

Design and Experimental Investigation of a Novel Solar Crop Dryer

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ABSTRACT

The motivation of this research project was in response to issues of increasing energy demand and the surge in energy scarcity and environmental problem. Various form of fuel like oil, natural gas, wood, and coal etc. can be used for drying process but they are not cheap, and most of them are not environmentally friendly. Renewable energies are one of the promising ways to tackle this global challenge. This work is centered on the investigation solar drying process.

A mix-mode solar dryer was designed for drying fruits, vegetables, and biomass. The dryer is made up of a flat plate solar collector, duct fan, two drying chamber module glazed from the top. The flat plate collector of length 200 cm, width 100 cm and height 20 cm was use to preheat the air before entering the drying chamber. The collector is made up of 3mm thick double layer of glass, V-corrugated sheet metal with 60° groove angle. A duct fan is used to provide air circulation. The drying chamber is manufactured from steel, wood, and glass.

Different tests were carried out to evaluate the performance of the dryer. The dryer was used to dry apple, banana, grapes and chili pepper. For the different tests carried out the temperature, humidity and solar radiation was recorded to enable evaluation for the performance parameters such as moisture content at the end of each day, drying rate, and drying efficiency.

The moisture content of apple, banana, grapes and chili pepper was reduced to their final moisture content within two days of sunshine hours. The average drying rate for apple, banana, chili pepper, and grapes were found to be 30.2 g/h, 82 g/h, 67.8 g/h and 98 g/h respectively per kg of each specimen.

Keywords: Solar drying, mix-mode solar dryer, food crop and drying chamber

ÖZ

Bu projenin temel motivasyonu artan enerji talebi, yetersizliği ve çevresel sorunları göz önünde bulundurarak enerji verimli bir meyve/sebze kurutma sistemi geliştirmektir. Kurutma prosesleri için gerekli enerjinin üretilmesinde petrol, doğal gaz, odun ve kömür gibi çeşitli kaynaklar kullanılabilir. Ancak bu kaynaklar yüksek maliyetli ve çevresel açıdan zararlı olarak nitelendirilmektedir. Yenilenebilir enerji kaynakları bu probleme çözüm üretmek için büyük öneme sahiptir. Bu çalışma güneş enerjisi kaynaklı kurutma sistemini incelemektedir.

Çalışma kapsamında meyve, sebze ve biyokütle malzemelerini kurutabilecek birleşik-mod bir güneş enerjili kurutucu sistemi tasarlanmıştır. Kurutuma sistemi düz plakalı güneş kolektörü, fan ve cam örtülü iki adet kurutma haznesinden meydana gelmektedir. Düz plakalı güneş kolektörü (200 cm x 100 cm x 20 cm) 3 mm kalınlığında çift cam geçirgen yüzey ve 60° açılı V şekilli oluklu plakadan üretilmiştir. Sistemde hava akışını sağlamak için motor tipi (OBR 200 M-2K) boru fanı kullanılmıştır. Kurutucu haznelere çelik, tahta, alüminyum oluklu plakalar ve cam malzemelerinden meydana gelmektedir.

Geliştirilen kurutucunun performansını değerlendirmek için çeşitli testler uygulanmıştır. Sistem elma, muz, üzüm ve biber kurutma için deneysel olarak incelenmiştir. Gerçekleştirilen testlerde sistem performansını değerlendirmek amacıyla, nem miktarı, kurutma süresi ve kurutma verimliliği temel parametreler olarak seçilmiştir.

Elma, muz, üzüm ve biber için uygulanan testlerde numuneler kuru ağırlıklarına 2 günlük gün ışığı süresinde ulaşmıştır. Elma, muz, biber ve üzüm için kg numune başına kurutma hızı sırasıyla 30.2 g/saat, 82 g/saat, 67.8 g/saat ve 98 g/saat olarak belirlenmiştir.

Anahtar kelimeler: Güneş enerjili kurutma, birleşik-mod kurutucu, tarımsal ürün kurutma haznesi

To My Parent

ACKNOWLEDGMENT

To my life-coach, my mother Ezenwali Irene: because I owe it all to you. Many Thanks!

I am grateful to my father Ezenwali Dennis and siblings Desmond, Misheal, and Ebenezer, who have provided me with moral and emotional support in my life. I am also grateful to my other family members and friends who have helped me along the way.

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LIST OF ABBREVIATIONS

D.T	Drying time
EES	Engineering Equation Solver
F.M.C	Final moisture content
I.M.C	Initial moisture content
LPG	Liquefied petroleum gas
MOFA	Ministry of Food and Agriculture
PCM	Phase changing material

LIST OF SYMBOLS

A	[m ²]	Area
C	[-]	Collector angle relationship
C _p	[kJ/kg.K]	Specific heat capacity of the specimen
e	[K]	Mean plate temperature relationship
f	[-]	Wind speed relationship
h	[kJ/kg]	Enthalpy
h _{fg}	[kJ/kg]	Latent heat of evaporation
h _w	[kJ/kg]	Wind speed
I	[w/m ²]	Solar intensity
\dot{m}	[kg/s]	Mass flow rate
M _i	[kg]	Initial moisture content
M _f	[kg]	Final moisture content
M _w	[kg]	Moisture content of specimen
M _{evap}	[kg/s]	Moisture removal rate
M _c	[kg]	Mass of the specimen
N	[-]	Number of glass cover
Q _r	[w]	Energy on the collector surface
Q _a	[w]	Absorber solar energy
Q _o	[w]	Heat loss
Q _u	[w]	Useful heat
RH	[%]	Relative humidity
T	[°C]	Temperature
TL	[-]	Turkish lira

t	[s]	Drying time
U	[w/m ² . °C]	Collector losses

Subscripts

a		Ambient temperature
b		Bottom loss
c		Collector
d		Drying chamber
e		Edge loss
g		Glass
L		Overall loss
p		Plate
pm		Mean plate temperature
t		Top loss
1		Collector inlet
2		Collector outlet
3		Cabinet outlet

Greek letters

τ	[-]	Transmittivity
α	[-]	Absorptivity
β	[°]	Collector tilt
ε	[-]	Emittance
η	[%]	Efficiency
ω	[%]	Absolute humidity

Chapter 1

INTRODUCTION

1.1 Background

Most developing nations are not able to solve their food issues for the entire population due to the unexpectedly increasing number of people in respective territories. This fast population growth has an instant effect on food stability. The quality and amount of food grains are deteriorating due to bad processing strategies and absence in storage centers. To keep the right balance between food supply and population growth, reducing food losses all through manufacturing time is mandatory, however, maximizing the food manufacturing competencies of small farmers in rural regions is hard. To clear up this trouble, drying has grown to be one of the primary processing techniques used to keep food products in sunny areas [1]. In Ghana agriculture is mostly carried out on a small scale. In 2011, MOFA estimated that 90% of farm holder in Ghana is on a small scale [2]. The rapid transfer of heat and mass during drying operation frequently end up changing of product quality, such as crystallization, puffing, and shrinkage. Occasionally chemical and biochemical reactions also occur, which is not acceptable; these involve changes in colour, odour and texture. Furthermore, the drying operation may want to potentially alter the effectiveness of certain catalysts by changing the internal surface region, which in turn generates discrepancy inside the anticipated catalytic activity. Research has shown that the commercial drying operation within the US, Canada, France and the United Kingdom

consumes 10 – 15 % of the countries' energy, while in Denmark and Germany using up to 20 – 25 % [3].

1.2 Problem statement

Moisture removal from agricultural products constitutes a significant role in the preservation process. Approximately 80 % of fruit contains water [4]. The simplest, cheapest and oldest way to counter this problem is the traditional open sun drying. But one issue with this method is the low product quality, difficulty in protecting the product from insects, animals and dust. Furthermore, open sun drying is a time-consuming method. As such, a more efficient and effective method is sought. One drying technology to solve this problem is solar drying. A novel solar dryer will be designed and constructed, numerical and experimental analyses will be carried out on a mix-mode solar dryer to help determine favorable condition to aid improving the solar drying technology.

1.3 Aim and objectives

The aim of this research was to design, construct and evaluate the performance of a mix-mode solar dryer experimentally by drying various products such as apple, grapes, chili pepper, and banana. The objective of this study are listed below:

- To design a solar crop dryer in accordance with relevant literature.
- To develop a numerical model to enable its investigation under various conditions.
- To develop an experimental testing rig and perform a test for the various specimen listed above.
- To compare the obtained result with the literature.

1.4 Research gap

Most agricultural products in Northern Cyprus has been dried through open sun drying or by the use of another source of energy. Also, the number of research relating the feasibility of solar crop drying in Northern Cyprus is insufficient in the literature. This indicates the need of investigating the mix mode solar dryer under Cyprus climate condition. Mixed mode solar dryers combine the working principle of indirect and direct type solar dryers during operation.

1.5 Novelty of the study

There are few researches carried out on a mix mode dryer, so developing a drying cabinet with perforated tray comprising different modules that can easily be adjusted in terms of number, and configuration depending on the collector area and weight of the product is novelty of this study.

Chapter 2

LITERATURE REVIEW

2.1 Background and state of the art on drying technologies

Removing or reducing the moisture content from food and agricultural products constitutes a significant role in the preservation process. microorganism such as bacteria, molds, and yeasts causes food to spoil, and they are more activated in a moist environment [5]. For this reason, it is important to reduce the final moisture content of agricultural products to help increase their edible life span. Today, drying technology is used in various industrial sectors (e.g., paper, wood, food, agriculture, waste management, etc.) by utilizing different techniques. As far as industry sectors are concerned, food and agriculture remain the most powerful sector with respect to the critical demand of drying process.

Drying is defined as a process of moisture removal from a material due heat and mass transfer occurrence [5]. Heat transfer must occur to change the temperature of the material to be dried, and mass exchange happens when dampness is expelled from inside the material accompanied by its evaporation from surrounding atmosphere [6]. To accomplish drying process, the right proportion of dry air must be circulated to drive the moisture out from the products basically without affecting the composition of the food.

Drying can also be define as a phenomenon of removal of liquid by evaporation from a solid [7].

2.1.1 Classification of drying technologies

Drying techniques and approaches can be categorized in numerous ways. It may be categorized as a batch, where the material is inserted into the drying system and drying proceeds for a given period, or as non-stop, in which the material is constantly delivered to the dryer and dried material continually removed. Dryer types have been described and categorized by Sloan via their methods of heat transfer, whether or not they may be batch or non-stop, through direct contact with gases or via heat exchange through walls of the chamber [8]. In forced convection solar dryers the air required for product drying is forced through the solar collector to the dryer chamber using a fan. While in natural convection solar dryers, the flow of the air required for product drying is due to natural or buoyancy force action. Figure 2.1 shows the schematic of drying technology. The schematic is based on the fuel type and dryer design. Fuel drying, electric drying, coal, wood, and oil drying which are proven efficient compared to solar drying but they are capital intensive. The concept of rotary, spray, vacuum band, vacuum shelf, fluid bed, drum, and conveyor are not very applicable in solar system compared with the cabinet design.

In recent years, most solar driers have been designed base on the concept of cabinet dryer. A cabinet dryer consists of an insulated cupboard equipped with shallow mesh or perforated trays, each of which includes a thin (i.e., 2 - 6 cm deep) layer of the specimen (food). Warm air circulated via the cabinet at a particular flow rate by the fan of the heater coils or flat plate collector as applied to the solar system, and is then blown throughout the specimen trays to exhaust. Furthermore, solar energy has proven

to be an excellent fuel source in drying technology based on the fact that it is environmentally friendly.

