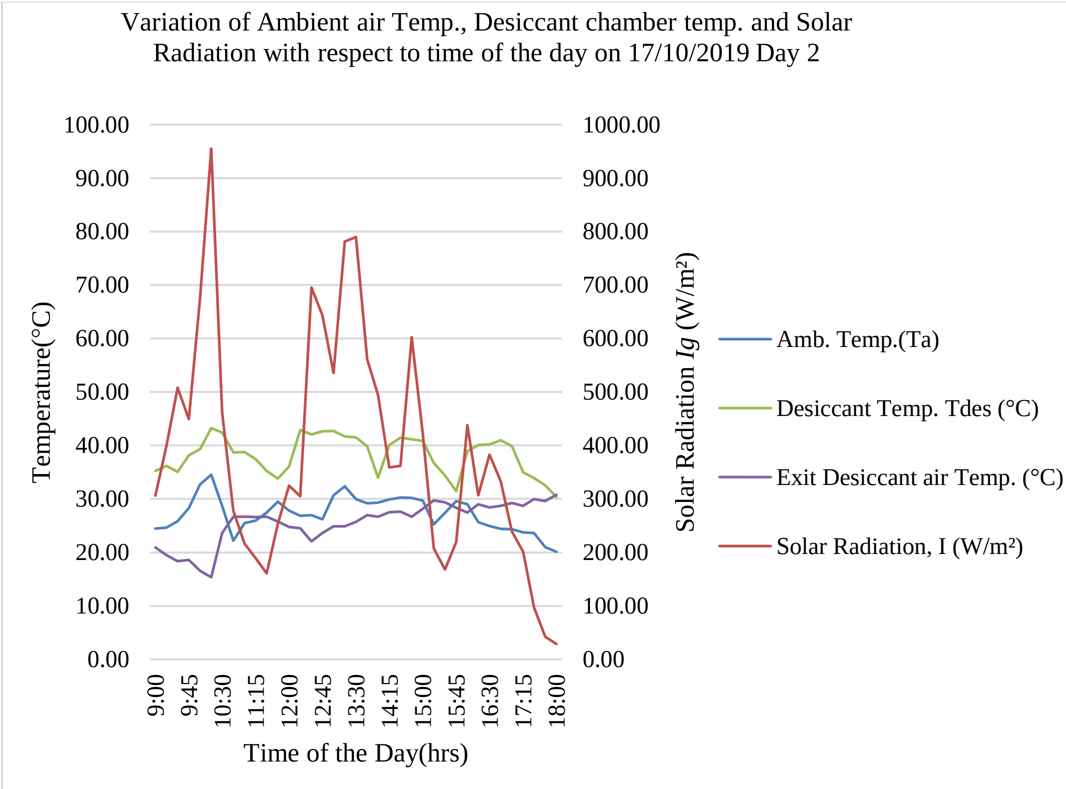

Figure 4.6(a): Variation of the ambient air temperature, desiccant temperatures and solar radiation with respect to of the day on Day 2

Likewise, relative humidity within the desiccant system was also low compared to ambient R.H and relative humidity leaving the desiccant chamber. From figure 4.6(b) relative humidity of the air exiting the system was high due to the moisture uptake from the desiccant bed. Therefore, a decrease in weight of the desiccant balls with temperature of the system is observed on Figure 4.6(c) meaning that the desiccant balls were being dried.

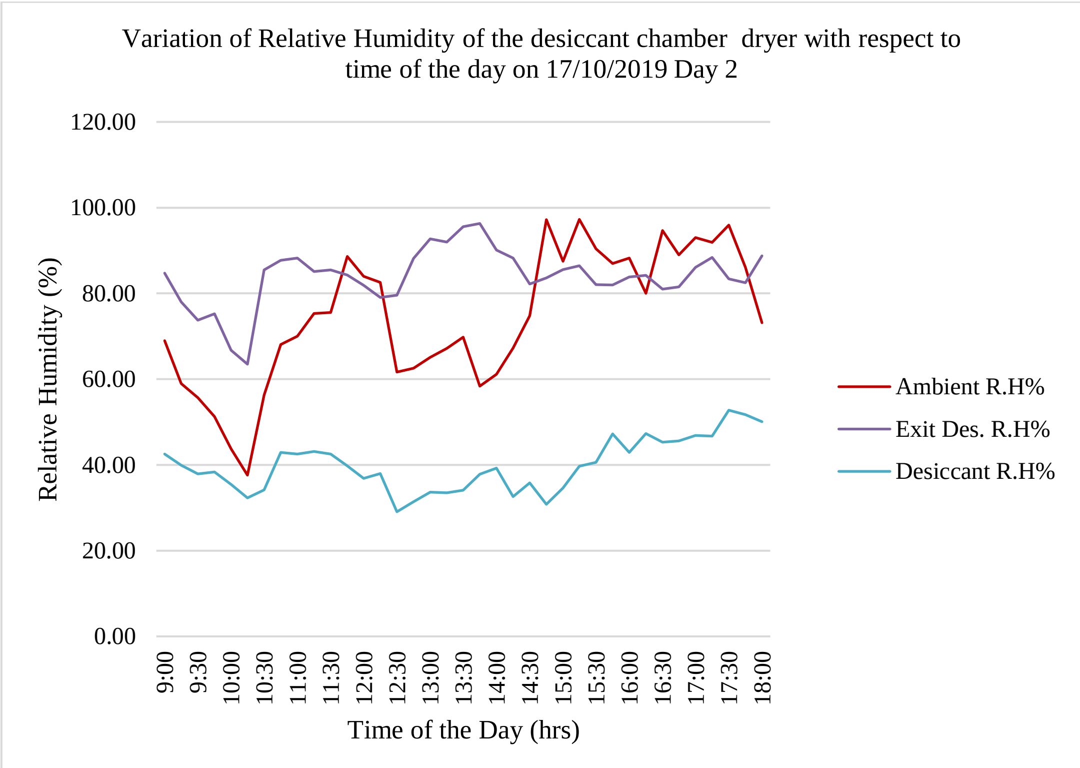

Figure 4.6(b): Variation of Relative Humidity of the desiccant drying chamber and ambient R. H. with respect to time of the day on Day 2

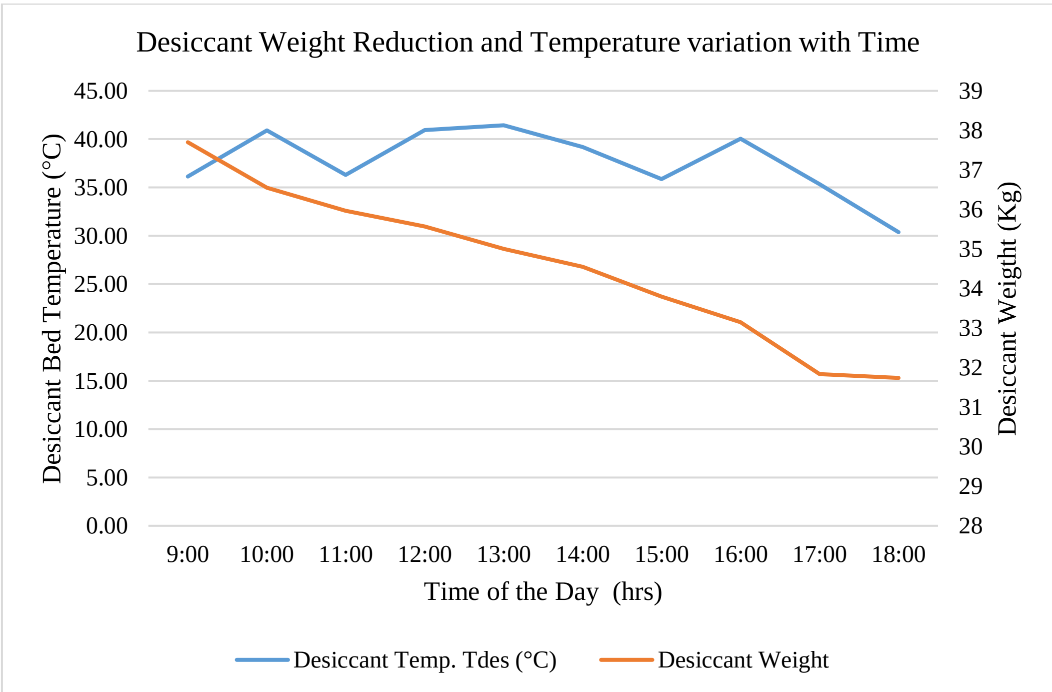

Figure 4.6(c): Desiccant weight reduction and temperature variation with time

4.7 Moisture Sorption Performance and Desorption of Desiccant Energy System with Desiccant Load

The desiccant is regenerated during day time to enable the materials to absorb moisture during the night. The solar greenhouse dryer with desiccant energy storage (Figure 3.5) operated in two modes; day time desorption mode and night time adsorption mode. During night time the air from the desiccant bed was circulated by a fan placed along the plenum chamber, at a flow rate of 0.07 m^3/s, to the drying chamber where the moisture was being removed. The sorption heat is transferred to the tomato drying chamber. Subsequently, the temperature of the air from the desiccant chamber was at an average value of 26.5 °C ± 6% while the average ambient temperature of 15.9 °C ± 6%, during the testing conditions whereby no other external source heat that was provided to the desiccant bed. The moisture removed from the fresh sliced tomato samples was 5.44 kg within the 15 hours with the rate of 6.044 grams of moisture/min removal as seen in test no. 6 which was conducted in November 2019. Thus, from Figure 4.7(a) It can be observed how the desiccant material was gaining weight during the moisture-sorption process. Therefore, the adsorption was at 0.00312 grams of moisture/grams of desiccant/sec, higher by 89% compare to that of the silica gel at 0.00034722 grams of moisture/gram of silica gel/sec as presented by Cecil May R. Ylagan, (2017). The moisture sorption of desiccant balls was about 37.3% of the total moisture to be removed from the tomato samples. The cool air from the dryer chamber was returned to the desiccant bed to lower the humidity level and further heat the air to continue the process. This study did not observe desiccant saturation since the desiccants were regenerated on the next day after a night shift of use thus, the process was continuous.

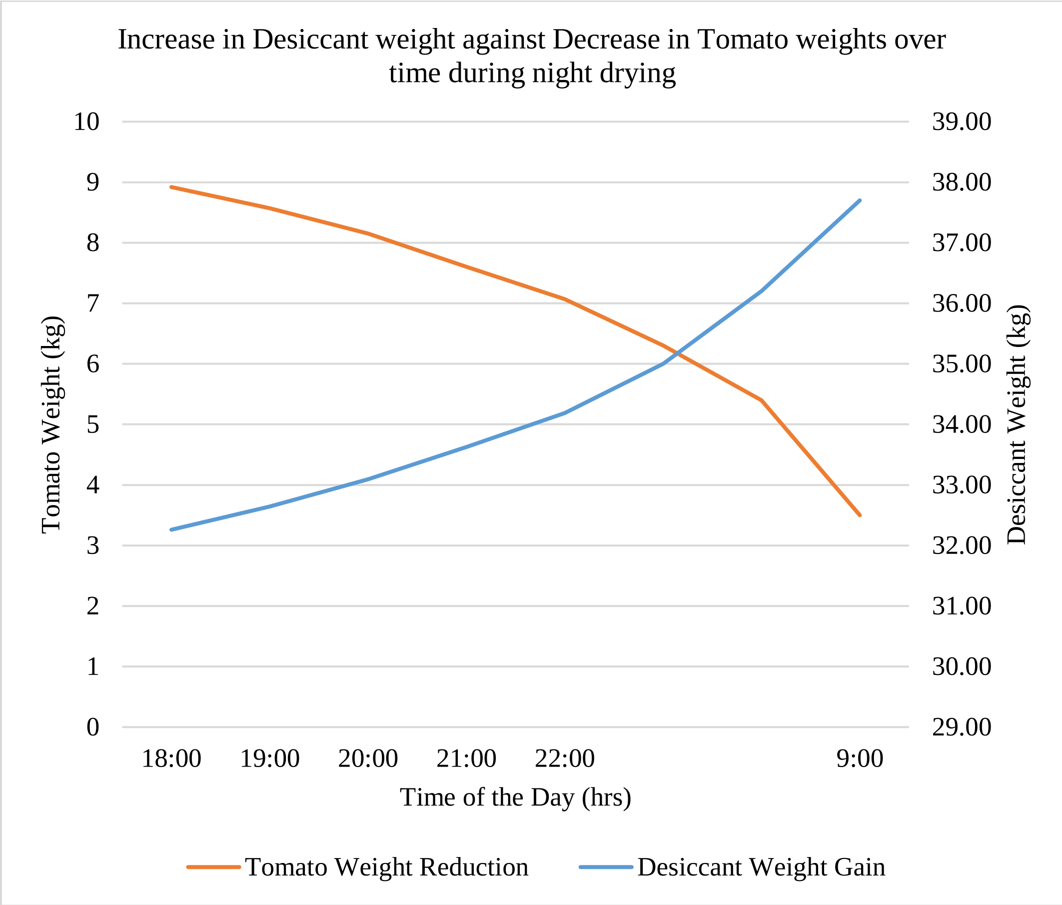

Figure 4.7(a): Desiccant Bed weight gain and Tomato weight reduction During Night Time drying

During the day, the desiccant system was operating independent from the drying chamber and both fans for exchanging air during night period were kept off and covered. The desiccant was regenerated by heating the ambient air by the solar energy being absorbed by the polyethylene paper and the black sheet on the ground of the desiccant chamber. Average temperature and R.H. of 41.3 °C and 27.5% respectively were attained within the desiccant chamber. Thus, the hot air was used to dry the desiccant and the moist air was vented out to the atmosphere via the roof top by an exhaust fan. Figure 4.7(b) shows the change of moisture content of the desiccant materials with respect to time of the day. The trend depicts the decrease of moisture content of the desiccant from 17% to 3% within the desiccant system.

