



**DESIGN AND FABRICATION OF AN INTELLIGENT
SOLAR-PHOTOVOLTAIC HYBRID TUNNEL DRYER
FOR TOMATOES WITH AUTOMATIC TEMPERATURE
CONTROL AND AIR RECIRCULATION.**

By

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A dissertation submitted to the University of Zambia in partial fulfilment of the requirements of the degree of Masters of Engineering in Renewable Energy Engineering.

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I, **Achalle Joseph Tambe** do hereby declare that the contents in this dissertation is my original work and have not been previously submitted to any University for the award of a degree or any other qualification.

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Certificate of Approval

This dissertation of Achalle Joseph Tambe has been approved as fulfilling the requirements for the award of the degree of Master of Engineering in Renewable Energy Engineering by the University of Zambia.

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Abstract

The agricultural sector in most developing countries encounters a lot of post-harvest losses due to a lack of appropriate drying and storage facilities for preservation. Though many drying technologies have been developed, there is an increasing demand for automation in drying. Concerning this limitation, this work presents the design and fabrication of an intelligent solar-photovoltaic hybrid tunnel dryer for tomatoes with automatic temperature control and air recirculation. The entire dryer assembly consists of the main dryer itself, a solar photovoltaic system, and a control unit. The dryer was tested through the performance of seven experiments; three experiments were done for the sake of testing and making adjustments on the control unit to check if the current from the Arduino digital pins is sufficient enough to energise the relay coils in which in the course of these three experiments, a current booster was designed and fabricated. The fourth experiment was the no-load experiment where the average drying chamber temperature was obtained to be 59.95°C. The fifth experiment was a load experiment, the sixth experiment was to determine the collector efficiency which was 67.06%, and the seventh experiment was another Load experiment whose main purpose was to determine the energy consumed by the electric heater for drying tomatoes and dryer performance. The dryer performance was determined using the two load experiments. In the Load experiments, freshly bought tomatoes from the local market were washed and sliced to a 700g mass and placed in the drying chamber. For the first and second load experiments, the tomato was dried from an initial moisture content of 95% (wet basis) to a final moisture content of 5.30% and 9% (wet basis) respectively. The respective drying chamber efficiencies were 10.24% and 16.16%, the drying efficiency of 31.53% and 41.41%, the drying rate of 66.31g/h and 73.51g/h for an average solar irradiance of 0.678KW/ m^2 and 0.572kw/ m^2 average ambient temperature of 22.706 °C and 31.482°C, and average drying chamber temperature of 60.33°C and 60.27°C, for 9 hours and 8 hours respectively. The total energy consumed by the heater in the second load experiment was 1562.87 kJ.

Keywords Design and fabrication, solar-photovoltaic hybrid tunnel dryer, automatic temperature control, air recirculation, tomato drying.

Dedication

This research work is dedicated to my family, friends, and MIRET (Mobility for Innovative Renewable Energy Technologies) for their financial and moral support to the completion of this research. May the almighty God replenish their sources of assistance.

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This work saw the light of today due to the benevolence of some personalities to whom I'm highly indebted. My sincere gratitude goes to

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LIST OF ABBREVIATIONS

AC	Alternating Current
SPV	Solar-Photovoltaic
UV	Ultraviolet
Wb	Wet basis
PVC	Polyvinyl Chloride
PV	Photovoltaic
IDE	Integrated Development Environment
GUI	Graphic User Interface
LCD	Liquid Crystal Display
LED	Light Emitting Diode
DM	Dry Matter
USB	Universal Serial Bus
RH	Relative Humidity

CHAPTER ONE: INTRODUCTION

This chapter presents the background of the study, the statement of the problem, the research aim, the research objectives, the research questions, the significance of the study, the research scope, and ethical considerations.

1.1. Background.

Drying refers to the removal of excessive water from a material with the use of heat energy while maintaining the quality of the material (Vishal , et al., 2015). It is one of the most common methods of preservation of fruits, seeds, vegetables, meat, fish, etc. The word preservation simply refers to extending the shelflife of a product while maintaining its quality. Drying is mostly applied to food products since they have large moisture contents of about 25 to 95% which are higher than industrial products (Prakash & Kumar, 2017). Many technologies for drying agricultural products that are better than open air sun drying have been developed. One which involved that done by Simate & Cherotich 2017 where the the efficiency of the dryer was quite good for a tunnel dryer but lack of an automatic control system and air recirculation path as well as those done by other researchers which will be seen in chapter 2. According to Ahmed, et al., (2016) open air sun drying possesses some setbacks such as:

- Intermittent sunshine due to cloud cover.
- The agricultural product is exposed to air and hence vulnerable to contamination by pests, bird droppings, insects, flies, and dust.
- A low value of the dried product as it may not be completely dry.
- The drying time may be long due to unfavorable weather conditions thereby increasing the level of contamination, low product quality, and additional rehydration during the night.
- It demands a lot of attention on the product such as removal of contaminants from birds, and pest, removal of product in case of rain, turning the product to ensure proper drying, etc.
- The appearance of dark spots indicating a loss of nutrients such as vitamins from the product.

- Lack of secondary heat supply during periods of low or no solar energy like at the night, in winter, and during the rainy season.

Solar drying involves mass transfer and heat transfer which involves the movement of air and heat to pick up moisture from the food substance for the purpose of drying (Simate & Cherotich, 2017).

Though many technological advancement has been made in solar drying to combat the very limitations offered by the conventional method of open air sun drying, many short comings are usually encountered such as intermittent sunshine due to cloud cover and the inability of drying at night which prevents continuous drying, waste of heat to the environment that exits the drying chamber of the dryer which is a poor means of energy management, and low product quality as a result of the absence of drying at optimum temperatures.

This project involves the designing and fabrication of a Solar-Photovoltaic (SPV) hybrid tunnel dryer for tomatoes. The dryer has air recirculation to achieve an efficient, high drying rate, reliable, automatic, and sensitive drying system for tomatoes (*Solanum lycopersicum*). The auxiliary heat source for this dryer was an AC-powered electric heater made of nichrome wire. Its function was to provide extra heat when the temperature of the air in the drying chamber was less than the desired temperature. Hot air recirculation from the drying chamber is a means of energy management and mitigation of heat lost to the surrounding. Low temperature may lead to inadequate drying of tomato and excess temperature may lead to loss of nutrients thereby reducing its quality. Therefore an intelligent system to monitor and control the temperature was implemented to ensure that the desirable drying condition was realized.

1.2. Statement of the problem

The intermittent nature of sunshine causes fluctuations in temperature inside solar dryers. Furthermore, during the rainy season, winter seasons, and at night, there is inadequate sunshine to provide the required temperature for drying. These setbacks from the sun usually lead to great post-harvest losses every year. These losses could be reduced if solar dryers had a means of maintaining the temperatures at the optimum

levels and if they had another source of energy to aid drying during the rainy seasons, winter seasons, and at night. In addition, the release of heat that exits the drying chamber of solar dryers to the environment is a means of wasting heat. This heat can be recirculated back to the dryer for drying. In addition, low product quality is another problem encountered with using solar dryers because the products are not dried at optimum temperatures using a temperature controllers. With all these problems, the performance of many solar dryers are usually low. Since there are no solar-photovoltaic hybrid dryers with the characteristics of drying at optimum temperature and recirculation of hot air in all seasons and at night, building a solar-photovoltaic hybrid tunnel dryer with air recirculation and automatic temperature control will be the solution to the mentioned problems.

1.3. Research objective

1.3.1. Main objective

To design and implement a Solar-Photovoltaic hybrid tunnel dryer with automatic temperature control and air recirculation for drying tomatoes.

1.3.2. Specific objectives

- i. To size the various dryer components on a given tomatoes quantity.
- ii. To build the dryer with all its components.
- iii. To determine the performance of the dryer.

1.4. Research questions

- i. What are the suitable sizes of the various components of the dryer considering the given quantity of tomatoes to be dried in a given time?
- ii. How can the dryer with its components be built?
- iii. How is the performance of the dryer?

1.5. Significance of the study

- The study findings will help the farmers and food industry significantly reduce the loss of tomatoes and other fresh fruits that are in abundance in the rainy season which presents challenges in terms of drying. This improved drying technology has the potential to improve both food and nutrition security.

- Automation of the air recirculation and temperature control sets the person drying free to have time to do other activities and opens up the other range of research topics which include cost-benefit analysis and optimisation.
- The information is critical to policymakers who are interested in poverty reduction and economic development.

1.6. Scope of the research

Hybrid drying of agricultural products from its name is a combination of various technologies of drying to increase efficiency and reliability of the system. However, this research will be limited to the use of a solar tunnel dryer with a supplementary heat source that uses alternating current, and a temperature monitoring and control unit for the drying process.

1.7. Ethical consideration

In conducting this research, some ethical considerations were taken into account. Clearance was obtained from the University of Zambia directorate of research and graduate studies prior to undertaking any aspects of field work relating to this research. The research was explained to everyone who wanted to know about it. The designed and implemented system is user-friendly, easy to operate, automated, and well-protected to prevent injury to the user.

CHAPTER TWO: LITERATURE REVIEW

Solar drying is an improved method of open-air sun drying that uses different forms of drying such as; direct mode solar drying, indirect mode solar drying, mixed mode solar drying, and hybrid solar drying.

2.1. Direct-mode solar drying

In the Direct mode solar dryer, also called the integral-type solar dryer, the solar energy from the sun comes in direct contact with the food or product to be dried by passing through a transparent glass or a transparent UV-treated polyethylene plastic (Prakash & Kumar, 2017). It is easy to construct and it is cheaper compared to the Indirect mode and Mixed mode, but the setback is the problem of overheating (Prakash & Kumar, 2017). A chimney can be added to improve airflow by increasing the buoyancy and hence increasing the drying rate (Prakash & Kumar, 2017). Figure 2.1 shows a direct-mode solar dryer. The circulation of air in solar dryers can be through natural convection or forced convection (with the use of a fan or a blower) (Simate & Cherotich, 2017).

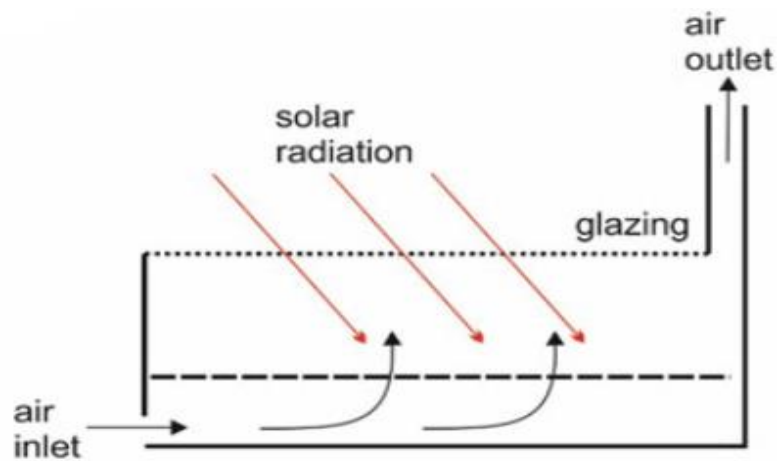


Figure 2.1: Direct-mode solar dryer (Prakash & Kumar, 2017).

2.2. Indirect-mode solar drying

The indirect-mode solar dryer has two chambers; the collector chamber and the drying chamber as seen in figure 2.2. Solar energy is received by the collector and then air from outside moves through the collector from an air inlet to pick up heat either through natural convection or forced convection (Chandrakumar & Jiwanlal, 2013). The hot air then moves into the drying chamber to pick-up the moisture present in the food which is to be dried. This dryer is usually called a distributed-type solar dryer. It is often recommended for products that are sensitive to direct solar radiation such as fruits, herbs, and spices whose vitamin C can be affected (Prakash & Kumar, 2017). Figure 2.2 shows an indirect-mode solar dryer.

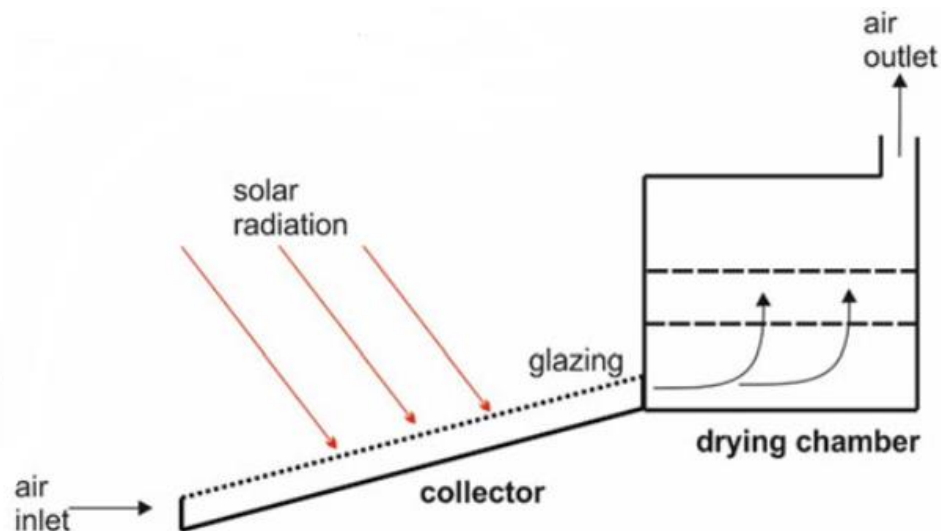


Figure 2.2: Indirect-mode solar dryer (Prakash & Kumar, 2017).

2.3. Mixed-mode solar drying

The dryer receives solar radiation from two chambers; the collector chamber and the drying chamber. The hot air from the collector moves to the food in the drying chamber to add more heat to the food and pick-up moisture from it (Chandrakumar & Jiwanlal, 2013). This dryer has a higher drying rate than the direct and indirect mode solar dryers (Prakash & Kumar, 2017). It combines both the direct and indirect mode solar drying methods (figure 2.3). The walls of this dryer are transparent to allow contact of solar radiation with the product.

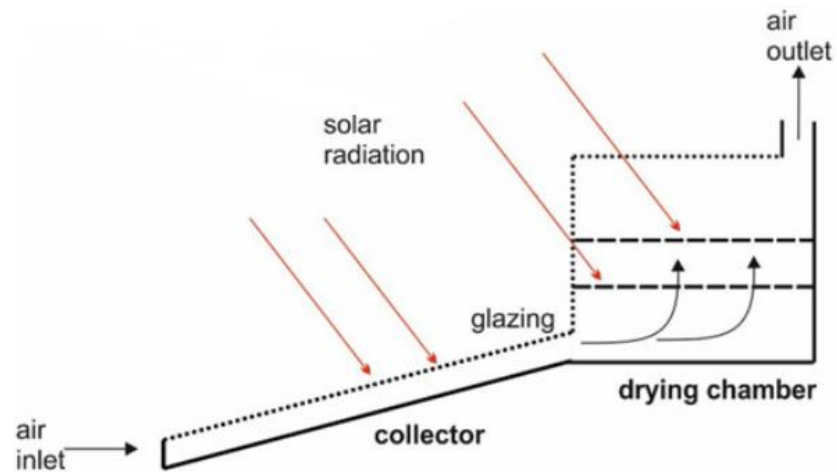


Figure 2.3: Mixed-mode solar dryer (Prakash & Kumar, 2017).

2.4. Hybrid solar dryers

Rupnar, et al (2020) designed, developed, and tested a greenhouse hybrid solar dryer involving the use of solar energy and biogas. The design capacity of the dryer was based on 8kg slices of onion. The temperature in the dryer was maintained at 60°C for 12 hours in hybrid mode for drying of the onion slices whose moisture content was reduced from 80.06% (w.b.) to 9.88% (w.b.). The drying efficiency of this dryer was 25%.

A hybrid tunnel dryer consisting of solar as the primary source of energy and biogas as a backup was developed by Sona (2015) to determine the effect of drying copra using only solar energy or using both solar energy and heat obtained by burning biogas. The experimented weight was 5kg. It was realized that with the use of only solar energy, the drying time of copra was 34 hours while with the use of the combination of solar energy and heat from the burning of biogas the drying time was reduced to 20 hours. It was further concluded that drying could also be done in times of low solar radiation with the help of the heat from the burning of biogas.

An automatic hybrid solar dryer with tomato being the test sample product was made by Akana and Kembou (2020) with the use of solar PV and direct solar insolation for

households and small industries. The experimented sample weight of tomatoes was 2kg. It was realized that the maximum chamber temperature was 46°C in the hybrid mode under average insolation of 318.74W/m² while 39.9°C was recorded in solar mode with average insolation of 303.7W/m². The average drying rate in the hybrid mode was 19.7g/h with 6.83% efficiency, whereas 10.5g/h was obtained in solar mode with 4.8% efficiency. The quality of the dried product using the hybrid system was better than that obtained using normal sunlight.

A Solar-Photovoltaic Green House mixed-mode solar dryer was designed by Pontheop, et al (2020) for the drying of Ganoderma. The temperature in the dryer ranged between 30°C to 52°C during the winter period. The maximum drying temperature of 52°C was obtained at 12:00 noon with the use of the hybrid system.

Simate and Cherotich (2017) designed and fabricated a natural convection solar tunnel dryer for mangoes of 3kg weight, with a maximum air temperature at the collector unit of 65.8°C, and the drying efficiency was 12.8%. though this efficiency was relatively high compared to other solar dryers, drying was not done at optimum temperature due to the lack of a temperature control unit, and also the heat that exits the drying chamber which could be reused was being desipated into the environment.

Sujata and Kapil (2017), designed a Photovoltaic thermal integrated indirect type hybrid solar dryer involving the use of direct solar radiation and a solar air heater (a collector) for drying agricultural products with the test product being white and compact cauliflower where the experiment was performed during summer. The drying time for this was two clear sunny days from 10:00 am to 5:00 pm daily in hybrid mode for which 350g of moisture was removed from 450g quantity of cauliflower. The maximum drying temperature was 48 °C in hybrid mode. The heat exiting the drying chamber was desipated into the environment and drying was not done at optimum temperature for this product due to the lack of a temperature control system, hence the product took long to dry and with a low end product quality.

An indirect hybrid solar-electric dryer was fabricated by (André, et al., 2018) for drying bananas from where the dryer performance was evaluated and compared with an

artificial dryer (electrical dryer), and natural sun drying. The experimented weight of sample was 4kg. It was realized that the banana got dried from an initial wet basis moisture content of 69% to 20% for 4 hours in the hybrid dryer, 8.5 hours in the electrical dryer, while the banana in the open sun drying could not reach this final moisture content even in 10 hours. The maximum temperature in the drying chamber of the hybrid dryer was 55°C which resulted in a significant decrease in the drying time. In this dryer, the collector efficiency was 44%, and the drying efficiency was 38%.

A hybrid solar dryer consisting of a heat exchanger whose working fluid was water heated by the sun and by an electric heater was designed by Amer, et al (2010) for drying ripe bananas. The fan blows ambient air through the heat exchanger to pick up heat and then to the drying chamber to pick up moisture from the food. During sunny days the dryer was operated as a normal solar dryer and during the cloudy day as a hybrid dryer. The capacity of the dryer was 30kg of sliced ripe bananas whose moisture content was reduced from 82% to 18% (wb) in 8 hours compared to sun drying where the moisture content was reduced only to 62%. Furthermore, the aroma, color, and texture of the hybrid dried product were better than the sun-dried product. The efficiency of the collector was 58.23%, while the drying efficiency was 25.3%.

Nandakumar et al (2018) carried out a performance study of a hybrid forced convection solar dryer with reflectors for the drying of cashew nuts of weight 6kg from a moisture content of 9.29% wet basis to 1% wet basis. The drying chamber efficiency of the dryer was 10%, the collector efficiency was 65.54%, and the drying efficiency was 16.12%.

Nabnean et al (2016) carried out an experimental performance of a new design of solar dryer consisting of a heat exchanger and a water type collector for drying osmotically dehydrated cherry tomatoes of 2kg weight. In this experiment, the collector efficiency was found to be 21% to 69%, and the drying efficiency was 13%. Though this system was efficient compared to pre-existing designs, it lacked an automatic control for drying at optimum temperature and also an waste energy management system such as an hot air recirculation path that exits the drying chamber of the dryer.