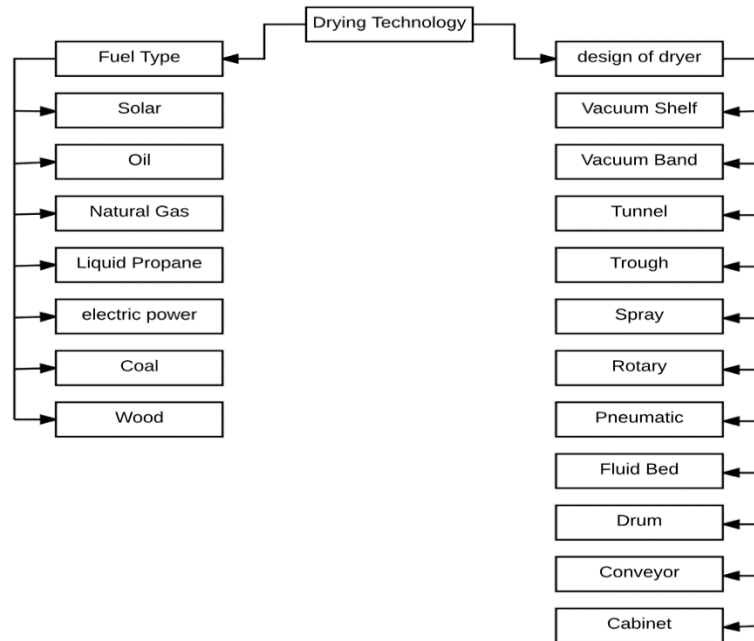


Figure 2.1: Schematic of drying technology

2.2 Sun Drying

Sun drying also known as traditional open sun drying is an ancient skill used in preserving agricultural products by exposing it directly under sun light. Traditional open sun drying is still commonly employed in some parts of the world due to their small capital, operational cost and requires little or no expatriate to manage the process. Schematic of solar drying processes are presented in Fig. 2.2.

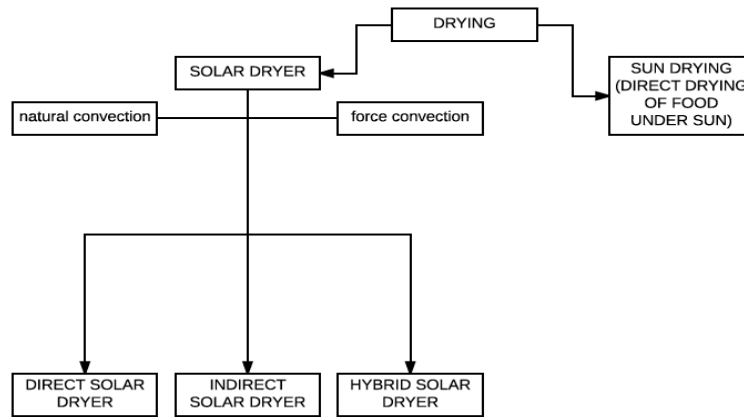


Figure 2.2: Schematic of solar drying processes

The primary impediments of this strategy are as per the following: environmental pollution due to open sun drying process, theft or damage by birds, slow or intermittent drying and no protection from rain or dew that wets the product [9].

2.3 Solar dryers

Solar drying is a better choice compared to open sun drying. Everitt and Stanley developed the first design of solar dryers in 1976 to avoid impediments of open sun drying as previously stated. After several years, many eminent researchers made several enhancements in solar drying technology making use of natural and forced circulation, auxiliary source heating like electricity and fossil fuel to improve the efficiency of the process. The main idea behind the dryer is heating air through a solar collector or glazing depending on the application. The heated air has a temperature varying from 45 °C - 60 °C with lesser relative humidity compared to the inlet air. Thus, increasing the moisture absorbing capacity of the air. Solar dryers can be classified base on the type of convection. In natural convection, the air required to dry the specimen is caused by buoyancy in the collector while in forced convection air is blown into the drying chamber using fan or blower. Numerous solar dryers were designed and advanced to conquer the drawbacks of the open solar drying. These solar

drying structures are, quite easy, low-value era, and permit the dried products to be dried under hygienic situations [10].

2.3.1 Direct solar dryer

Direct solar dryers are made up of an insulated box with a transparent cover of glass or plastics and having air holes at the side to enable forced or natural convection. As sunlight falls on the cover, reflection and transmission frequently occur.

The useful heat gained by the air depends on the transmitted part of the solar radiation. Part of the transmitted radiation is also reflected by the drying specimen while the absorbed radiation by the specimen reduce the moisture content due to temperature change in the specimen

Medugu in 2010 designed and studied the performance of a direct solar dryer with forced convection. The design consists of the chimney and a PV module for power generation for the fan. This design was able to dry 50 kg of tomato having an initial moisture content of 90 % in 129 hrs. Medugu also evaluated the performance of the chamber without chimney which increases the drying time about 9 hrs [11].

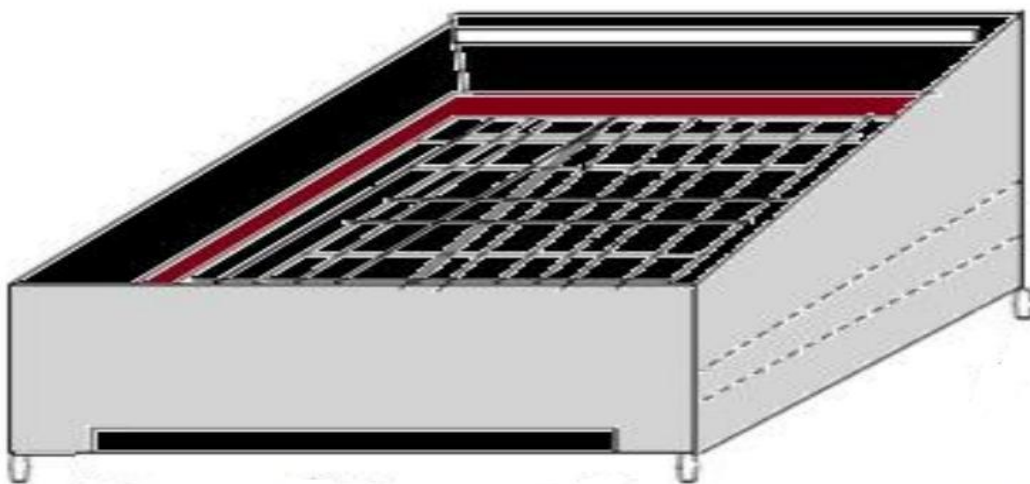


Figure 2.3: Direct solar dryer [9].

Figure 2.3 shows the design and manufacture a direct solar dryer with dimension $0.100 \times 0.103 \times 0.76 \text{ m}^3$ fabricated from galvanized steel, wood, and glass at the top of the cabin. With an inlet air temperature of $30 \text{ }^\circ\text{C}$ at the 5 cm inlet hole, $60 \text{ }^\circ\text{C}$ optimum temperature can be reached. The drying chamber was designed for drying various kinds of vegetables. 3 kg of potatoes was placed in the cabinet for two days, at the end of the second day, the weight was measured to be 0.47 kg and compared to the control experiment (sun drying) which has a weight of 0.79 kg [9].

Benaet et al. design a direct solar dryer with back-up heater powered by biomass. The biomass burner was recorded to have an overall efficiency of 22 % and a combined efficiency of 9 % while tested with pineapple sliced of 0.01 m thickness [12]. In the other study, Ahmad designed and manufactured a model which utilized a solitary sheet cylindrical collector having black interior with transparent insulation [13].

Zomorodian et al examined another strategy for utilizing a direct sun oriented dryer. Their design consists of dryer cabinet, collector, and blower. The working mechanism of this system is to absorb solar radiation thus increasing crop temperature. Limitation of this system are; discoloration of crops and moisture are trapped in glass cover which reduces transitivity [14]. Ondier et al. constructed design a dryer for rough rice. From its experiment, it was observed that rice needs low temperature and relative humidity to have a uniform drying [15].

Yefri et al. design a direct solar dryer coupled with a pneumatic conveyor to create a homogenous drying. As the grains are transported in the pneumatic conveyor speedy heat, and mass transfer occur which leads to an even drying manner and make the final

consequences of the drying sample homogeneous. The entire solar dryer was made from a feed hopper, centrifugal blower, pneumatic conveyor and an obvious structure acting as drying chamber containing a hopper with vortex at the pinnacle. Pneumatic conveyor turned into used to make recirculation of the grain and to carry out non-stop drying process. 104 kg of rough rice was dried from 28.4 % w.b (wet bulb temperature) to a final moisture of 14.3 % w.b. the chamber was maintained at a temperature of 50.1°C [16].

2.3.2 Indirect solar dryer

In indirect solar dryers, air is heated in a solar collector and pass on to drying cabinet either by force or free convection to reduce the moisture content of crops or biomass place in the drying chamber [6]. Sharma et al. observed that an indirect solar dryer under poor weather condition still gives favourable output. Sharma et al. design consist of a flat-plate collector which absorbed solar radiation that heats incoming air, drying cabinet and insulated pipes. They conclude in their study that the indirect solar dryer gives quality dried products by reduction in drying rate [17].

Svenneling (2012) carried out an experiment on an indirect solar dryer use for drying pineapples. Svenneling performed an experiment on pineapples in the laboratory before using the solar dryer. The solar collector has an area of 1.05 m² and the air duct has a gap of 0.2 m. A 1.2 m long chimney with a diameter of 0.1 m was made from metal sheet and is connected to the drying chamber. It was noted that drying pineapples at 70 °C case hardened under 5 hrs. But when dried at 50 °C the pineapples piece has a moisture content of 10 % and drying time of 23.43 hrs. Svenneling indirect solar dryer has a temperature ranging from 50 °C to 60 °C and it took 16 hrs of sunshine to dry the same pineapple from 90 % on the wet basis to about 10 %.

Svenneling also compared the drying with respect to the tray position. It was noted that the lower shelf closer to the collector dry faster than the upper shelf. Figure 2.4 shows the experiment Schematic of Svenneling design [18].

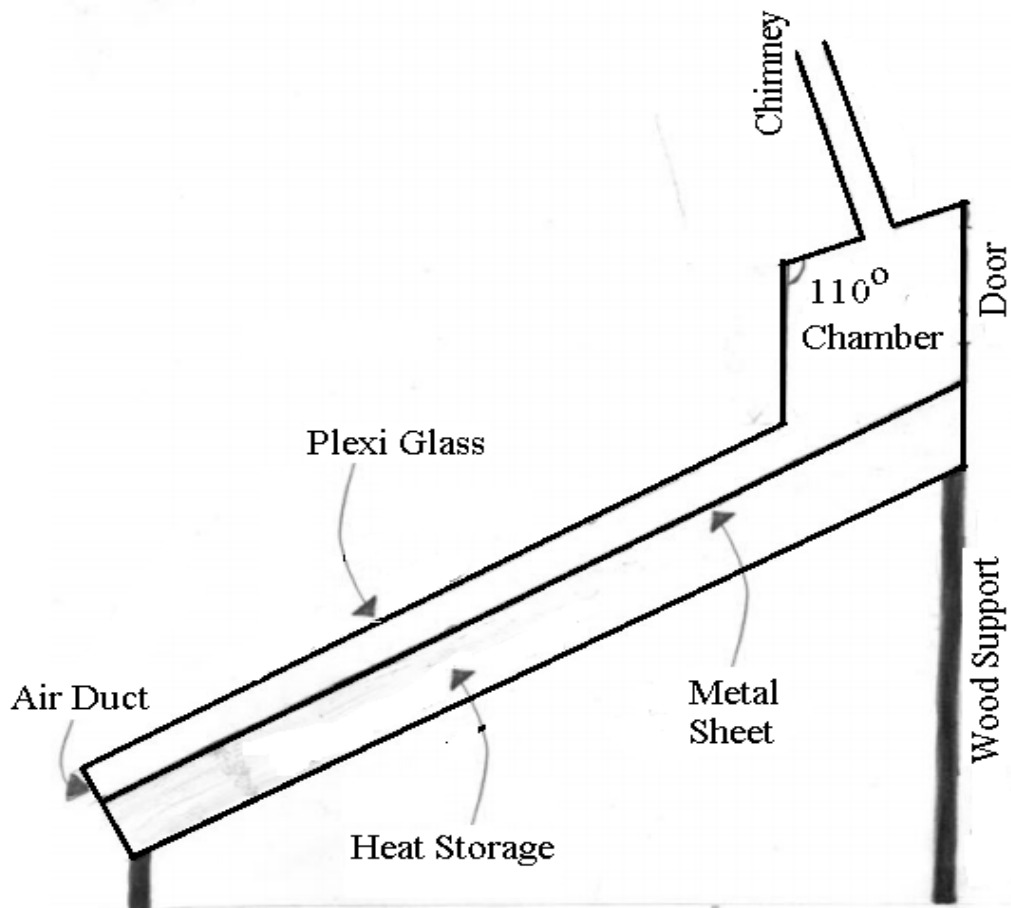


Figure 2.4: Indirect solar dryer [18].