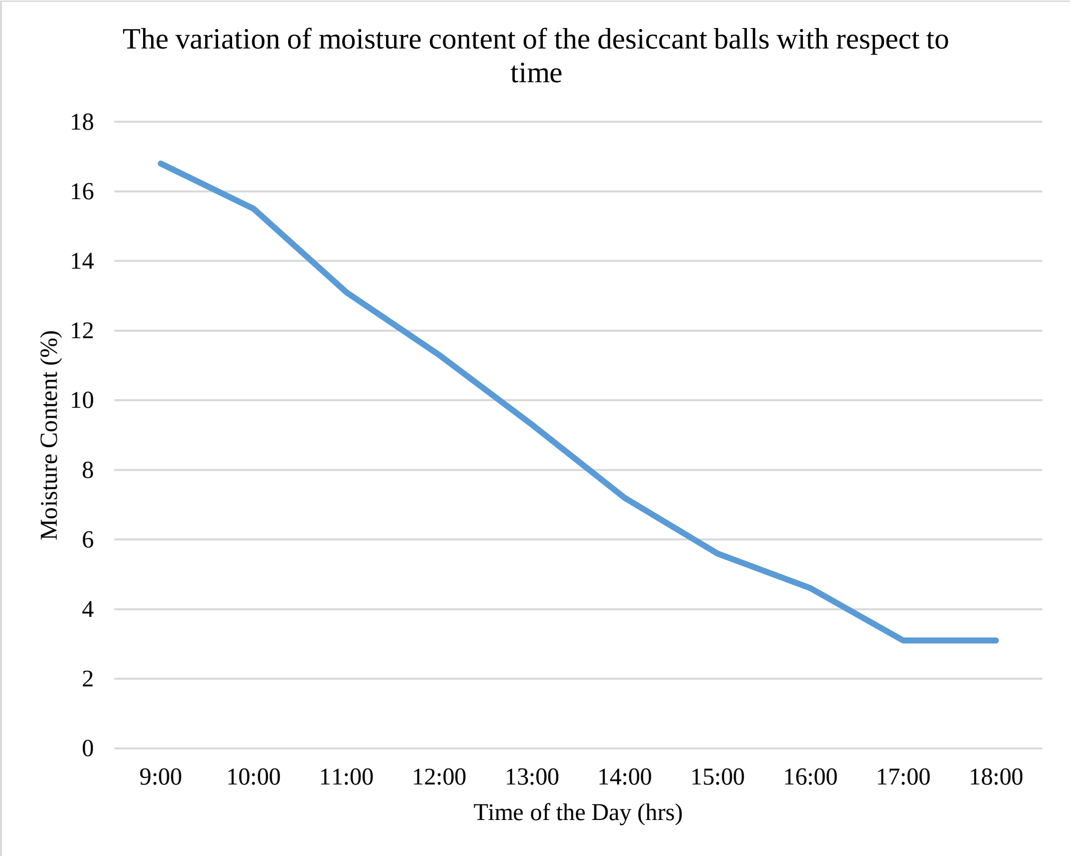

Figure 4.7 (b): Moisture content reduction with respect to time of the day for the desiccant balls during regeneration time

4.8 Thermal Collector Efficiency and Drying Efficiency of the Solar Greenhouse Dryer with Desiccant Energy Storage

From Appendix D thermal collector and drying efficiencies was calculated based on equations 2.7.1 and 2.7.2(ii) respectively. Thermal collector efficiency was measuring the thermal performance of the system i.e., the useful energy gain of the solar greenhouse dryer chamber and the desiccant chamber. The collection efficiency calculated under no load for the dryer and desiccant chamber was found to be 46.2% and 40.8% respectively. The values are in agreement with Prakash *et al.*, (2016) which gave the efficiency ranging from 30% to 78% under active mode. Other researchers reported higher values of thermal efficiency of the solar greenhouse dryer during experiment to be 57.2% (Elkhadraoui *et al.*, 2015; Almuhanna, 2012).

The collector for both drying and desiccant chamber were well insulated with a cardboard to avoid the heat loss at the bottom. However, heat loss could have occurred at the top of the transparent polyethylene collector sheet. Therefore, the collector efficiency of this greenhouse dryer and desiccant unit was enhanced by sealing well its paper at the top.

Under load test, the average drying efficiency of the solar greenhouse dryer using solar energy on day times was found to be 23%. There are no distinctive values reported on drying efficiency recommended for a forced convection solar greenhouse dryer. Nayak *et al.,* (2011) reported a drying efficiency of 34.2% for a photovoltaic-thermal (PVT) forced greenhouse dryer which was used to dry mint from initial moisture content of 80% (dwb) to 11% (dwb). The value is less than the reported one because their testing conditions were different.

The drying efficiency when using desiccant energy storage was found to be 19.9%. It is a lower rate compared with the estimated average drying efficiency of 21% stated by Mohanrajand Chandrasekar, (2009, July), for a forced convection solar dryer integrated with gravel as heat storage material. Additionally, the drying efficiency when desiccant energy storage was used was less than the solar greenhouse dryer efficiency on day times. This was due to the fact that the heat obtained from the desiccant energy storage did not come directly to the material to be dried. Instead, the air temperatures from desiccant chamber were lowered by the extractive fan before reaching the drying chamber to heat the drying air. Therefore, drying efficiency was reduced. Also, the drying efficiency of 21% as reported by Mohanrajand Chandrasekar (2009, July) is less than that of solar greenhouse dryer during day time drying in the current study.

The drying process took place within 27 hours. The time is less compared with the other developed greenhouse dryer with desiccant energy storage. Aritesty and Wulandani, (2014) did a performance evaluation of the solar greenhouse dryer for drying ginger slices from the initial moisture content of 80% (dwb) to a final moisture content of 8% - 11% (dwb) in 30hrs. The drying time achieved is greater. On the other hand, the researcher reported a drying efficiency of 8% which was less for the system. Therefore, the current developed solar greenhouse dryer with desiccant energy storage demonstrated less drying time and higher drying efficiency, hence making it appropriate for use at farm level.

4.9 Economic Evaluation of the Solar Greenhouse Dryer with Desiccant Energy Storage System

Economic evaluation of the developed solar greenhouse dryer with desiccant energy storage system was evaluated using four methods viz.: Discount cash flow method (Net present value), Simple payback period, accounting rate of return and benefit – cost ratio (life cycle analysis) as follows:

4.9.1 Assumptions

The economic analysis of the developed Solar Greenhouse dryer (SGD) with desiccant energy storage (DES) prototype considered assumptions as presented under Table 4.9.1. The calculations in Appendix B_5 in Appendix B showed how fixed and annual variable costs of the system were derived. With the capital cost of the SGD with DES as Ksh 93,689, the operational cost of the system yearly was estimated to be Ksh 259,864. The total annual capital cost of the dryer was Ksh 353,553. The total amount of dried product under this system per year was 213.5 kg. Cost to produce 1kg of dried tomatoes was estimated to be Ksh 1,233.58. Selling price of 1 kg of dried tomatoes Ksh 2,054 thus the revenue obtained per every kilogram is Ksh 820.43.

Table 4.9.1: Assumptions for the Economic Analysis of the Solar Greenhouse Dryer with Desiccant Energy Storage

S/N	Assumptions	Unit Values
1	Investment Cost of the SGD and DES	Ksh 93,689
2	Capacity of the dryer per batch	16.8 kg
3	Drying time	72 hours
4	Dryer operation time in a year	122 day(batches)/year
5	Expected Life of the dryer	15 years
6	Weight after drying	1.75kg
7	Labour required per batch	1-man day/batch
8	Labour charges	500 Ksh/day
9	Interest rate	18%
10	Salvage value	10% of the system cost
11	Repair and Maintenance	3% of the investment cost
12	Amount of Desiccant used during night	32.26kg

4.9.2 Cost Breakdown of drying fresh tomatoes

From Table 4.9.1 the initial cost of the dryer be Ksh 93,689. The economic visibility of the system for drying tomatoes was calculated by considering repair and maintenance costs as well as cost of raw materials. Therefore, the initial investment cost was derived by adding the material costs of all components of the system, total costs and the annual operation costs based on research by Dhanushkodi *et al.,* (2015), Dhanushkodi et al., (2014) and Barnwel and Tiwari, (2008). The calculations are as shown on Appendix B_5 in Appendix B. Also, Appendix B_6 showed an average annual savings of Ksh 175, 160 was obtained.

4.9.3 Discount Cash Flow Method (Net Present Value)

From the analysis under B_7 in Appendix B it is observed that the calculated NPV value is a positive figure which means that the project can be considered financially viable. It is also an indication that there is payback period. It is reported by economists that any negative NPV value implies that one has to invest on an alternative project (Prakash *et al.,* 2017; Fudholi *et al.,* 2011). Also, from Table B_7 it can be concluded that the cumulative present value of the future benefits of the system is to be Ksh. 891,840.73. The investment of the solar Greenhouse dryer with desiccant energy storage was Ksh 93,689 and from the discounted Cash flow technique we see that the value lies within the first year.

4.9.4 Simple Payback Period

In Table B_3 of Appendix B, it is seen that the Annual Cash Benefit is Ksh 172,349. With the estimated initial and annual operating costs of the solar greenhouse dryer with desiccant energy storage for drying tomatoes, the payback period for the system was found to be 0.54 years (Table B_8) which is equivalent to 66 drying days. Therefore, we can conclude that the payback period of the system is within 1 year.

4.9.5 Accounting Rate of Return

Using the accounting rate of return method was able to indicate the profitability of this individual solar greenhouse dryer with desiccant energy storage. It can be seen from the table B_9 in Appendix B that when the average income was divided by average investment after depreciation the results shows that rate of return is 198% which indicates that the project is profitable.

4.9.6 Benefit-Cost Ratio (B/C) (Life Cycle Analysis)

The purpose of this economic analysis method was to justify the decision to invest on the solar greenhouse system incorporated with desiccant energy storage. It was found that the cost of drying 1kg of fresh tomatoes was Ksh 1,234 in this system. From Table B_10 in Appendix B the B/C ratio was 8.42. The value is greater than one which implies that the dryer is economically viable, thus it is worth investing.

Generally, the economic analysis of the developed system cost results is as shown in Table 4.9.

Table 4.9: Economic Indicators for the Solar Greenhouse dryer with desiccant energy storage for tomato drying

S/N	Economic Indicators	Value
1	Net Present Value	Ksh. 891,840.73
2	Payback Period	0.54 years
3	Accounting rate of return	198%
4	Benefit-Cost Ratio	8.42

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The study focused on development of a solar greenhouse dryer with desiccant energy storage for tomato drying, along with the clay-$CaCl_2$ solid desiccant materials for extending the drying process during night time. The following new research findings were achieved from the study:

a) Four types kaolin clay-$CaCl_2$ solid desiccants was developed and exhibited the following moisture sorption under constant humidity (75% R.H., 25 ^oC) generated by bottled $NaCI_2$ solution as follows:

- Type 1 Clay-$CaCl_2$ desiccant: Kaolin Clay: $CaCl_2$: Vermiculite: Cement: at ratios: 13:1:4:2 exhibited 16% (dwb) after 168 hours
- Type 2: Clay- $CaCl_2$desiccant: Kaolin Clay: $CaCl_2$: Vermiculite: Cement: at ratios: 13:1:4:2 exhibited 27.6% (dwb) after 168 hours
- Type 3: Clay- $CaCl_2$ desiccant: Kaolin Clay: $CaCl_2$: Vermiculite: Cement: at ratios: 6:1:2:1 exhibited 16% (dwb) after 168 hours
- Type 4: Clay- $CaCl_2$ desiccant: Kaolin Clay: $CaCl_2$: Vermiculite: at ratios: 3.8:1:3.3 exhibited 30.2% (dwb) after 168 hours

Hence on the basis of moisture sorption performance test, type 4 clay- $CaCl_2$ desiccant exhibiting 30.2% (dwb) was selected for mass production.

b) The Solar Greenhouse Dryer with Clay-$CaCl_2$ Desiccant Energy storage powered by a photovoltaic solar panel to power the fans was designed and constructed using locally available materials [sized 2m×3.5m×2.1m (width, length and height)]. The dryer demonstrated capability of drying tomatoes continuously from 94.3% (dwb) to 8.3% (dwb) within 27 hours.

c) The prototype solar greenhouse dryer with desiccant energy storage system demonstrated typical tomato drying efficiency of 23.7% and 22.6% during day 1 and 2 respectively while operating with an average solar radiation of 559.2 W/m^2 and 389 W/m^2 respectively.

d) The average drying rate of solar greenhouse dryer with desiccant energy storage system during the two-day operation was 0.985 kg/h and 0.875 kg/h (during solar drying mode) while night drying using desiccant energy storage system demonstrated an average drying rate of 0.34 kg/h.

e) The economic analysis of the drying system shows a payback period of less than a year (0.54 year) with benefit-cost ratio of 8.4 implying that the system is economically viable.