The drying temperature of agricultural products is also an important aspect that must be considered during drying to maintain the quality of the product in terms of nutrients. An experiment was carried out on the control of a solar dryer using a hybrid solar gas collector which involved the use of a programmable integral (PI) controller and control valves to monitor and control the drying temperature. It was concluded from the results of the simulation that the drying chamber temperature could be well-regulated in the suitable range, and the time response could be improved (Ahmed , et al., 2016). Hossain, et al (2008) fabricated a solar dryer which had a concentrating solar collector, a supplementary heating unit that involved a tank of hot water heated by the sun during the day to release heat energy at night through a heat exchanger for drying, and a drying unit for drying tomatoes with 3kg test sample. The tomatoes were pre-treated with UV light and chemicals among which was sodium metabisulphite to prevent microbial growth on the tomatoes at lower temperatures of about 45°C. However, their systems were not equipped with recirculation paths for the hot air which exits the dryer. This hot air can be reheated to a higher temperature so that its moisture-carrying capacity is increased and then fed back to the product to pick out more moisture instead of it being wasted to the environment. In this dryer, the collector efficiency was 24.31%, while the drying efficiency was 10%.

According to Tracy, et al., (2004) below 32°C, tomatoes will dry slowly thereby encouraging the growth of mold, whereas, at a temperature greater than 77°C, the tomatoes can get cooked and not dry and so it was stated that the optimum drying temperatures are between 57.2°C and 60°C where the tomatoes will properly dry indicating a required physical property. According to Ahmad, et al., (2012) drying of agricultural products preserves their vitamins, and the quality of the dried product is dependent on the drying temperature and the drying time. Therefore if the product is dried at a very high temperature above the optimum, the vitamins and other minerals which make up the food quality will be destroyed, but below a minimum threshold temperature, the food will develop mold.

In addition, many dryer designs consist of exhaust to evacuate the air leaving the food. This air is usually unsaturated in terms of moisture and carries some quantity of heat which is wasted to the surrounding. This air can be recirculated and reheated to an

optimum temperature and then sent back to the food to pick up more moisture from the food.

2.5. Conclusion and research gaps

From the above literature, it was realized that the issue of energy management, drying rate, efficiency, and temperature control for quality end products needs improvement. According to Simate & Cherotich (2017), forced convection solar tunnel dryers have higher efficiencies than natural convection solar tunnel dryers. This makes forced convection solar tunnel dryers an attractive technology to be used in many drying applications such as drying tomatoes. Hence the design and fabrication of an intelligent solar-photovoltaic hybrid tunnel dryer for tomatoes with air recirculation was done in this research to solve the limitations encountered with the use of the reviewed and existing dryers.

CHAPTER THREE: MATERIALS AND METHODS

This chapter presents the materials and methods used based on each objective.

3.1. To size the various dryer components on a given tomatoes quantity.

In this study, the general design of the solar tunnel dryer as described by Simate & Cherotich (2017) was adopted but with the reduction of the dryer size, the use of fans for forced convection, air recirculation, a heater for auxiliary heating, and an automatic temperature control unit. The components of the dryer were arranged as shown in figure 3.1a. The electric heater was mounted inside the dryer on the galvanized collector, between the air recirculation fan and the inlet air duct. This arrangement was made to be in the dryer to minimize heat loss from the dryer to the surrounding. The black-painted galvanized collector makes the floor of the dryer from the heater position to the tray. It was positioned to increase the surface area for energy absorption from the sun. The exhaust fan was placed at the end of the tray to expel warm moist air from the dryer in case of high temperatures above the set range. The PVC recirculation pipe was connected beside the exhaust fan to link the two air recirculation fans together. After the collector is the drying chamber where the tray lies. It is located after the collector and the heater so that the ambient and recirculated air can be heated properly so that it can pick up much moisture from the food.

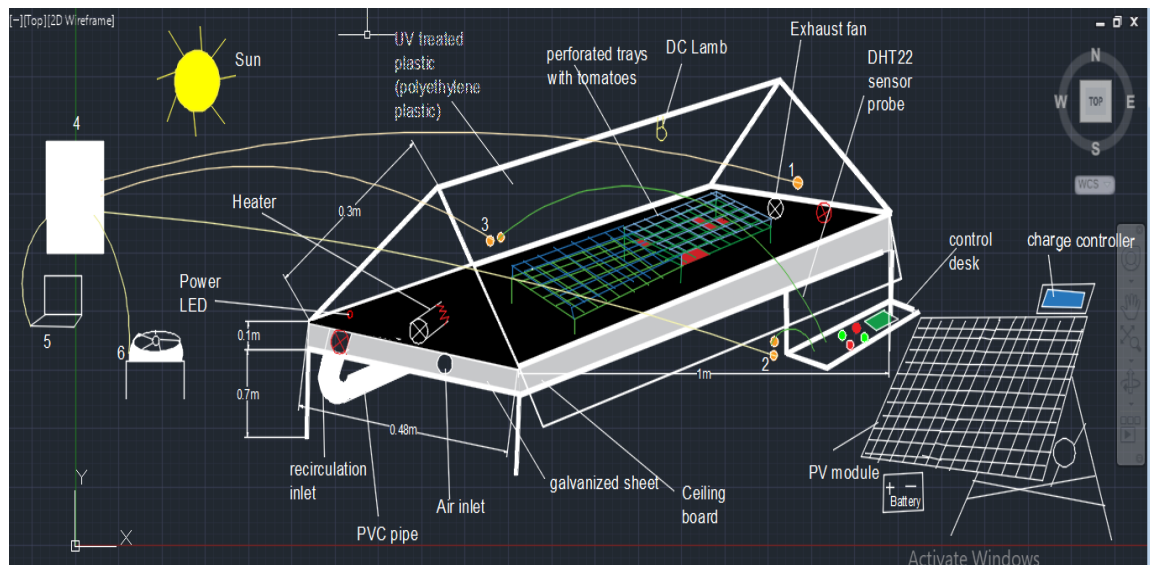


Figure 3.1a: The Hybrid Solar PV tunnel dryer with air recirculation and automatic control.

(1) Temperature sensor for air leaving the tray, (2) Temperature and humidity sensor for ambient air, (3) Temperature and humidity sensor for air entering the tray, (4) Data Logger(model: CR 1000), (5) Computer, (6) Solarimeter.

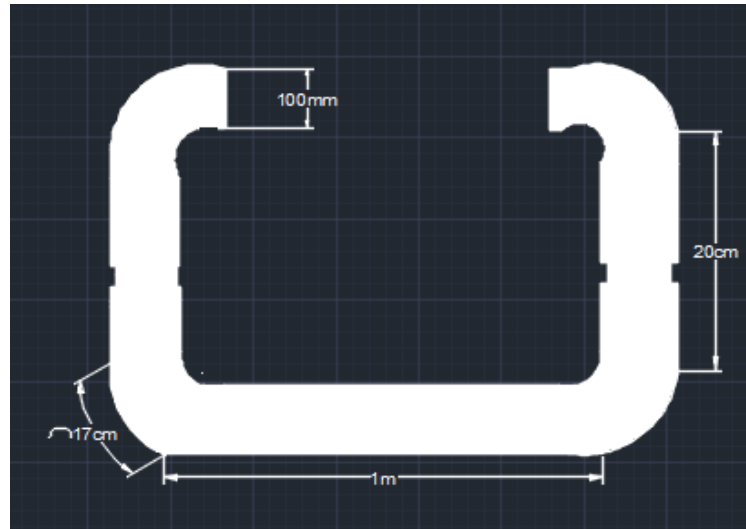


Figure 3.1b:100mm PVC pipe design.

The dryer was made from locally available materials such as steel square tubes, galvanized iron sheet collector, and UV-treated polyethylene plastic while the recirculation path was made of PVC pipe. The dryer was designed based on the quantity of tomatoes to be dried. It was designed to dry a maximum of 700grams of tomatoes. However, the dryer can dry other fruits and vegetables.

3.1.1 Determination of the dryer dimension.

The dimensions of the various components used are shown in Table 3.1 and Table 3.2, while Figures 3.1a and 3.1b show the detailed construction drawing.

The dryer was made from a frame of square steel tubes welded together. A galvanized sheet was riveted to the frame and formed the floor of the collector and drying chamber. A wire mesh tray for loading tomatoes was positioned in the drying chamber. A PVC pipe of 100mm diameter was used to recirculate the warm moist air that leaves the food in the drying chamber to the collector for reheating. It consisted of bends to allow flexibility during connection. The AutoCAD design of figure 3.1a and 3.2b shows the position of the various components of the dryer and Table 1 and 2 gives their

dimensions. The dryer consists of a control desk on which the control unit was placed. Also on the design is the Solar-Photovoltaic (SPV) system having the PV module, the charge controller, the battery, and the frame where the module was placed.

Table 3.1: Dimensions of the solar tunnel dryer.

<i>S/N</i>	<i>Dryer component</i>	<i>Length (m)</i>	<i>Width (m)</i>	<i>Height(m)</i>	<i>Surface area (m²)</i>
1	Drying chamber	0.52	0.48	-	0.25
2	Tray	0.52	0.29	-	0.15
3	Dryer legs(20mmx20mm square tubes)	-	-	0.80	-
4	Collector	0.48	0.48	-	0.23

Table 3.2: PVC pipe dimension for hot air recirculation

<i>S/N</i>	<i>PVC pipe component</i>	<i>Quantity</i>	<i>Length(m)</i>	<i>Diameter(mm)</i>	<i>Arc length(m)</i>
1	Main Pipe	1	1.00	100	-
2	Bends	4	-	100	0.24

Figure 3.2a, 3.2b, and 3.2c show the complete Proteus Integrated Development Environment (IDE) simulated power circuit, current booster circuit for the control unit, and the entire design of the automatic control unit respectively. The power circuit consists of electronic devices such as the LM7805 voltage regulator, 1N4007 rectifier diode, and two polarised capacitors which are wired together to a circuit to step down the 12V from the solar battery to 5V which is needed by the Arduino board to function. The entire control unit of figure 3.2c consists of a nextion LCD, four fans, five relays, and the Arduino board which carries the programmable ATMEGA328P microcontroller chip for automatic monitoring and control of drying chamber temperature. In figure 3.2c, each relay coil was energised from a current booster circuit by sending the current from the Arduino digital pin to the “INPUT” pin of that relay block. The current provided by the Arduino digital pin was not sufficient enough to directly energise the relay coils, hence a current booster circuit system was added. The current booster amplifies the

current to an amount which can energise the relay coil in other to control the actuators. This additional circuit was added because energising the relay alone from the current produced by the Arduino digital pins without this booster during the experiment was not possible, so the booster was designed and added to aid the relay. Figure 3.2b shows the Proteus circuit of the current booster. The testing of the current booster was done in three experiments just by connecting it to the control unit and experimenting at no-load in the entire assembly system of the dryer as shown in figure 18 by putting and adjusting the components until the unit was able to switch and control all the actuators as desired.

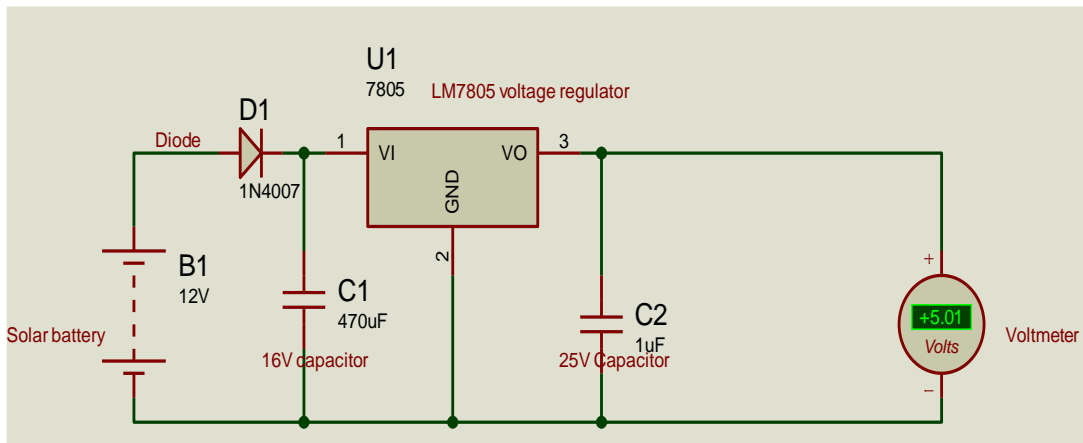


Figure 3.2a: Power supply circuit to Arduino board (Proteus IDE design).

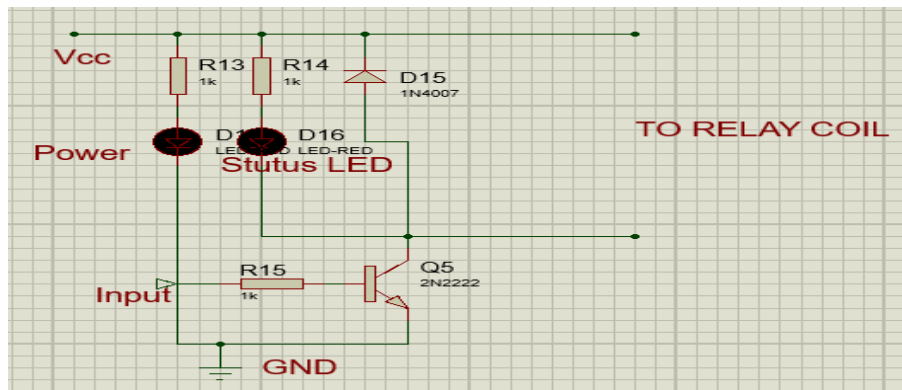


Figure 3.2b: Current booster circuit to the relay coil

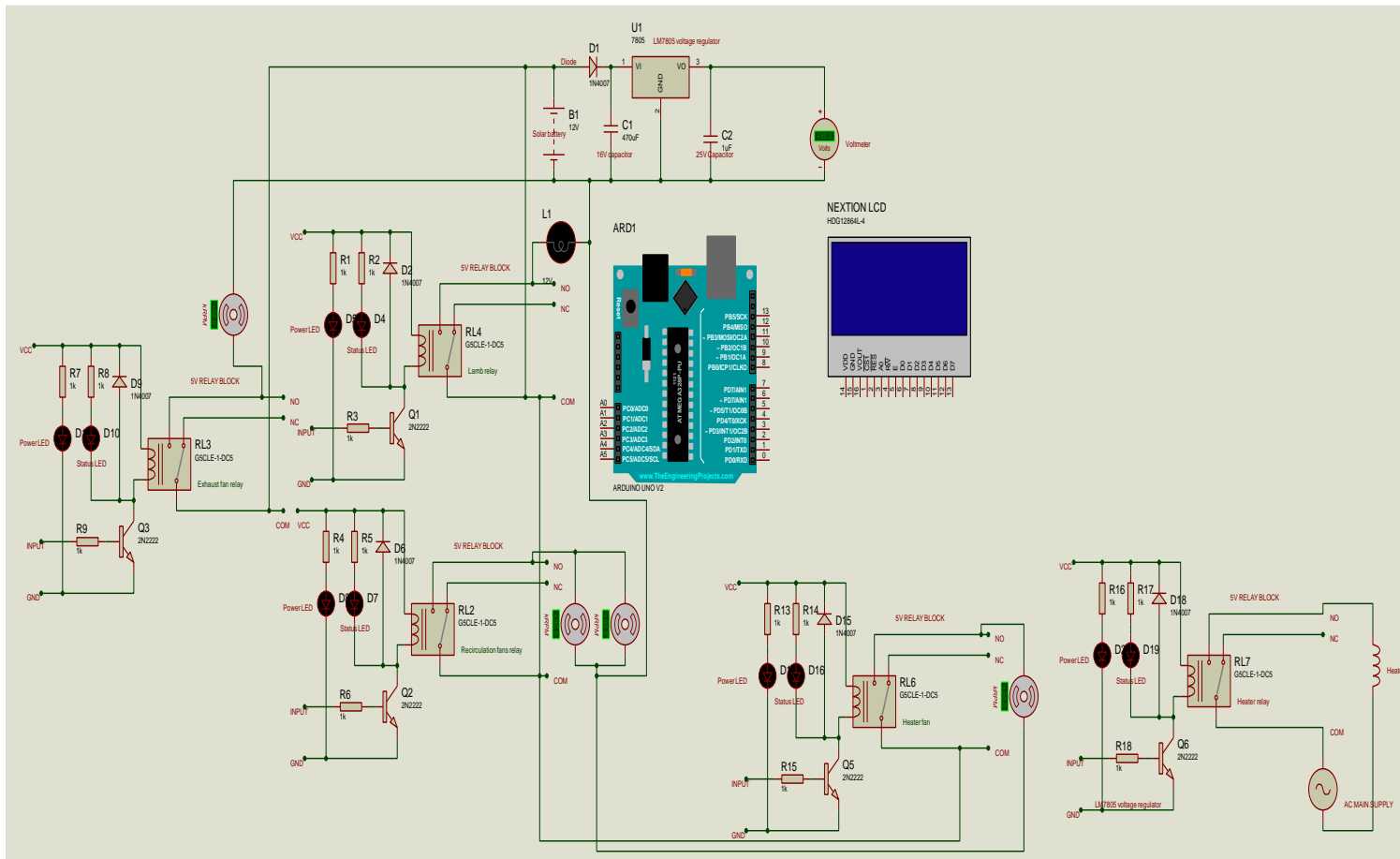


Figure 3.2c: Proteus design of the automatic temperature monitoring and control unit.

3.1.2. Sizing the various components of the dryer automatic control system.

A series of steps were considered for the sizing of the various components of the dryer which include the heater element, and the PV system.

For the purpose of design, a 700g mass of tomato was considered for drying to a moisture content of 10% which is safe for storage (Om & Anil, 2013).

The total amount of moisture to be removed was determined according to the expression given by Sharma, et al., (1986) as

$$M_w = \frac{M_{is}(M_{iwb} - M_{fwb})}{(100\% - M_{fwb})} \quad (3.1)$$

Where M_w is the amount of moisture to be removed, M_{is} is the initial mass of the sample, M_{iwb} is the wet basis initial moisture content and, M_{fwb} is the wet basis final moisture content

The initial moisture content of the tomatoes used was obtained by performing the experiment explained in section H which was obtained to be 95% (wet basis).

Therefore,

$$M_w = \frac{0.7(0.95 - 0.1)}{(1 - 0.1)}$$

$$M_w = 0.661 \text{ kg}$$

Drying tomato which is initially at ambient temperature involves two stages whereby in the first stage, its temperature is raised to the desired level for which the moisture can be removed.

The quantity of heat energy required to raise the temperature of the wet sample to this desired level is given by Donald (2007) as ;

$$Q_1 = M_{is} C_p (\Delta T) \quad (3.2)$$

Where ΔT is the difference in temperature between the optimum drying temperature and the average ambient temperature.

$$\Delta T = T_{opt.} - T_{av.} \quad (3.3)$$

For *Lusaka*,

$T_{av.} = 20.4^{\circ}\text{C}$ (European Centre for Weather Forecasts, 2022), and for tomatoes,
 $T_{opt.} = 60^{\circ}\text{C}$ (Tracy , et al., 2004).

$C_p = 3.98\text{KJ}/\text{kg}^{\circ}\text{C}$ is the specific heat capacity of a tomato (EngineeringToolBox, 2003).

$$Q_1 = 0.7 \times 3.98 \times (60 - 20.4) = 110.3256\text{kJ}$$

The second stage involves the evaporation of the moisture from the sample (heat of vaporization). The water starts to evaporate when the sample is warmed up and the quantity of heat needed for this second stage is given as,

$$Q_2 = M_w(h_g - h_f) \quad (3.4)$$

Where h_g is the enthalpy of water in the gaseous state and h_f is the enthalpy of water in the liquid state as obtained from steam tables at a temperature of 60°C and absolute pressure of 0.1994 bar.

$$h_g = 2609.6\text{kJ}/\text{kg} \text{ and } h_f = 251.1\text{kJ}/\text{kg}$$

$$Q_2 = 0.6611111(2609.6 - 251.1)$$

$$Q_2 = 1559.231 \text{ kJ}$$

Therefore the total heat energy required was finally determined as

$$Q_{total} = Q_1 + Q_2 = 110.3256\text{KJ} + 1559.230556\text{KJ} \quad (3.5)$$

$Q_{total} = 1669.556\text{kJ}$ Which was the quantity of heat required to dry 0.0.7kg of tomato.