Rabha et al. did a detailed study on the drying feature of thin layer ghost chili pepper using an indirect solar dryer which consists of two solar collectors connected in series, a shell and tube heat exchanger for energy storage and blower. The drying experiments have been carried out consecutively for five days from 29th September 2015 to 3rd October 2015. The temperature and relative humidity of ambient air has been found to vary from 29 °C to 37 °C and 57.4 % - 85.5 %, respectively throughout the experiments. The intensity of the solar radiation was between 166 W/m² and 1011 W/m² with an

average of 641 W/m^2 . Rabha concluded the solar dryer is faster than open sun drying and gives better quality [19].

Aymen et al. carried out a study on an indirect solar dryer using a phase changing material (PCM). The dryer consists of a solar air panel for a right away heating of the drying agent, a solar power accumulator (solar air collector with PCM hollow space) and a drying chamber. Experiments had been conducted to assess the charging and the discharging traits of the latent storage unit (PCM cavity). The results show that after using the solar power accumulator, the temperature of the drying cabin is higher than the ambient temperature with $4 \text{ }^\circ\text{C} - 16 \text{ }^\circ\text{C}$ all night [20].

Shrivastava et al. carried out an experiment on an indirect solar dryer which includes drying chamber having metallic wire mesh trays, solar air heater and the air-imparting unit having 12 V DC fan. The chamber has a size of $0.91 \text{ m} \times 0.76 \text{ m} \times 0.76 \text{ m}$. A 2 kg of mass fenugreek was placed on each tray. Drying process took two days for of completion [21].

Margarita et al. dehydrated the red chili pepper using an indirect solar dryer. Firstly, a controlled experiment was carried in an oven for various temperature $45 \text{ }^\circ\text{C}$, $55 \text{ }^\circ\text{C}$ and $65 \text{ }^\circ\text{C}$ and their respective drying time 2.75 hrs, 3 hrs and 6.25 hrs. In the solar dryer, for air velocity ranging between $1.4 \text{ m/s} - 2.6 \text{ m/s}$ at a temperature varying between $31 \text{ }^\circ\text{C} - 45 \text{ }^\circ\text{C}$ the drying time was recorded to be 16hrs while for air velocity ranging from $0.7 \text{ m/s} - 1.48 \text{ m/s}$ at the same temperature the drying time was 21 hrs [22].

Yahya et al. carried out a comparison on the performance of an indirect solar dryer, and a solar assisted heat pump dryer. Both systems were used to reduce the mass of cassava from 30.8 kg to 17.4 kg with drying time of 3 hrs and 9 hrs at average temperatures of 40 °C and 45 °C, respectively. The maximum efficiencies varied from 3.9 % to 65.5 % and 15.9 % to 70.4 % for Solar dryer and solar assisted heat pump dryer, with mean values of 39.3 % and 43.6 %, respectively. The heat pump used has a coefficient of performance ranging from 3.23 to 3.47 with an average of 3.38 [23].

2.3.3 Hybrid and mixed mode solar dryer

Mixed mode sun dryers combine the basic traits of indirect and direct type sun dryers during operation [6]. Hybrid solar dryers, in addition to the usage of only solar energy, hybrid structures comprise every other method of heating the air for drying a product [24]. Figure 2.4 shows the experiment setup of Soponronnarit et al. design. The study was carried out on three modes/stages. Which are using the dryer as natural convection solar dryer, LPG drying process and solar forced convection, with additional heat from LPG. The cost ratio for this dryer was found to be 1.2, 2.9 and 0.6 respectively [25].

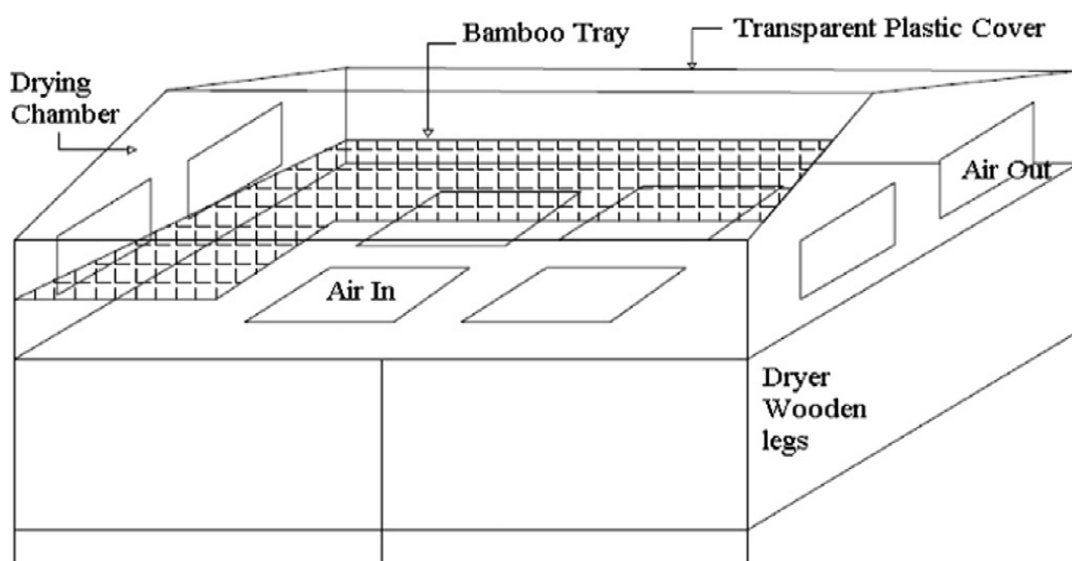


Figure 2.5: Solar assisted drying system [25].

Thanaraj et al. reported the thermal efficiency of a hybrid solar dryer used in drying copra 15.5 % [26]. Forson *et al.* in 2007 designed and suggested a combined mode natural convection solar dryer. Where the check place for their test was Kumasi, Ghana. They recognized three fundamental components of the dryer as an air-heater (primary collector), a drying chamber and a chimney.

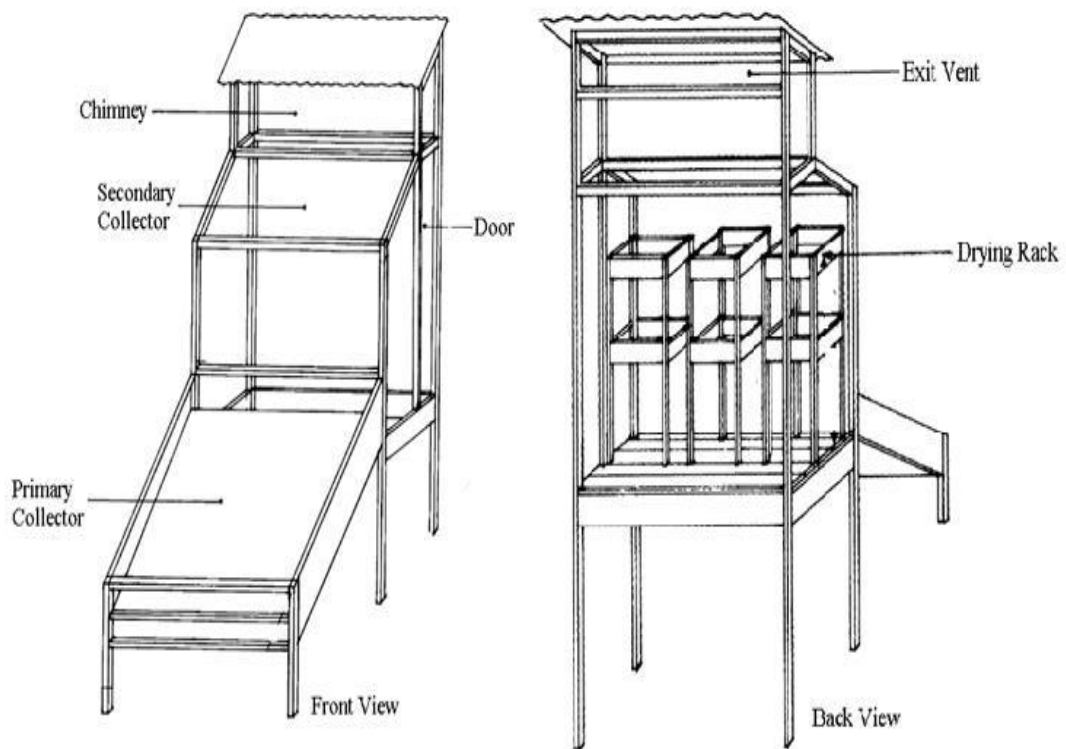


Figure 2.6: Mix mode solar dryer [27]

The top cover and sidewalls of the drying chamber are made to be transparent so that they function a secondary collector. The test specimen was cassava and has an efficiency of 12.3 %. Initial weight and moisture content were noted to be 162 kg and 66 % respectively. The chamber operates at a temperature of 39.1 °C and a drying time of 35.5 hrs. Figure 2.4 shows the experiment setup of Forson *et al* design [27].

Table 2.1: Literature Review Summary

S/N	Researchers	Year	Dryer Type	Crop	Crop Mass (Kg)	Expriment Location	I.M.C %	F.M.C %	D.T (hrs)
1	Medugu	2010	direct solar dryer	tomato	50	Mubi	90	58	129
2	Raju <i>et al</i>	2013	direct solar dryer	potatoes	3	x	x	x	48
3	Bena et al	2002	direct solar dryer	pineapples	20 – 22	Melnourne	x	x	84
4	ondier et al.	2010	direct solar dryer	rice	X	x	19.6	12.5	5.7 - 23.8
5	Yefri et al.	2014	direct solar dryer	rice	104	x	28	14.3	5
6	sharma et al.	1993	indirect solar dryer	grapes	40	Trisaia	80	15	120 -168
7	svenneling	2012	indirect solar dryer	pineapples	X	edumafa	90	10	16
8	Abhay et al.	2017	indirect solar dryer	Banana ghost chilli	2	India	x	x	x
9	Rabha et al.	2015	indirect solar dryer	pepper	9	x	x	x	123
10	Amer et al	2010	hybrid solar dryer	banana	30	x	82	18	8
11	margarita et al.	2014	indirect solar dryer	red chilli pepper	x	Temixco	x	x	16 - 21
12	yahya et al.	2016	indirect solar dryer	cassava	30.8	x	61	10.5	13
13	Soponronnarit et al.	1997	Hybrid solar dryer	banana	x	thailand	x	x	x
14	Thanaraj et al.	2007	Hybrid solar dryer	copra	147	x	50	7	71
15	Forson <i>et al.</i>	2007	mixed-mode	cassava	100	kumasi	66	17.3	35.5

Chapter 3

DESIGN AND MODELLING OF SOLAR CROP DRYER

The Mix-mode solar dryer design for this experiment consists of two major units which are the flat-plate solar collector and the drying chamber. Proper steady state modeling has been carried for both the collector and drying chamber by considering the fundamental law of thermodynamics to enable investigate this system for various conditions; simulation was done using Engineering Equation Solver.

3.1 Drying chamber

The design of the solar dryer took into attention distinct layout standards and parameters. A number of those design standards and parameters have been from literature overview. These designs Parameters blanketed environmental conditions of the test vicinity, drying temperature, amount of moisture to be eliminated, heat energy requirement and determination of flow rate requirement. The design of the chamber was made possible by the SolidWorks. SolidWorks is a cad software that provides the user with better visualization and which in turn aids in designing better products and faster integration. The chamber is made of L shape steel, sheet metal, wood, and glass. The drying tray was constructed from stainless steel to avoid rusting effect. Figure 3.1 shows the drying chamber module. The chamber consists of four trays two at the top close to the glass and the other at the bottom. The chamber is made up of 2 module which can be increased depending on the collector area, weight of material to be dry. Each module consists of two trays; the top tray is perforated to enable air flow between

the top and bottom tray. Figure 3.2 shows the general setup of the system. The solar collector used was double glass collector with V- corrugated Absorber plate.