On the basis of these results, it was concluded that prototype solar greenhouse dryer with Clay-$CaCl_2$ energy storage system has great potential for tomato drying and other high moisture agricultural products in East African countries.

5.2 Recommendation

a) Solar greenhouse dryer with desiccant energy storage system needs further evaluation to improve on the desiccant moisture uptake under the desiccant bed by improving the desiccant porosity.

b) Best configuration for air flows should be investigated to optimize moisture adsorption and regeneration

c) Design modification are required to optimize air flows in the system by blowing air through the inlet vent and also to facilitate uniform temperature distribution or heat transfer across the layers of drying trays.

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APPENDICES

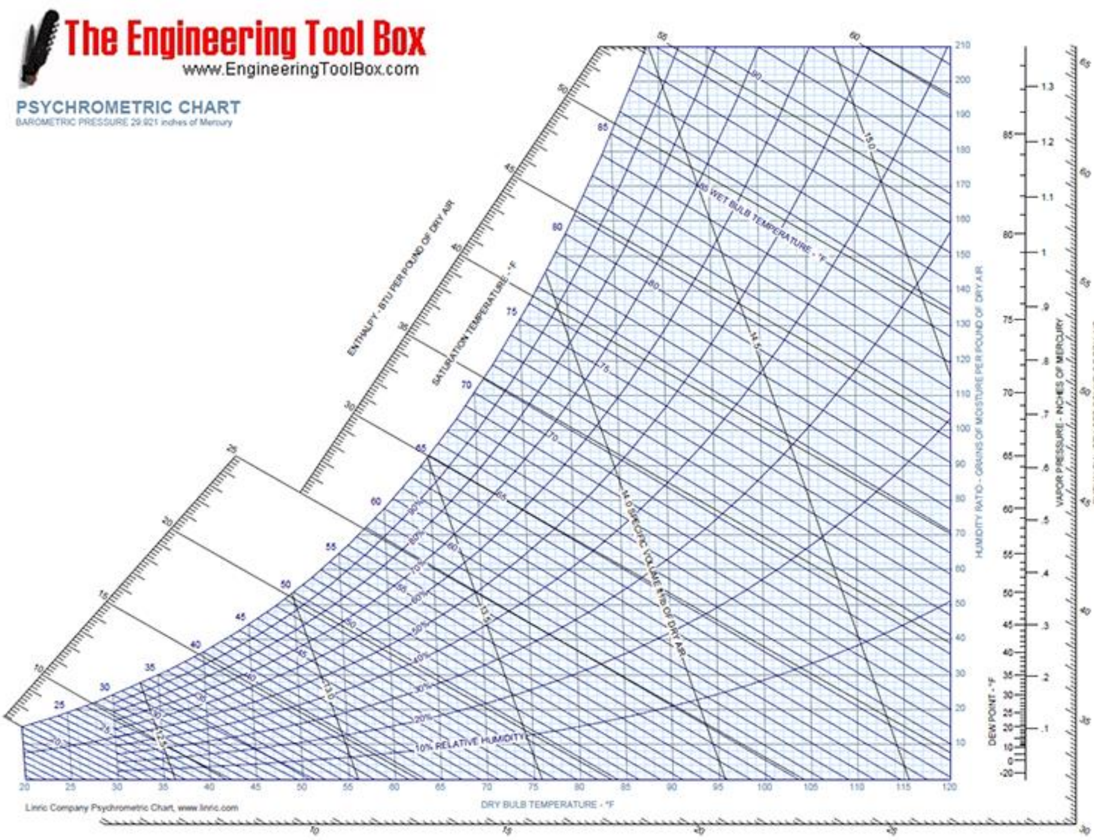
Appendix A

Table A_1 Proximate Composition of Fresh Tomatoes

Parameters	Content (%)
Moisture Content	93.0
Protein	1.0
Fat	0.1
Ash	0.6
Carbohydrate	4.3
Ice	0.0
Fiber	0.6

Source: Chuku *et al.*, 2008

A_2 Psychrometric Chart



Appendix B:

With the locally available exhaust fans there were two categories identified under Table B_1 with their specification.

Table B_1 Fan Specification

Specification	**Category 1**	**Category 2**
Manufacturers	Interfan, Metuchen, New Jersey, Indonesia	Delta Electronics of China
Model Number	PM240-24D-1751B-2TP	AFB1212SH
Rated Voltage and	24 V and 900mA	12V and 0.9A
Power consumption	22W	10.8W
Speed	3350 RPM	
Noise	58 dBA	
Air Flow	251 CFM	113.11CFM
Maximum air pressure	0.88in. H_2O	
Operating temperature	-20 to +70 °C	
Dimensions	172 mm diameter× 51 mm	
Weight	792g	
	5 blade thermoplastic impeller	
	Ball bearing	
	12" long flexible power leads	
	Aluminum alloy casing	

Table B_2: Investment Cost of the Construction of the Solar Greenhouse Dryer with Desiccant Energy Storage

ITEMIZED BUDGET				
S/N	**Quantity**	**Description of materials**	**Unit**	**Amount**
1	67m	2'x 4' & 2'x3' Timber	132	8,844
2	38m²	(4x9.5) m Greenhouse paper (200µm	80	3,040
3	8m²	(1x8) m 0.5mm dam liner	210	1,680
4	1pc	Greenhouse tape	1000	1,000
5	3pcs	(1.2x2.37) m 2mm galvanized iron sheet	1500	4,500
6	3pcs	(1.2192x2.4384) m plywood board	400	1,200
7	1pc	½ kg Wood glue	150	150
8	1pc	¼ kg Wood glue	80	80
9	4kg	4'(2kg); 3'(1kg) and 2'(1(kg) Nails	140	560
10	¾kg	1' Special Nails	200	150
11	4pcs	3' Hinges	30	120
12	2pcs	Pad bolts	120	240
13	11.7m	Coffee Tray Wire	350	4,095
14	6pcs	¾' 6.096m Square tubes	490	2,940
15	6pcs	¾' 6.096m Angle lines	500	3,000
16	3pcs	¾' 6.096m Flat bars	570	1,710
17	54kg	Vermiculite	60	3,240
18	2bags	Kaolin (White)-25kg	475	950
19	1bag	Kaolin Yellow 50kg	1050	1,050
20	1bag	Calcium Chloride - 25kg	1740	1,740
21	2pcs	Solar module 50 W	5000	10,000
22	1pcs	10A Solar Charger Controller	5000	5,000
23	4pcs	Fans (Large 24V DC Round Fan 172 mm x 51 mm - 250 CFM - 3350 RPM - Interfan PM240-24D-1751B-2TP)	3000	12,000
24	1pc	Lead Acid Solar Battery 12V 200Ah	25000	25,000
25	40m	2.5mm electrical wire	35	1,400
		Total		93,689

Table B_3 Cost and Economic analysis parameters of the SGD with DES

Item description	Cost and Economic parameters
Investment Cost of the SGD and DES	Ksh 93,689
Capacity of the dryer per batch	16.8 kg
Drying time	72 hours
Dryer operation time in a year	122 day(batches)/year
Expected Life of the dryer	15 years
Initial Moisture Content (wet basis)	94.35%
Final Moisture Content (wet basis)	8.96%
Weight after drying	1.75kg
Labour required per batch	1-man day/batch
Labour charges	500 Ksh/day
Interest rate	18%
Salvage value	10% of the system cost
Repair and Maintenance	3% of the investment cost
Cost of Tomatoes	Ksh 80/kg during drying season
Selling price of dried tomatoes	Ksh 2054/kg
Amount of Desiccant used during	32.26kg

Table B_4 Initial Investment cost and Annual Cash Flow Data

1	Initial Investment(P)	93,689
2	Salvage Value (S) @10%	9,369
3	Annual Savings	175,160
4	Annual Operating Cost (Fuel consumption and Cost annually)	0
5	Annual Cash Flow (3) – (4)	175,160
6	Maintenance and Repair Costs (3% of P)	2,811
7	Total Cost (4) + (6)	2,811
8	Economic life Expected	15years
9	Time value for money (annual interest rate in %)	18%
10	Annual Cash benefit (3) – (7)	172,349

B_5 Fixed costs of the solar greenhouse dryer with desiccant energy storage

Fixed Costs

a) Cost of the dryer Ksh 93,689

b) Depreciation @10% salvage value = $\frac{Purchase\ price - Salvage\ Value}{Number\ of\ useful\ life\ years}$ = (93,689 – 9,369)/15

= 5,621

c) Interest on Capital cost @18% = $\frac{Purchase\ price + Salvage\ Value}{2} \times \frac{Interest\ Rate}{100}$

= (93,689 +9,369)/2 × (18/100)

=9,275

Total fixed cost of the SGD with DES =93, 689+5,621+9275 = 108,585

Annual Variable Cost

Labour Cost for 1man/day @ Ksh 500 for 122 days = 61,000

Battery maintenance (1 battery for 15years @20,000) = 20,000

Cost of Fresh Tomatoes (16.8kg per day @Ksh 80 for 122 days) = 163,968

Total Variable Cost = 61,000+20,000+163,968 = 244,968

Total Cost = Fixed costs +Variable Cost

=108,585 + 244,968

= 353,553

The operation cost of the SGD with DES yearly = Depreciation +Interest +Variable Costs

=5,621 + 9,275 +244,968

= 259,864

B_6 Annualized Cost Method

Annualized Cost (AC) = Annual capital recovery (ACR) + Annual Operation Maintenance and Repair (AOMR)

Annual Capital Recovery = Capital recovery factor (CRF) × Capital Investment Cost (I)

Capital Recovery Factor (CRF) = $\frac{r}{1-(1+r)^{-n}}$

Where n = expected life of the dryer in years
r = annual discount rate

Total Cost of the dryer = Ksh 93,689
Expected life of the system = 15 years
Discount rate = 18%
CRF = 0.18/ (1 – (1+0.18) ^ (-15)) = 0.1964

ACR = CRF × I

= 0.1964 × 93,689

= 18,401

AOMR (Assumed to be equal to the total variable costs) = 244,968

AC = ACR + AOMR
= 18,401 + 244,968
= 263,369

Annual Output of the SGD and DES (1.75 kg of dried tomatoes per batch for 122 days) = 213.5 kg

Annualized Cost for drying 1 kg of tomatoes = 263,369/213.5 = Ksh 1,233.58

Selling price per kg of sun-dried tomatoes = Ksh 2,054

Net Revenue per kg of dried tomatoes = 2,054 – 1,233.58 = Ksh 820.42

Annual Savings = 820.42 × 213.5 = Ksh 175,160

B_7 Discount Cash Flow Method

Present worth Factor (P/F) can be calculated using the following formula

$$\frac{1}{(1+i)^n} \text{ Where i = 18\%}$$

Net Present Value

N	P/F	N	P/F	N	P/F
1	0.8475	6	0.3704	11	0.1619
2	0.7182	7	0.3139	12	0.1372
3	0.6086	8	0.2660	13	0.1163
4	0.5158	9	0.2255	14	0.0985
5	0.4371	10	0.1911	15	0.0835

$$\sum \quad \left(\frac{1}{(1.18)^{15}}\right) = 5.0916 \text{ (for 15 years)}$$

$$\sum \quad \left(\frac{1}{(1.18)^{10}}\right) = 4.4941 \text{(for 10 years)}$$

$$\sum \quad \left(\frac{1}{(1.18)^{5}}\right) = 0.4371 \text{(for 5 years)}$$

For Salvage value

$$\frac{1}{(1.18)^{15}} = 0.0835$$

$$\frac{1}{(1.18)^{10}} = 0.1911$$

$$\frac{1}{(1.18)^{5}} = 0.4371$$

Present Value of the Future benefits

Net Worth = -93,689 + (172,349 * 5.0916) + (9369*0.0835) = 784,625.4799

Table B_7 Calculated Annual Savings, the present worth of the annual savings and the cumulative present worth of the annual saving

Year	Annualized Cost of the dryer	Annual Savings	Present Worth of Annual Savings	Present Worth of Cumulative Savings
1	263,369	175,160	148,440.68	148,440.68
2	263,369	175,160	125,797.18	274,237.86
3	263,369	175,160	106,607.78	380,845.65
4	263,369	175,160	90,345.58	471,191.23
5	263,369	175,160	76,564.05	547,755.28
6	263,369	175,160	64,884.79	612,640.06
7	263,369	175,160	54,987.11	667,627.17
8	263,369	175,160	46,599.24	714,226.42
9	263,369	175,160	39,490.89	753,717.30
10	263,369	175,160	33,466.85	787,184.16
11	263,369	175,160	28,361.74	815,545.89
12	263,369	175,160	24,035.37	839,581.27
13	263,369	175,160	20,368.96	859,950.23
14	263,369	175,160	17,261.83	877,212.06
15	263,369	175,160	14,628.67	891,840.73

Table B_8 Simple payback period

S/No	Factor	Value
1	Initial Investment (P)	93,689
2	Annual Cash Benefit	172,349
3	Pay-back Period in years	0.54

Table B_9 Accounting rate of return

S/No	Factor	Value
1	Annual Cash benefit	172,349
2	Initial Investment(P)	93,689
3	Salvage Value (S) @10%	9,369
4	Net Investment (2) – (3)	84,320
5	Expected Life of Project	15 years
6	Average net Investment (4)/(5)	5,621
7	Average net Income (1) – (6)	166,728
8	Accounting Rate of Return (7)/(4)	198%