3.1.3. Sizing the Electric Heater.

From $P_E = \frac{\text{Energy}}{\text{time}}$, where P_E is the power of the heater. (3.6)

According to Jelili, et al., 2016) for drying tomatoes with an initial moisture content of 95%, to an expected final moisture content of 10%, a drying temperature of 60°C, and a tomato slice thickness of between 4mm and 8mm, the drying time taken was 8 hours.

$$\text{Therefore, } P_E = \frac{1669.5562kJ}{8 \times 3600s} = 0.05797kJ/s = 58W$$

To minimize heat losses from the drying chamber to the environment, and due to the availability of materials, a 240VAC/828W heater, used previously in another project, was adopted and installed inside the dryer to provide electrical heating. A 240V AC/828W Heater was designed as follows,

$$\text{From } P = IV \tag{3.7}$$

$$I = \frac{P}{V} = \frac{828}{240} = 3.45A$$

$$\text{Hence } V = IR \Rightarrow R = \frac{V}{I} = \frac{240}{3.45} = 69.56\Omega \text{ resistive nichrome wire} \tag{3.8}$$

It was required to raise the ambient temperature from an average value of 20.4°C to 60°C. Therefore;

$$E = mC_{pair}\Delta T \tag{3.9}$$

Where m is the mass of air, $C_{pair \text{ at } 20.4^\circ\text{C}} = 1.006kJ/kgK$ is the specific heat capacity of air, and ΔT is the temperature change.

$$m = \rho Ah \tag{3.10}$$

Where A is the floor area of the dryer and h is the dryer height from the floor.

The density of air at 20.4°C, $\rho = 1.202Kg/m^3$

$$m = 1.202 \times 1 \times 0.48 \times 0.3 = 0.1731kg$$

$$E = 0.1731 \times 1.006 \times 39.6 = 6.8959KJ$$

How long it will take to raise this temperature of the air using an 828W heater element was gotten as

$P = \frac{E}{\Delta t}$, where Δt is the time duration.

$$\Delta t = \frac{E}{P} = \frac{6.8959KJ}{0.828KJ/s} = 8.328 \text{ seconds}$$

$\Delta t \approx 8.33 \text{ seconds}$.

3.1.4. Sizing the PV system

The PV system was included to provide the electrical energy needed by the automatic control components. The PV module of the PV system converts solar energy into electrical energy which is stored in the battery with the help of the charge controller. The energy needed by the control unit is accessed from the battery. Sizing of the various components of the PV system was done according to the mathematical models given by Niri, (2022),

$$\text{PV array size (Wh)} = \frac{\text{Daily energy demand(Wh)}}{\text{Inverter efficiency} \times \text{Battery efficiency}} \quad (3.11)$$

$$\text{PV array size (Wp)} = 1.3 \times \frac{\text{Daily PV array (Wh)}}{\text{Sun hours}} \quad (3.12)$$

$$\text{Number of solar panels} = \frac{\text{Array size Wp}}{\text{Panel size}} \quad (3.13)$$

$$\text{Battery bank capacity (Ah)} = \frac{\text{Daily energy demand} \times \text{Autonomy}}{\text{Inverter efficiency} \times \text{Depth of discharge} \times \text{System voltage}} \quad (3.14)$$

$$\text{Required charge current} = 1.2 \times \frac{\text{PV array Size}}{\text{Battery Bank Voltage}} \quad (3.15)$$

Where Wh is a unit called watt-hour, Wp is the watt-peak, and Ah is the ampere-hour.

Table 3 shows the various components which were powered by the electrical energy from the PV system.

Table 3.3:Active Components for PV System Energy.

<i>Component</i>	<i>Active power (W)</i>	<i>Quantity</i>	<i>Hours of operation (h)</i>	<i>Total active power (W)</i>	<i>Energy (Wh)</i>
<i>Arduino board</i>	0.492	1	7	0.492	3.444
<i>Nextion LCD</i>	2.5	1	7	2.5	17.5
<i>LED</i>	0.088	1	7	0.088	0.616
<i>12V LED Lamb</i>	3	1	7	3	21
<i>Exhaust fan</i>	1.7	1	5	1.7	8.5
<i>Air recirculation fans</i>	1.7	2	7	3.4	23.9
<i>Temperature and humidity sensors</i>	0.005	2	7	0.01	0.07
<i>Buzzer</i>	0.15	1	5	0.15	0.75
<i>Heater fan</i>	6.24	1	7	6.24	6.24
<i>Total</i>	15.875	11	59	17.58	82.02

Battery efficiency = 0.85 according to Akana & Kembou (2020), and Niri (2022).

Inverter efficiency = 0.90

Sun hour for worst day = 5.5 hours (World weather online, 2022)

Panel size = $\frac{82.02Wh}{5.5h} = 14.912W$. 200W panel size was chosen since it was readily available.

Since all devices to be used were 12V/DC so a system voltage of 12V/ DC was chosen.

Battery depth of discharge = 0.6

Battery autonomy = 1 day

From equation 3.11, PV array watt-hour(Wh) = 107.215Wh

From equation 3.12, PV array watt peak (Wp) = 25.342Wp

From equation 3.13, the number of solar panels = 1 panel (12V/14.912W monocrystalline) 200W panel size was chosen since it was readily available.

From equation 3.14, battery capacity (Ah) = 13.402Ah. Therefore, a 100Ah battery was chosen since it was readily available.

From 3.15, the required solar charge current = 15.3A. A 30A solar charge controller was chosen at Pulse Width Modulation(PWM) since it was readily available.

The PV system was installed without the use of an inverter since all the appliances and components required DC voltage to operate.

Lusaka, Zambia is located on latitude -15.39463° and longitude 28.33722° . According to (Energy Sector Management Assistance Program, 2022) optimum tilt angle of the PV module in Lusaka, Zambia is 19° from the ground. Figure 3.3 shows the installed PV system for the dryer.

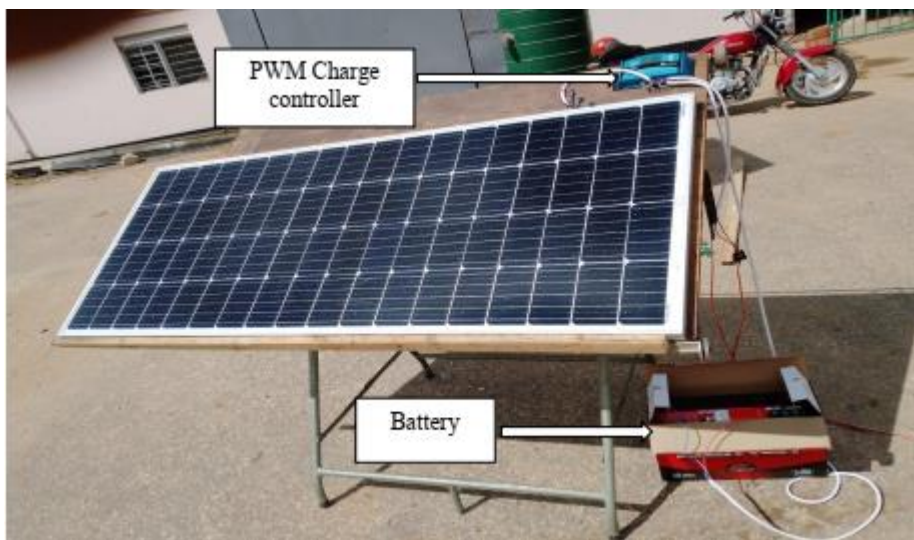


Figure 3.3: Installed PV system.

The heater was supplied by AC main supply and had a full capacity of 828W.

3.2. To build the dryer with all its components.

3.2.1. Material procurement and dryer fabrication.

The materials used were procured from the local store and after procurement, the dryer was fabricated at the Department of Agricultural Engineering workshop following the

dimensions given in table 3.1, table 3.2, and the construction drawing of figure 3.1a and figure 3.1b. Figure 3.4a and figure 3.4b show the dryer which was constructed.

The Dryer was covered with a greenhouse plastic riveted to the frame of the dryer. The greenhouse plastic was used due to its heat properties which only allow the infrared rays to penetrate to the food and prevent UV light which destroys food nutrients. The dryer was designed with three suction fans; one is an exhaust fan and two are hot air recirculation fans operating on 100% recirculation. The two air recirculation fans are connected using a 100mm diameter PVC pipe consisting of four bend connectors. These fans suck the warm air exiting the food and force it through the black-painted collector for reheating to increase its moisture-carrying capacity and then back to the food. Inside the dryer is a heater made from a nichrome element which was sized and powered by the AC main and a fan attached to it which was powered by the solar photovoltaic system to blow ambient and recirculated air for heating. A light bulb was installed inside the dryer to provide lighting when using the dryer at night.



Figure 3.4a: Front view of solar tunnel dryer with air recirculation path



Figure 3.4b: Side view of the solar tunnel dryer with air recirculation path.

3.2.2. Dryer description and its components

The designed and fabricated solar tunnel dryer with automatic temperature control and air recirculation shown in figure 3.4a and 3.4b above consists of four main units: the collector unit, the removable wire mesh tray, the air recirculation path, and the automatic temperature monitoring and control unit.

A. The collector unit

The solar collector unit is a black-painted galvanized iron sheet (absorber) that was covered with a UV-treated polythene plastic sheet. The arrangement allowed air to flow between the galvanized sheet and the polyethylene sheet, allowing air to be heated in the process. This collector design according to Ekechukwu & Norton (1999) is called the *front-pass covered-plate solar-energy air-heating collector* (Figure 3.5) consisting of low thermal losses. The absorber plate was insulated at the bottom with a 20 mm thick Styrofoam sheet to minimize thermal losses. The collector unit dimensions were 0.48m x 0.48m (LxW) as seen in Table 3.1 and figure 3.1a. The entire surface where the tray was located was considered to be part of the collector and hence was painted black.

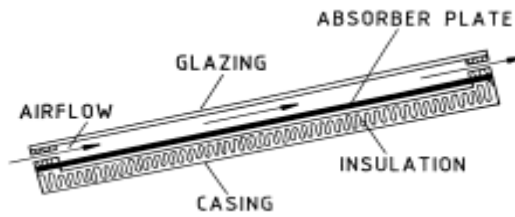


Figure 3.5: Front-pass covered-plate solar-energy air-heating collector (Ekechukwu & Norton, 1999).

B. The removable wire mesh tray

As seen in figure 3.6, the tray was made of a wire mesh supported by a steel frame and positioned about 20 mm above the floor. This arrangement allowed air to flow both under and above the tray. It was made to be removable and had dimensions of 0.52 m x 0.29 m (LxW).

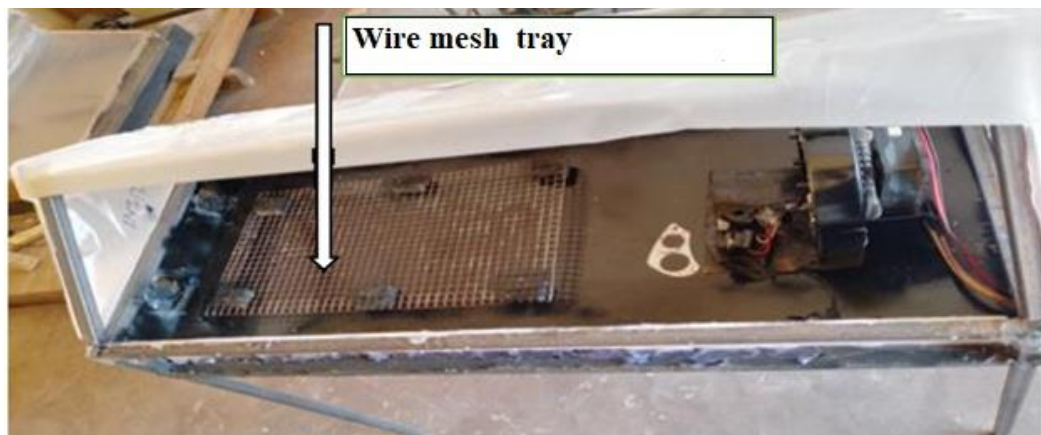


Figure 3.6: Solar tunnel dryer with collector unit and wire mesh tray.

C. Air recirculation path

This unit shown in figure 3.7 serves to recirculate hot air which was to be expelled as exhaust from the food on the tray back to the collector for reheating and then to the food. This recirculation path consists of a PVC pipe with bends as seen in Table 3.2 above and two suction fans. One of the suction fans sucks the air that leaves the tray and passes through the PVC pipe, while the other sucks the air from the PVC pipe and passes it to the collector surface for reheating and back to the food. This air relative humidity is usually less than 100%.



Figure 3.7: Solar tunnel dryer with air recirculation path.

D. The automatic temperature monitoring and control unit

The control unit comprises a circuit of active electronic components and sensors connected to a system brain called the Microcontroller which was programmed to automatically monitor and control the internal parameters of the dryer such as temperature, and relative humidity and then communicate to the operator through a touch screen graphic user interface Liquid crystal display (LCD) and signaling Light Emitting diodes (LEDs). The quantity of interest which was controlled was the drying temperature.

Components and description of the automatic temperature control unit

Arduino Uno board

It consists of the ATMEGA 328P microcontroller which is the brain of the entire dryer mounted on the circuit board together with other surface-mounted and integrated circuit components. The Arduino board was powered by a 5V DC source. The automatic temperature monitoring and control program code that runs in the system was written in an Arduino Integrated development environment (Arduino IDE) version 1.6.9.0 in C++ programming language on a PC and then uploaded from the PC through an Arduino USB cable to the microcontroller on board. The board consists of digital and analog pins which give current and voltage signals to the actuators which are connected to the microcontroller through the pins for control. Figure 3.8 shows the Arduino Uno circuit board.

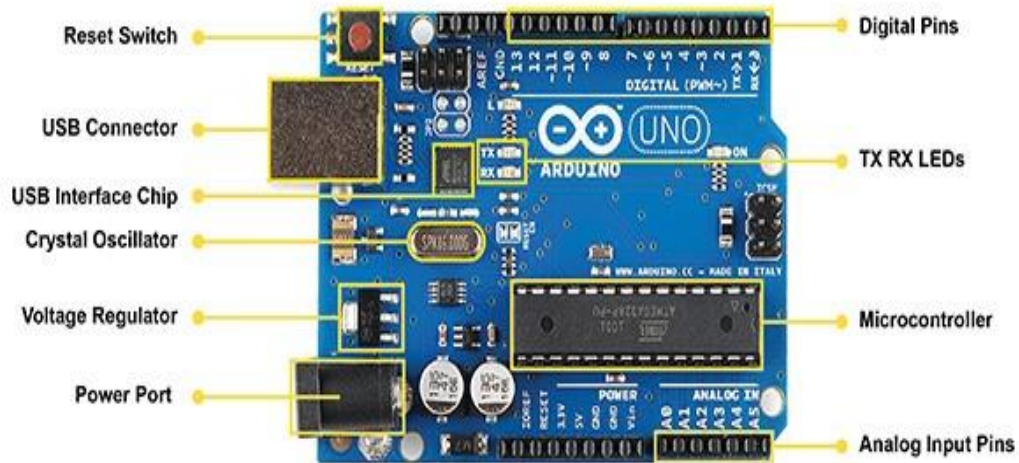


Figure 3.8: Arduino Uno circuit board with ATMEGA 328P microcontroller (Vasudhendra , 2016).

Nextion LCD for Graphic User Interface (GUI).

This serves the purpose of allowing the user to start the system by clicking the start button, to monitor the varying parameters of the dryer such as temperature and relative humidity, to monitor the weather for the day, the state of the fans, the state of the heater, performing numerical calculations for the moisture quantity that can be withdrawn from a food sample through its in-built calculator, putting ON and OFF the DC lamp in the dryer with a soft touch in-built switch on the LCD.

The nextion LCD is a human-machine interface consisting of a microprocessor integrated into the board. The Code and the graphics that run in the system were written on Nextion Integrated Development Environment (IDE) version 1.63.3.2015, debugged, and then uploaded to the microprocessor through serial communication port. Figure 3.9 shows the programmed graphics on the nextion screen for the dryer in this study



Figure 3.9: Nextion LCD for GUI.

Light-emitting diodes (LEDs).

These are devices that communicate a message to an operator in case of an emergency, action, or the state of the power button. When the automatic control switches ON the heater, the heater LED comes ON to indicate the state of the heater, and at the same time, the state of the heater is displayed on the nextion LCD. The fans also had LEDs on the control box that indicate their states when ON or OFF and also on the nextion LCD (figure 3.10a and 3.10b).

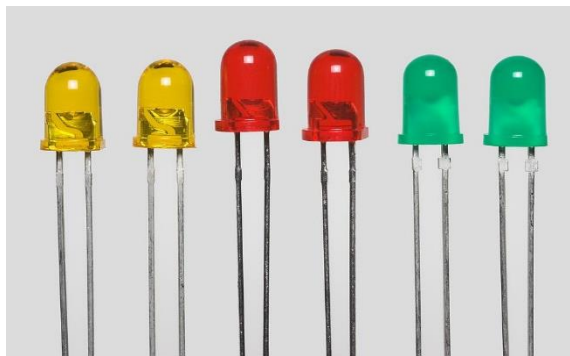


Figure 3.10a: Light emitting diodes (LEDs) (Esl, 2022).

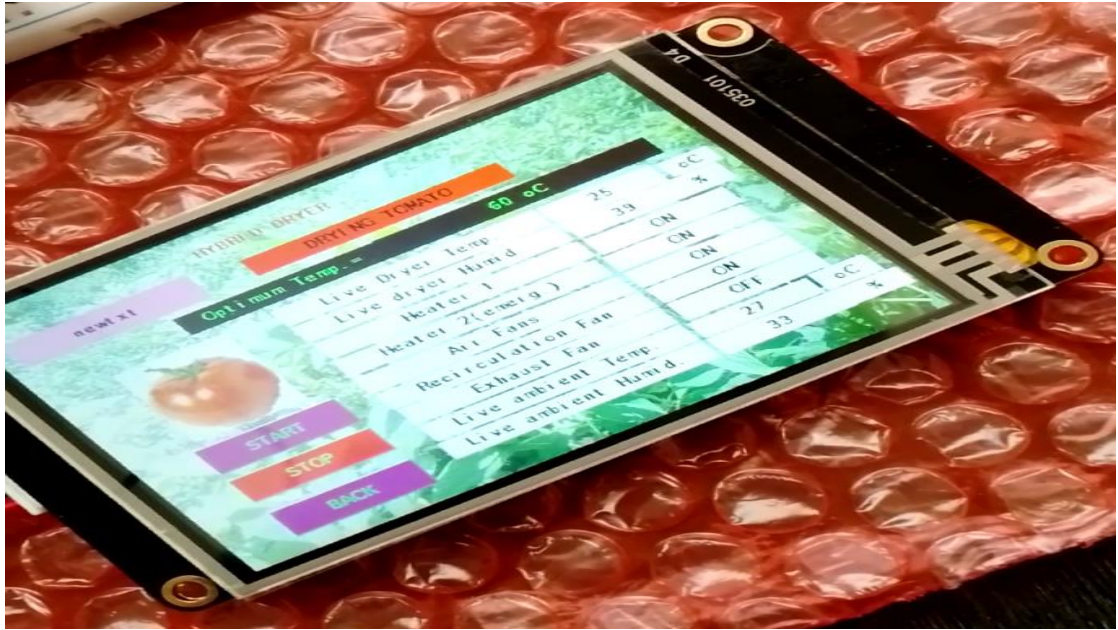


Figure 3.10b: Nextion LCD showing the state of components in the dryer.

Air temperature and humidity sensor

As shown in figure 3.11, two AM2302 Model DHT22 temperature and humidity sensors were used, one was used to measure the ambient temperature and humidity, and the other to measure the temperature and humidity of the air in the drying chamber. The temperature and humidity measurements of these AM2302 Model DHT22 sensors range between -40°C and 80°C , and between 0% - 100% RH respectively (Kuongshun Electronic, 2022). The DHT22 sensor has 3 pins; the VCC pin, the data, and the Ground pin. When the sensors are powered, they read and send the temperature and relative humidity of the air in the environment where they are placed to the microcontroller for processing. The values of the temperature and relative humidity will then be transmitted through a serial port to the Nextion LCD for viewing. The data collected and displayed occurs at a very fast baud rate of 9600 where the systems were synchronized to communicate and display live data of temperature and humidity as well as the states of the components in the dryer at a second interval.