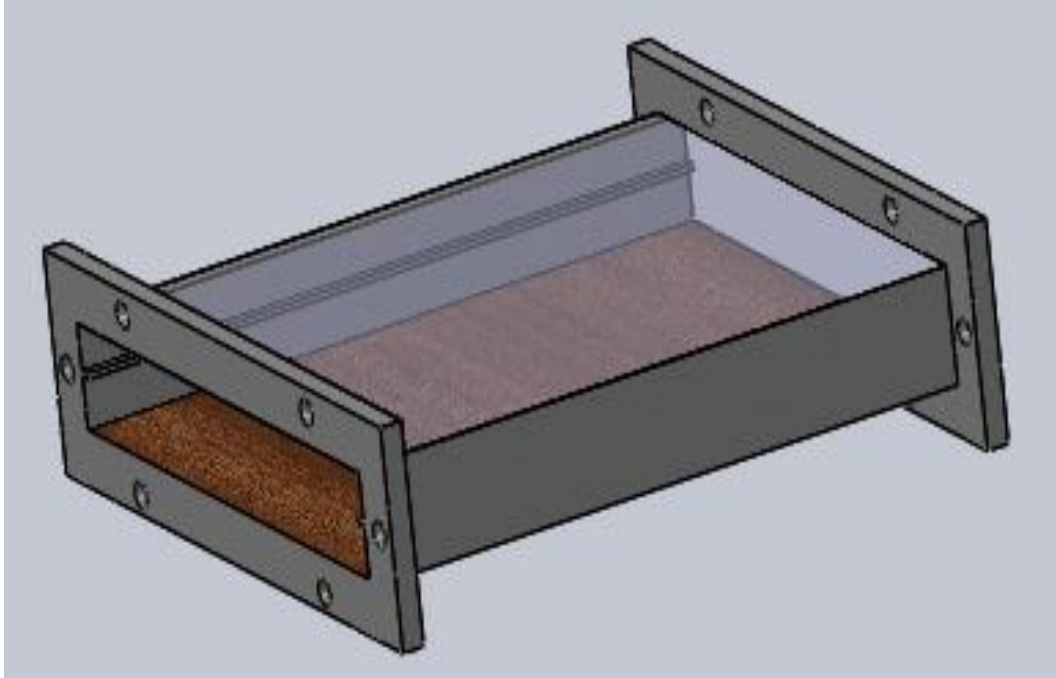


Figure 3.1: Drying chamber module

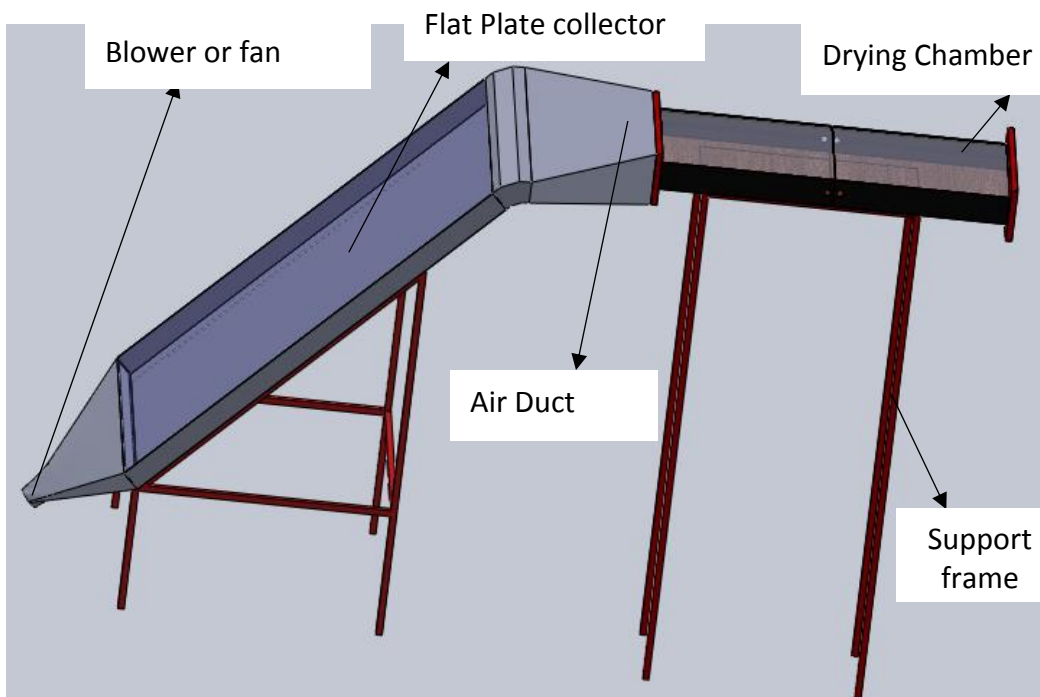


Figure 3.2: Side view of drying system

Figure 3.3 shows the perforated and smooth tray used in the drying process for storing specimen during drying period. The component of the solar cabinet dryer is shown in Table 3.1 below

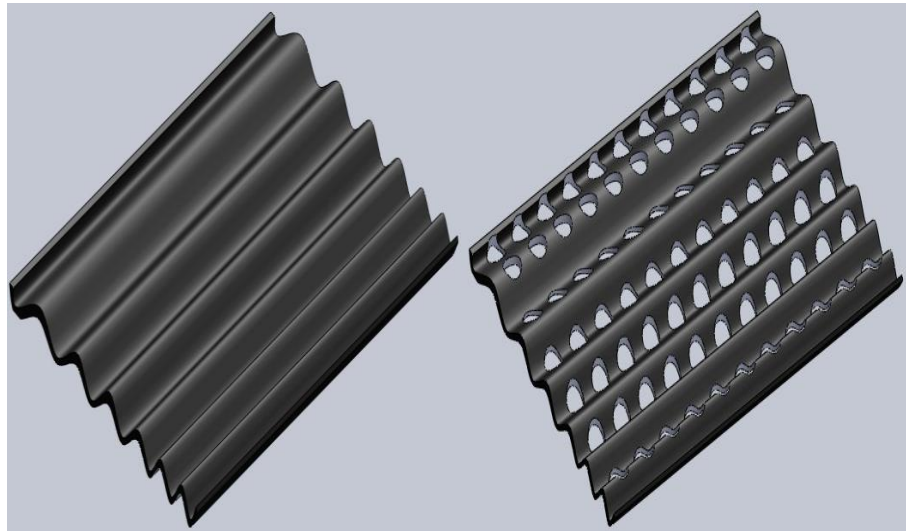


Figure 3.3: Drying trays

Table 3.1: Materials for manufacturing drying chamber.

Component	Description
Back cover	For the bottom cover of the chamber, wood was used as the material with dimensions (L:57 cm x W:43.5 cm)
Top cover	For the top cover of the chamber, glass was used as the material with dimensions (L:57 cm x W:43 cm)
Frames	The frame of the chamber is constructed with the L-shaped beam. (L:58 cm x W:44.5 cm)
Side cover	Made from sheet metal (L:57 cm x W:12 cm)
Trays	L:57 cm x W:43 cm
collector	Collector area 1.82 m ²

3.2 Flat plate collector

Solar collectors are the key component of active solar heating systems. Solar energy collectors are special sort of heat exchangers that rework solar radiation. The dimension of the collector are L:200 cm * W:100 cm * H: 20 cm

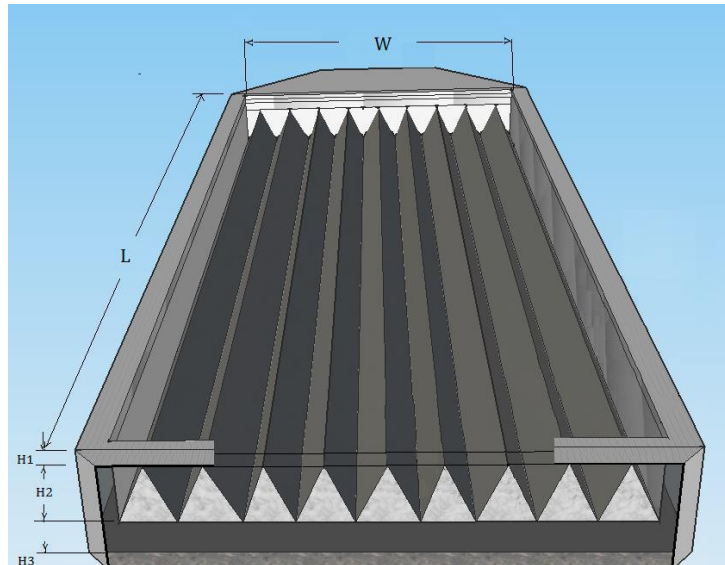


Figure 3.4: Section view of flat plate collector [31]

From Figure 4.4, the V-shape in array form is known as the V- corrugated Absorber plate. The design helps to increase the surface area of the absorber plate which improves the rate of heat transfer to the air.

Table 3.2: Description of solar collector material

Component	Description
Glass cover	Two transparent glass cover. Dimensions (L:194 cm x W:94 cm)
Absorber plates	V- corrugated made with galvanized steel and painted black.
Insulation	polystyrene layers, (for each side W:15 cm x L:197 cm, with thickness 2cm) (for the Back: L: 197 cm x W:97 cm with thickness 2 cm)
Fan	(60-220 V with Controller Tool on the fan speed)

3.3 Modelling and thermodynamics analysis of the system

3.3.1 Thermodynamics analysis of solar collector

The objective of this analysis is to evaluate the heat transfer to the inlet air of the chamber.

If the intensity of the solar radiation is given as W/m^2 , the power or intensity of the radiation on the collector surface:

$$Q_r = IA \quad 3.1$$

Where, Q_r is power of the solar radiation on the collector surface, I is the solar radiation and A is the area of the collector. Nevertheless, a fraction of the solar radiation is reflected back to the sky, while the fraction of it component is absorbed by the glazing and the remaining is transmitted through the glazing and reaches the absorber plate as short wave radiation. The absorber radiation is very important in the study. The absorbed radiation is a product of transmission-absorption ratio and intensity of the radiation on the collector surface (Q_a):

$$Q_a = I\tau\alpha A \quad 3.2$$

τ and α are the transmissivity and Absorptivity ratio. The heat loss from the solar collector is important to evaluate the useful heat from the collector. The heat loss depends on the heat transfer coefficient and the solar collector temperature.

$$U_L = U_t + U_e + U_b \quad 3.3$$

$$U_L = U_t = \left(\frac{N}{\frac{C}{T_{pm}} \left[\frac{T_{pm} - T_a}{(N+f)} \right]^e + \frac{1}{h_w}} \right)^{-1} + \frac{\sigma(T_{pm} - T_a)(T_{pm}^2 + T_a^2)}{\frac{1}{\varepsilon_p + 0.00591Nh_w} + \frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g} - N} \quad 3.4$$

U_t is the top loss from the collector surface.

When:

$$C = 520(1 - 0.000051\beta^2) \quad 3.5$$

$$f = (1 + 0.089h_w - 0.1166h_w\varepsilon_p)(1 + 0.07866N) \quad 3.6$$

Equation (3.3 - 3.6) [32] was used to evaluated to total heat loss from the collector (U_L). The heat losses from the edge (U_e) and bottom (U_b) are neglected.

Then the heat loss:

$$Q_o = U_L A (\Delta T) \quad 3.7$$

Evaluating the useful heat:

$$Q_U = Q_a - Q_o \quad 3.8$$

The exit temperature which is the inlet temperature of the drying chamber can be derived from:

$$Q_U = \dot{m}(T_2 - T_1) \quad 3.9$$

Collector efficiency is given as:

$$\eta_c = \frac{Q_U}{IA} \quad 3.10$$

3.3.2 Thermodynamics analysis of drying chamber

The initial humidity ratio and enthalpy values were determined using psychometrics chart from exit air temperature of the flat plate collector. The final enthalpy and humidity ratio depends on the moisture content of the material and the heat loss from

the chamber. In this study, heat loss from the chamber will be neglected. The moisture content of the specimen is given by (Ampratwum, 1998) [28].

$$M_w = \frac{M_s(M_i - M_f)}{100 - M_f} \quad 3.11$$

When M_w is the moisture content of the specimen, M_s is the mass of one slice of the specimen while M_i and M_f represent the initial and final moisture content of the specimen. The time required to reduce the specimen from M_i to M_f was estimated by

$$t = \frac{M_w}{\dot{M}_{evap}} \quad 3.12$$

When t is the drying time and \dot{M}_{evap} is the moisture removal rate.