Table B_10 Cost-Benefit ratio

S/N	Factor	Value
1	Initial Investment(P)	93,689
2	Salvage Value (S) @10%	9,369
3	Annual Savings	175,160
4	Annual Operating Cost (Fuel consumption and Cost	0
5	Annual Cash Flow (3) – (4)	175,160
6	Maintenance and Repair Costs (3% of P)	2,811
7	Total Cost (4) + (6)	2,811
8	Expected Economic life	15years
9	Time value for money (annual interest rate in %)	18%
10	Annual Cash benefit (3) – (7)	172,349
11	Capital Recovery Factor	0.1964
12	Annualized Uniform Cost (R) (1) * (11)	18,401
13	Annualized Salvage Value R' = $\frac{S}{(1+i)^n-1}$	854
14	Annualized Cost (12)-(13)	17,547
15	Cost of Drying	1,234
16	Total Benefits (10) – (14)	154,802
17	Benefit-Cost Ratio (16)/(12)	8.41

Appendix C: Experimental Data

Table C_1: Calibration Data for Thermocouples

Time (Minutes)	Mercury Bulb Thermometer (°C)	K-type TC Sensor_1 (°C)	K-type TC Sensor_2 (°C)
0	0	0	0
5	22	23.7	24.4
10	28	31.8	31.0
15	44	43.8	44.6
20	56	56.0	57.1
25	66	66.6	66.4
30	77	75.1	77.7
35	82	80.0	81.3

Table C_2: Amount of water adsorbed by the desiccant during the sorption study

Time (hrs)	Sample 1 13:2:4:2		Sample 2 13:1:4:2 fired at 500°C		Sample 3 6:1:2:1		Sample 4 3.8:1:3.3		Control Sample Silica Gel	
	Amount in g	Water adsorbed (g)	Amount in g	Water adsorbed (g)	Amount in g	Water adsorbed (g)	Amount in g	Water adsorbed (g)	Amount in g	Water adsorbed (g)
0	60.45	0	75.02	0	61.83	0	69.65	0	60.00	0
24	65.18	4.72	79.78	4.77	66.58	4.75	74.75	5.1	63.73	3.72
48	67.29	6.83	84.96	9.94	68.76	6.92	79.88	10.23	73.15	13.15
72	68.31	7.86	87.68	12.67	69.86	8.03	82.41	12.77	76.15	16.15
96	69.1	8.65	89.7	14.68	70.7	8.87	84.53	14.89	78.33	18.33
120	69.69	9.23	91.29	16.27	71.33	9.49	86.07	16.42	80.20	20.20
144	70.07	9.62	93.38	18.36	71.75	9.92	88.6	18.95	81.68	21.68
168	70.33	9.87	95.68	20.67	71.91	10.07	90.67	21.03	82.68	22.68

C_3: Weight Reduction of Tomato slices samples with time on Layers of Trays

Time of the Day (hrs)	Lower Layer Trays					Upper Layer Trays					Grand Total (kg)
	H1	H3	H5	H7	Total	H2	H4	H6	H8	Total	
09:00	2.1	2.1	2.1	2.1	8.4	2.1	2.1	2.1	2.1	8.4	16.80
10:00	1.92	1.88	1.92	1.96	7.68	1.90	1.90	1.94	1.94	7.68	15.36
11:00	1.80	1.79	1.70	1.82	7.11	1.69	1.72	1.87	1.76	7.04	14.15
12:00	1.69	1.70	1.50	1.66	6.55	1.68	1.70	1.79	1.66	6.83	13.38
13:00	1.56	1.64	1.46	1.52	6.18	1.62	1.68	1.72	1.62	6.64	12.82
14:00	1.48	1.55	1.35	1.47	5.85	1.55	1.57	1.65	1.53	6.30	12.15
15:00	1.26	1.42	1.30	1.23	5.21	1.27	1.30	1.45	1.33	5.35	10.56
16:00	1.18	1.30	1.28	1.16	4.92	1.22	1.24	1.36	1.24	5.06	9.98
17:00	1.14	1.23	1.23	1.11	4.71	1.20	1.19	1.16	1.14	4.69	9.40
18:00	1.10	1.22	1.20	1.08	4.60	1.16	1.12	1.00	1.04	4.32	8.92
09:00	0.38	0.54	0.38	0.36	1.66	0.48	0.50	0.46	0.40	1.84	3.50
10:00	0.24	0.44	0.29	0.26	1.23	0.30	0.35	0.29	0.33	1.27	2.50
11:00	0.22	0.26	0.18	0.21	0.87	0.28	0.25	0.15	0.20	0.88	1.75
12:00	0.22	0.26	0.18	0.21	0.87	0.28	0.25	0.15	0.20	0.88	1.75

C_4: Determined Initial Moisture Content of Fresh Tomato slices by Oven Dry

Layers	**Tray Labels**	**Initial weight of tomatoes in kg**	**Final weight of Oven dried tomatoes in kg**	**Initial Moisture Content (%)**
Lower Layer Trays	H1	2.1	0.14	93.3
	H3	2.1	0.15	92.9
	H5	2.1	0.14	93.3
	H7	2.1	0.13	93.8
Upper Layer Trays	H2	2.1	0.11	94.8
	H4	2.1	0.12	94.3
	H6	2.1	0.11	94.8
	H8	2.1	0.12	94.3
		16.8	**1.02**	**93.9**

C_5: Calculated Moisture Content Reduction of Tomato samples with time

Time of the Day (hrs)	Lower Layer Trays					Upper Layer Trays				
	H1	H3	H5	H7	Average	H2	H4	H6	H8	Average
09:00	93.3	92.9	93.3	93.8	93.3	94.8	94.3	94.8	94.3	94.5
10:00	89.5	87.6	91.4	90.0	89.6	86.7	88.1	92.9	90.5	89.5
11:00	88.6	79.0	86.2	87.6	85.4	85.7	83.3	86.2	84.3	84.9
12:00	81.9	74.3	81.9	82.9	80.2	77.1	76.2	78.1	81.0	78.1
13:00	47.6	41.9	42.9	48.6	45.2	44.8	46.7	52.4	50.5	48.6
14:00	45.7	41.4	41.4	47.1	43.9	42.9	43.3	44.8	45.7	44.2
15:00	43.8	38.1	39.0	44.8	41.4	41.9	41.0	35.2	41.0	39.8
16:00	40.0	32.4	38.1	41.4	38.0	39.5	38.1	31.0	36.7	36.3
17:00	29.5	26.2	35.7	30.0	30.4	26.2	25.2	21.4	27.1	25.0
18:00	25.7	21.9	30.5	27.6	26.4	22.9	20.0	18.1	22.9	21.0
09:00	19.5	19.0	28.6	21.0	22.0	20.0	19.0	14.8	21.0	18.7
10:00	14.3	14.8	19.0	13.3	15.4	19.5	18.1	11.0	16.2	16.2
11:00	8.6	10.5	8.6	6.7	8.6	9.5	9.5	7.6	7.6	8.6
12:00	8.6	10.5	8.6	6.7	8.6	9.5	9.5	7.6	7.6	8.6

Table C_6 Summary of the average values, maximum and minimum reading for both greenhouses, lower & upper layers, ambient air temperatures and solar radiation

Flow Rate	Parameters	Average Value	Maximum Reading	Minimum Reading
0.19m³/s	Greenhouse Dryer Air Temperature °C	43.10	54.83	35.29
	Lower Layer Trays Temperature °C	43.85	53.46	37.17
	Upper Layer Trays Temperature °C	44.49	53.99	38.46
	Solar Radiation W/m²	554.74	921.24	33.83
	Ambient Air Temperature °C	28.53	34.85	20.65
0.28m³/s	Greenhouse Dryer Air Temperature °C	41.91	45.86	35.82
	Lower Layer Trays Temperature °C	44.53	49.71	34.36
	Upper Layer Trays Temperature °C	43.69	50.63	36.51
	Solar Radiation W/m²	397.19	871.22	9.29
	Ambient Air Temperature °C	27.22	36.77	16.36
0.45m³/s	Greenhouse Dryer Air Temperature °C	41.02	43.93	37.49
	Lower Layer Trays Temperature °C	39.2	48.12	33.50
	Upper Layer Trays Temperature °C	42.25	49.81	37.80
	Solar Radiation W/m²	510.82	870.07	20.96
	Ambient Air Temperature °C	27.01	35.13	17.77

Appendix D: SOLAR GREENHOUSE DRYER WITH DESICCANT ENERGY STORAGE EFFICIENCY CALCULATIONS

Efficiency in drying is very important factor in the assessment and selection of the optimum dryer for a particular task. Factors that affect drying efficiency are categorized in three groups (i) Factors related to the environment, in particular, ambient air conditions; (ii) Factors which are specific to the crop; and (iii) Factors which are specific to the design and operation of the dryer. Again, there are several ways of expressing the efficiency of drying, among others; the sensible heat utilization efficiency (SHUE), the fuel efficiency, and the drying efficiency are the most useful. But because of the purpose of the design and operation of the solar greenhouse dryer with desiccant energy storage, the drying efficiency was calculated by the following expression:

$$Drying\ Efficiency\ \boldsymbol{\eta} = \frac{Heat\ Utilized\ for\ Moisture\ Removal}{Heat\ Available\ for\ Moisture\ Removal}$$

The expression is mostly used to evaluate the dryer design or can also be used for comparison between dryers, since it is a measurement of the degree of utilization of the sensible heat in the drying air.

Also, another useful measure for air drying such as in spray dryers, is to look at a heat balance over the air, treating the dryer as adiabatic system with no exchange of heat with the surroundings. Therefore, the useful heat transferred to the food for its drying corresponds to the drop in temperature in the drying air, and the heat which has to be supplied corresponds to the rise of temperature of the air in the storage materials. Then, for this adiabatic process- drying efficiency, $\boldsymbol{\eta}$ due to use desiccant energy storage materials can be calculated by the following expression:

$$\eta = \frac{(T_1) - (T_2)}{(T_1) - (T_{\mathrm{a}})}$$

Where the T_1 is the average inlet (high) air temperature into the drying chamber, T_2 is the average outlet air temperature from the dryer, and T_a is the average ambient air temperature during the night drying process. The numerator, the gap between T_1 and T_2 is a major factor in the drying efficiency.

Collector efficiency is of the solar greenhouse dryer with desiccant energy storage was calculated. The whole greenhouse dryer and desiccant unit was treated as a collector. Since not all the solar radiation incident on the greenhouse and desiccant chamber flow, side and top surface is converted into heat energy. Part is reflected back to the sky and other part is absorbed by the polyethylene paper. Therefore, once the collector absorbs heat, temperature rises being above the ambient. There will be heat loss to the atmosphere by convection and radiation (Struckmann, 2008). Using the property of dry air at the atmospheric condition efficiency of the system can be calculated.

$$Thermal\ Efficiency, \eta c = \frac{\nu\rho\Delta \mathrm{TCp}}{\mathrm{IcAc}}$$

Where the ν is the volumetric flow rate of air, m^3/s, ρ is the density of air, kg/m^3, ΔT is the air temperature elevation, °C, Cp is the air specific heat capacity, J/kg°C, Ic is the Insolation on collector surface, W/m^2 and Ac is the is Collector Area, m^2.

Using Cp = 1005J/kg°C and ρ = 1.225kg/m^3 the collector efficiency of the system was calculated.