Figure 3.11: DHT22 Air temperature and humidity sensor (INVENT electronics, 2022).

Fans

Figure 3.12, shows the fan which was used in the dryer. They serve the purpose of circulating, recirculating, and expelling air in and from the dryer to offer an optimum drying condition in the drying chamber. The dryer was fabricated with a total of four fans where each having a rating of 12VDC/1.7 W; two recirculation fans, one exhaust fan, and a heater fan attached to the heater.



Figure 3.12: 12V DC/1.7W fan.

Electric heating element.

As seen in figure 3.13, the heating element was made from Nichrome wire with a resistance of 69.56Ω which was powered by AC electricity to produce heat. AC power was used due to its affordability than buying a big battery and a panel which was too expensive if it was to power the sized heating element.



Figure 3.13: Nichrome heating element (Blake , 2018).

Figure 3.14 depicts the complete setup of the hybrid tunnel dryer and the fabricated control unit. The complete system consists of the main dryer itself and the solar-photovoltaic system.

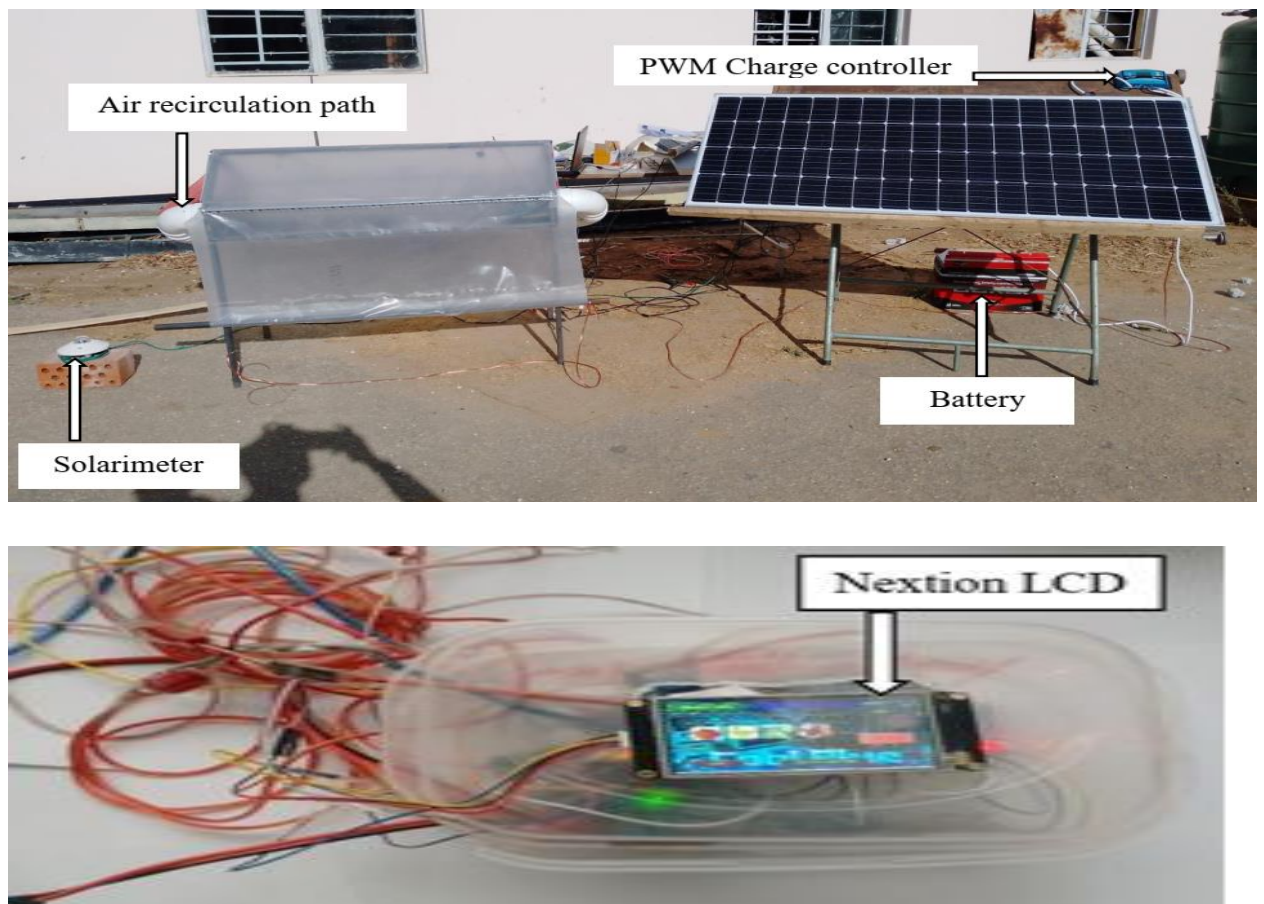


Figure 3.14: Complete setup of the hybrid tunnel dryer with the fabricated control unit.

E. Mode of operation of the dryer with automatic temperature control.

The mode of operation of the dryer with air flow is illustrated in Figure 3.15. The control unit was set to monitor and control the drying temperature at the range between 58°C and 62°C such that the average drying temperature at the end would lie at the

optimum range for tomato drying. The air from the heater and collector should therefore lie within this range on reaching the food on the tray. When the dryer is loaded and the start button is pressed, the control system reads the air temperature in the dryer and its relative humidity and displays it to the nextion LCD. If the temperature of the air in the dryer is less than or equal to 58°C (especially in the morning), the heater in the dryer comes ON at the same time with its fan and the air recirculation fans. Ambient air is forced by the heater fan through the heating element to raise the temperature of the air. As shown in figure 3.15 solar radiation falling on the collector unit through the transparent plastic cover provides additional heating to the air in the collector. Air movement is through forced convection. At the tray where the food lies, mass and heat transfer between the air and the food occurs which causes the temperature of the air to reduce and the relative humidity of the air to increase. The air is recirculated back to the collector by the suction fans for reheating to increase its moisture-carrying capacity and then back to the food. The simultaneous and continuous mass and heat transfer between the air and the food causes the food to dry with time. In addition to drying with air, the solar radiation through the transparent plastic also falls to the food causing it to be dried directly. This gives an advantage to the use of solar tunnel dryers in that the food is dried through a convective heat transfer and direct heating through a transparent surface hence increasing the drying rate. If the temperature in the dryer lies between 59°C and 61°C, the heater goes OFF at the same time as its fan, while the recirculation fans remain ON. This condition is good for energy management when the sun is at its peak during the day. If the temperature of the air in the dryer goes above 62°C, the heater goes OFF at the same time as its fan, the air recirculation fans goes OFF while the exhaust fan comes ON to expel hot air from the dryer as ambient air flows in to reduce the temperature to the required range. The process continues over and over till the tomatoes get dry.

It was seen that the air leaving the tomatoes on the tray was at a lower temperature and higher relative humidity than the air entering the tray. With no product loaded on the tray, the air from the collector inlet continues to further heat up until it leaves the tray.

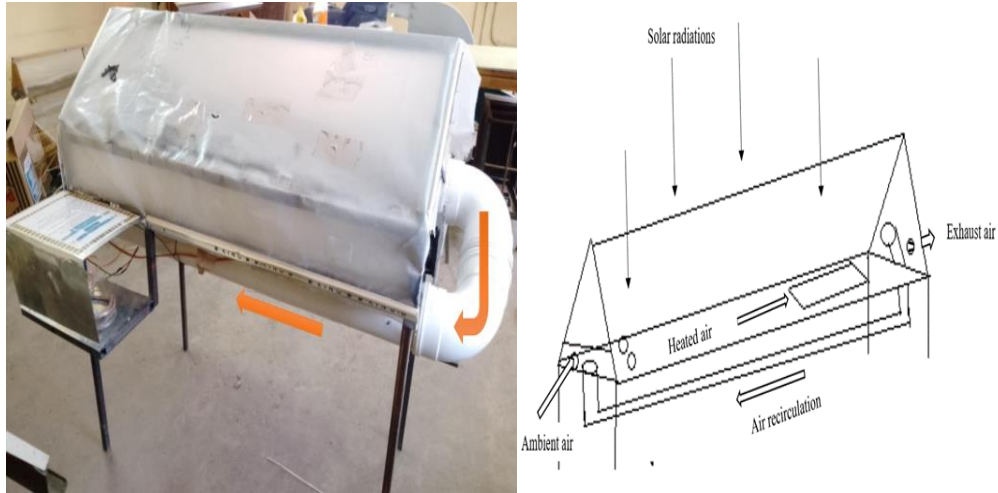


Figure 3.15: Air flow in the solar tunnel dryer.

Figure 3.16 shows the operational control block diagram of the dryer where energy from the sunlight is converted into DC electricity by the PV module. The energy from the PV module then flows to the 12V battery for storage through the charge controller. The charge controller monitors and regulates the amount of current that flows to the battery thereby preventing the battery from being damaged due to over charging. The Arduino board was powered through a 12V/5V DC voltage regulator. The Arduino needs 3.3V to 5V to operate. So, the voltage regulator steps down the 12V from the battery to the 5V needed by the Arduino. The ATMEGA328P programmed microcontroller on the Arduino board controls the heater, the exhaust fan, the recirculation fans, and the lamp, through the relays. The Arduino also communicates with the nextion LCD and the DHT22 temperature and humidity sensors by sending and receiving information through serial communication ports. The Arduino also sends a signal to the 5V buzzer to raise an alarm to the operator in case of any system malfunction such as the inability of sensors to operate due to excessive temperatures.

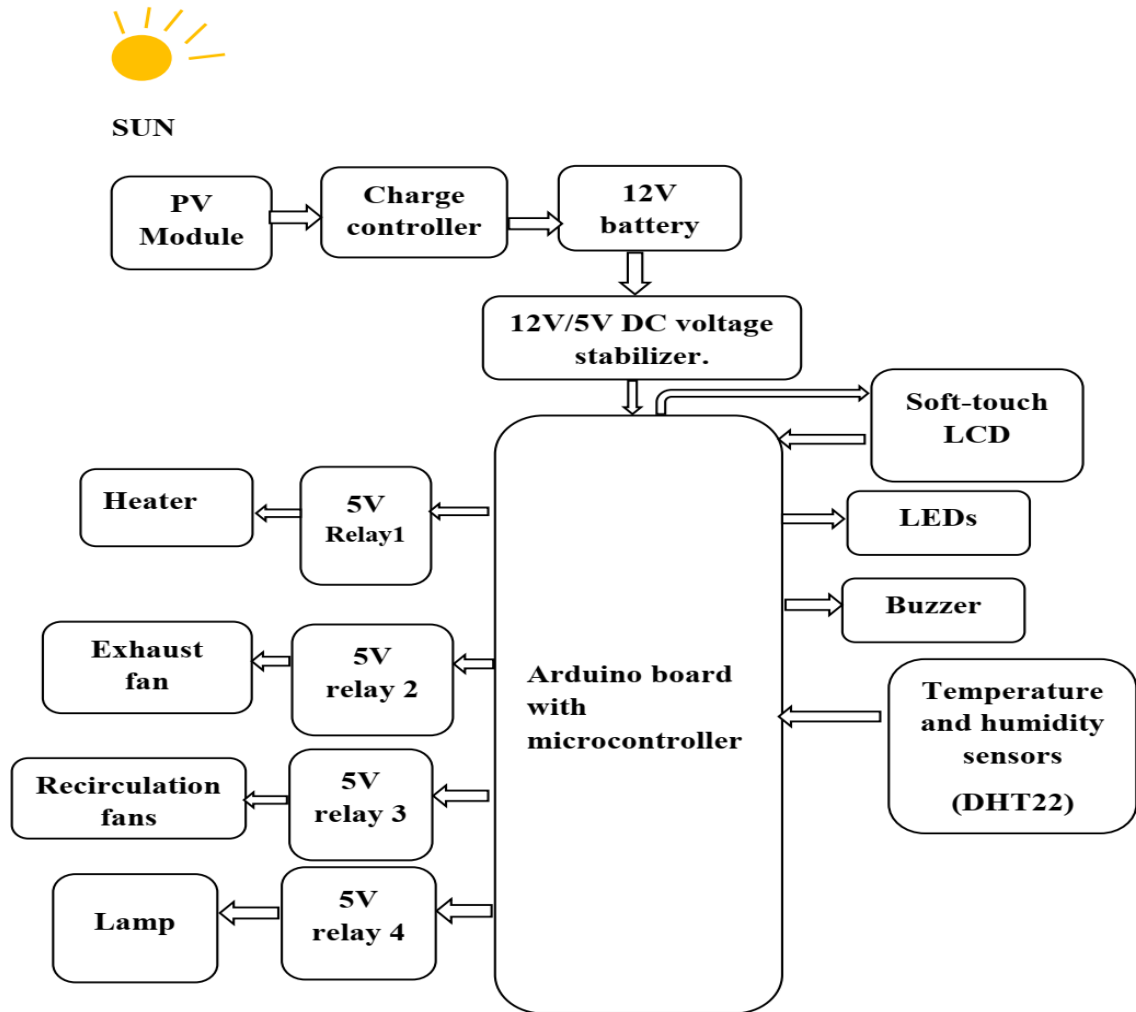


Figure 3.16: Operational control block diagram of the dryer.

F. Description of the Area of Study.

The experiment was conducted at the Department of Agricultural Engineering field station at the University of Zambia with coordinates; Longitude $28.3^{\circ}E$ and latitude $15.3^{\circ}S$. The entire dryer setup was placed outside on a flat ground surface in front of the Department of the Agricultural Engineering field workshop. The experimental setup is as shown in figure 3.1a.

A multi-probe Campbell Scientific Inc data logger (Model: CR 1000) was used together with the fabricated control circuit for obtaining dryer and ambient air temperature, relative humidity, and solar irradiance to compare data values. It was realized that the

data values were the same for these two devices. The air temperature was recorded by the data logger through a thermocouple-type temperature probe (model: 108-L and accuracy of $\pm 0.01^{\circ}\text{C}$). The probes were capable of recording temperatures in the range between -5°C and 95°C . The relative humidity was measured using a relative humidity probe (model: HMP60-L). This relative humidity probe could measure the temperature and relative humidity of the air at the same time in the range of -40°C to 60°C and 0% to 100%, respectively. The fabricated control circuit consists of DHT22 temperature and humidity sensor probes (model: AM2302) which could measure temperature and relative humidity in the range of -40°C to 80°C and 0% to 100% respectively with an accuracy resolution of 0.1, humidity measurement precision of $\pm 2\%RH$, temperature measurement precision of ± 0.5 (Frank, 2022). The solar irradiance was measured by the Solarimeter (Kipp & Zonen Delt BV, Model: CM11, irradiance range of 0-1,400W/m², sensitivity between 4 and $6\mu\text{V}/\text{Wm}^{-2}$) placed near the solar tunnel dryer on a horizontal ground surface.

The ambient air temperature (T_{amb}) and its relative humidity (R_{hamb}), the inlet air temperature to the tray (T_{in}) and its relative humidity (R_{hin}), the exit air temperature (T_{out}) from the tray and its relative humidity (R_{hout}), and the solar irradiance were all measured and recorded from these devices during the experiments as will be discussed in subsequent sections.

G. Dryer Test Experiments

A two hours test was conducted on the dryer on the 16th of July 2022 from 8:52 am to 11:00 am. At this time, the dryer was allowed to run under automatic monitoring and control without any tomato in order to investigate its performance prior to the drying process so as to help inform for any necessary adjustments. The dryer experiment was conducted according to the two steps below without any product.

- i. The dryer equipment was arranged as seen in figure 3.1a. The experiment began at exactly 8:52 am by switching on the dryer from the soft touch programmed switch of the nextion LCD.

- ii. The variables of interest were collected manually on a note book from the nextion LCD and from the data logger which was automatically saved on the computer at intervals of one minute.

After the dryer test experiment, the initial moisture content of the tomato was determined followed by the tomato drying experiments in the hybrid solar tunnel dryer with automatic temperature control as discussed in the next section.

H. Experimental Determination of the Initial Moisture Content of Tomato.

The quantity of moisture in a product is described based on the weight of water in it and it is usually denoted as a percentage. The moisture content by wet basis of the product can be obtained by dividing the weight of the water in the product by the total weight of the product.

According to John et al., (2018), the moisture content is calculated as;

$$\%Moisture = \frac{m_{initial} - m_{dried}}{m_{initial}} \times 100 \quad (3.16)$$

Where $m_{initial}$ is the initial mass of the sample, m_{dried} is the final mass when the sample is dry.

The moisture content experiment was conducted at the Agricultural Engineering laboratory of the School of Engineering, University of Zambia using the evaporation method in the electrical oven shown in figure 3.17 where the mass of two trays (tray 1 and tray 2) was measured using an electrical balance and recorded.



Figure 3.17: Apparatus for determining the moisture content of tomatoes.

The fresh tomatoes were washed with water and sliced into 0.5 cm thick slices. The tomato slices were then placed on the tray at equal spacing and the combined mass of the tomato and tray was recorded. A sample of fresh tomato of 336.3g was used in the experiment. The following data was recorded.

Mass of tray 1 = 214.1g

Mass of tray 2 = 215.4g

Mass of tray 1 and tomato = 391.9g

Mass of tray 2 and tomato = 373.7g

Mass of tomato from tray 1 = $391.9 - 214.1 = 177.8\text{g}$

Mass of tomato from tray 2 = $373.9 - 215.4 = 158.5\text{g}$

Total mass of fresh tomato before drying = $177.8 + 158.5 = 336.3\text{g}$

The temperature of the electric oven was manually set at 60 °C (the optimum temperature for drying tomatoes) and the tray carrying the sliced tomatoes was placed in the oven. The tomato was allowed to dry for 24 hours in the oven for which the following data were collected;

Mass of tray 1 and tomato = 222.8g

Mass of tray 2 and tomato = 223.5g

Mass of tomato from tray 1 = $222.8 - 214.1 = 8.7\text{g}$

Mass of tomato from tray 2 = $223.5 - 215.4 = 8.1\text{g}$

Total mass of dried tomato = $8.7 + 8.1 = 16.8\text{g}$

Weight of water lost (moisture lost) = $336.3 - 16.8 = 319.5\text{g}$

$$\%Moisture = \frac{336.3 - 16.8}{336.3} \times 100$$

$$\%Moisture = 95.0\%$$

Figure 3.18a and 3.18b respectively shows the fresh and dried tomatoes on the trays.



Figure 3.18a: Before drying.

Figure 3.18b: After drying.

I. Procedure for Drying.

The experiment was conducted on Monday 18th July 2022 and continued on Tuesday 19th July 2022 at the University of Zambia, Department of Agricultural Engineering. The experiment could be continued to completion in the very first day with the use of the backup electric heater but the desire was to manage electrical energy by involving solar energy.

- i. Ripe tomatoes were purchased from the market the previous day before the day of the experiment and kept overnight in the refrigerator to avoid rotting.
- ii. At 08:00 am on the day of the experiment, the mass of the tomato was measured and recorded using an electronic scale balance (model: PE 3000, accuracy, $\pm 0.1g$).

Mass of tray = 271.3g

Mass of sample tray = 4.3g

Mass of tray + sample tray = 275.6g

The experimented mass of tomatoes was 700g.

The tomatoes were washed with clean water and sliced with a knife at a thickness of 0.5cm on a chopping board and placed on a sample tray (figure 3.19a) and a tray (figure

3.19b). A smaller mass of tomatoes was placed on a sample tray as shown in figure 3.19a in order to ease removal of the sample tray with its tomatoes for measurement at certain time intervals for which in this case was 1 hour so as to determine the moisture content of the tomatoes in the dryer after every 1 hour during the drying process. The target was to dry the tomatoes at a moisture content less than or equal to 10% for long term preservation. The following data were measured and recorded.



Figure 3.19a: Sample tray before drying.



Figure 3.19b: Tray with sample tray before drying.