The energy balance for the chamber is required to enable simulate the system under the various condition like low solar radiation and various moisture content.

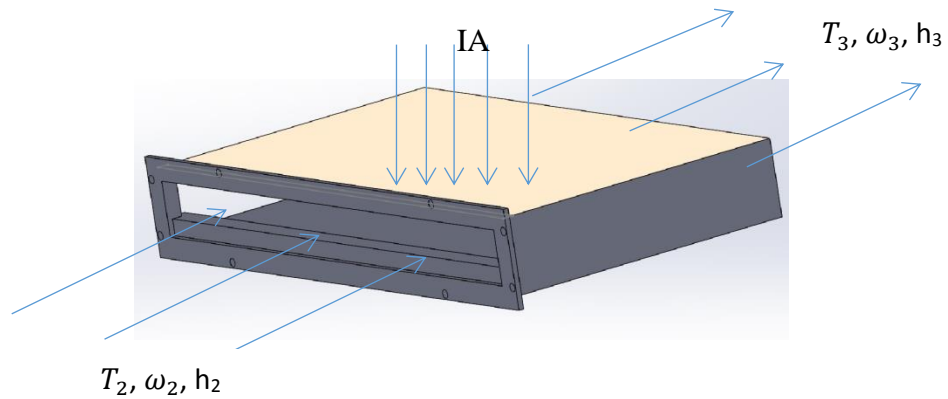


Figure 3.5: Schematic of Solar drying processes

$$IA - \dot{M}_{evap} h_{fg} - (M_c C_p \Delta T) / t = \dot{m} (h_3 - h_2) \quad 3.13$$

ΔT is the temperature change of the specimen. The variables h_3 and h_2 are the enthalpy of the inlet and exit air of the chamber, which are evaluated from the enthalpy equation of moist air:

$$h_i = 1.006T_i + \omega_i(1.84T_i + 2501) \quad 3.14$$

The absolute humidity of air based on its RH (relative humidity) and T (temperature) in any particular moment could be determined with:

$$\omega_i = 216.7 \left[\frac{\left(\frac{RH}{100\%} \right)^{6.112} \left(\exp \left(\frac{17.62T_i}{243.12+T_i} \right) \right)}{273.15+T_i} \right] \quad 3.15$$

M_C and C_p Represent the mass of specimen and specific heat capacity of the specimen respectively and the temperature (ΔT) of the crop is assume to change in respect to the inlet and exit air of the chamber.

The drying chamber efficiency can be defined as how much input heat to the system is used to cause a drying effect.

$$\eta_d = \frac{\dot{M}_{evap} h_{fg}}{IA} \quad 3.16$$

3.4 Cost of drying chamber

The total cost of the design and manufacturing of the drying chamber is 200 TL. Detail cost breakdown in the appendix. The exchange rate in the period of the manufacturing process (September – December) is 3.72 TL – 1 \$.

Chapter 4

EXPERIMENTAL PROCEDURE

4.1 Material preparation for drying

Specimen preparation mostly involve washing, peeling, cutting, slicing, coring, pitting, trimming, or chopping [29]. Sometimes it is necessary to pre-treat the specimen to avoid quick softening and browning. Fruits like mango, banana, and apples quickly turn brown if not treated. Ethylene action inhibitors and 1-methyl cyclopropane are known for delaying this reaction in industrial application. In this study, 1 % of citric acid is used. Also, the thickness of the specimen plays a significant role in the drying process. SolarFlex suggested that the slice thickness of very wet food should not exceed 5mm. For this experiment, the specimen is cut into 4mm thickness [30].

4.2 Apparatus used for data collection

4.2.1 Xplorer glx datalogger

Temperature readings at the inlet of the collector and the exit of collector and dryer, wind speed and humidity changes with time so close monitoring are essential in this study. The GLX is a useful tool to counter this challenge. This data logger can be connected to the temperature sensor, humidity sensor, and anemometer. Figure 4.1 shows a Xplorer GLX use in this experiment. The temperature sensors are able to measure temperatures in the range of -30 °C to approximately 105 °C with accuracy of ± 0.5 °C



Figure 4.1: Xplorer glx datalogger.

4.2.2 Pyranometer

The Pyranometer is used to measure the solar radiation on a surface. Figure 4.3 shows the Pyranometer utilized for this study. It can measure 180° view, which gives us the leverage to place it at the same angle with the collector. For this study, solar radiation on both the collector surface and horizontal surface will be measured. Reading from the pyranometer is measured in voltage by a voltmeter.

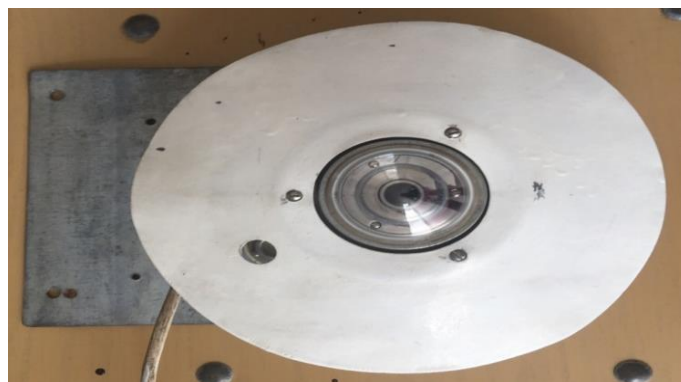


Figure 4.2: Pyranometer.

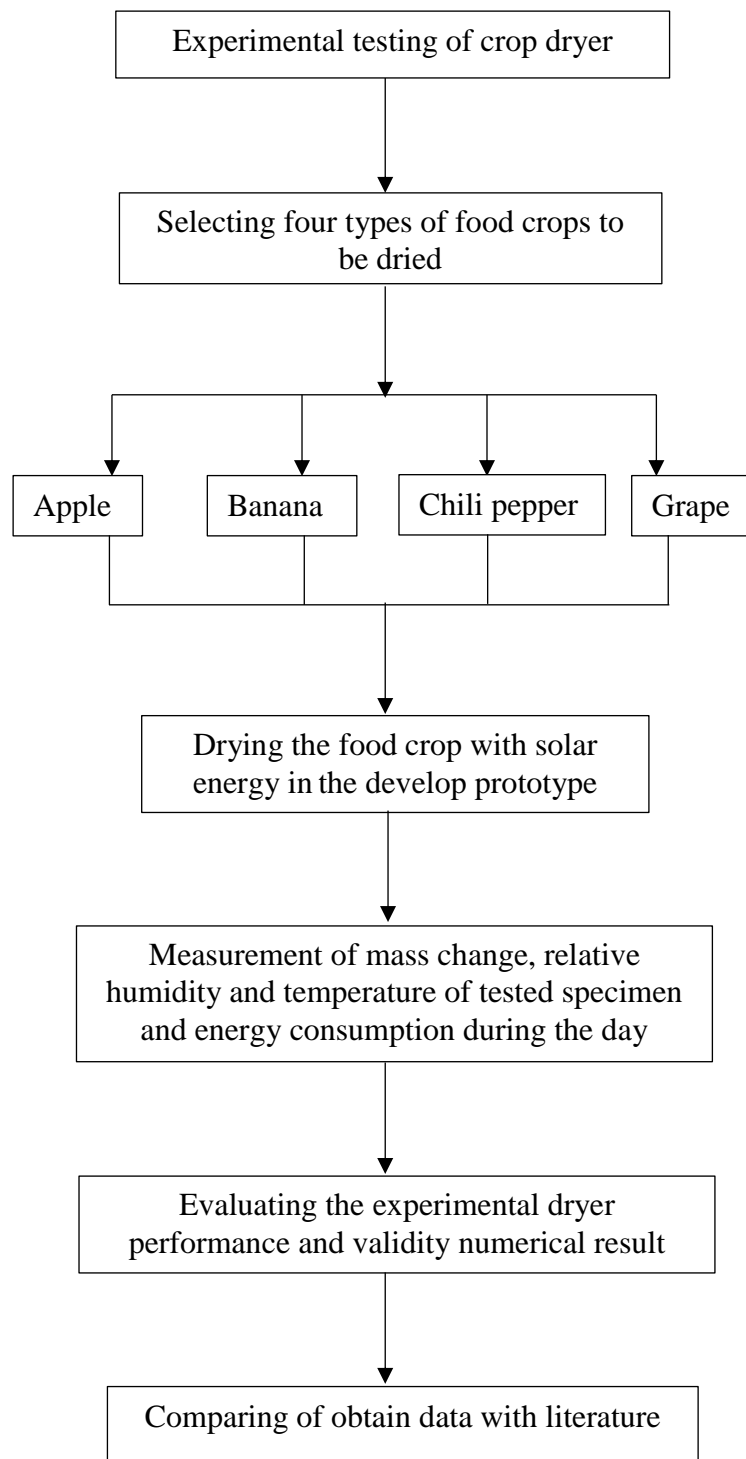
4.3 Experimental setup

The system was tested in Famagusta, North Cyprus (35.125° N and 33.95° E). The tilt angle of the collector is 45° [31]. The test was carried out using 1.19 kg of banana, 0.96 kg of apple, 0.87 kg of grape and 0.6 kg of chili pepper under different load batch.



Figure 4.3: Experimental setup

Table 4.1: Experimental methodology applied in the study of the solar crop dryer



The detailed testing procedure is given as follows:

- The specimen was sliced into 4-5 mm thickness and placed in a solution of citric acid.
- Before loading the exact weight of the material is recorded.
- The loading is carried out by 9:00 am.
- The temperature and humidity sensors are connected to their various data logger.
- The system is turned on at exactly 10:00 am throughout the drying days.
- The humidity reading and solar radiation were recorded hourly while the temperature reading at T1, T2 and T3 was recorded every 15mins.
- The experiment is carried out for 7 hrs daily, and the final weight of the specimen is measured.

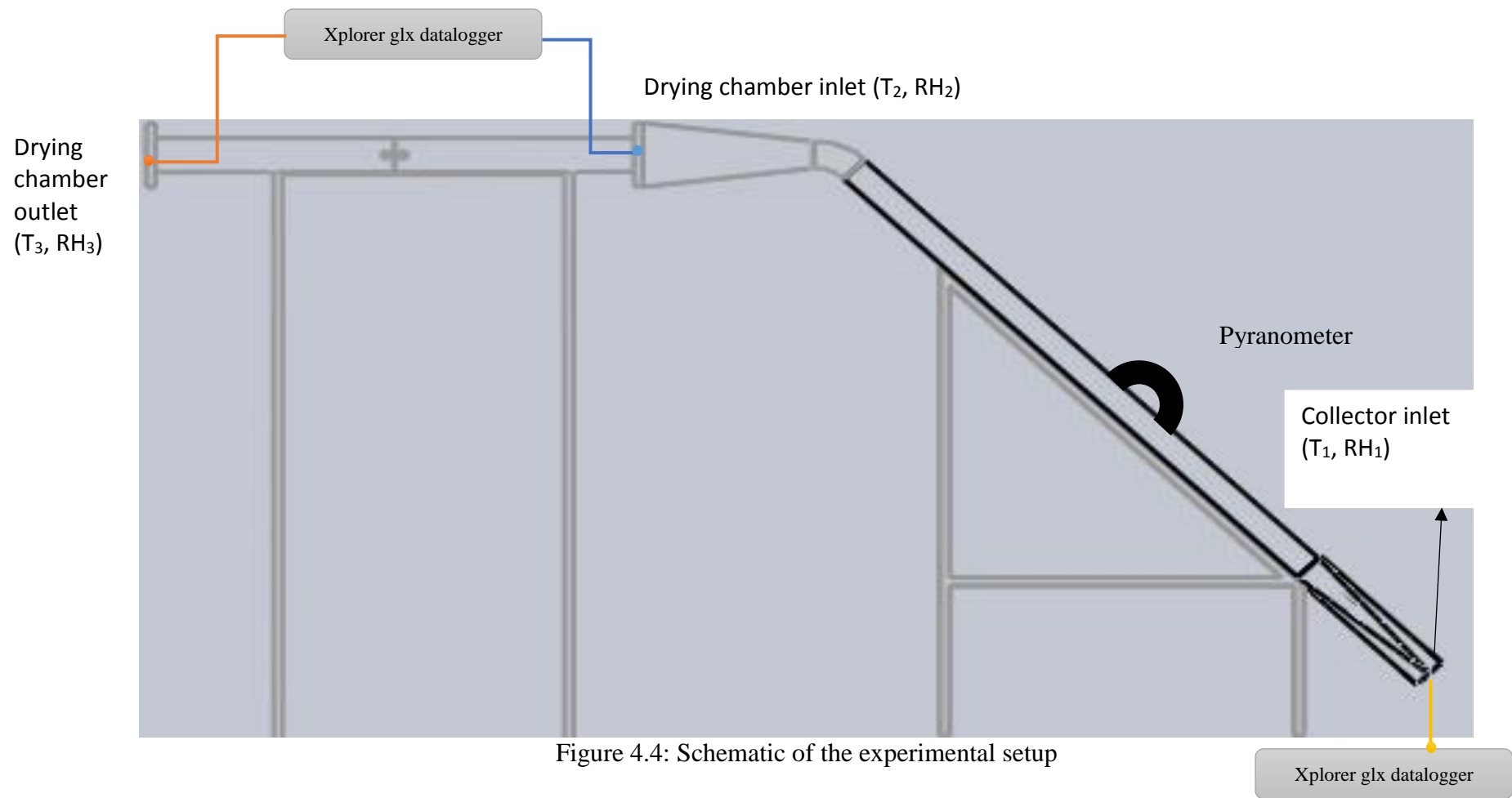


Figure 4.4: Schematic of the experimental setup

Chapter 5

RESULTS & DISCUSSION

After completing the construction of the dryer, different tests were performed to evaluate its performance. Apple, banana, chili pepper and grapes were dried during the test period. The result of different tests performed is presented below.