Greenhouse Chamber	0.19m^3/s	0.28m^3/s	0.45m^3/s	Desiccant Chamber	0.07m^3/s	0.17m^3/s	0.36m^3/s
Ta°C	28.5	27.2	27.1	Ta°C	28.5	27.2	27.1
Tgr°C	43.1	41.9	41	Tdec°C	42.1	40.6	39.2
Ic W/m^2	554.7	397.2	510.2	Ic W/m^2	554.7	397.2	510.2
Ac m^2	27.585	27.585	27.585	Ac m^2	5.179	5.179	5.179
ηc%	22.3	46.2	34	ηc%	40.8	12.2	30.7

Based on the averaged drying conditions figures collected the following efficiencies were calculated;

Data for efficiency calculation:

Initial Moisture Content = 93.9%, Final Moisture Content = 8.6%, Mass of the wet product = 16.8kg, Mass of the dried product = 1.75kg, Average drying temperature on the day light 1 = 40.64°C, Drying time on day light 1= 8hours, Average Solar Radiation on the day light 1 = 510.41W/m^2, Mass of the wet product at the end of day light 1 = 8.92kg, Mass of the wet product on the day light 2 = 3.5kg Average Solar Radiation on the day light 2 = 512.76W/m^2, Average drying temperature on the day light 2 = 41.39°C, Dry time on the day light 2 = 2hours, Drying area = 5m^2

Drying Efficiencies during day light 1

Amount of moisture removed M_w = 16.8 – 8.92 = 7.88kg

Heat Utilized for Moisture removal = M_w *L_v; the latent heat of evaporation was taken at an average drying air temperature of 40.64°C which was recorded to (2404.64 – 170.21) = 2234.43 KJ/kg

Heat Utilized for moisture removal = 7.88 *2234.43 = 17607.3084KJ

Heat available for moisture removal = (I_g*A_c+P_t) *t_d

= ((510.41*5) + 25) *8 = 20616.4 W *60*60 = 74,219,040 J

Drying Efficiency day 1 = ((17607.3084 KJ *1000)/ 74219040J) *100 = 23.72%

For day light 2

M_w = 3.5 – 1.75 = 1.75kg; L_v = 2576 – 173.34 = 2402.66KJ/kg;

Drying Efficiency day 2 = (1.75*2402.66*1000*100)/ ((512.76*5+25) *2*60*60) = 22.56%

Efficiency based on the exchange of drying air between the desiccant energy storage chamber and drying chamber

The system was treated as adiabatic system

The average air temperature entering the drying chamber T_1 = 26.53°C

Average Temperature of the air leaving the drying camber T_2 = 23.11°C

Ambient air temperature T_a = 15.9°C

η = (26.53 – 23.11)/ (26.53 – 15.9) = 13.36%

Drying Rate

$D.R_{d1}$ = (Wi – W_f)/ t_d = 7.88kg/8hrs = 0.985 kg/h

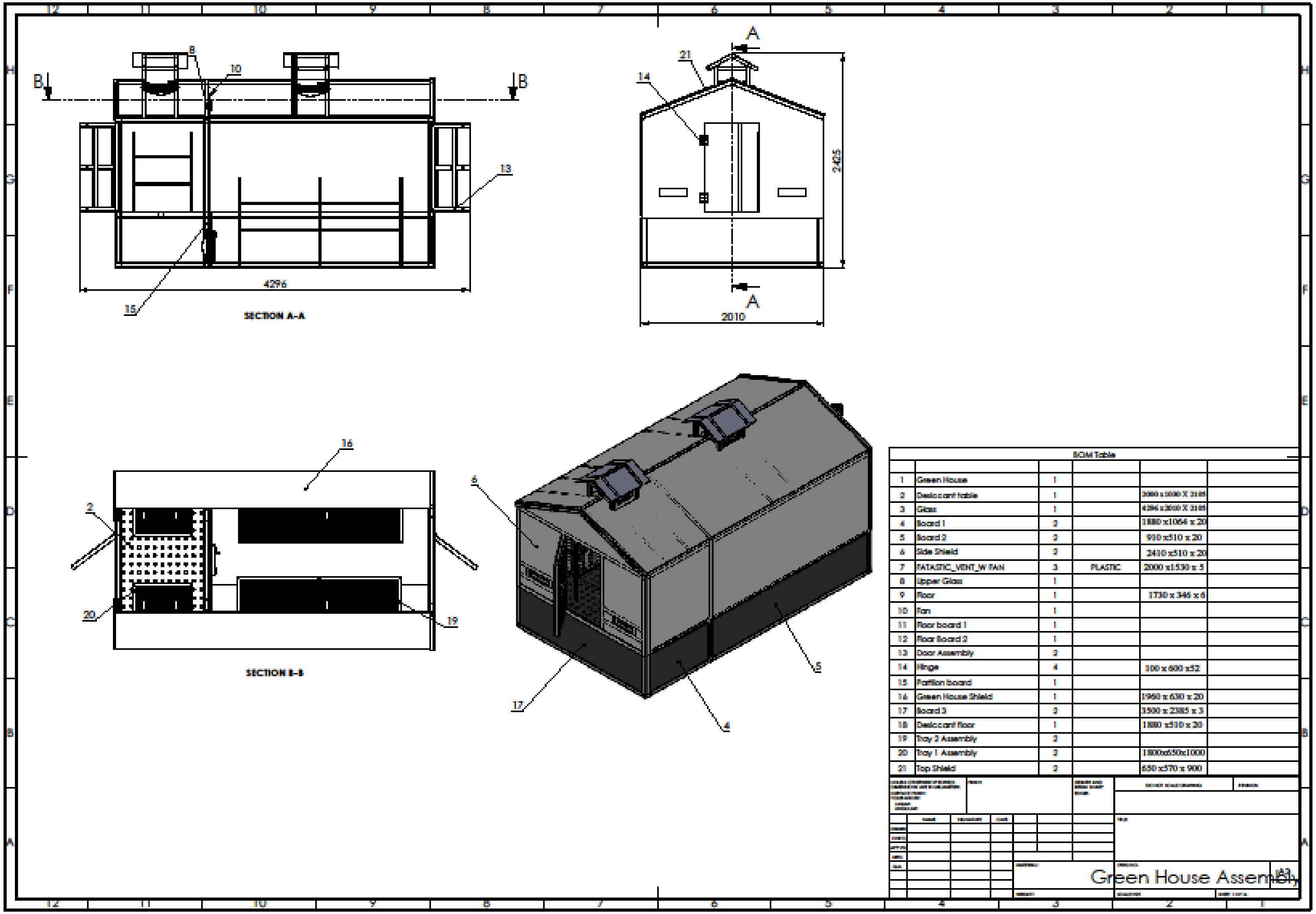
$D.R_{d2}$ = 1.75kg/2hrs = 0.875 kg/h

D.R using desiccant = 5.44/16 = 0.34kg/h

Appendix E:

Engineering Drawing of the Solar Greenhouse dryer with Desiccant Energy Storage

Greenhouse Assembly



BOM Table					
1	Green House	1			
2	Desiccant table	1		2000 x 1000 X 2105	
3	Glass	1		4296 x2010 X 2105	
4	Board 1	2		1880 x1064 x 20	
5	Board 2	2		910 x510 x 20	
6	Side Shield	2		2410 x510 x 20	
7	FATASTIC_VENT_W FAN	3	PLASTIC	2000 x1530 x 5	
8	Upper Glass	1			
9	Floor	1		1730 x 346 x 6	
10	Fan	1			
11	Floor board 1	1			
12	Floor Board 2	1			
13	Door Assembly	2			
14	Hinge	4		100 x 600 x52	
15	Partition board	1			
16	Green House Shield	1		1960 x 630 x 20	
17	Board 3	2		3500 x 2385 x 3	
18	Desiccant floor	1		1880 x510 x 20	
19	Tray 2 Assembly	2			
20	Tray 1 Assembly	2		1800x650x1000	
21	Top Shield	2		650 x570 x 900	

Appendix F: PERFORMANCE OF THE SGD WITH DES DRYING RAW DATA

Performance Data under No Load Conditions

28.11.2019 – 0.19m^3/s and 0.07m^3/s

Time of the day	Greenhouse Temp. Tgr °C	Lower layer Trays Temp. °C	Upper Layer Trays Temp. °C	Ambient Temp. Ta °C	Inlet Air Temp. Tin °C	Solar Rad. (mV)	Solar Radiation, I(W/m²)	Desiccant Temp. Tdes	Desiccant R. H%	Inlet Air Temp. Des. °C	Lower layer Trays des. °C	Upper layer Trays Des.°C	Ambient R. H %	R.H% Greenhouse
9:00	35.29	39.29	40.37	20.58	22.38	5.47	501.10	38.65	38.65	23.69	37.70	37.75	76.35	31.40
9:15	35.51	39.51	42.02	23.16	22.43	6.05	555.02	32.90	32.90	24.30	39.07	38.71	78.69	33.13
9:30	36.05	40.05	42.11	23.66	22.91	5.83	534.25	38.01	25.21	23.72	38.44	38.57	80.72	34.41
9:45	36.93	40.93	42.22	24.57	23.02	7.61	697.57	38.28	20.57	23.01	40.26	39.37	81.40	38.38
10:00	47.55	43.62	46.93	25.10	22.86	7.97	730.93	39.16	25.63	23.06	41.48	40.83	82.36	42.70
10:15	46.62	43.84	46.82	25.06	23.46	6.78	621.88	38.67	22.18	23.07	41.38	42.78	82.84	39.04
10:30	46.42	45.14	47.21	30.04	23.58	8.61	789.01	38.81	31.09	22.43	42.32	43.49	85.69	34.48
10:45	46.64	45.07	44.21	31.70	23.51	8.79	805.57	43.41	32.40	22.42	43.15	43.42	83.51	32.84
11:00	46.95	45.06	48.91	30.02	23.49	9.02	827.26	43.72	37.05	22.82	43.82	44.39	85.36	34.55
11:15	46.42	48.95	49.25	30.42	23.71	8.84	810.51	42.92	26.54	22.48	42.91	44.53	86.15	23.55
11:30	46.40	49.62	48.76	29.89	23.68	9.08	832.57	43.15	26.43	23.01	41.20	44.96	88.04	22.50
11:45	46.64	48.74	49.52	31.20	23.50	9.11	835.42	43.61	30.64	23.66	41.73	44.49	87.38	29.30
12:00	45.99	50.51	47.08	31.19	23.65	9.29	852.00	43.30	24.72	23.44	40.56	45.13	86.61	25.16
12:15	46.09	50.30	47.40	32.22	23.67	9.45	866.20	43.36	23.45	23.61	40.30	45.04	86.29	23.31
12:30	45.83	49.74	47.33	32.13	24.06	9.53	873.69	43.31	24.53	23.77	43.97	45.30	85.84	26.36
12:45	45.46	49.21	47.23	33.09	24.12	9.70	889.13	43.57	25.08	24.21	39.94	45.13	86.22	25.37

13:00	45.01	48.38	47.11	31.97	24.39	9.75	894.22	42.95	30.04	23.89	43.05	44.75	87.42	29.01
13:15	47.72	51.22	44.60	34.85	24.62	10.05	921.24	53.33	29.28	23.63	44.09	46.37	83.37	28.62
13:30	54.83	53.46	53.99	34.25	24.65	10.04	920.75	54.88	32.46	24.25	41.06	45.59	85.08	41.45
13:45	45.80	43.88	42.34	33.90	24.59	6.23	571.13	42.43	35.81	24.87	40.82	38.57	83.70	43.03
14:00	51.73	51.25	48.00	33.93	25.28	9.04	829.16	50.52	36.95	24.61	40.71	43.11	83.40	42.38
14:15	41.99	42.34	43.48	32.70	25.55	5.20	477.19	42.41	38.19	24.80	40.62	39.46	84.04	46.38
14:30	42.39	42.13	44.19	33.30	24.26	4.27	391.50	42.57	42.61	24.84	40.44	39.06	84.01	46.96
14:45	43.00	41.08	44.94	28.91	25.31	3.11	285.00	43.25	47.22	25.27	40.42	39.05	83.95	49.10
15:00	41.75	42.08	43.63	28.79	25.29	6.73	616.67	42.53	46.05	25.24	40.27	39.80	83.51	47.09
15:15	41.52	42.41	43.84	30.51	25.65	3.45	316.73	42.36	47.41	24.98	38.98	39.69	82.55	47.12
15:30	44.13	39.39	47.28	27.18	24.80	2.18	199.45	44.68	49.25	25.70	38.88	39.88	85.21	49.29
15:45	41.13	42.00	43.40	27.52	26.67	5.47	501.48	42.24	46.79	24.92	39.55	40.03	83.59	46.99
16:00	39.08	40.54	40.43	28.49	25.54	2.86	261.76	40.01	49.91	25.62	39.13	40.43	82.84	48.26
16:15	37.25	42.07	38.46	29.20	26.29	5.09	466.70	38.78	46.23	25.50	39.59	40.03	80.04	46.34
16:30	39.93	39.64	41.51	27.80	25.18	1.81	166.34	40.61	49.18	25.99	39.71	39.96	84.14	47.16
16:45	39.21	38.98	40.44	25.98	25.60	2.25	206.51	40.09	48.03	26.04	39.91	40.49	85.20	47.10
17:00	40.23	38.59	41.95	24.71	24.70	1.06	97.09	40.56	49.58	26.13	39.85	40.90	84.96	47.10
17:15	39.38	38.64	40.48	22.85	25.19	1.31	120.29	39.72	46.70	26.09	39.59	39.59	85.59	45.64
17:30	38.83	38.88	39.36	21.92	25.21	1.27	116.84	39.11	45.58	26.00	39.71	39.25	85.85	43.26
17:45	39.12	38.90	39.82	22.28	25.15	1.19	109.24	38.98	39.90	25.89	38.87	38.03	84.85	43.85
18:00	39.77	37.17	39.41	20.65	24.70	0.37	33.83	37.14	47.45	26.08	38.65	37.90	86.13	45.67
Average	**43.10**	**43.85**	**44.49**	**28.53**	**24.40**	**6.05**	**554.74**	**42.00**	**36.53**	**24.41**	**40.68**	**41.51**	**84.13**	**38.60**