Initial Mass of sample tray +tomatoes = 34.6g

Initial mass of tomatoes on sample tray = $34.6 - 4.3 = 30.3\text{g}$

Initial mass of tray +sample tray + tomatoes = 975.7g as shown in figure 23b

Initial mass of tomatoes = $975.7 - 275.6 = 700.1\text{g}$

Mass of water in fresh sample = $95\% \times \text{mass of fresh sample}$

= 0.95×30.3

= 28.785g

Dry matter = $\text{mass of fresh sample} - \text{mass of water in fresh sample}$

= $30.3 - 28.785$

= 1.515g

- iii. The whole tray and sample tray of sliced tomatoes were placed in the dryer and the dryer was switched on at 10:42 am. At intervals of 1 hour, the combined mass of the sample tray and its tomato was measured and recorded. The temperature and relative humidity of the air entering and leaving the tray, the ambient temperature of air and its relative humidity, and the solar irradiance were recorded automatically and saved in the computer. The weight of the sample tray with its tomatoes was measured at regular intervals of 1 hour in order to determine the moisture content of the product in the drying chamber at that particular time in order to know if the desired moisture content has reached for which the product is dry.

$$\text{The moisture content at any time} = \frac{\text{mass of sample at any time} - \text{dry matter}}{\text{mass of sample at any time}} \times 100\% \quad (3.17)$$

For the first day, the experiment ended at 16:42 pm when the tomatoes were left overnight on the tray in the dryer, well covered by the UV-treated polyethylene plastic at room temperature to avoid in and out moisture migration to and from the tomatoes.

- iv. The experiment was continued the next day where the weight of the sample was re-measured and was noted to be the same as the previous day. The experiment started at 9:00 am and ended at noon when the tomato was dried to the desired and safe moisture content for preservation. Figure 3.20 shows the dried tomatoes. The tomatoes took 9 hours to dry to a moisture content of less than 5.30% at an average temperature of 60.331°C and average solar insolation of 0.678KW/m².



Figure 3.20: Dried tomatoes (less than 10% moisture content).

3.3. Determine of Dryer Performance

This section shows how the collector efficiency, the electric heater efficiency, and the dryer efficiency were determined.

3.3.1 Collector Efficiency

This is the heat gained as a ratio of the solar insolation falling on it and it is defined by the equation (Shitu , et al., 2019).

$$\eta_c = \frac{\dot{m}_a C_p (T_o - T_a)}{A_c I_T} \quad (3.18)$$

Where: η_c is the collector efficiency, \dot{m}_a is the air mass flow rate, C_p is the specific heat capacity of air (J/kg K), T_o is the temperature of outgoing air from the collector ($^{\circ}\text{C}$), T_a is the ambient temperature of air ($^{\circ}\text{C}$), A_c is the collector surface area (m^2), and I_T is the amount of solar insolation on the collector surface (W/m^2).

$$\dot{m}_a = \rho_a \dot{v} = \rho_a V A_x \quad (3.19)$$

Where: \dot{v} is the volumetric flow rate of air (m^3/s), V is the velocity of air at the collector, A_x is the cross-sectional area of the collector, and ρ_a is the density of air (kg/m^3).

3.3.2 Drying Chamber Efficiency

This was determined during the drying process of the tomato.

According, to Nandakumar, et al. (2018) the drying chamber efficiency η_{dc} is defined as;

$$\eta_{dc} = \frac{T_{in} - T_{out}}{T_{in} - T_{amb}} \times 100\% \quad (3.20)$$

Where T_{in} for this case is the average drying chamber inlet air temperature, T_{out} is the average drying chamber outlet air temperature, T_{amb} is the average ambient temperature of the air.

3.3.3 Drying Efficiency

This is the ratio of the thermal energy used to evaporate moisture from the food in the drying chamber to the thermal energy supplied in the dryer (Akana & Kembou, 2020). The equation is expressed as

$$\eta_d = \frac{W_p C_p (T_d - T_a) + M_w L_v}{I A_c t + Q_{heater}} \quad (3.21)$$

Where W_p is the weight of the product, C_p is the specific heat capacity of the product (which in this case is for tomatoes), T_d is the average drying temperature, T_a is the average ambient temperature, M_w is the quantity of moisture to be removed, L_v is the latent heat of vaporization of moisture from the product, I is the average irradiance, t is the time of drying, Q_{heater} is heat from the electric heater (heat generated by resistive wire).

The drying efficiency was determined on a load test with the backup heater during the drying process of the tomato.

3.3.4 Drying Rate

It is the amount of moisture that is evaporated from the food product over a period of time.

$$DR = \frac{dM}{dt} = \frac{M_{it} - M_{f(t+\Delta t)}}{\Delta t} \quad (3.22)$$

Where M_{it} is the initial product weight at time t , M_f is the final product weight at time $t + \Delta t$.

Δt is the time interval for obtaining the rate of mass reduction of the product. It was chosen to be every 1 hour (every 3600seconds). After every time interval, the product was removed and weighed using an electronic scale balance.

3.3.5 Air humidity for recirculation.

The annual average value of the dry bulb air temperature and relative humidity in Lusaka, Zambia is 20.4°C (European Centre for Weather Forecasts, 2022), and 61.5% (climate and temperatures, 2017), respectively. From the psychometric chart, plotting 20.4°C and 61.5% will give a humidity ratio (moisture content) of 0.010 kg of water/ kg of dry air. From the psychometric chart, during heating, the dry bulb temperature of the air increases while the humidity ratio remains constant throughout that particular process. Also, at a dry bulb temperature of 31.5°C downward, the relative humidity (percentage saturation) of air is 100% and hence the highest humidity ratio occurs at 31.5°C at 0.030kg of water/kg of air. The relative humidity value was never 100% throughout the experiments.

CHAPTER FOUR: DATA COLLECTION AND ANALYSIS.

This chapter presents the results and discussions of the study. This chapter involves the no-load test, load test with tomatoes, and dryer performance analysis such as collector efficiency, drying chamber efficiency, dryer efficiency, and drying rate.

4.1. Experiment I: No load and Load experiment, Collector efficiency experiment.

Three experiments were conducted namely; no load, load and collector efficiency experiments

4.1.1. No Load Experiment

A no-load test was conducted on the dryer after fabrication. This was done to know the temperature behavior outside and inside the dryer as well as the respective relative humidity. The test was conducted to observe the functionality of the control system in maintaining the temperature needed for drying around the desired and set range. This range was between 58°C and 62 °C such that the average temperature will be around the optimum drying temperature of 60°C. This test was conducted for 2 hours on Saturday 16th July 2022 from 9:00 am to 11:00 am Zambian time and data were collected at intervals of 8 minutes. The data collected was the temperature of the air in the dryer and its relative humidity using the DHT22 temperature and humidity sensor, the ambient temperature, and its relative humidity using another DHT22 temperature and humidity sensor, and the solar insolation using the Solarimeter (Kipp & Zonen Delt BV, Model: CM11). These quantities were all varying with time. Humidity was measured and displayed on the Nextion LCD screen. These values were at the same time measured by a standard multi-probe Campbell Scientific Inc. data logger (Model: CR 1000) to verify whether the values were matching with those measured by the control unit. It was noticed that the values from the control unit which was fabricated and those from the standard data logger were matching and were the same thereby validating the control system. Figure 4.1 shows a plot of the temperature, and time versus solar irradiance for the no-load test.

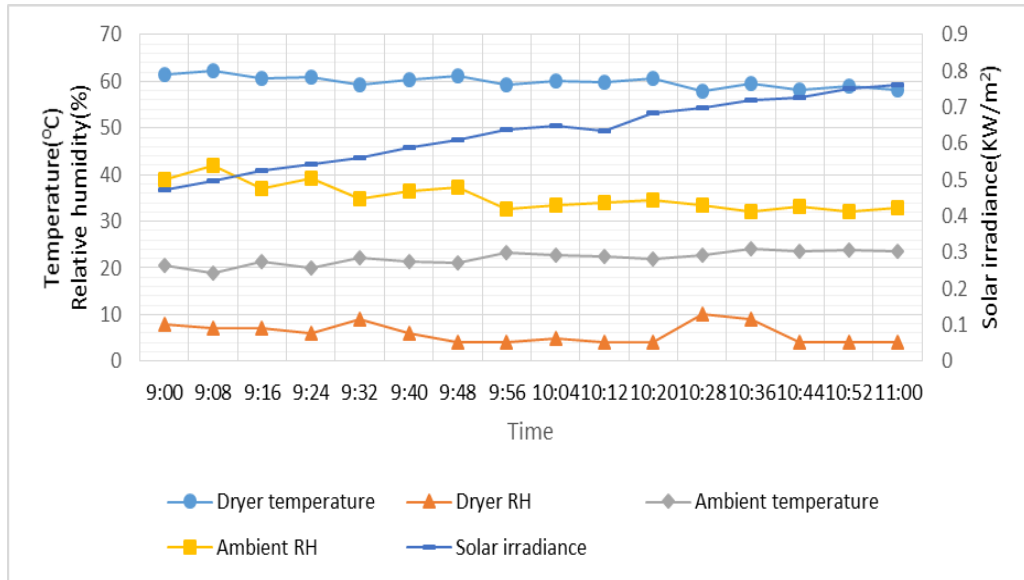


Figure 4.1: Temperature and solar irradiance versus time for the no-load test.

During this test, the average temperature in the dryer was obtained as 59.951°C, the average solar irradiance was 0.629 kW/m², the average chamber relative humidity was 5.94%, the average ambient relative humidity was 35.24%, and the average ambient temperature was 22.14°C. The temperature inside the dryer was maintained at the desired range even at low solar irradiance by the help of the control system and the electric heater.

4.1.2. Load Experiment with tomatoes

The experiment was conducted on Monday 18th July 2022 and continued on Tuesday 19th July 2022 at the University of Zambia, department of agricultural engineering. The data were collected and recorded in a table at intervals of one hour. The moisture content was calculated using equation 17.

On this day, the maximum drying chamber temperature was 61.9°C at a solar irradiance of 0.927 kW/m². The product weight was reduced to 2g with a moisture content of 24.3% (wet basis). Tables 4.1a and 4.1b show the results obtained.

Table 4.1a: Day I Temperature, Relative Humidity and Solar Radiation

<i>Time (hour)</i>	<i>T_{in} (°C)</i>	<i>R_{hin} (%)</i>	<i>T_{out} (°C)</i>	<i>R_{hout} (%)</i>	<i>T_{amb} (°C)</i>	<i>R_{hamb} (%)</i>	<i>I (kW/m²)</i>
10:42	61.55	12	55.05	41	21.22	39.85	0.711
11:42	59.23	11	55.79	40	22.46	36.65	0.813
12:42	61.9	11	57.05	31	25.84	28.57	0.927
13:42	61.9	10	58	20	26.13	25.98	0.818
14:42	57.22	6	56.34	15	27.18	24.94	0.765
15:42	61.12	3	55.14	13	21.34	34.22	0.104
16:42	60	2	53.78	12	20.45	39.14	0.081

Rhin = Relative humidity of air entering the tray.

Rhout = Relative humidity of air leaving the tray

Rhamb = Relative humidity ambient air

I (kW/m²) = Solar irradiance.

Table 4.1b: Day I Weight and moisture content of tomato

<i>Time (hour)</i>	<i>Weight of Sample (g)</i>	<i>Moisture Content (% wet basis)</i>
10:42	30.3	95.0
11:42	22.7	93.3
12:42	15.7	90.4
13:42	9.4	83.9
14:42	5.6	72.9
15:42	3.1	51.1
16:42	2	24.3

The next day, the weight of the tomatoes was re-measured and was noted to be the same as left the previous day. The experiment started at 9:00 am up to noon and data where

recorded in table 4.2a and table 4.2b. The maximum drying chamber temperature for this day was 60.9°C at solar insolation of 0.841 kw/m²

The final weight of the product was obtained as 1.6g with a moisture content of 5.31% (wet basis).

Table 4.2a: Day II Temperature, Relative Humidity, and Solar Radiation

<i>Time(hour)</i>	<i>Tin(°C)</i>	<i>Rhin(%)</i>	<i>Tout(°C)</i>	<i>Rhout(%)</i>	<i>Tamb(°C)</i>	<i>Rhamb(%)</i>	<i>I(kw/m²)</i>
10:00	60.49	4	57.09	19	19.26	58.25	0.846
11:00	59	3	57.85	12	19.9	55.61	0.876
12:00	60.9	2	58.71	10	23.28	43.22	0.841

Table 4.2b: Day II Weight and moisture content of tomatoes.

<i>Time (Hour)</i>	<i>Weight of Sample (g)</i>	<i>Moisture Content (% wet basis)</i>
10:00	1.8	15.83
11:00	1.7	10.88
12:00	1.6	5.31

Table 4.2c shows the combined data obtained for Day I and Day II.

Table 4.2c: Combined drying data for Day I and Day II Temperature, Relative Humidity, Solar Radiation, weight, and moisture content of tomatoes

<i>Time (hour)</i>	<i>T_{in} (°C)</i>	<i>R_{hin} (%)</i>	<i>T_{out} (°C)</i>	<i>R_{hout} (%)</i>	<i>T_{amb} (°C)</i>	<i>R_{hamb} (%)</i>	<i>I (Kw/m²)</i>	<i>moisture content (%wet basis)</i>	<i>weight of tomatoes (g)</i>	<i>weight of sample (g)</i>
10:42	61.55	12	55.05	41	21.22	39.85	0.711	95	700.1	30.3
11:42	59.23	11	55.79	40	22.46	36.65	0.813	93.3	524.497	22.7
12:42	61.9	11	57.05	31	25.84	28.57	0.927	90.4	362.757	15.7
13:42	61.9	10	58	20	26.13	25.98	0.818	83.9	217.192	9.4
14:42	57.22	6	56.34	15	27.18	24.94	0.765	72.9	129.391	5.6
15:42	61.12	3	55.14	13	21.34	34.22	0.104	51.1	71.627	3.1
16:42	60	2	53.78	12	20.45	39.14	0.081	24.3	46.211	2
10:00	60.49	4	57.09	19	19.26	58.25	0.846	15.83	41.59	1.8
11:00	59	3	57.85	12	19.9	55.61	0.876	10.88	39.279	1.7
12:00	60.9	2	58.71	10	23.28	43.22	0.841	5.31	36.968	1.6

On the first day, the average air temperature entering the drying chamber was 60.417 °C, the average air temperature leaving the drying chamber for recirculation was 55.88°C, and the average solar irradiance was 0.602kW/m². The total time of drying (from the first day to the second day) was 9 hours. This led to a reduction of moisture from 95.0% to a final moisture content of 5.30% under an average drying chamber temperature of 60.33°C, average solar insolation of 0.678kW/m², an average ambient relative humidity of 38.643%, and an average ambient temperature of 22.71°C. Figure 4.2 shows the dried tomatoes while Figure 4.3 shows a plot of the temperature, relative humidity, and solar irradiance against the time of drying.



Figure 4.2: Dried tomatoes (5.30% moisture content w.b.).

At 14:42 pm, the chamber temperature was observed to fall to 57.22°C due to wind invasion through the exhaust space but the control system was able to restore the temperature to its set range within a few seconds.

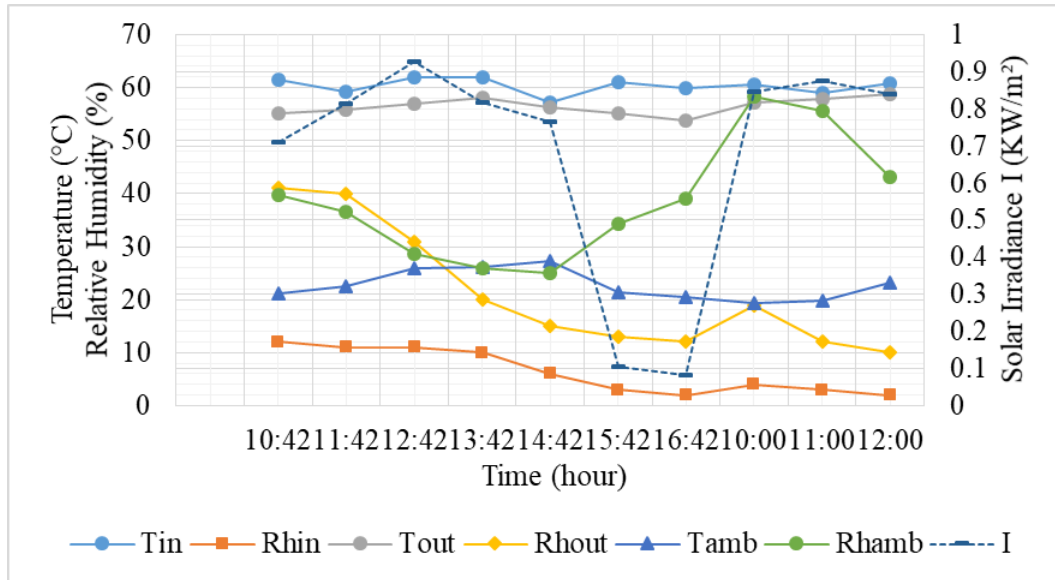
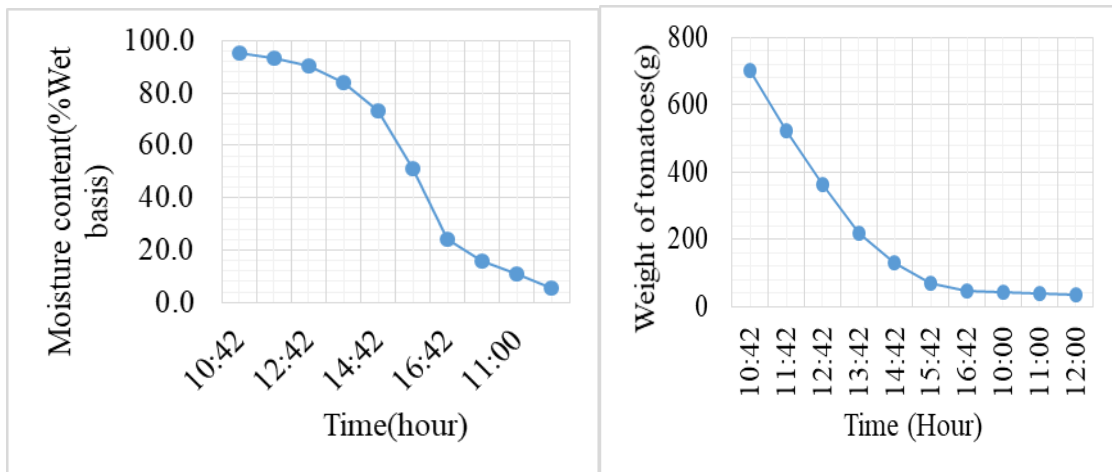


Figure 4.3: Temperature, humidity, solar irradiance versus time graph for load test

A plot of the moisture content against the time of drying for the tomatoes and the weight of the tomatoes against time can be seen in Figures 4.4a and 4.4b respectively. The moisture content as well as the weight of the tomatoes significantly reduced continuously from 95% (wet basis) to 5.30% (wet basis) and from 700g to 36.968g respectively.



a. Drying Chamber Efficiency

The inlet air temperature to the drying chamber and the outlet air temperature were obtained and for each interval of one hour, the drying chamber efficiency was obtained as explained in equation 18. Figure 4.5 shows the drying chamber efficiency versus time. From the proceeding calculation, the average drying chamber efficiency was obtained to be 10.24%.