5.1 Relative humidity and temperatures

The relative humidity of air is an essential aspect same as that of temperature due to the fact humidity gradient between air, and the product can be a prime driving force in a natural convection system. The decrease in relative humidity of the air can increase the drying rate and will assist in decreasing the drying time. Figure 5.1 shows the relationship between temperatures at the inlet the collector, and both the inlet and outlet of the drying chamber. The collector inlet temperature (T1) plays a vital role in the drying process the inlet temperature is mostly affected by the high relative humidity during sunrise. Also, the inlet temperature is higher than the outlet temperature with an average 10 °C - 13 °C. The average inlet, and the outlet temperature was obtained as 32 °C and 44 °C respectively. The relative humidity of the inlet and outlet of the drying system is shown in Figure 5-2. The moisture from the specimen contributes to the change in the exit humidity. The average relative humidity recorded for the inlet of the collector, inlet and outlet of the drying chamber during the drying of apple was found to be 28.25 %, 16.62 %, and 30.08 % respectively while chili pepper has an average relative humidity of 21.8 %, 12.5 %, and 24.85 %. It was

observed that the relative humidity on the second day of the experiment was lower than that of the first day because of reduction in moisture.

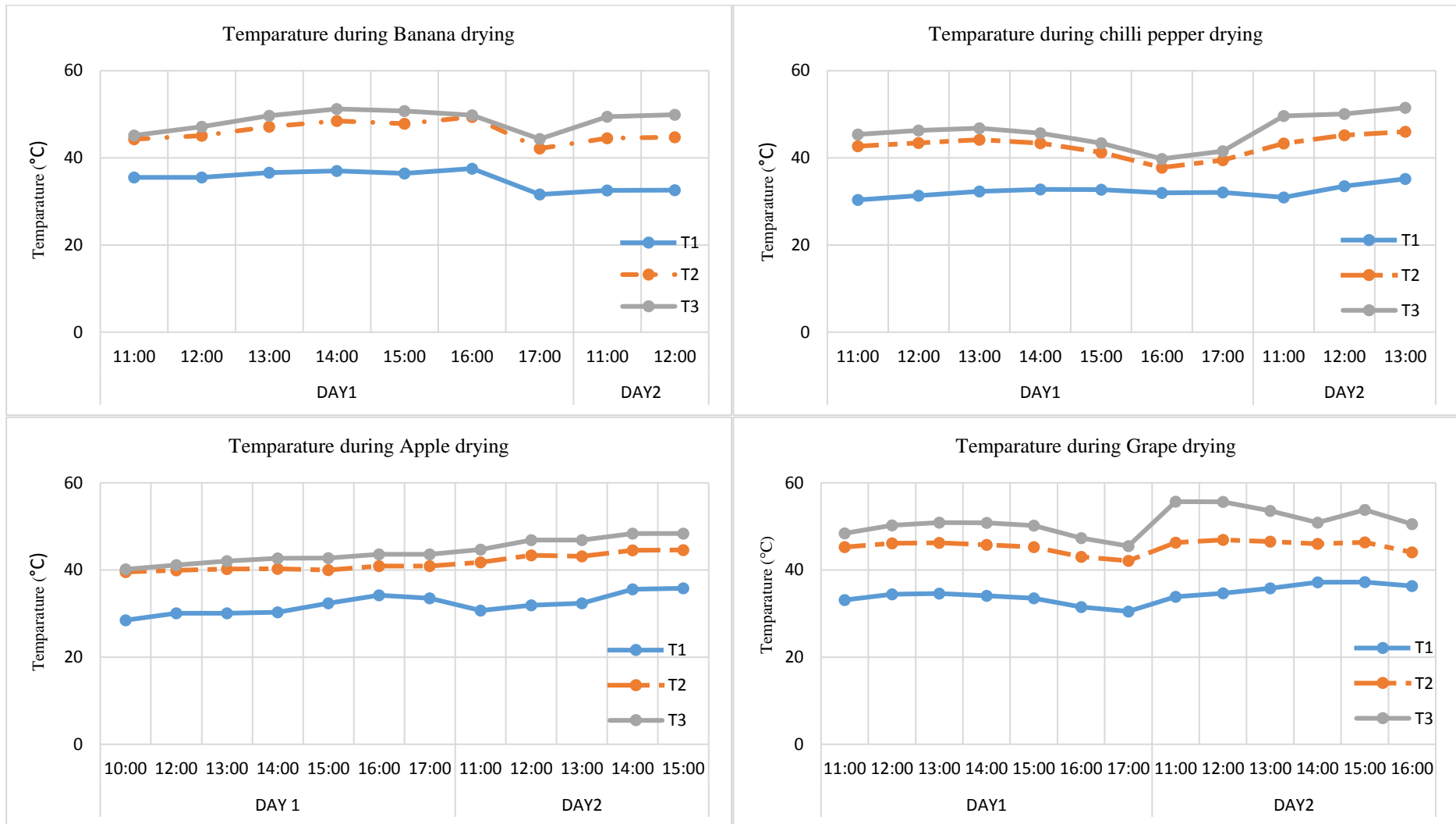


Figure 5.1: Temperatures at the solar collector inlet, inlet and outlet of drying chamber

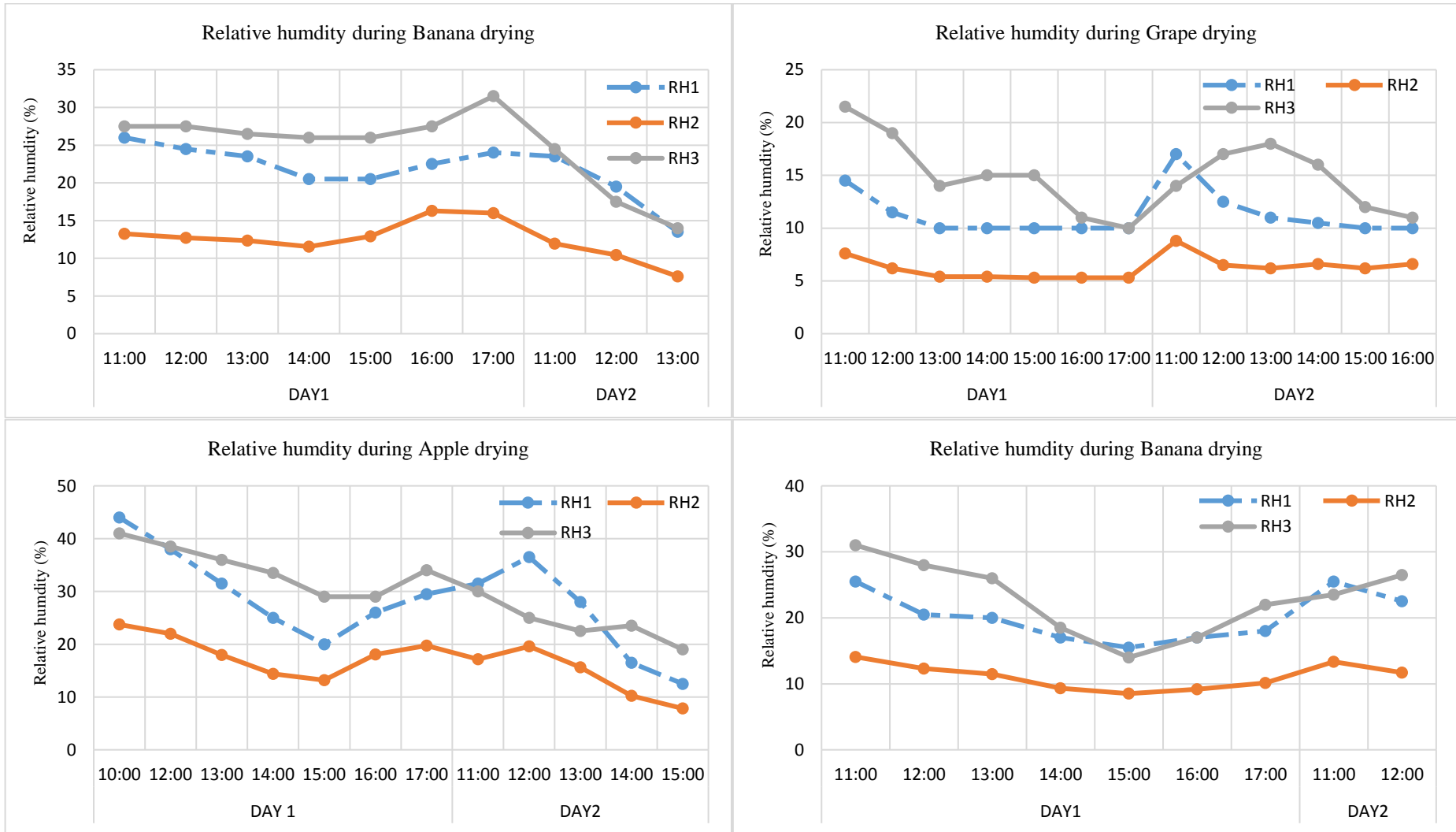


Figure 5.2: Relative humidity.

5.2 Moisture content in air

The properties of the air flowing across the drying grain are a prime aspect in determining the rate of elimination of moisture. The potential of air to get rid of moisture is structured upon its preliminary temperature and humidity; the more the temperature and lower the humidity the greater the moisture removal capacity of the air. Figure 5.3 illustrates how the amount of moisture in the outlet air changes on the moisture content of the inlet air. The difference in mass between the inlet air and the outlet air was greater on the first day compared to the second day of the experiment.

5.3 Enthalpy and energy input and consumption

The average energy supplied by the sun to the drying chamber during the test period of apple, banana, chili pepper and grape are 202.68 W, 199.71 W, 201.98 W and 201.02 W respectively while the energy used through evaporation of the water from the specimen is 77.20 W, 88.62 W, 81.44 W and 94.39 W. From Figure 5.4, The wide range of the energy supplied and consume towards the end of the experiment is because most heat input in the system is not used to evaporate any water from the specimen due to the high presence of bound moisture in the specimen. The ratio of energy input and consumption for each hour gives an expression of the hourly efficiency of the system. The peak energy input for each test day was recorded at 13:00 and the minimum energy input was recorded by 17:00. Figure 5.5 represents the enthalpy values at various point. From the graph, the changes between h_1 and h_2 are less due to the low efficiency of the solar collector used in this study. While the high difference between h_3 compared to h_1 and h_2 is due to the moisture content in the air.