10.10.2019 – 0.28m^3/s and 0.17m^3/s

Time of the day	Greenhouse Temp. Tgr °C	Lower layer Trays Temp. °C	Upper Layer Trays Temp. °C	Ambient Temp. Ta °C	Inlet Air Temp. Tin °C	Solar Rad. (mV)	Solar Radiation, I(W/m²)	Desiccant Temp. Tdes	Desiccant R. H%	Inlet Air Temp. Des. °C	Lower layer Trays des.°C	Upper layer Trays Des.°C	Ambient R. H %	R.H% Greenhouse
9:01	37.65	39.98	40.99	18.32	23.21	2.59	237.00	37.94	27.86	22.59	35.88	42.99	87.88	28.57
9:16	37.38	39.05	39.28	21.92	23.28	3.75	343.64	38.93	32.19	23.15	37.74	43.54	77.50	40.08
9:31	38.10	41.92	41.27	22.38	23.31	2.60	237.91	40.14	32.90	23.04	38.11	44.04	81.75	43.66
9:46	40.21	43.43	43.68	21.91	23.46	2.60	237.96	40.57	30.79	22.84	37.58	43.97	92.91	38.54
10:01	39.91	43.53	42.73	20.93	23.66	3.80	348.09	40.28	29.47	22.44	36.56	43.30	98.72	30.20
10:16	39.87	44.89	41.67	23.97	24.01	5.93	543.51	39.43	32.03	23.00	38.66	44.32	87.42	48.80
10:31	41.62	44.14	42.78	25.08	24.04	3.48	318.62	40.99	30.41	22.27	37.37	43.45	97.60	34.04
10:46	42.07	45.72	40.52	25.58	24.35	6.00	549.72	39.91	28.10	23.41	38.49	44.13	79.79	26.48
11:01	42.74	47.60	41.96	28.90	24.66	6.87	629.80	40.81	38.98	24.58	42.04	45.77	76.25	48.21
11:16	45.32	47.42	45.48	25.61	24.60	2.63	241.01	41.40	31.05	24.00	38.00	44.51	83.16	36.41
11:31	43.85	47.90	43.92	27.83	24.84	4.34	397.50	38.76	37.76	25.04	41.42	46.05	79.73	49.42
11:46	45.03	48.58	46.90	25.96	24.93	2.60	238.61	41.24	33.65	24.25	38.93	45.27	79.60	39.09
12:01	43.83	48.30	44.42	27.32	25.15	4.05	371.47	41.60	30.82	24.33	38.43	45.19	81.07	35.44
12:16	43.40	49.25	43.35	28.93	25.21	5.17	474.23	41.31	10.28	24.22	36.11	44.40	90.81	28.45
12:31	45.86	49.71	50.63	36.77	25.66	9.50	871.22	45.03	18.49	26.96	46.60	48.47	83.97	34.36
12:46	42.39	48.78	43.24	34.23	25.67	7.73	708.33	42.92	22.52	26.62	39.86	47.82	90.08	22.65
13:01	42.64	48.47	43.86	33.75	26.09	6.39	585.64	40.43	24.69	26.70	40.30	47.51	84.30	25.54
13:16	43.36	48.24	45.21	35.19	26.30	5.54	508.09	40.63	27.10	24.30	39.76	46.08	87.64	31.41
13:31	43.01	48.11	44.94	34.04	26.60	7.96	729.74	40.92	25.71	24.60	40.13	46.24	69.17	33.30

13:46	42.81	48.12	44.36	31.12	26.82	8.47	776.79	41.19	34.57	25.24	41.31	46.95	72.86	40.47
14:01	44.76	46.22	48.29	34.23	26.77	6.21	569.63	41.63	32.22	24.99	35.60	46.68	69.35	22.19
14:16	41.60	47.74	50.55	35.22	27.44	9.48	869.44	39.64	38.95	25.50	39.07	47.01	67.58	40.16
14:31	43.18	46.85	46.39	34.90	27.57	9.12	836.49	40.54	42.00	25.31	39.39	45.54	68.68	38.14
14:46	43.59	46.49	47.45	33.37	27.47	6.25	573.21	40.75	46.07	25.72	42.63	43.75	71.04	44.20
15:01	45.68	45.69	42.33	33.43	27.22	2.97	272.53	42.54	45.78	26.24	41.98	42.54	79.39	42.60
15:16	45.73	44.84	42.40	29.79	27.13	4.18	383.47	42.39	41.99	25.40	39.61	42.39	66.43	32.53
15:31	43.82	46.18	47.78	32.82	27.74	5.97	546.98	41.00	50.24	24.02	40.86	42.00	77.12	42.56
15:46	42.07	46.37	48.68	30.05	26.75	1.79	164.27	39.76	45.86	23.91	43.01	41.76	83.65	41.29
16:01	44.19	46.23	46.19	26.71	26.71	3.06	280.48	40.69	46.54	23.97	41.66	40.69	85.37	43.75
16:16	43.30	45.88	45.27	24.96	26.74	2.54	232.43	42.08	42.39	23.34	36.98	38.08	97.22	34.46
16:31	43.58	42.29	44.98	25.33	27.37	2.30	211.09	41.32	40.07	23.30	36.98	35.32	96.02	33.76
16:46	43.31	41.82	44.84	22.94	26.85	1.56	143.45	41.20	40.70	23.49	35.50	33.20	93.18	36.03
17:01	38.53	37.46	39.78	20.87	26.80	1.34	122.56	40.59	40.46	23.63	33.62	30.59	87.95	36.27
17:16	37.29	36.04	38.37	19.37	26.73	1.16	106.29	39.26	37.25	23.84	32.16	30.26	89.33	33.29
17:31	37.24	35.77	38.26	19.07	26.40	0.17	15.38	38.16	38.62	23.79	29.42	29.16	88.09	36.38
17:46	36.09	34.35	37.11	18.17	26.28	0.11	10.35	38.01	34.71	23.60	30.73	29.01	90.11	31.91
18:01	35.82	34.36	36.51	16.36	26.04	0.10	9.29	37.73	34.44	23.42	29.97	28.73	89.87	33.30
Average	**41.91**	**44.53**	**43.69**	**27.22**	**25.78**	**4.33**	**397.19**	**40.59**	**34.53**	**24.24**	**38.17**	**41.91**	**83.31**	**36.16**

27.11.2019 – 0.45m^3/s and 0.36m^3/s

Time of the day	Greenhouse Temp. Tgr °C	Lower layer Trays Temp. °C	Upper Layer Trays Temp. °C	Ambient Temp. Ta °C	Inlet Air Temp. Tin °C	Solar Rad. (mV)	Solar Radiation, I(W/m²)	Desiccant Temp. Tdes	Desiccant R. H%	Inlet Air Temp. Des. °C	Lower layer Trays des.°C	Upper layer Trays Des.°C	Ambient R. H %	R.H% Greenhouse
9:00	37.95	37.10	37.80	18.83	21.72	5.65	518.06	37.82	34.64	23.82	38.59	39.04	75.12	33.61
9:15	38.60	36.81	39.03	18.86	22.13	6.27	575.10	38.03	39.78	23.88	38.74	42.61	80.58	36.11
9:30	38.52	35.29	39.62	19.13	22.26	6.88	630.46	38.33	36.89	23.28	39.01	39.65	80.50	40.43
9:45	38.11	34.86	39.69	19.06	23.93	7.32	671.45	38.43	39.80	23.04	39.36	39.51	83.11	41.21
10:00	37.73	34.76	39.45	20.16	22.87	6.07	556.73	38.49	36.87	22.88	39.27	39.71	84.28	39.54
10:15	37.49	34.58	39.50	19.85	22.64	6.52	597.76	39.15	37.69	22.66	39.65	40.28	84.92	38.99
10:30	39.93	35.79	38.14	21.94	24.37	8.77	804.26	42.48	33.92	21.84	39.47	41.85	83.70	33.11
10:45	40.26	36.49	38.22	21.79	23.01	6.37	583.94	42.37	34.88	21.77	40.01	39.41	85.16	28.79
11:00	40.08	40.02	41.57	25.10	23.29	8.89	814.91	43.36	28.23	22.30	39.58	41.66	84.01	22.89
11:15	42.42	39.73	41.54	25.49	23.24	7.43	680.89	43.39	27.88	22.49	42.31	42.41	84.07	22.10
11:30	42.23	45.25	40.84	26.38	23.31	9.25	848.25	42.71	28.11	22.95	42.11	43.67	85.25	24.40
11:45	42.07	45.99	49.81	28.17	24.02	9.19	842.98	42.73	29.64	23.14	40.65	42.31	85.27	23.59
12:00	43.93	48.12	49.20	32.16	23.14	9.37	858.86	43.45	28.66	22.89	42.29	44.62	86.93	24.43
12:15	43.59	48.05	48.79	35.13	23.34	9.49	870.07	39.53	27.82	23.70	42.96	46.54	87.34	24.20
12:30	43.62	47.36	49.33	33.08	23.48	9.20	843.49	39.34	36.19	23.30	40.78	45.68	85.76	24.98
12:45	43.42	45.30	49.27	34.28	23.83	7.88	722.48	39.94	40.56	23.54	39.01	41.05	84.88	31.58
13:00	43.15	44.40	47.28	34.61	23.91	8.32	763.22	39.49	48.46	23.16	42.12	42.55	84.50	36.38
13:15	43.26	43.31	47.89	34.68	23.84	7.05	646.03	39.02	47.43	23.39	40.89	39.93	83.98	39.70
13:30	42.93	42.70	47.63	34.07	24.45	7.45	682.87	39.24	47.77	23.72	42.13	40.86	85.35	41.76

13:45	43.78	40.93	42.64	33.63	24.20	5.67	519.98	39.92	32.61	24.16	41.38	42.67	84.69	45.41
14:00	42.55	41.77	40.76	33.25	24.72	6.81	624.18	39.06	30.23	23.89	40.89	42.81	84.73	43.53
14:15	43.33	40.47	42.57	34.20	24.36	5.60	513.47	38.91	39.09	24.08	40.72	39.63	83.08	46.69
14:30	42.47	41.26	44.36	33.22	25.06	7.90	724.42	38.70	43.44	24.06	40.29	41.58	84.60	45.52
14:45	41.54	38.99	42.05	33.12	24.36	5.37	492.48	38.54	48.96	24.92	40.17	40.09	84.90	49.20
15:00	41.66	38.21	42.23	31.89	24.45	3.72	341.04	38.82	47.85	24.99	40.14	40.21	84.29	48.76
15:15	40.36	38.34	40.80	30.38	25.19	3.77	345.21	38.84	45.09	24.85	40.07	40.33	83.83	46.98
15:30	42.02	36.93	42.63	29.99	24.43	2.49	227.86	39.06	49.33	25.09	39.93	40.30	84.20	47.65
15:45	41.41	37.39	41.42	28.89	24.74	2.63	241.57	39.02	46.69	24.96	39.90	40.21	84.98	46.53
16:00	41.46	36.89	41.47	28.09	24.80	2.52	230.97	39.22	46.54	25.01	39.71	40.77	85.07	46.39
16:15	39.82	38.93	40.41	29.63	25.60	4.45	408.15	39.07	46.02	24.98	39.35	40.77	82.61	44.65
16:30	39.38	37.05	39.35	26.06	24.62	2.33	213.57	39.06	49.15	25.24	39.53	40.52	82.54	46.42
16:45	40.31	35.59	40.61	24.25	24.52	1.79	164.53	39.15	48.63	25.32	39.40	40.69	84.82	47.55
17:00	40.14	35.40	40.19	22.77	24.46	1.33	122.34	38.96	48.29	25.37	39.20	40.96	85.13	46.51
17:15	39.80	34.88	39.78	21.05	24.31	0.95	86.84	38.64	48.29	25.40	38.86	39.75	85.80	45.58
17:30	39.51	34.30	39.38	19.86	24.21	0.71	65.44	38.76	47.01	25.51	38.72	39.62	86.16	44.74
17:45	39.37	33.80	39.08	18.58	23.99	0.50	45.67	38.52	46.40	25.70	38.70	39.33	87.27	44.48
18:00	39.36	33.50	39.02	17.77	23.93	0.23	20.96	38.34	47.31	25.72	38.59	38.76	87.44	44.30
Average	**41.02**	**39.20**	**42.25**	**27.01**	**23.91**	**5.57**	**510.82**	**39.67**	**40.44**	**23.97**	**40.16**	**41.21**	**84.35**	**38.88**

Performance Data under Load Conditions

16.10.2019 – Day 1 Drying

Time of the Day (Hrs)	Green house Temp. (Tgr)	Amb. Temp. (Ta)	Inlet air (Tin)	Solar Rad. (mV)	Solar Radiation, I (W/m²)	Amb. R.H (%)	Exit R.H (%)	Exit Air Temp. (°C)	Exit Green house R.H%	Green house R.H %	Amb. R.H%	Desiccant Temp. Tdes °C	Inlet Air Temp. Des. °C	Exit Des. Temp. °C	Exit Des. R.H %	Desiccant R.H%
9:00	39.97	21.91	22.84	6.44	590.45	52.36	70.72	34.67	70.72	36.13	52.36	37.28	21.60	13.18	50.55	31.08
9:15	35.24	23.39	23.17	3.58	327.82	70.22	68.81	36.89	68.81	57.76	70.22	38.41	23.16	21.61	90.52	43.28
9:30	41.70	21.34	23.38	6.95	636.88	41.50	64.23	37.31	64.23	29.70	41.50	37.90	22.37	13.95	54.27	30.73
9:45	43.41	23.50	24.20	7.54	691.68	42.55	51.28	36.59	51.28	26.03	42.55	37.85	22.22	14.74	60.79	30.69
10:00	42.65	24.82	24.59	7.55	692.46	47.85	46.84	30.59	46.84	30.73	47.85	38.21	22.40	17.35	72.00	35.03
10:15	44.51	24.96	25.28	8.43	772.60	44.70	39.00	36.55	39.00	19.88	44.70	38.17	21.71	16.72	72.38	32.28
10:30	44.63	26.66	25.69	8.59	787.29	48.10	38.01	37.48	38.01	19.99	48.10	40.61	22.04	20.06	99.21	33.20
10:45	44.99	25.86	26.37	8.85	811.43	43.79	45.04	39.02	45.04	20.00	43.79	40.87	22.31	23.48	89.64	33.77
11:00	44.92	30.09	26.25	8.94	819.85	58.66	53.64	32.90	53.64	21.19	58.66	41.82	22.71	24.12	92.77	34.55
11:15	44.89	26.81	27.29	8.84	810.52	45.58	58.93	27.08	58.93	21.03	45.58	41.39	23.00	23.38	85.88	34.78
11:30	43.97	28.51	27.72	8.87	813.03	50.18	65.23	35.40	65.23	24.22	50.18	42.20	23.56	23.98	88.37	35.20
11:45	44.11	29.96	27.40	8.81	807.28	56.19	69.83	34.65	69.83	26.27	56.19	42.15	24.23	24.22	85.02	33.49
12:00	44.65	29.30	28.18	8.96	821.42	56.31	76.15	33.81	76.15	28.10	56.31	42.10	24.46	25.21	82.22	33.43
12:15	45.04	30.47	28.17	9.16	839.87	60.84	80.69	33.25	80.69	29.95	60.84	42.48	24.51	25.71	82.68	34.14
12:30	45.26	31.50	28.55	9.44	865.84	64.82	87.81	32.03	87.81	31.88	64.82	42.07	24.73	26.33	80.02	36.37
12:45	45.24	30.93	28.48	9.48	869.34	64.95	89.22	33.25	89.22	34.42	64.95	41.87	25.10	26.67	82.31	39.95
13:00	42.73	31.85	28.43	7.57	693.70	73.06	90.26	38.97	90.26	53.27	73.06	40.23	25.62	28.24	86.17	37.74
13:15	45.09	33.85	29.07	10.26	940.67	68.08	95.25	31.63	95.25	37.45	68.08	40.35	25.42	27.15	87.45	32.40