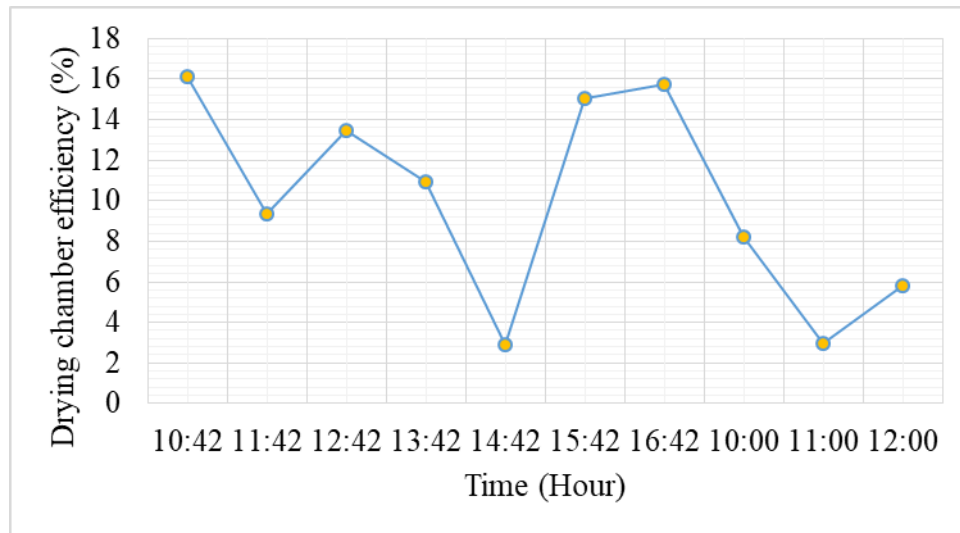


Figure 4.5: Drying chamber efficiency- time graph.

By substituting the obtained parameters, the drying chamber efficiency was determined as.

$$\eta_{dc} = \frac{60.331 - 56.48}{60.331 - 22.706} \times 100\%$$

$$\eta_{dc} = 10.24\%$$

This value agrees with that obtained in Nandakumar, et al.(2018) which was 10% with the use of reflectors in the hybrid system for drying cashew nuts.

b. Drying efficiency

$$\eta_d = \frac{0.7 \times 3.98(60.331 - 22.706) + (0.661 \times 2257)}{0.6782 \times 0.2304 \times (9 \times 3600) + 0.828} \times 100\%$$

$$\eta_d = 31.53\%$$

This value is slightly higher than that obtained by Hossain, et al.(2008) which was 29.35% for the drying of tomatoes during the daytime with the use of solar concentrators, and direct sunlight.

c. Drying rate

Figure 4.6a and 4.6b show the drying rate versus the time of the tomato for the sample tray and the entire 700g respectively. The graphs are similar showing that the sample drying rate was a true representation of the entire 700g mass of tomato. As it approaches noon on the second day, the drying rate decreases insignificantly due to less moisture left in the tomatoes as it becomes difficult to pull out moisture from the tomatoes to the surface for evaporation.

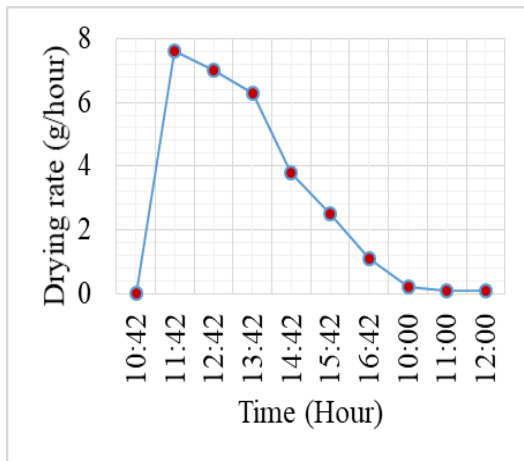


Figure 4.6a

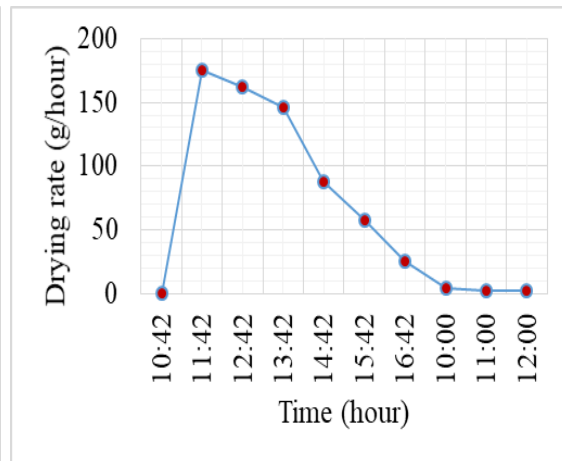


Figure 4.6b

Figure 4.6: Tomato drying rate versus time.

The average drying rate computed for the tomato on the sample tray was 2.87g/hour while that of the entire 700g of tomato was 66.31g/hour. The final mass of the 700g tomato after drying was measured to be 36.96g at a final moisture content of less than 10% (i.e 5.30%) as seen below;

$$\text{Mass of water in fresh sample} = 95\% \times \text{mass of fresh sample}$$

$$= 95\% \times 700g$$

$$= 665g$$

$$\begin{aligned}
 \text{Dry matter (DM)} &= \text{mass of fresh sample} - \text{mass of water in fresh sample} \\
 &= 700g - 665g \\
 &= 35g
 \end{aligned}$$

$$\begin{aligned}
 \therefore \text{The final moisture content of dried product} &= \frac{\text{final mass of dried product} - \text{dry matter}}{\text{final mass of dried product}} \\
 &= \frac{36.96 - 35}{36.96} \times 100\% \\
 &= 5.30\%
 \end{aligned}$$

4.1.3. Collector Efficiency

This test was conducted from 11:10 am to 16:40 pm on the 26th of July 2022 where the data was collected and recorded automatically at intervals of 30 minutes in a computer using the data logger (Model: CR1000) as shown in Table 4.3. The velocity of air V at each interval was recorded and the collector efficiency was calculated at each interval. An average collector efficiency of 67.06% was obtained for average solar insolation of 0.721kW/m². Average values of air velocity, collector air temperature, and ambient air temperature were also obtained as 0.135 m/s, 42.07°C, and 26.83°C respectively. The data obtained is given in Table 4.3; and Figure 4.7 shows the variation of the collector efficiency with time.

Table 4.3: Collector efficiency determination table.

Time(hour)	V(m/s)	Ta(°C)	To(°C)	I _T (KW/m ²)	Ta(K)	To(K)	To-Ta (K)	Collector Efficiency(%)
11:10	0.11	24.4	39.99	0.898	297.55	313.14	15.59	45.192
11:40	0.14	24.62	41.72	0.903	297.77	314.87	17.1	62.349
12:10	0.12	24.61	41.25	0.923	297.76	314.4	16.64	50.968
12:40	0.16	26.67	45.85	0.92	299.82	319	19.18	77.467
13:10	0.13	28.39	47.52	0.888	301.54	320.67	19.13	64.688
13:40	0.14	26.39	45.19	0.847	299.54	318.34	18.8	72.297
14:10	0.15	27.04	44.59	0.796	300.19	317.74	17.55	77.083
14:40	0.11	28.99	42.42	0.709	302.14	315.57	13.43	48.915
15:10	0.16	28.55	42.47	0.627	301.7	315.62	13.92	83.389
15:40	0.13	31.78	43.21	0.517	304.93	316.36	11.43	67.290
16:10	0.12	26.55	36.9	0.372	299.7	310.05	10.35	79.700
16:40	0.15	23.95	29.3	0.255	297.1	302.45	5.35	75.851

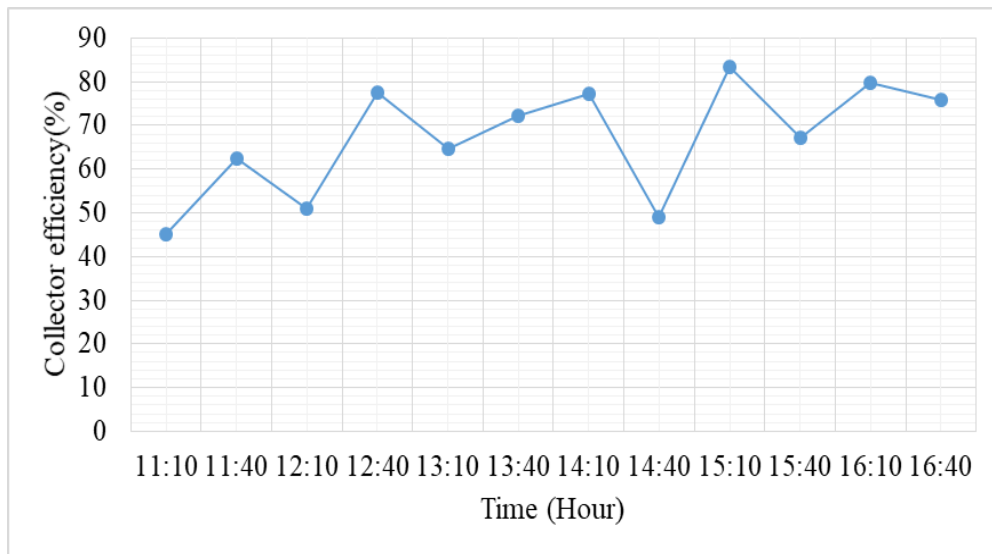


Figure 4.7: Graph of Collector Efficiency.

- Collector area , $A_c = 0.48 \times 0.48 = 0.2304m$
- Mean solar insolation , $I_s = 721.25W/m^2$
- Mean collector air temperature = $42.0708^\circ C = 315.2208K$
- Mean ambient air temperature = $26.8283^\circ C = 299.9783K$
- C_p of air at mean collector air temperature = $1007J/KgK$
- Air density at $42^\circ C = 1.12Kg/m^3$
- Velocity of air at collector = $0.135m/s$

- The cross-sectional area of the collector, $A_x = 0.48 \times 0.1 = 0.048m^2$
 $\dot{m}_a = \rho_a \dot{v} = \rho_a V A_x = 1.12 \times 0.135 \times 0.048 = 0.00726kg/s$

$$\eta_c = \frac{0.00726 \times 1007 \times (315.2208 - 299.9783)}{0.2304 \times 721.25} \times 100\%$$

$$\eta_c = 67.06\%$$

The collector efficiency of 67.06% was within the range of 21% to 69% reported by Nabnean et al.(2016).

4.2. Experiment II: Load experiment with tomatoes and heater energy consumption analysis.

The experiment was conducted on Monday 28th September 2022 at the University of Zambia, Department of Agricultural Engineering to determine the energy consumed by the heater for drying the same mass of tomatoes.

- Ripe tomatoes were purchased from the market the day before the experiment and kept overnight in the refrigerator to avoid rotting.
- At 6:00 am on the day of the experiment, the mass of the tray, sample tray, and tomatoes were measured as was done in section 4.2 using an electronic scale balance (model: PE 3000, accuracy, $\pm 0.1g$).

Initial Mass of sample tray +tomatoes = 31.6g

Initial mass of tomatoes on sample tray = 31.6-4.3 = 27.3g

Initial mass of tray +sample tray + tomatoes = 975.7g

Initial mass of tomatoes = 975.7-275.6 = 700.1g

Mass of water in fresh sample = 95% \times *mass of fresh sample*

= 0.95 \times 27.3g

= 25.935g

Dry matter = *mass of fresh sample* – *mass of water in fresh sample*

$$= 27.3 - 25.935$$

$$= 1.365g$$

iii. The whole tray and sample tray of sliced tomatoes were placed in the dryer and the dryer was powered at 8:00 am. At intervals of 1 hour, the combined mass of the sample tray and its tomato was measured and recorded automatically in the computer with the use of the data logger (Model: CR 1000). The air temperature and relative humidity entering the tray, the air temperature and relative humidity leaving the tray, the ambient temperature and relative humidity, and the solar irradiance, were also measured and recorded.

The moisture content at any time (wet basis) was determined using equation 17.

Table 4.4 shows the data which was recorded throughout this experiment. On this day, the average air temperature entering the drying chamber was 60.277 °C (the average drying temperature), the average air temperature leaving the drying chamber for recirculation was 55.622°C, the average solar irradiance was 0.572kW/m², the average ambient relative humidity was 25.405%, and the average ambient temperature was 31.482°C. The total time of drying was 8 hours. Figures 4.8 and 4.9 show the tomatoes before and after drying respectively. Figure 4.10 shows the temperature, relative humidity, and solar irradiance against drying time throughout the process of drying. The average drying rate was 73.515g/hour leading to a final product weight of 38.46g with a final moisture content of 9% (wet basis). From Figure 4.10, it can be seen that the drying temperature, T_{in} , fluctuates around 60°C which is the optimum drying temperature for tomatoes.



Figure 4.8: Tomatoes before drying.



Figure 4.9: Dried tomatoes (9% moisture content).

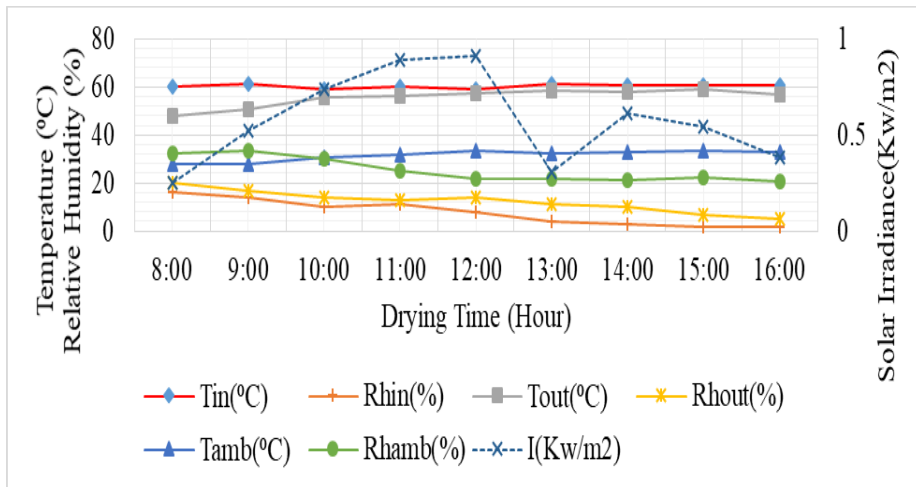


Figure 4.10: Temperature, humidity, solar irradiance versus time graph for load test

Table 4.4: Experiment II data obtained from load test with tomatoes.

<i>Drying Time (Hour)</i>	<i>Tin (°C)</i>	<i>Rhin (%)</i>	<i>Tout (°C)</i>	<i>Rhout (%)</i>	<i>Tamb (°C)</i>	<i>Rhamb (%)</i>	<i>I(Kw/m2)</i>	<i>Weight of sample (sample tray)</i>	<i>Moisture content (% wet basis)</i>	<i>Weight of product (g)</i>	<i>Drying rate (g/hour)</i>
8:00	60.13	16	48.14	20	28.1	32.48	0.25	27.3	95	700.1	0
9:00	61.2	14	50.71	17	27.82	33.21	0.52	20.3	93.27	520.58	179.52
10:00	59.23	10	55.83	14	30.47	30.38	0.74	15.1	90.96	387.23	133.35
11:00	60.18	11	56.03	13	31.86	25.07	0.89	10.2	86.62	261.57	125.66
12:00	58.78	8	57.51	14	33.51	21.95	0.91	5.8	76.46	148.73	112.84
13:00	61.11	4	58.66	11	32.47	21.64	0.71	3	54.5	76.93	71.8
14:00	60.78	3	58.03	10	32.64	21.17	0.61	2	31.75	51.28	25.65
15:00	60.55	2	58.93	7	33.49	22.11	0.54	1.7	19.71	43.59	7.69
16:00	60.54	2	56.76	5	32.98	20.64	0.38	1.5	9	38.46	5.13

Figure 4.11a and 4.11b respectively show the change in the moisture content and weight of the tomatoes during the drying period. The moisture content as well as the weight of the tomatoes significantly reduced continuously from 95% (wet basis) to 9% (wet basis) and from 700g to 38.46g respectively. From 14:00 to 16:00, the reduction of moisture content and the weight of the tomatoes reduces slowly because the product is approaching the weight of the dry matter.

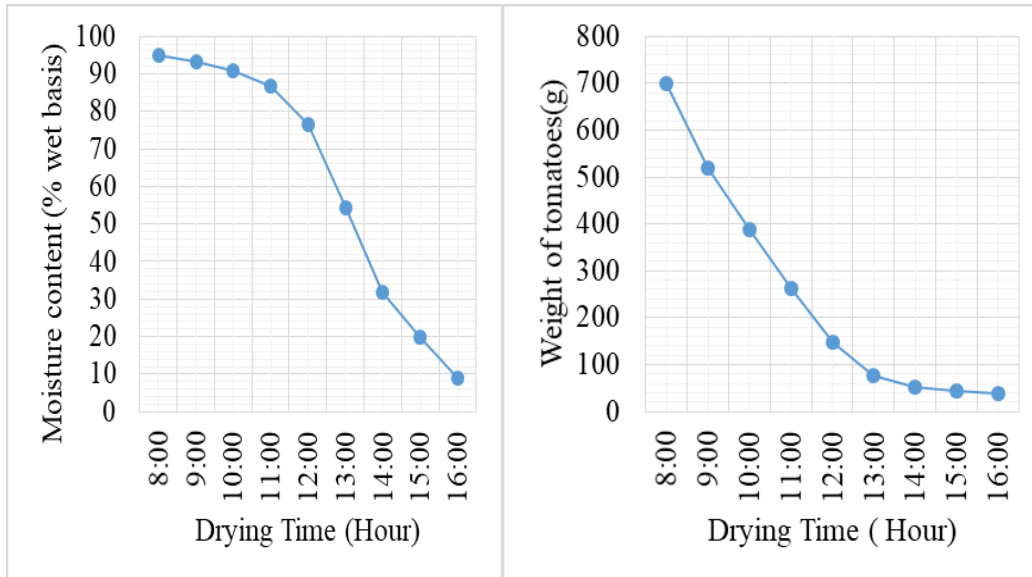


Figure 4.11a: Moisture content versus time. Figure 4.11b: Weight of sample versus time.

4.2.1. Drying chamber efficiency

Figure 4.12 shows the graph of drying chamber efficiency versus time.

There was a fall in the drying chamber efficiency from 8:00 to 10:00 because at this time, the moisture content of the tomatoes was still very high and the temperature of the air entering the drying chamber was already at optimum, so most of the heat supplied is being absorbed by the tomatoes to evaporate the moisture and since it was still morning, the ambient temperature was low. From 10:00 to 15:00, the drying chamber efficiency fluctuated due to periodic cloud cover and wind, causing the ambient temperature which is a key parameter to determining the drying chamber efficiency to also fluctuate. From 15:00 to 16:00, the drying chamber efficiency rised again because of the absence of

cloud cover and wind, hence the ambient temperature increased leading to a rise in the drying chamber efficiency.

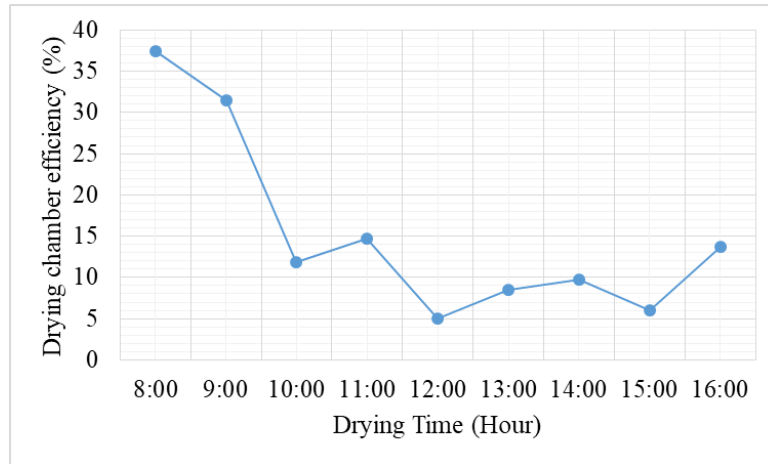


Figure 4.12: Drying chamber efficiency- time graph.

By substituting the obtained average parameters, the drying chamber efficiency was determined as.

$$\eta_{dc} = \frac{60.27778 - 55.62222}{60.27778 - 31.48222} \times 100\%$$

$$\eta_{dc} = 16.16\%$$

This value is higher than the 10% obtained by Nandakumar, et al., (2018) who used reflectors in the hybrid system for drying cashew nuts.

4.2.2. Drying efficiency

$$\eta_d = \frac{0.7 \times 3.98(60.277 - 31.482) + (0.661 \times 2257)}{0.572 \times 0.2304 \times (8 \times 3600) + 0.828} \times 100\%$$

$$\eta_d = 41.41\%$$

This drying efficiency is about two times higher than the efficiency of 20.92% obtained by Velmurugan, et al., (2013) who dried grapes with recirculation of hot air.