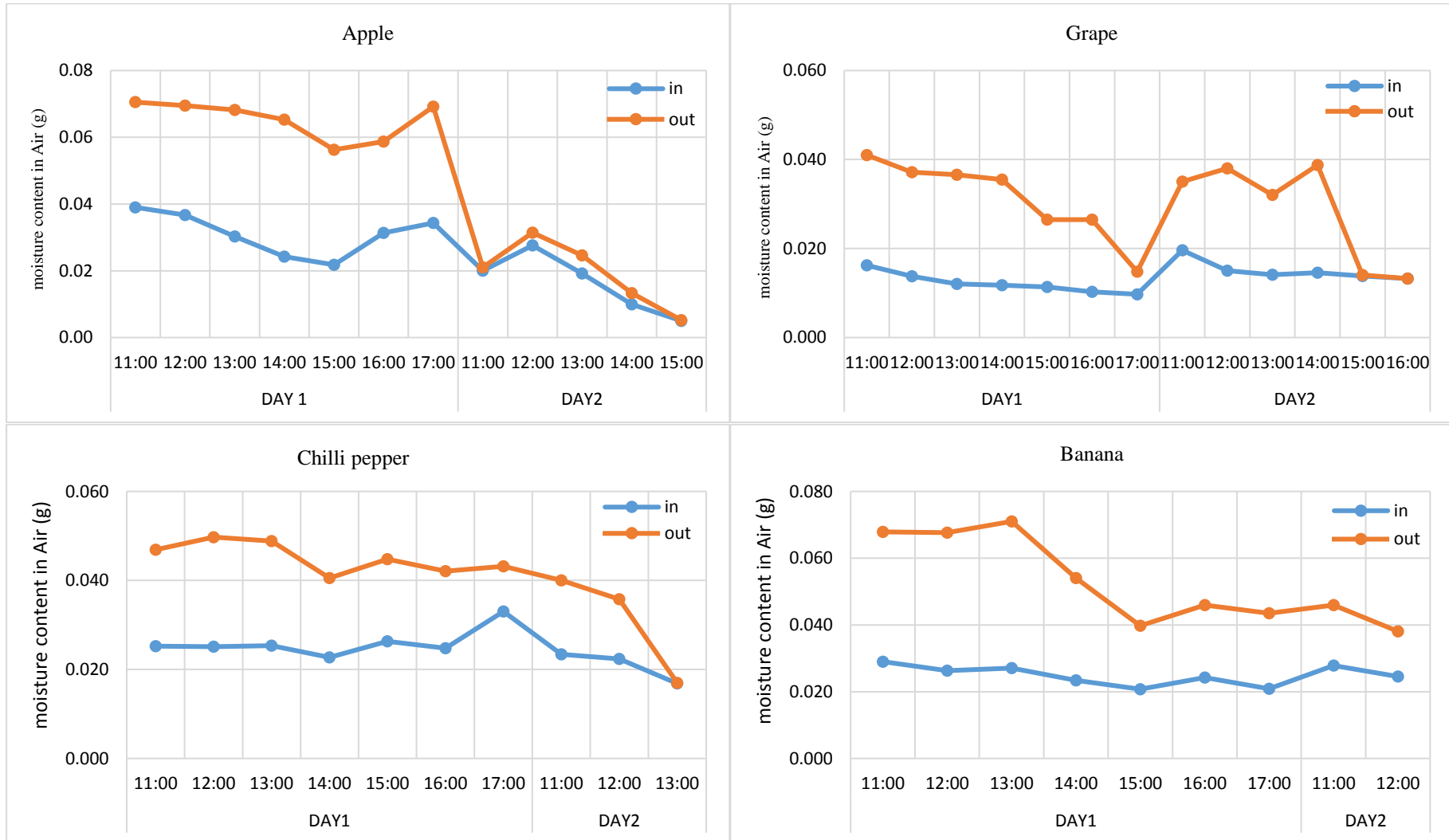


Figure 5.3: Moisture content in inlet and outlet air

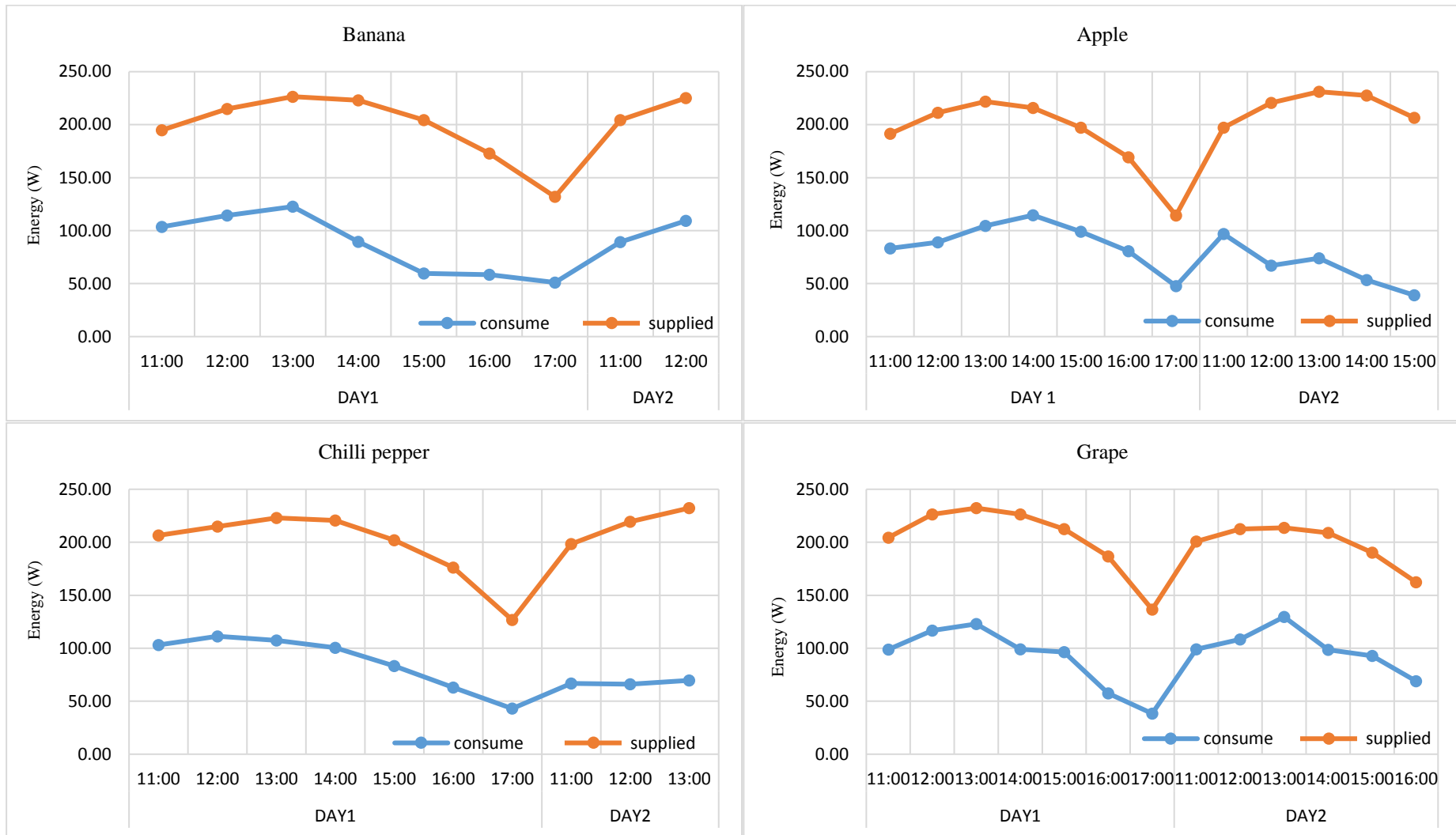


Figure 5.4: Energy consumed and supplied during the drying process.

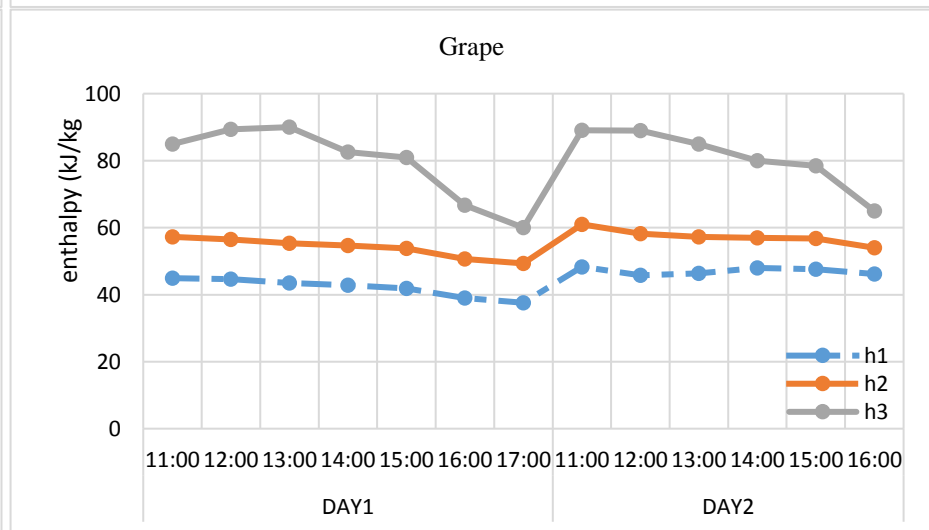
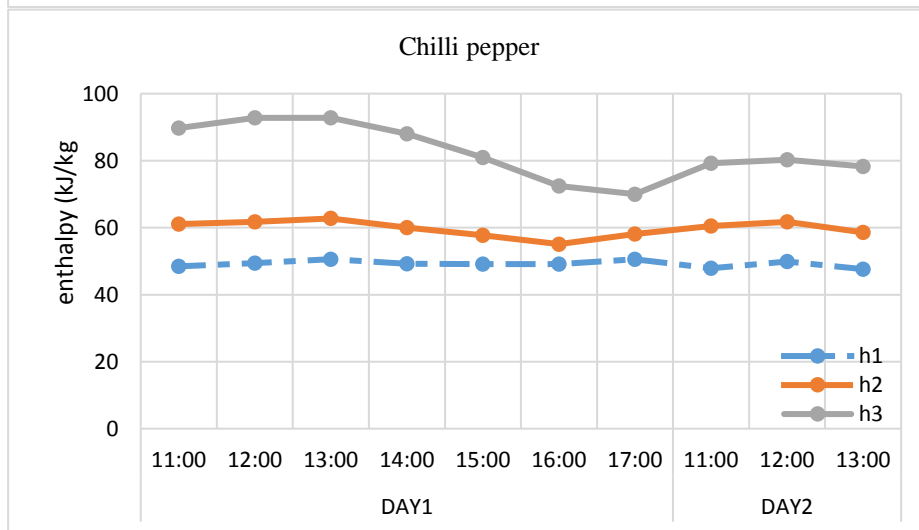
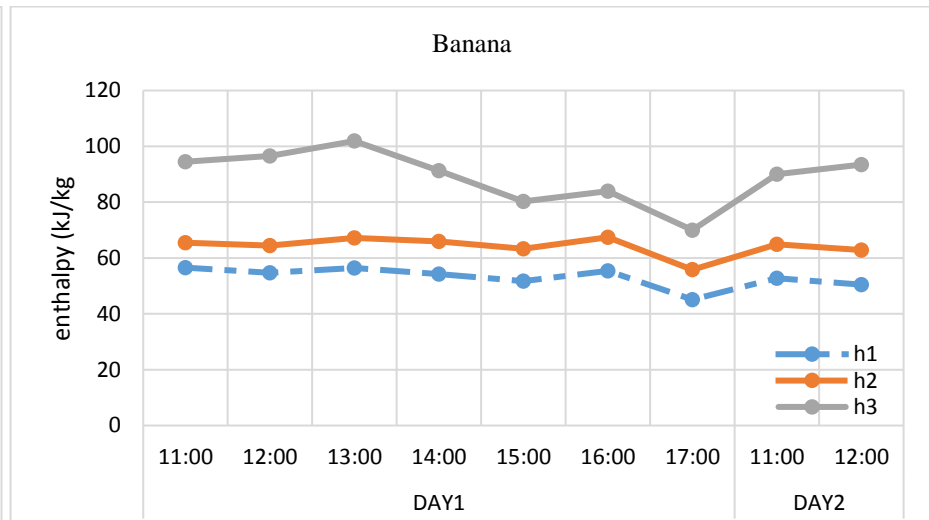
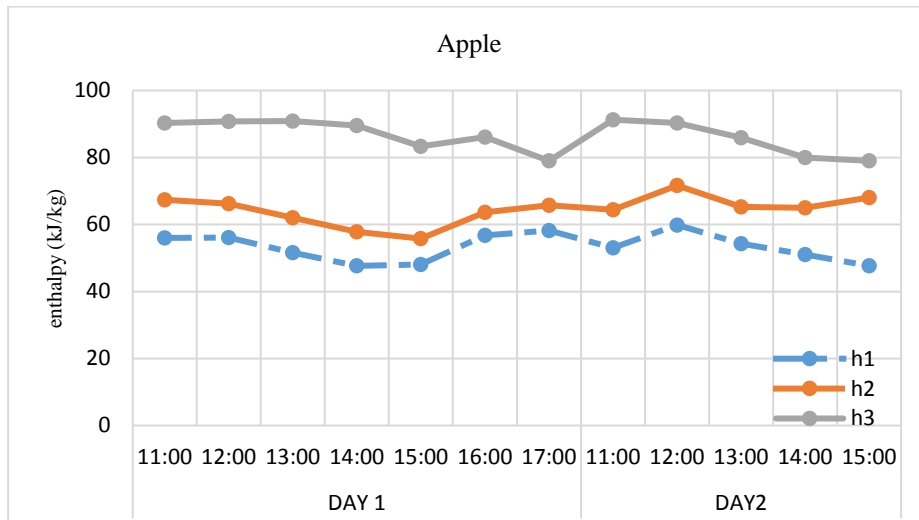