13:30	44.31	31.61	29.59	7.77	712.32	69.12	97.18	23.68	97.18	46.95	69.12	41.58	25.65	28.09	86.30	35.68
13:45	43.58	33.37	29.72	7.49	686.26	75.31	99.87	27.46	99.87	51.96	75.31	41.48	25.89	28.35	83.76	36.90
14:00	43.74	33.27	30.43	7.96	729.40	79.79	94.74	24.94	94.74	52.90	79.79	41.13	26.30	28.92	82.71	38.76
14:15	43.61	33.84	30.51	8.88	813.91	84.14	95.65	27.49	95.65	31.41	84.14	41.17	26.22	29.15	82.17	39.80
14:30	41.71	33.39	30.49	6.65	609.58	89.22	99.16	21.40	99.16	39.36	89.22	41.37	26.53	29.96	78.45	44.27
14:45	40.17	30.71	29.97	5.04	462.32	85.22	90.97	26.51	90.97	40.74	85.22	41.64	27.16	30.09	69.77	48.37
15:00	38.07	30.27	29.49	1.79	164.19	95.27	88.11	27.60	88.11	49.59	95.27	41.80	27.88	30.88	68.79	51.82
15:15	38.52	30.08	29.72	5.46	500.97	94.01	97.59	26.37	97.59	45.01	94.01	41.55	27.19	29.48	65.09	48.61
15:30	40.95	31.82	29.84	7.24	663.41	96.12	95.11	26.01	95.11	37.91	91.12	41.63	26.13	29.16	66.51	46.04
15:45	39.38	32.60	30.30	4.61	422.37	88.91	85.49	27.48	85.49	47.42	93.91	39.95	26.66	30.64	66.43	50.50
16:00	37.87	30.41	29.53	2.99	273.90	84.20	83.36	27.84	83.36	48.79	89.20	39.79	27.52	30.68	64.24	52.19
16:15	38.32	30.40	30.14	4.06	371.86	90.57	72.44	27.38	72.44	39.93	85.57	39.50	26.99	29.68	62.93	48.57
16:30	36.90	29.85	29.48	2.08	190.58	88.91	79.13	27.96	79.13	48.01	83.91	39.19	27.95	30.95	64.29	52.06
16:45	34.79	26.59	28.90	1.10	101.16	75.03	84.48	27.91	84.48	52.54	80.03	38.79	28.95	30.57	63.83	52.25
17:00	33.89	25.26	28.50	1.40	128.80	98.94	86.40	27.75	86.40	50.96	98.94	38.72	29.00	30.29	64.49	51.60
17:15	34.73	25.51	28.72	1.34	122.41	78.76	87.50	27.21	87.50	44.25	93.76	38.41	28.43	29.79	66.82	49.72
17:30	32.97	23.93	27.65	0.79	72.11	96.35	88.30	27.74	88.30	50.85	96.35	38.57	29.16	30.25	63.50	51.80
17:45	32.99	23.27	27.70	0.57	52.68	97.77	87.78	27.34	87.78	45.02	97.77	38.42	28.85	29.56	65.52	48.59
18:00	31.65	22.31	26.97	0.20	18.20	97.20	89.86	27.64	89.86	48.97	97.20	38.28	28.71	29.90	62.25	52.52
Average	**40.84**	**28.49**	**27.91**	**6.10**	**559.15**	**71.75**	**78.22**	**30.53**	**78.22**	**38.39**	**72.15**	**40.24**	**25.47**	**26.01**	**74.87**	**41.14**

Night Drying

Time of the Day (Hrs)	Green house Temp. (Tgr)	Amb. Temp. (Ta)	Inlet air (Tin)	Solar Rad. (mV)	Solar Rad. I (W/m2)	Exit Greenhouse Temp. °C	Exit Greenhouse R.H%	Greenhouse R.H %	Amb. R.H%	Desiccant Temp. Tdes °C	Inlet Air Temp. Des. °C	Exit Des. Temp. °C	Exit Des. R.H %	Desiccant R.H%
18:15	26.70	21.26	26.89	0.06	5.21	28.51	89.05	77.48	90.00	31.34	28.62	29.48	60.58	62.18
18:30	26.41	20.42	26.58	0.00	0.18	27.89	91.43	76.96	89.19	31.31	28.63	29.29	60.88	61.20
18:45	26.15	19.85	26.38	0.00	-0.44	27.54	92.71	76.45	88.08	31.29	28.52	29.20	60.73	60.97
19:00	26.01	19.57	26.20	-0.01	-0.79	27.40	91.13	74.49	90.51	31.07	28.00	28.68	61.08	59.24
19:15	25.92	19.29	26.06	-0.01	-0.86	27.10	92.51	74.18	91.21	30.98	28.15	28.58	60.89	59.26
19:30	25.87	18.98	26.03	-0.01	-1.02	27.16	91.64	73.65	91.97	30.92	28.11	28.59	61.01	59.49
19:45	25.86	18.76	25.99	-0.01	-1.17	26.92	91.86	73.08	91.77	30.86	28.09	28.54	60.89	59.56
20:00	25.72	18.56	25.97	-0.01	-0.50	26.91	91.41	73.14	91.45	30.86	28.05	28.57	60.94	59.64
20:15	25.59	18.43	25.89	-0.01	-0.74	26.82	91.51	73.15	91.93	30.88	28.01	28.55	60.91	59.51
20:30	25.54	18.48	25.81	-0.01	-0.80	26.69	91.72	72.95	92.49	30.64	27.63	28.17	60.74	58.82
20:45	25.58	18.50	25.77	-0.01	-0.68	26.40	92.28	72.40	92.73	30.54	27.41	27.93	60.35	58.34
21:00	25.26	18.24	25.61	-0.01	-0.64	26.46	91.79	72.85	92.35	30.56	27.43	27.97	60.20	58.52
21:15	25.34	18.14	25.50	-0.01	-0.69	26.06	92.87	72.01	91.59	30.51	27.44	27.86	59.90	58.40
21:30	25.23	18.40	25.41	-0.01	-0.47	25.83	93.49	71.77	94.19	30.53	27.51	27.81	59.72	58.23
21:45	25.12	18.59	25.36	-0.01	-0.59	25.66	93.90	71.61	95.76	30.52	27.57	27.82	59.73	58.31
22:00	24.82	18.25	25.29	-0.01	-0.90	25.99	92.10	72.31	94.53	30.44	27.55	27.71	59.90	58.00
22:15	24.66	18.22	25.20	-0.01	-0.78	26.01	91.32	72.33	95.78	30.24	27.20	27.45	60.07	57.51
22:30	24.56	18.36	25.14	-0.01	-1.01	25.91	91.02	72.31	96.96	30.23	27.16	27.52	60.35	57.71

22:45	24.67	18.14	25.22	-0.01	-0.60	25.93	91.04	72.38	95.36	30.20	27.09	27.42	60.08	57.53
23:00	24.61	18.07	25.13	0.00	-0.41	25.79	92.21	72.92	94.76	30.20	27.07	27.41	60.17	57.43
23:15	24.63	18.17	25.16	-0.01	-0.56	25.69	92.18	72.72	94.88	30.19	27.02	27.38	60.05	57.38
23:30	24.47	18.04	24.99	-0.01	-0.55	25.65	92.24	72.64	94.62	30.21	26.91	27.38	59.23	57.82
23:45	24.36	17.94	24.86	0.00	-0.33	25.40	92.42	72.41	94.46	30.12	26.71	27.14	59.46	56.87
0:00	24.09	18.37	24.91	-0.01	-0.67	25.40	91.98	72.35	98.93	29.94	26.62	26.93	60.57	56.03
0:15	23.87	18.10	24.81	-0.01	-1.04	25.39	91.01	71.98	97.36	29.92	26.65	26.91	60.12	56.24
0:30	23.82	17.68	24.61	0.00	-0.40	25.51	89.87	71.83	95.61	29.92	26.70	26.98	60.57	56.34
0:45	23.70	17.62	24.56	-0.01	-0.62	25.39	89.69	71.99	95.93	29.89	26.68	26.98	61.01	56.18
1:00	23.71	18.00	24.36	-0.01	-0.74	25.00	91.27	71.81	99.11	29.89	26.64	26.95	60.98	56.04
1:15	23.70	17.85	24.37	-0.01	-0.90	24.93	90.86	71.46	98.01	29.80	26.41	26.78	60.90	55.66
1:30	23.65	17.73	24.37	-0.01	-0.72	24.75	91.30	71.49	96.21	29.59	26.00	26.31	60.41	54.62
1:45	23.77	17.50	24.18	0.00	-0.26	24.54	92.06	71.20	95.21	29.59	25.95	26.14	59.56	54.32
2:00	23.78	17.50	24.39	-0.01	-0.57	24.40	92.92	71.06	95.92	29.60	25.86	26.13	59.05	54.51
2:15	23.67	17.62	24.45	0.00	0.16	24.46	92.64	71.48	96.56	29.63	25.86	26.20	59.30	54.61
2:30	23.78	17.58	24.38	0.00	-0.30	24.40	92.74	71.55	95.83	29.64	25.82	26.16	59.40	54.31
2:45	23.67	17.59	24.41	0.00	-0.37	24.48	92.08	71.41	95.75	29.67	25.83	26.23	59.61	54.38
3:00	23.59	17.58	24.25	0.00	-0.06	24.39	92.16	71.19	95.71	29.67	25.79	26.23	59.42	54.51
3:15	23.40	17.50	24.26	0.00	-0.19	24.72	90.70	71.73	96.87	29.73	25.91	26.42	60.16	54.73
3:30	23.41	17.65	23.86	0.00	-0.31	24.70	90.36	71.36	98.12	29.66	25.84	26.43	60.46	54.87
3:45	23.50	17.72	23.84	0.00	-0.26	24.51	91.25	71.42	98.42	29.64	25.83	26.37	60.37	54.72
4:00	23.41	17.33	23.96	0.00	-0.01	24.50	91.33	71.86	96.00	29.34	25.31	25.79	59.72	53.62
4:15	23.06	17.47	23.91	-0.01	-0.56	24.43	91.25	71.54	99.55	29.36	25.41	25.95	59.76	54.24
4:30	23.12	17.25	23.96	-0.01	-0.68	24.41	90.56	71.42	97.14	29.32	25.37	25.94	60.17	54.10

4:45	23.19	17.14	23.85	0.00	-0.26	24.16	91.23	71.19	95.91	29.32	25.39	25.78	60.20	53.36
5:00	23.14	17.20	23.71	0.00	-0.42	24.02	91.79	71.14	97.45	29.34	25.39	25.74	60.29	53.08
5:15	23.21	17.04	23.56	-0.01	-0.50	23.85	92.38	70.85	96.55	29.33	25.31	25.68	59.93	53.03
5:30	23.09	16.95	23.48	0.00	0.05	23.75	93.23	71.09	96.67	29.33	25.29	25.67	59.77	53.03
5:45	23.04	16.87	23.37	0.00	-0.18	23.72	92.90	70.92	96.57	29.06	24.78	25.19	59.60	51.98
6:00	22.94	16.77	23.42	0.00	-0.21	23.62	93.00	71.24	96.46	29.09	24.77	25.17	59.27	51.99
6:15	22.75	16.81	23.22	0.01	0.89	23.58	92.49	71.17	97.46	29.09	24.78	25.21	59.25	52.20
6:30	22.51	16.72	22.85	0.01	1.01	23.51	91.82	71.02	98.04	29.13	24.89	25.31	59.46	52.38
6:45	22.47	16.85	22.72	0.07	6.57	23.35	91.49	70.67	95.53	28.91	24.50	24.92	59.49	51.43
7:00	22.48	16.89	22.70	0.21	18.91	23.01	91.61	69.97	94.55	28.80	24.23	24.61	59.41	50.47
7:15	22.34	16.83	22.62	0.21	19.25	22.83	92.21	70.08	94.23	28.80	24.24	24.60	59.28	50.47
7:30	22.41	16.92	22.53	0.27	25.12	22.84	92.01	69.82	94.15	28.83	24.34	24.58	59.33	50.25
7:45	23.06	17.57	22.66	0.72	65.70	22.36	92.63	67.50	93.38	28.74	24.15	24.11	58.20	49.12
8:00	23.87	20.93	22.80	1.13	103.53	21.82	94.09	65.70	91.86	28.72	23.88	23.74	59.12	47.03
8:15	24.05	21.07	23.46	1.17	107.25	22.15	91.34	65.12	90.00	28.81	23.90	23.68	58.21	46.88
8:30	24.59	21.41	23.38	1.40	128.50	21.93	94.31	65.43	83.87	28.86	23.87	23.54	57.30	46.57
8:45	25.75	21.06	23.72	2.10	192.24	21.57	93.15	64.28	76.52	28.80	23.63	22.80	55.67	44.43
Average	**24.18**	**18.16**	**24.51**	**0.12**	**11.01**	**24.95**	**91.89**	**71.59**	**94.37**	**29.85**	**26.23**	**26.59**	**59.88**	**55.15**