4.2.3. Drying rate

Figure 4.13 shows the drying rate versus the time graph of the tomato. The average drying rate was 73.515g/hour. The final mass of the initially 700g tomato was measured to be 38.46g after drying with a final moisture content of 9%.

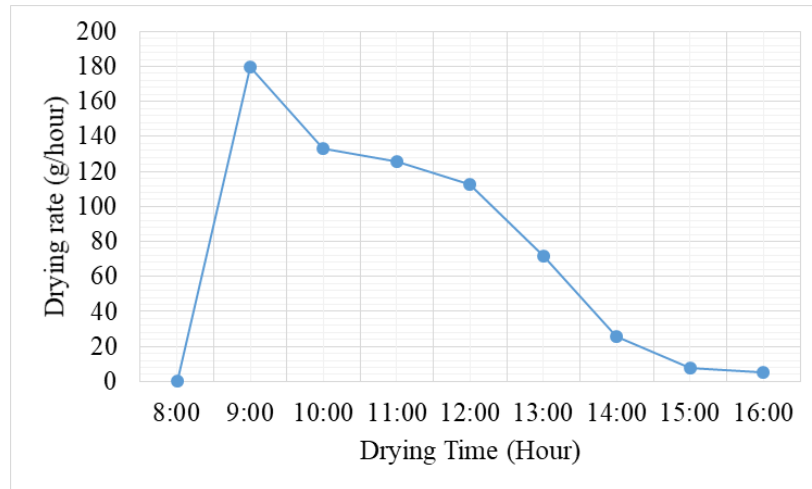


Figure 4.13: Drying rate versus time graph of tomato.

Mass of water in fresh sample = 95% \times mass of fresh sample

$$= 95\% \times 700g$$

$$= 665g$$

Dry matter (DM) = mass of fresh sample – mass of water in fresh sample

$$= 700g - 665g$$

$$= 35g$$

\therefore Final moisture content of dried product = $\frac{\text{final mass of dried product} - \text{dry matter}}{\text{final mass of dried product}}$

$$= \frac{38.46 - 35}{38.46} \times 100\%$$

$$= 9\%$$

4.2.4. Electrical energy consumption.

Appendix II shows the table of the energy consumed by the electric heater versus time during the drying period. During this experiment, the ON time of the heater was measured each moment the heater came on using a stopwatch together with the current it draws using a Clamp Ammeter. These data were recorded and analyzed throughout the experiment until the tomatoes got dried. Figure 4.14 shows the graph of the energy consumed by the heater versus the time of consumption throughout the process of drying.

The total energy consumed by the heater was obtained by summing the individual energies per time of consumption which was obtained to be 1562.87KJ. The energy required for drying to 10% moisture content as analyzed earlier in section 3.2 was 1669.5562KJ.

4.2.5. Total energy received by dryer.

The total energy received by the dryer E_{Total} is the sum of the solar energy reaching the dryer E_{Solar} and the electrical energy supplied by the heater E_{heater} .

$$E_{Total} = E_{Solar} + E_{heater}$$

$$E_{Total} = (I_{total} \times (A_d) \times 1hour) + E_{heater}$$

$$E_{Total} = 5.425 \times (0.5) \times 1 \times 3600 + 1562.87KJ$$

$$E_{Solar} = 9765KJ$$

$$E_{heater} = 1562.87KJ$$

$$\text{Hence, } E_{Total} = 9765KJ + 1562.87KJ$$

$$E_{Total} = 11327.87KJ$$

Some of this energy is shielded by the polyethylene plastic such as UV light while other is lost through low insulation.

The energy required for drying to 10% wet basis moisture content was 1669.5562KJ.

Therefore the energy lost is $11327.87\text{KJ} - 1669.5562\text{KJ} = 9658.314\text{KJ}$

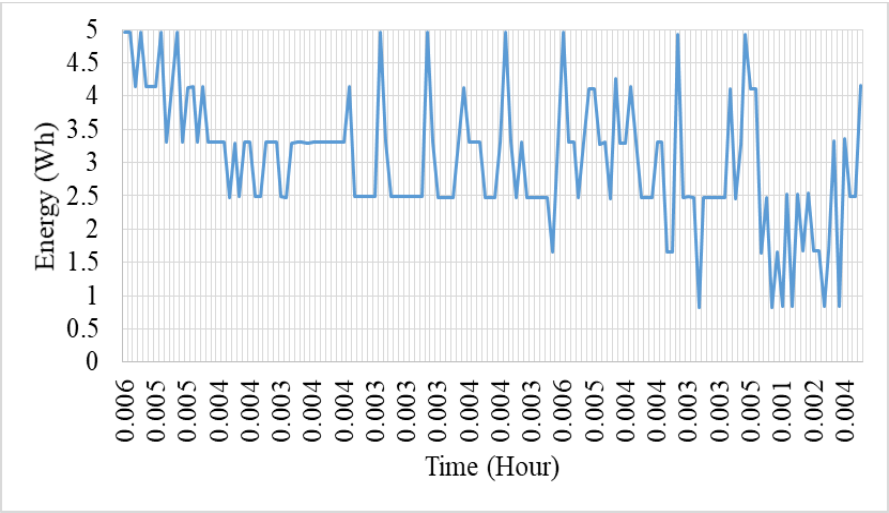


Figure 4.14: Energy consumed versus time of consumption.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the conclusions and recommendations drawn from the study. The conclusions were drawn based on the achievement of each stated specific objective.

5.1. Conclusions

5.1.1 To size the various dryer components on a given tomatoes quantity.

- A forced convection hybrid solar tunnel dryer was designed with Auto Cad showing the position of the various dryer components such as the tray, PVC pipe, the control unit, the collector, etc.
- The automatic temperature monitoring and control unit was designed in Proteus IDE.
- The sizes of the various components of the control unit in terms of energy consumption were selected and the PV system needed to provide this energy for a particular time per component was appropriately sized.

5.1.2 To build the dryer with all its components.

- The forced convection hybrid solar tunnel dryer was completely fabricated with automatic temperature monitoring and a control circuit.
- The PV system was installed.
- The entire hybrid solar-Photovoltaic tunnel dryer with automatic temperature control and air recirculation was a bit complex and fairly affordable having a basic cost of USD 1,467 as seen in Appendix I.

5.1.3 To determine the performance of the dryer.

- After the fabrication of the temperature monitoring and control unit, it was less sensitive and slow to respond to a fluctuation in temperature by switching ON and OFF the active elements through the relays due to insufficient current provided by the Arduino board to energize the relay coils. Sometimes the coils would be energized and sometimes they would not be energized at all. This led to the design, fabrication, and incorporation of a current booster circuit into each relay as shown in figure 3.2b. This circuit amplifies the small current leaving the

Arduino digital pins to the relay coil to enhance its sensitivity and energization. The adjustment and testing of this current booster circuit of the control unit was done with the entire assembly of the dryer at no-load in three experiments by testing and adjusting until at the third adjustment where the system worked at desired.

- In the no-load experiment, an average drying chamber temperature of 59.951°C was obtained under automatic control which is in the set range of optimum drying temperature of tomatoes. During the load experiments with tomatoes, the respective average drying chamber air temperature for Experiment I and Experiment II were 60.331°C and 60.277°C respectively, which also could be rounded down to the optimum temperature of drying which is 60°C.
- From the load Experiments I and II, the dryer performance was determined where the drying chamber efficiencies were obtained as 10.24% and 16.16%, drying efficiency of 31.53% and 41.41%, and a drying rate of 66.31g/hour to a final moisture content of 5.30% (wet basis) and 73.515g/hour respectively. These are typical for forced convection solar dryers in hybrid mode from reviewed literature. The presence of the backup heater was what enabled the high drying rate. The dryer automatic control unit and active components such as fans were powered by a PV system thereby making it sustainable and suitable for areas without access to an electricity grid. The use of AC mains power supply and direct solar energy makes a hybrid sustainable system. The dryer can therefore be used to dry tomatoes at any time irrespective of the weather conditions as far as there is electricity.
- The collector efficiency was obtained from a no-load experiment with the heater off and automatic control unit as stated in reviewed literature. It was determined as 67.06% which is typical from the reviewed literature (Nandakumar, et al., 2018).
- The dryer was designed and fabricated to dry tomatoes. However, it can also dry bananas and vegetables which have lower moisture contents than tomatoes. The dryer has an in-built weather station and a programmed calculator which shows the operator the average amount of moisture in grams that will be removed from

the food product based on the food mass and the desired final moisture content which was inputted by the operator at the control unit.

- From the above conclusions, the hybrid solar-photovoltaic tunnel dryer is well suitable for use by both farmers and small-scale industries.

5.2 Recommendation

- Drying of meat and fish can be done on this dryer but before that, the program code of the automatic control system will need to be updated from the Arduino IDE and Nextion IDE and then loaded to their microcontroller and microprocessor respectively.
- The dryer can be designed with the control being capable to calculate and display the electrical energy consumed per time by the heater from the time when it comes ON to stabilize the temperature to when it goes OFF throughout drying until when the product gets dried, to determine the total amount of electrical energy consumed from the AC main throughout the drying process.
- A study can be done by comparing the performance of the dryer when the recirculated air that exits the drying chamber is reheated and fed to the drying chamber with another dryer in which only the ambient air is heated and sent to the drying chamber.
- Further works will look at the modelling of the airflow in the dryer and PVC pipe, heat distribution in the drying chamber to minimise heat losses, and to obtain optimal design parameters for the drying chamber from a software to fabrication.
- A study can be done by increasing the number of trays in the drying chamber and increasing the quantity of tomatoes to investigate the drying time and energy consumption.
- The dryer can be optimise for continuous drying and automatic measurement of the product moisture content in the drying chamber and then gives a signal to the operator when the product is dried to a desired moisture content.

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Appendix I: Energy consumed versus current by the heater throughout drying time.

CURRENT (A)	TIME (S)	TIME (Min)	TIME (Hour)	Energy (Wh)	Energy (kJ)
3.45	21	0.35	0.005833	4.83	17.388
3.45	21	0.35	0.005833	4.83	17.388
3.45	20	0.333	0.005556	4.6	16.56
3.45	20	0.333	0.005556	4.6	16.56
3.45	18	0.3	0.005	4.14	14.904
3.45	18	0.3	0.005	4.14	14.904
3.45	19	0.317	0.005278	4.37	15.732
3.44	20	0.333	0.005556	4.586667	16.512
3.44	14	0.233	0.003889	3.210667	11.5584
3.44	18	0.3	0.005	4.128	14.8608
3.44	20	0.333	0.005556	4.586667	16.512
3.45	13	0.217	0.003611	2.99	10.764
3.44	17	0.283	0.004722	3.898667	14.0352
3.45	18	0.3	0.005	4.14	14.904
3.45	14	0.233	0.003889	3.22	11.592
3.45	18	0.3	0.005	4.14	14.904
3.45	16	0.267	0.004444	3.68	13.248
3.45	15	0.25	0.004167	3.45	12.42
3.45	14	0.233	0.003889	3.22	11.592
3.45	13	0.217	0.003611	2.99	10.764
3.44	12	0.2	0.003333	2.752	9.9072
3.43	13	0.217	0.003611	2.972667	10.7016
3.45	12	0.2	0.003333	2.76	9.936
3.45	14	0.233	0.003889	3.22	11.592
3.44	13	0.217	0.003611	2.981333	10.7328
3.45	11	0.183	0.003056	2.53	9.108
3.45	10	0.167	0.002778	2.3	8.28
3.45	15	0.25	0.004167	3.45	12.42
3.45	14	0.233	0.003889	3.22	11.592
3.45	16	0.267	0.004444	3.68	13.248
3.45	12	0.2	0.003333	2.76	9.936

3.44	10	0.167	0.002778	2.293333	8.256
3.43	17	0.283	0.004722	3.887333	13.9944
3.45	16	0.267	0.004444	3.68	13.248
3.44	16	0.267	0.004444	3.669333	13.2096
3.43	15	0.25	0.004167	3.43	12.348
3.45	14	0.233	0.003889	3.22	11.592
3.45	16	0.267	0.004444	3.68	13.248
3.44	15	0.25	0.004167	3.44	12.384
3.45	13	0.217	0.003611	2.99	10.764
3.45	14	0.233	0.003889	3.22	11.592
3.45	13	0.217	0.003611	2.99	10.764
3.45	14	0.233	0.003889	3.22	11.592
3.45	17	0.283	0.004722	3.91	14.076
3.45	11	0.183	0.003056	2.53	9.108
3.45	10	0.167	0.002778	2.3	8.28
3.45	21	0.35	0.005833	4.83	17.388
3.45	12	0.2	0.003333	2.76	9.936
3.45	12	0.2	0.003333	2.76	9.936
3.45	20	0.333	0.005556	4.6	16.56
3.45	13	0.217	0.003611	2.99	10.764
3.45	10	0.167	0.002778	2.3	8.28
3.45	12	0.2	0.003333	2.76	9.936
3.45	11	0.183	0.003056	2.53	9.108
3.45	12	0.2	0.003333	2.76	9.936
3.45	11	0.183	0.003056	2.53	9.108
3.45	10	0.167	0.002778	2.3	8.28
3.45	12	0.2	0.003333	2.76	9.936
3.45	13	0.217	0.003611	2.99	10.764
3.45	13	0.217	0.003611	2.99	10.764
3.43	12	0.2	0.003333	2.744	9.8784
3.43	13	0.217	0.003611	2.972667	10.7016
3.43	11	0.183	0.003056	2.515333	9.0552
3.43	15	0.25	0.004167	3.43	12.348
3.44	13	0.217	0.003611	2.981333	10.7328
3.44	17	0.283	0.004722	3.898667	14.0352
3.44	14	0.233	0.003889	3.210667	11.5584

3.44	13	0.217	0.003611	2.981333	10.7328
3.44	16	0.267	0.004444	3.669333	13.2096
3.44	12	0.2	0.003333	2.752	9.9072
3.44	11	0.183	0.003056	2.522667	9.0816
3.44	12	0.2	0.003333	2.752	9.9072
3.44	15	0.25	0.004167	3.44	12.384
3.44	21	0.35	0.005833	4.816	17.3376
3.44	13	0.217	0.003611	2.981333	10.7328
3.44	12	0.2	0.003333	2.752	9.9072
3.44	13	0.217	0.003611	2.981333	10.7328
3.44	11	0.183	0.003056	2.522667	9.0816
3.44	12	0.2	0.003333	2.752	9.9072
3.44	9	0.15	0.0025	2.064	7.4304
3.44	9	0.15	0.0025	2.064	7.4304
3.43	9	0.15	0.0025	2.058	7.4088
3.44	8	0.133	0.002222	1.834667	6.6048
3.44	15	0.25	0.004167	3.44	12.384
3.44	13	0.217	0.003611	2.981333	10.7328
3.45	15	0.25	0.004167	3.45	12.42
3.44	13	0.217	0.003611	2.981333	10.7328
3.44	12	0.2	0.003333	2.752	9.9072
3.44	18	0.3	0.005	4.128	14.8608
3.43	15	0.25	0.004167	3.43	12.348
3.43	18	0.3	0.005	4.116	14.8176
3.42	13	0.217	0.003611	2.964	10.6704
3.44	12	0.2	0.003333	2.752	9.9072
3.41	12	0.2	0.003333	2.728	9.8208
4.44	16	0.267	0.004444	4.736	17.0496
3.43	16	0.267	0.004444	3.658667	13.1712
3.43	16	0.267	0.004444	3.658667	13.1712
3.45	19	0.317	0.005278	4.37	15.732
3.45	14	0.233	0.003889	3.22	11.592
3.44	12	0.2	0.003333	2.752	9.9072
3.44	13	0.217	0.003611	2.981333	10.7328
3.43	12	0.2	0.003333	2.744	9.8784
3.44	15	0.25	0.004167	3.44	12.384

3.45	15	0.25	0.004167	3.45	12.42
3.44	8	0.133	0.002222	1.834667	6.6048
3.44	6	0.1	0.001667	1.376	4.9536
3.42	23	0.383	0.006389	5.244	18.8784
3.44	9	0.15	0.0025	2.064	7.4304
3.45	9	0.15	0.0025	2.07	7.452
3.43	10	0.167	0.002778	2.286667	8.232
3.43	5	0.083	0.001389	1.143333	4.116
3.43	11	0.183	0.003056	2.515333	9.0552
3.43	12	0.2	0.003333	2.744	9.8784
3.43	17	0.283	0.004722	3.887333	13.9944
3.43	11	0.183	0.003056	2.515333	9.0552
3.43	11	0.183	0.003056	2.515333	9.0552
3.43	21	0.35	0.005833	4.802	17.2872
3.42	12	0.2	0.003333	2.736	9.8496
3.42	15	0.25	0.004167	3.42	12.312
3.42	21	0.35	0.005833	4.788	17.2368
3.42	19	0.317	0.005278	4.332	15.5952
3.42	18	0.3	0.005	4.104	14.7744
3.43	8	0.133	0.002222	1.829333	6.5856
3.43	9	0.15	0.0025	2.058	7.4088
3.46	5	0.083	0.001389	1.153333	4.152
3.46	7	0.117	0.001944	1.614667	5.8128
3.5	4	0.067	0.001111	0.933333	3.36
3.5	9	0.15	0.0025	2.1	7.56
3.47	6	0.1	0.001667	1.388	4.9968
3.5	11	0.183	0.003056	2.566667	9.24
3.5	8	0.133	0.002222	1.866667	6.72
3.52	9	0.15	0.0025	2.112	7.6032
3.47	7	0.117	0.001944	1.619333	5.8296
3.5	8	0.133	0.002222	1.866667	6.72
3.47	4	0.067	0.001111	0.925333	3.3312
3.48	6	0.1	0.001667	1.392	5.0112
3.46	15	0.25	0.004167	3.46	12.456
3.5	3	0.05	0.000833	0.7	2.52
3.5	13	0.217	0.003611	3.033333	10.92

3.46	10	0.167	0.002778	2.306667	8.304
3.46	11	0.183	0.003056	2.537333	9.1344
3.47	18	0.3	0.005	4.164	14.9904

Appendix II: Written and uploaded Arduino microcontroller code for automatic temperature monitoring and control.

```
#include <SimpleDHT.h>

#include <SoftwareSerial.h> //adding serial ports

// Created by santosomar Ωr using SimpleDHT library to read data from two DHT11
sensors

// for DHT11,

// VCC: 5V or 3V

// GND: GND

// SENSOR 1 is in Digital Data pin: 2

// SENSOR 2 is in Digital Data pin: 4

//...HOW TO USE THE SYSTEM.....

//.. FIRST PUT ON THE LAMP.

//...SET THE DRYER CALCULATOR THE AMOUNT OF WATER TO BE
WITHDRAWN.

//...ON THE HOME PAGE, CHOSE THE FOOD TO BE DRIED AND PRESS START.

//... VIEW WEATHER STATTION BY GOING BACK TO THE HOME PAGE

//...YOU CAN GO BACK AND FORT FROM WEATHER STATION TO DRYER
DETAILS PAGE

//...FOR ANY DISTURBACNCE,RESET THE MICROCONTROLLER BY
PRESSING THE RESET BUTTON FOR PROPER FUNCTIONALITY.

SoftwareSerial mySerial(0,1); // RX, TX

int dataPinSensor1 = 2;

int dataPinSensor2 = 4;

SimpleDHT22 dht1(dataPinSensor1); // setting DHT22 SENSORS 1 and 2 data pins

SimpleDHT22 dht2(dataPinSensor2);
```

```

//float Mis; //mass of food to be dried

//float Mfwb ; //desired level of dryness // this was not executed as was not an
objective

float humcT;

float humcB;

float humcC;

float fMfwb;

float num1;

float num;

float denum;

float Mw;

float MiwbT=0.95; //standard initial wet basis moisture content of tomato=95.0%

float MiwbB=0.80; //Standard initial wet basis moisture content for banana=80%

float MiwbC=0.80; //Standard initial wet basis moisture content for cabbage=80%

float grams;

String fresults;

/* this function is mainly to send data to the nextion screen that is text and values */

void sendText(String location, String data) {

    Serial.print(location);

    Serial.write(0x22);

    Serial.print(data );

    Serial.write(0x22);

    //PROTOCOLS WHICH THE MUST BE SEND TO THE NEXTION DISPLAY
    FROM ARDUINO FOR IT TO UNDERSTAND THAT IT MUST DISPLAY TEXT

    Serial.write(0xFF);

    Serial.write(0xFF);