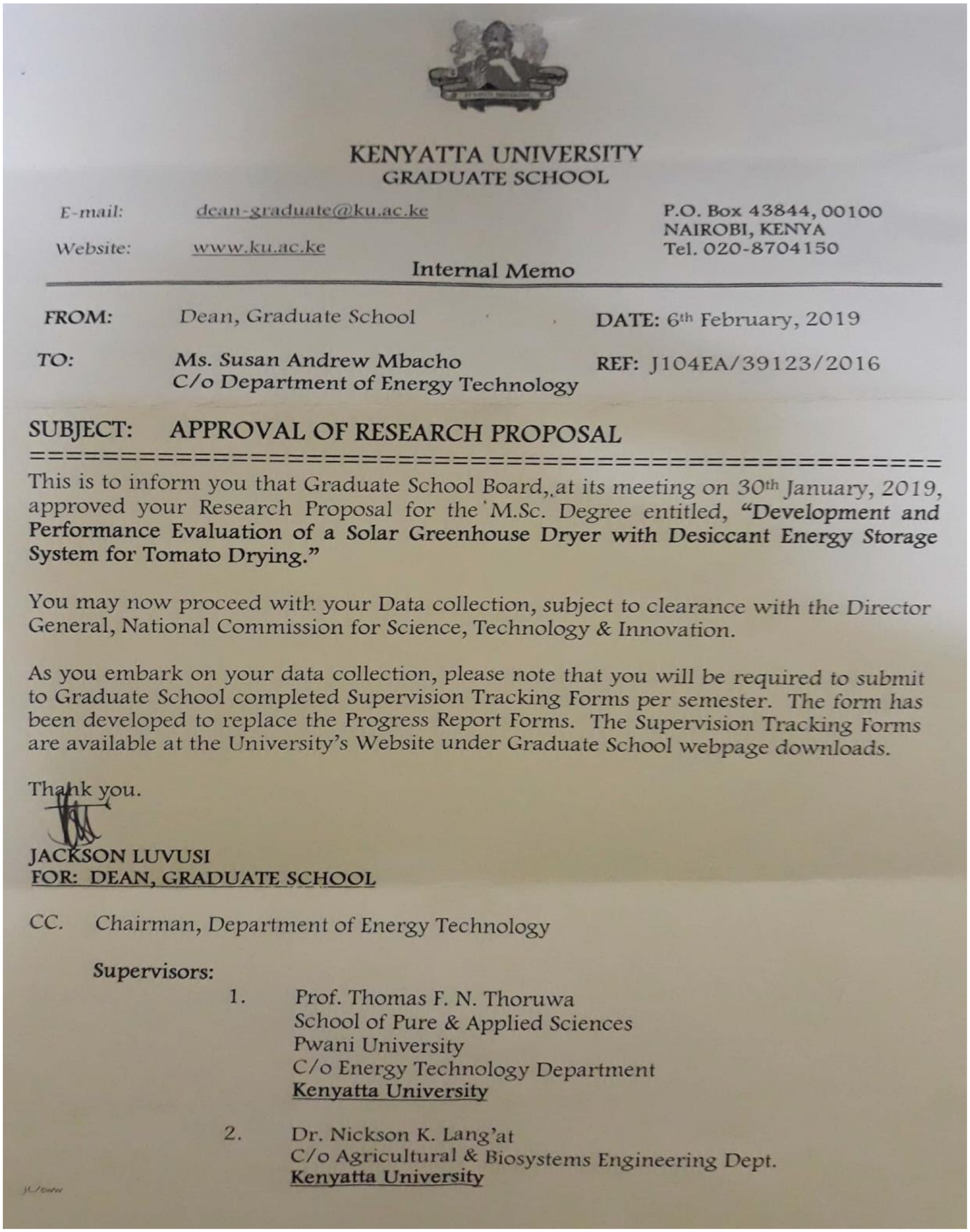
17.10.2019 – Day 2 Drying

Time of the Day (Hrs)	Green house Temp. (Tgr)	Amb. Temp. (Ta)	Inlet air (Tin)	Solar Rad. (mV)	Solar Radiation, I (W/m²)	Amb. R.H%	Exit R.H (%)	Exit Green house Temp. (°C)	Exit Green house R.H%	Green house R.H %	Amb. R.H%	Desiccant Temp. Tdes (°C)	Inlet Air Temp. Des. (°C)	Exit Desiccant air Temp. (°C)	Exit Des. R.H%	Desiccant R.H%
9:00	36.93	24.48	23.65	3.34	306.14	68.96	75.04	34.73	75.04	32.50	68.96	35.22	23.32	20.95	84.75	42.55
9:15	39.41	24.65	24.19	4.35	399.23	58.94	89.21	34.96	89.21	27.32	58.94	36.18	23.27	19.49	78.03	39.94
9:30	41.41	25.82	24.58	5.54	507.97	55.68	76.99	35.13	76.99	21.16	55.68	35.04	23.09	18.38	73.78	37.93
9:45	42.46	28.26	25.26	4.90	449.45	51.28	70.54	35.49	70.54	21.32	51.28	38.14	22.99	18.59	75.22	38.37
10:00	45.37	32.73	25.92	7.37	675.63	43.70	61.53	44.64	61.53	33.72	43.70	39.29	22.45	16.58	66.75	35.47
10:15	49.17	34.53	26.39	10.42	955.08	37.61	46.99	39.26	46.99	21.54	37.61	43.26	21.81	15.37	63.49	32.28
10:30	44.87	28.73	26.43	5.04	461.82	56.28	58.24	36.81	58.24	26.87	56.28	42.40	23.68	23.64	85.50	34.16
10:45	39.88	22.19	26.25	3.03	277.82	68.09	77.57	35.43	77.57	27.00	68.09	38.71	24.81	26.67	87.71	42.93
11:00	39.47	25.47	26.16	2.36	216.29	70.06	89.14	31.49	89.14	28.75	70.06	38.74	25.14	26.71	88.25	42.57
11:15	38.22	25.96	25.72	2.06	188.85	75.29	91.92	36.45	91.92	30.60	75.29	37.45	25.40	26.61	85.12	43.10
11:30	37.57	27.48	26.01	1.75	160.71	75.58	91.81	33.22	91.81	30.42	75.58	35.26	25.70	26.67	85.46	42.55
11:45	37.99	29.50	25.72	2.77	253.65	88.59	90.86	36.16	90.86	23.22	88.59	33.83	25.47	25.80	84.27	39.73
12:00	38.68	27.79	26.06	3.54	324.93	84.01	91.67	35.74	91.67	18.16	84.01	36.08	24.98	24.79	81.90	36.89
12:15	38.90	26.88	26.11	3.32	304.84	82.58	93.92	35.85	93.92	20.33	82.58	42.89	24.61	24.53	79.05	37.95
12:30	42.72	27.00	27.21	7.58	695.06	61.63	90.55	33.84	90.55	19.43	61.63	42.07	23.64	22.07	79.56	29.07
12:45	44.42	26.17	27.54	7.02	643.90	62.54	95.41	34.29	95.41	20.31	62.54	42.68	24.20	23.60	88.19	31.39
13:00	45.40	30.66	28.27	5.84	535.33	65.09	95.49	34.78	95.49	25.24	65.09	42.70	24.09	24.90	92.69	33.61
13:15	46.37	32.38	28.45	8.52	781.50	67.20	94.94	34.36	94.94	20.76	67.20	41.67	23.91	24.91	91.94	33.46
13:30	46.57	29.99	29.18	8.62	789.99	69.81	94.05	34.68	94.05	24.49	69.81	41.53	24.50	25.74	95.60	34.06

13:45	45.21	29.18	29.49	6.12	561.08	58.34	88.73	35.91	88.73	34.52	58.34	39.85	24.81	26.99	96.31	37.85
14:00	44.46	29.30	28.91	5.39	494.25	61.12	88.79	36.13	88.79	36.91	61.12	34.00	24.99	26.69	90.13	39.26
14:15	42.95	29.89	28.51	3.92	358.95	67.27	89.30	36.68	89.30	43.71	67.27	40.06	25.80	27.54	88.25	32.62
14:30	41.55	30.25	28.39	3.95	362.08	74.80	92.19	36.76	92.19	46.03	74.80	41.44	26.13	27.66	82.20	35.81
14:45	44.47	30.23	29.49	6.57	602.42	97.24	94.06	35.17	94.06	30.06	97.24	41.18	25.15	26.70	83.65	30.83
15:00	43.71	29.68	29.80	4.58	420.26	87.48	82.36	36.94	82.36	37.77	87.48	40.88	25.68	28.18	85.55	34.62
15:15	40.35	25.24	28.26	2.27	207.70	97.26	85.88	37.11	85.88	32.08	97.26	36.74	27.36	29.72	86.45	39.69
15:30	38.48	27.42	27.61	1.83	168.12	90.38	80.13	37.61	80.13	33.84	90.38	34.43	27.96	29.37	82.04	40.58
15:45	38.61	29.61	27.51	2.39	219.35	86.97	83.99	37.49	83.99	49.34	86.97	31.46	27.72	28.36	81.97	47.21
16:00	40.51	29.04	28.18	4.78	438.16	88.22	78.03	38.27	78.03	37.76	88.22	38.93	26.22	27.45	83.80	42.90
16:15	39.49	25.65	27.66	3.35	307.16	80.04	72.57	38.00	72.57	42.39	80.04	40.11	26.77	29.02	84.23	47.28
16:30	39.95	24.94	27.93	4.18	382.80	94.65	63.83	32.35	63.83	37.07	94.65	40.20	26.26	28.40	81.00	45.32
16:45	39.61	24.43	28.23	3.64	333.47	88.97	67.29	36.05	67.29	39.85	88.97	40.96	27.07	28.70	81.54	45.60
17:00	38.96	24.35	28.08	2.61	239.13	93.04	66.13	28.99	66.13	41.85	93.04	39.91	27.07	29.22	86.08	46.89
17:15	39.30	23.73	28.35	2.20	201.72	91.93	65.05	35.23	65.05	40.40	91.93	34.99	26.58	28.70	88.36	46.75
17:30	37.86	23.61	27.20	1.06	97.36	95.92	75.90	34.64	75.90	41.60	95.92	33.93	27.70	29.96	83.38	52.76
17:45	36.41	20.98	26.62	0.46	42.43	86.11	81.97	31.26	81.97	44.90	86.11	32.52	28.13	29.63	82.50	51.68
Average	**41.18**	**27.75**	**27.15**	**4.24**	**389.01**	**74.48**	**81.14**	**35.57**	**81.14**	**31.87**	**74.48**	**38.25**	**25.29**	**25.65**	**83.88**	**39.88**

APPENDIX G: APPROVAL AND PERMITS

G_1: Approval Letter from Graduate School



KENYATTA UNIVERSITY
GRADUATE SCHOOL

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P.O. Box 43844, 00100
NAIROBI, KENYA
Tel. 020-8704150

Internal Memo

FROM: Dean, Graduate School — DATE: 6th February, 2019

TO: Ms. Susan Andrew Mbacho
C/o Department of Energy Technology — REF: J104EA/39123/2016

SUBJECT: APPROVAL OF RESEARCH PROPOSAL

This is to inform you that Graduate School Board, at its meeting on 30th January, 2019, approved your Research Proposal for the M.Sc. Degree entitled, **"Development and Performance Evaluation of a Solar Greenhouse Dryer with Desiccant Energy Storage System for Tomato Drying."**

You may now proceed with your Data collection, subject to clearance with the Director General, National Commission for Science, Technology & Innovation.

As you embark on your data collection, please note that you will be required to submit to Graduate School completed Supervision Tracking Forms per semester. The form has been developed to replace the Progress Report Forms. The Supervision Tracking Forms are available at the University's Website under Graduate School webpage downloads.

Thank you.

JACKSON LUVUSI
FOR: DEAN, GRADUATE SCHOOL

CC. Chairman, Department of Energy Technology

Supervisors:

1. Prof. Thomas F. N. Thoruwa
School of Pure & Applied Sciences
Pwani University
C/o Energy Technology Department
Kenyatta University

2. Dr. Nickson K. Lang'at
C/o Agricultural & Biosystems Engineering Dept.
Kenyatta University

JL/cww

G_2: Research Permit from NACOST