```

```

Serial.write(0xFF);

delay(1);

}

// function for sending numbers to the nextion screen.

void sendNum(String location, int data) {

  Serial.print(location);

  // Serial.write(0x22); // don't put dis for numbers

  Serial.print(data );

  // Serial.write(0x22); // don't put dis for numbers

  Serial.write(0xFF);

  Serial.write(0xFF);

  Serial.write(0xFF);

  delay(1);

}

// set data as written in command code

void sendData(String location, String data) {

  Serial.print(location);

  //Serial.write(0x22);

  Serial.print(data );

  // Serial.write(0x22);

  Serial.write(0xFF);

  Serial.write(0xFF);

  Serial.write(0xFF);

  delay(1);

```

```

}

//.....setting buttons which will be pressed.....

byte buttons=0;

byte val[7]= {0}; // buffer to hold buttons

void serialEvent(){

  Serial.flush(); //ignore any other data until the present one is completely transmitted

  Serial.readBytes(val,7);

  delay(1);

  // Serial.println(val[4]);

  //from the nextion screen the procedure for sending a data in bytes is as follows

  // 65 07 02 01 FF FF FF ... where converting it to bytes we have 65=101 07=7 02=2
  01=1 FF FF FF

  buttons= val[0] + val[1] + val[2]+ val[3]; // all first bytes to know which button is
  pressed

  for(int i=0; i<7;i++){ // clear all saved bytes

    val[i]=0;

  }

  //Serial.println(buttons);

}

int Recirculationfans = 7; //Air recirculation fan

int Exhaustfan = 11; //exhaust fan

int Heater1 = 5; //80W heate

int Buzzer = 3; //buzzer pin

int Lamb = 9; //Lamb pin

int sensors = 8; // power pin of two sensors

int Hfan = 10; //Heater fan

```

```

//.....
void setup() {
  // Begin I2C

  pinMode(Recirculationfans,OUTPUT);    //Configuring all the pins as output pins
  pinMode(Exhaustfan,OUTPUT);
  pinMode(Heater1,OUTPUT);
  pinMode(Buzzer,OUTPUT);
  pinMode(Lamb,OUTPUT);
  pinMode(sensors,OUTPUT); //DHT22 SENSORS POWER PINS
  pinMode(Hfan,OUTPUT);
  Serial.begin(9600);
  mySerial.begin(9600);
}

void loop() {
  if(buttons==111){
    sendText("t72.txt=", "clear");

    buttons=0;          //clear contents of button in the microcontroller to receive
more data.

  }

  //putting ON lamb during the night
  while(buttons==115){

    digitalWrite(Lamb, HIGH); //if button is 444 first time put lamb ON

    buttons=0;

  }

  while(buttons==116){

```

```

digitalWrite(Lamb,LOW); // if button is pressed 444 second time, put lamb OFF.

buttons=0;

}

//digitalWrite(signalpin,HIGH);

//delay(1000);

//digitalWrite(signalpin, LOW);

// delay(1000);

// end of code for LAMB ON

while(buttons==119){

    //PUT MAIN CODE HERE TO RUN REPEATEDLY

    calculatorT();

    humcT=Mfwb;    //assign the set level of dryness to humcT

    buttons=0;    //clear buttons to hold more data

}

while(buttons==120){

    //PUT MAIN CODE HERE TO RUN REPEATEDLY

    calculatorB();

    humcB=Mfwb;    //assign the set level of dryness to humcB

    buttons=0;    //clear buttons to hold more data

}

while(buttons==121){

    //PUT MAIN CODE HERE TO RUN REPEATEDLY

    calculatorC();

    humcC=Mfwb;    //assign the set level of dryness to humcT

    buttons=0;    //clear buttons to hold more data

```

```

}

while(buttons==112){

    digitalWrite(sensors, HIGH);

    tomato();

    buttons=0;

}

while(digitalRead(sensors)==HIGH){ // while the sensors are still High, then continue
testing tomatoe.

tomato();

}

while (buttons==131){

    digitalWrite(sensors,LOW);

    buttons=0;

}

while(buttons==113){

    digitalWrite(sensors, HIGH);

    banana();

    buttons=0;

}

while(digitalRead(sensors)==HIGH){ // while the sensors are still High, then continue
testing tomatoe.

banana();

}

while (buttons==141){

    digitalWrite(sensors,LOW);

    buttons=0;

```

```

}

while(buttons==114){

    digitalWrite(sensors, HIGH);

    cabbage();

    buttons=0;

}

while(digitalRead(sensors)==HIGH){ // while the sensors are still High, then continue
testing tomatoe.

cabbage();

}

while (buttons==151){

    digitalWrite(sensors,LOW);

    buttons=0;

}

}

//..... CREATING FUNCTIONS THE PRODUCTS TO BE DRIED AS
STATED.....

//.....drying tomato.....

void tomato(){

    // Reading data from sensor 1...

    mySerial.println("=====");

    // Reading data from sensor 1...

    //mySerial.println("Getting data from sensor 1...");

```

```

// read without samples.

byte temperature = 0;

byte humidity = 0;

int err = SimpleDHTErrSuccess;

if ((err = dht1.read(&temperature, &humidity, NULL)) != SimpleDHTErrSuccess) {
    mySerial.print("Read      Sensor      1      failed,      err=");
mySerial.print(SimpleDHTErrCode(err));

    mySerial.print(","); mySerial.println(SimpleDHTErrDuration(err));delay(1000);

return;
}

mySerial.print("Sample OK: ");

mySerial.print((String)temperature); mySerial.print(" *C, ");

mySerial.print((String)humidity); mySerial.println(" H humidity");

// Reading data from sensor 2...

// =====

mySerial.println("Getting data from sensor 2...");

byte temperature2 = 0;

byte humidity2 = 0;

if ((err = dht2.read(&temperature2, &humidity2, NULL)) != SimpleDHTErrSuccess) {
    mySerial.print("Read      Sensor      2      failed,      err=");
mySerial.print(SimpleDHTErrCode(err));

    mySerial.print(","); mySerial.println(SimpleDHTErrDuration(err)); delay(1000);

return;
}

```

```

mySerial.print("Sample OK: ");

mySerial.print((String)temperature2); mySerial.print(" *C, ");
mySerial.print((String)humidity2); mySerial.println(" H humidity");

sendText("t222.txt=", (String)temperature);
sendText("t223.txt=", (String)humidity); //display value on nextion for tomato
sendText("t305.txt=", (String)temperature2);
sendText("t306.txt=", (String)humidity2);
sendText("t224.txt=", (String)temperature2);
sendText("t225.txt=", (String)humidity2);

//..... testing conditions .....

if((int)temperature<=58){
    digitalWrite(Hfan, HIGH);

    digitalWrite(Heater1, HIGH);// Air fans air switched ON through a relay at pin2 of
    arduino.

    //if temperature is between 58 oC and 62 oC, then no heater but else,
    heater 1(100W) ON and after 50 minutes temperature has not reach 58 oC, emergency
    heater ON.

    sendText("t5.txt=", "ON"); //display state of heater1 on nextion
    digitalWrite(Recirculationfans, HIGH); //air recirculation fan ON
    sendText("t11.txt=", "ON"); //recirculation fan ON on nextion.
    digitalWrite(Exhaustfan, LOW);
    sendText("t13.txt=", "OFF"); // Exhaust fan OFF on nextion
}

```

```

if((int)temperature>=59&&(int)temperature<=62){
digitalWrite(Heater1,LOW); //heater1 OFF
digitalWrite(Hfan,LOW); //heater fan OFF
digitalWrite(Recirculationfans,HIGH); // recirculation fans OFF
digitalWrite(Exhaustfan, LOW); // exhaust fan comes on
sendText("t5.txt=", "OFF"); //display state of heater1 on nextion
sendText("t11.txt=", "OFF"); //recirculation fan OFF on nextion.
sendText("t13.txt=", "OFF"); // Exhaust fan ON on nextion
}

if((int)temperature>=63){
digitalWrite(Heater1,LOW); //heater1 OFF
digitalWrite(Hfan,LOW);
digitalWrite(Recirculationfans,LOW); // recirculation fans OFF
digitalWrite(Exhaustfan, HIGH); // exhaust fan comes on
sendText("t5.txt=", "OFF"); //display state of heater1 on nextion
sendText("t11.txt=", "OFF"); //recirculation fan OFF on nextion.
sendText("t13.txt=", "ON"); // Exhaust fan ON on nextion
}

if((int)humidity==humcT){
digitalWrite(Buzzer,HIGH); //product is dry
sendText("t18.txt=", "OFF-LOAD"); //OFF-LOAD dryer
}

while(buttons==117){

```

```

digitalWrite(Buzzer,LOW);

sendText("t18.txt=", "Waiting");

buttons=0;

}

//testing conditions

// DHT11 sampling rate is 1HZ.

delay(1000);          //1 second delay
}

//.....drying bananas.....

void banana(){

// Reading data from sensor 1...

mySerial.println("=====");

// Reading data from sensor 1...

//mySerial.println("Getting data from sensor 1...");

// read without samples.

byte temperature = 0;

byte humidity = 0;

int err = SimpleDHTErrSuccess;

if ((err = dht1.read(&temperature, &humidity, NULL)) != SimpleDHTErrSuccess) {

    mySerial.print("Read          Sensor          1          failed,          err=");
mySerial.print(SimpleDHTErrCode(err));
}
}

```

```

    mySerial.print(","); mySerial.println(SimpleDHTErrDuration(err));delay(1000);
return;
}

mySerial.print("Sample OK: ");
mySerial.print((String)temperature); mySerial.print(" *C, ");
mySerial.print((String)humidity); mySerial.println(" H humidity");

// Reading data from sensor 2...

// =====
mySerial.println("Getting data from sensor 2...");

byte temperature2 = 0;

byte humidity2 = 0;

if ((err = dht2.read(&temperature2, &humidity2, NULL)) != SimpleDHTErrSuccess) {
    mySerial.print("Read      Sensor      2      failed,      err=");
mySerial.print(SimpleDHTErrCode(err));

    mySerial.print(","); mySerial.println(SimpleDHTErrDuration(err)); delay(1000);
    return;
}

mySerial.print("Sample OK: ");

mySerial.print((String)temperature2); mySerial.print(" *C, ");
mySerial.print((String)humidity2); mySerial.println(" H humidity");

sendText("t226.txt=", (String)temperature);
sendText("t227.txt=", (String)humidity);    //display value on nextion for tomato
sendText("t305.txt=", (String)temperature2);
sendText("t306.txt=", (String)humidity2);

```

```

    sendText("t228.txt=", (String)temperature2);

    sendText("t229.txt=", (String)humidity2);

    //..... testing conditions .....

    while((int)temperature<=68){

        digitalWrite(Heater1, HIGH); // Air fans air switched ON through a relay at pin2 of
        arduino.

        //if temperature is between 58 oC and 62 oC, then no heater but else,
        heater 1(100W) ON and after 50 minutes temperature has not reach 58 oC, emergency
        heater ON.

        sendText("t37.txt=", "ON"); //display state of heater1 on nextion

        digitalWrite(Recirculationfans, HIGH); //air recirculation fan ON

        sendText("t40.txt=", "ON"); //recirculations fan ON on nextion.

        sendText("t41.txt=", "OFF"); // Exhaust fan OFF on nextion
    }

    while((int)temperature>=72){

        digitalWrite(Heater1, LOW); //heater1 OFF

        digitalWrite(Recirculationfans, LOW); //Recirculation fans OFF

        digitalWrite(Exhaustfan, HIGH); // exhaust fan comes on

        sendText("t37.txt=", "OFF"); //display state of heater1 on nextion

        sendText("t40.txt=", "OFF"); //recirculations fan OFF on nextion.

        sendText("t41.txt=", "ON"); // Exhaust fan ON on nextion
    }

    if((int)humidity==humcT){

        digitalWrite(Buzzer, HIGH); //product is dry

        sendText("t111.txt=", "OFF-LOAD"); //OFF-LOAD dryer
    }

```

```

if(buttons==117){
    digitalWrite(Buzzer,LOW);
    sendText("t111.txt=", "Waiting");
    buttons=0;
}

//testing conditions

// DHT11 sampling rate is 1HZ.
delay(1000);
}

//.....drying cabbage.....

void cabbage(){
    // Reading data from sensor 1...

mySerial.println("=====");

    // Reading data from sensor 1...

//mySerial.println("Getting data from sensor 1...");

// read without samples.

byte temperature = 0;

byte humidity = 0;

int err = SimpleDHTErrSuccess;

if ((err = dht1.read(&temperature, &humidity, NULL)) != SimpleDHTErrSuccess) {
    mySerial.print("Read          Sensor          1          failed,          err=");
mySerial.print(SimpleDHTErrCode(err));

    mySerial.print(","); mySerial.println(SimpleDHTErrDuration(err));delay(1000);

return;
}

```

```

}

mySerial.print("Sample OK: ");

mySerial.print((String)temperature); mySerial.print(" *C, ");

mySerial.print((String)humidity); mySerial.println(" H humidity");

// Reading data from sensor 2...

// =====

mySerial.println("Getting data from sensor 2...");

byte temperature2 = 0;

byte humidity2 = 0;

if ((err = dht2.read(&temperature2, &humidity2, NULL)) != SimpleDHTErrSuccess) {

    mySerial.print("Read          Sensor          2          failed,          err=");
mySerial.print(SimpleDHTErrCode(err));

    mySerial.print(","); mySerial.println(SimpleDHTErrDuration(err)); delay(1000);

    return;

}

mySerial.print("Sample OK: ");

mySerial.print((String)temperature2); mySerial.print(" *C, ");

mySerial.print((String)humidity2); mySerial.println(" H humidity");

sendText("t300.txt=", (String)temperature);

sendText("t301.txt=", (String)humidity); //display value on nextion for tomato

sendText("t305.txt=", (String)temperature2);

sendText("t306.txt=", (String)humidity2);

sendText("t302.txt=", (String)temperature2);

```

```

    sendText("t303.txt=", (String)humidity2);

//..... testing conditions .....

while((int)temperature<=52){

    digitalWrite(Heater1, HIGH); // Air fans air switched ON through a relay at pin2 of
    arduino.

        //if temperature is between 58 oC and 62 oC, then no heater but else,
        heater 1(100W) ON and after 50 minutes temperature has not reach 58 oC, emergency
        heater ON.

    sendText("t57.txt=", "ON"); //display state of heater1 on nextion
    digitalWrite(Recirculationfans, HIGH); //air recirculation fan ON
    sendText("t60.txt=", "ON"); //recirculation fan ON on nextion.
    sendText("t61.txt=", "OFF"); // Exhaust fan OFF on nextion
}

while((int)temperature>=56){

    digitalWrite(Heater1, LOW); //heater1 OFF
    digitalWrite(Recirculationfans, LOW); //recirculation fans OFF
    digitalWrite(Exhaustfan, HIGH); // exhaust fan comes on
    sendText("t57.txt=", "OFF"); //display state of heater1 on nextion
    sendText("t60.txt=", "OFF"); //recirculation fan OFF on nextion.
    sendText("t61.txt=", "ON"); // Exhaust fan ON on nextion
}

if((int)humidity==humcT){

    digitalWrite(Buzzer, HIGH); //product is dry
    sendText("t64.txt=", "OFF-LOAD"); //OFF-LOAD dryer
}

if(buttons==117){

```

```

digitalWrite(Buzzer,LOW);

sendText("t64.txt=", "Waiting");

buttons=0;

}

//testing conditions

// DHT11 sampling rate is 1HZ.
delay(1000);
}
//..... HYBRID Calculator .....
//FOR TOMATO
void calculatorT(){
  while (Serial.available()>0){
  }

  Mis=Serial.parseFloat(); //this reads the floating number of mass of food and assign to
Mis variable but the dryer will be limited to 0.7kg of food for best performance.

  while (Serial.available()>0){ //waiting for level of dryness.

  }

  Mfwb=Serial.parseFloat(); //this reads the level of dryness and assign to Mfwb
variable

  sendText("t75.txt=", "processing");

  num1=MiwT-Mfwb;

  num=Mis*num1;

  denum=1-Mfwb;

  Mw=(num/denum); //which is the amount of moisture to be removed.

```

```

grams=(1000*Mw);      //convert to grams of water
fresults=round(grams); //round up floating value
sendText("t400.txt=",fresults); //display results on nextion
sendText("t75.txt=", "complete");

//END OF CALCULATOR CODE FOR TOMATO
}

// FOR BANANA
void calculatorB(){
    while (Serial.available()>0){
    }

    Mis=Serial.parseFloat(); //this reads the floating number of mass of food and assign to
    Mis variable but the dryer will be limited to 0.7kg of food for best performance.

    while (Serial.available()>0){ //waiting for level of dryness.
    }

    Mfwb=Serial.parseFloat(); //this reads the level of dryness and assign to Mfwb
    variable

    sendText("t75.txt=", "processing");

    num1=MiwB-Mfwb;

    num=Mis*num1;

    denum=1-Mfwb;

    Mw=(num/denum); //which is the amount of moisture to be removed.

    grams=(1000*Mw); //convert to grams of water
    fresults=round(grams); //round up floating value
    sendText("t400.txt=",fresults); //display results on nextion

```

```

sendText("t75.txt=", "complete");

//END OF CALCULATOR CODE FOR TOMATO
}

// FOR CABBAGE

void calculatorC(){

while (Serial.available() != 0){

}

Mis=Serial.parseFloat(); //this reads the floating number of mass of food and assign to
Mis variable but the dryer will be limited to 0.7kg of food for best performance.

while (Serial.available() != 0){ //waiting for level of dryness.

}

Mfwb=Serial.parseFloat(); //this reads the level of dryness and assign to Mfwb
variable

sendText("t75.txt=", "processing");

num1=MiwbC-Mfwb;

num=Mis*num1;

denum=1-Mfwb;

Mw=(num/denum); //which is the amount of moisture to be removed.

grams=(1000*Mw); //convert to grams of water

fresults=round(grams); //round up floating value

sendText("t400.txt=", fresults); //display results on nextion

sendText("t75.txt=", "complete");

//END OF CALCULATOR CODE FOR TOMATO
}

```

Appendix III: Written and Uploaded Nextion Microprocessor code for automatic temperature monitoring and control.

// to move from one page to the next on Nextion Screen

page 1

page 2

page 3

page 4 // nextion code for pages. This allows you to move from one page of the screen to the next

page 5

page 6

page 7

page 8

print 115

print 116

print 117

print 112 // These are functions used to tell the Arduino microcontroller to perform the respective functions as stated in the Arduino code and as explained in the methodology.

print 113

print 114

print 131

print 119

page 9

// Code of Nextion LCD programed calculator for calculation of moisture content to be withdrawn

t70.txt=t70.txt+"1"

t70.txt=t70.txt+"2" // These are just codes for a programmed calculator in the system that allows the user to perform any calculation he wishes

```

t70.txt=t70.txt+"3"

cov t70.txt,va2.val,0
if(va1.val==1)
{
  va3.val=va0.val+va2.val
  cov va3.val,t70.txt,0
}
if(va1.val==2)
{
  va3.val=va0.val*va2.val
  cov va3.val,t70.txt,0
}
t70.txt=t70.txt+"4"

t70.txt=t70.txt+"5"
t70.txt=t70.txt+"6"

t70.txt=t70.txt-1

t70.txt=t70.txt+"7"

t70.txt=t70.txt+"8"

t70.txt=t70.txt+"9"

t70.txt=t70.txt+"."

va0.val=0
va1.val=0
va2.val=0
va3.val=0
va4.val=0
t70.txt=t70.txt-10
t70.txt=t70.txt+"0"

cov t70.txt,va0.val,0
va1.val=1
t70.txt=t70.txt-10

cov t70.txt,va0.val,0
va1.val=2
t70.txt=t70.txt-10

print t70.txt
t70.txt=t70.txt-10

print t72.txt

```

```
t72.txt=t72.txt-10
```

```
// Code for timer
```

```
j0.val+=10
```

```
if(j0.val==100)
```

```
{
```

```
  page 1
```

```
}
```