Figure 5.5: Enthalpy across the drying system.

5.4 Moisture removal rate and mass change

The quantity of moisture that can be eliminated and the rate at which it may be eliminated during this experiment doesn't depend much on the intensity of the sun rather relies upon the type of specimen, the amount of bound and unbound moisture, whether they are hygroscopic or non-hygroscopic and the physical properties of air used. Hygroscopic materials will usually have a few residual moisture while Non-hygroscopic materials can be dried to zero moisture stage. This moisture in the hygroscopic fabric can be an unbound or bound moisture. The bound moisture is held inside material due to closed capillaries or surface forces. The unbound moisture within the material is held by the surface anxiety of water. The test specimen is all hygroscopic material.

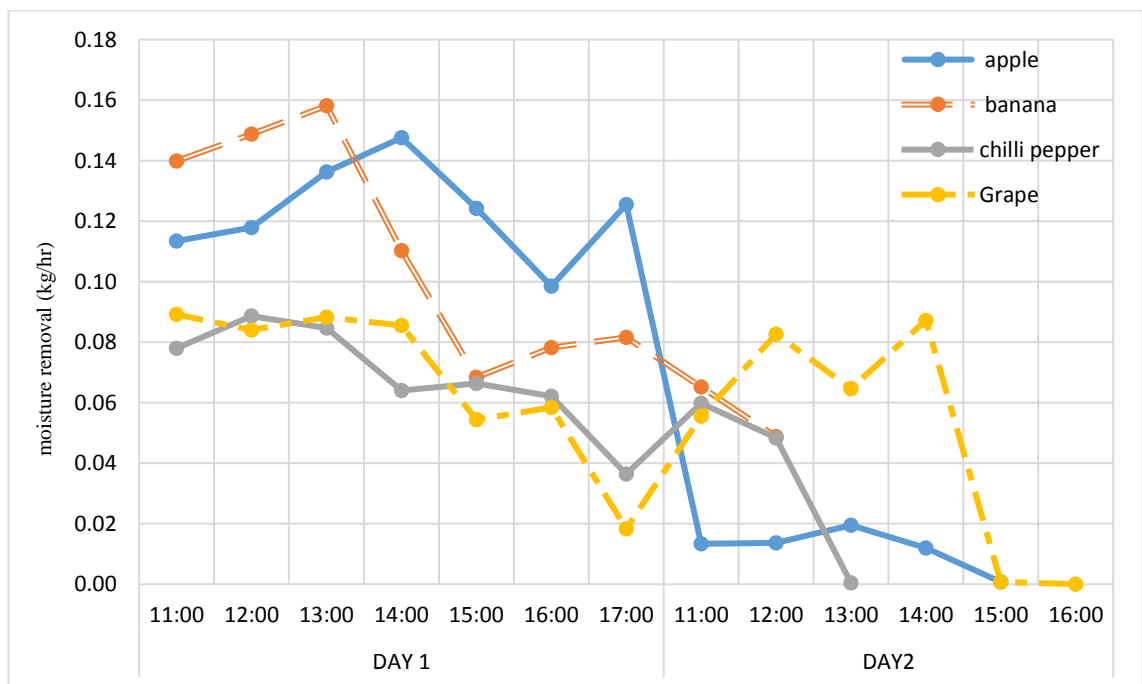


Figure 5.6: Moisture removal rate for the various test specimen.

From Figure 5.6 which represents the moisture removal rate of the specimen, it was observed that the moisture removal rate towards the final test hour of day two was close to zero, due to the hygroscopic properties of the specimen.

The four specimen tested showed different behavior towards losing moisture to the inlet air from the collector. The average moisture removal rate of apple, banana, grapes and chili pepper during this experiment are 0.08 kg/hr, 0.1 kg/hr, 0.06 kg/hr and 0.06 kg/hr. The energy supplied and consume during grape and chili pepper drying was more compared to the of apple and banana. The poor moisture removal rate for the chili pepper and grape is as a result of the complex structure of both materials.

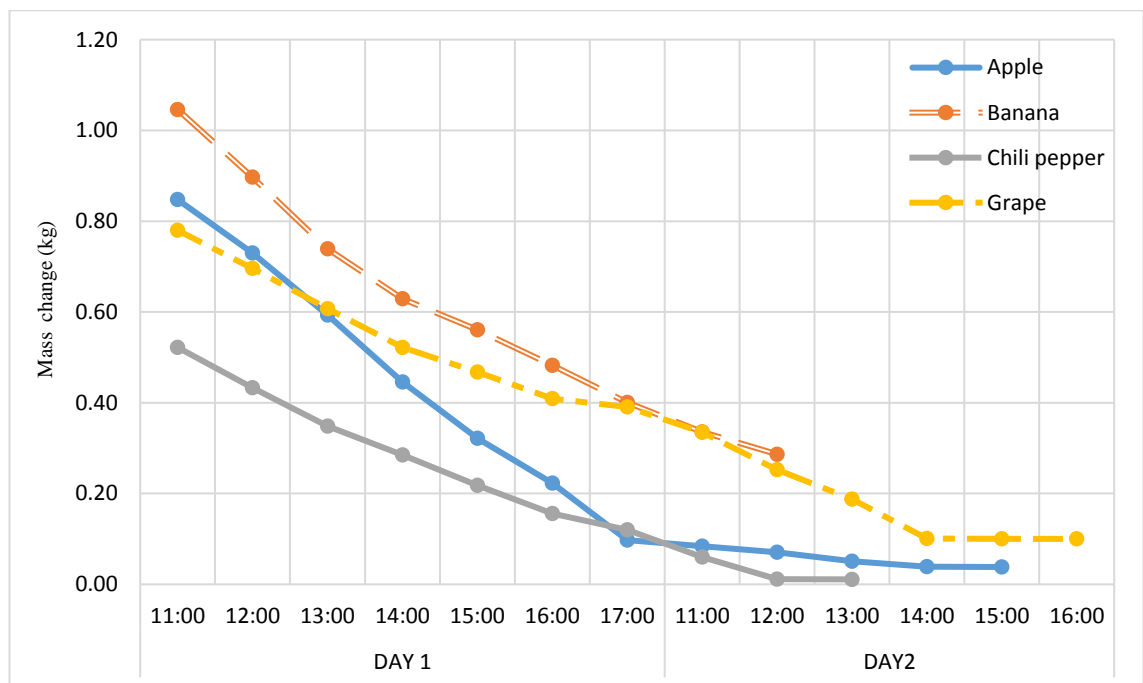


Figure 5.7: Hourly mass change

The figure above represents the hourly mass change in each specimen. From the figure, it is observed that there is a greater change in mass during the start of the experiment compared to the preceding day. 80 % - 90 % reduction in the mass of Apple, Banana, chili pepper and grapes was recorded, about 60 – 70 % mass change took place within

the first day of the experiment. There is a linear relationship between moisture removal rate for the first day of the mass change of the first day. Moisture removal rate for the first day of the experiment was greater, thus causing the large difference between the mass change of the first day and second day.

5.5 Cumulative moisture removal

Cumulative frequency is described as a running total of frequencies. The frequency of an element in a set refers to how many of that element there are inside the set. Cumulative frequency can also be described as the sum of all preceding frequencies as much as the present day point.

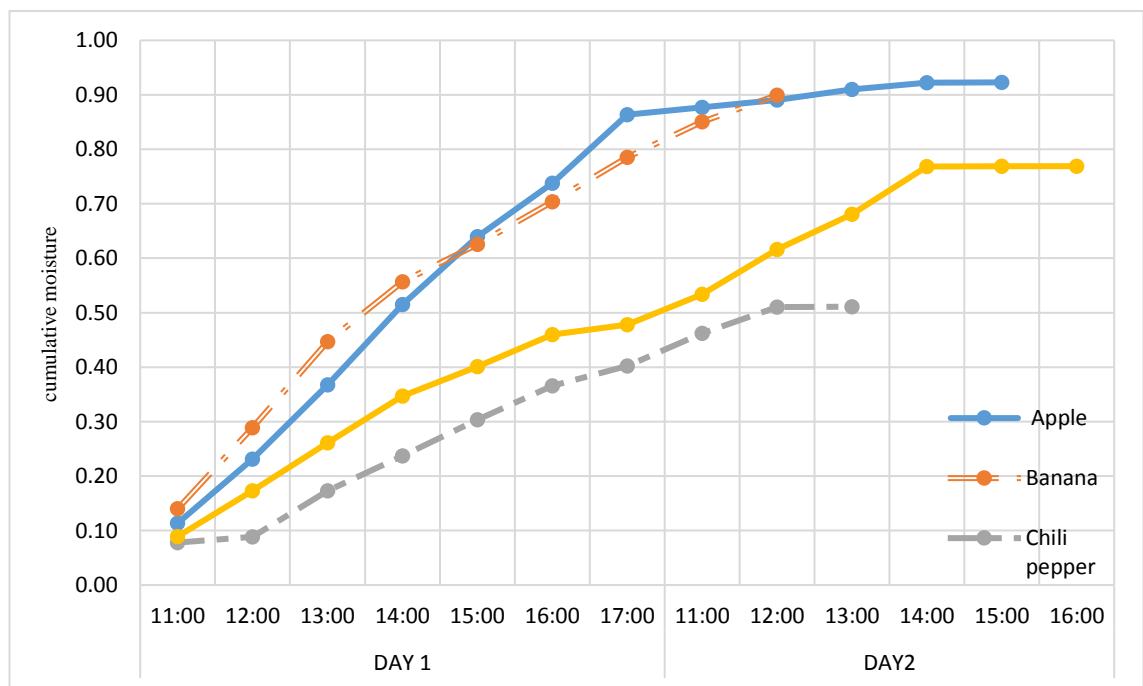


Figure 5.8: Cumulative moisture removal

The Figure above gives a clear insight on how the specimens lose moisture to the air. The running total of the frequency from 11:00 - 13:00 for the first day is drastic compared with day two. Surface moisture is quickly given off by the specimen; this causes the sharp increase in the cumulative frequency at the start of the experiment.

Towards the end of day one most surface moisture is lost, and the running total begins to equalize the previous total which is more visible on the second day of the experiment.

5.6 Efficiency of drying chamber

Based on the equations in the literature, the efficiency of the solar dryer was evaluated, and the results were given based on different drying hours. The drying chamber performance depends on several factors; since the system is a mix-mode dryer, the inlet air is preheated by the collector before entering the chamber.

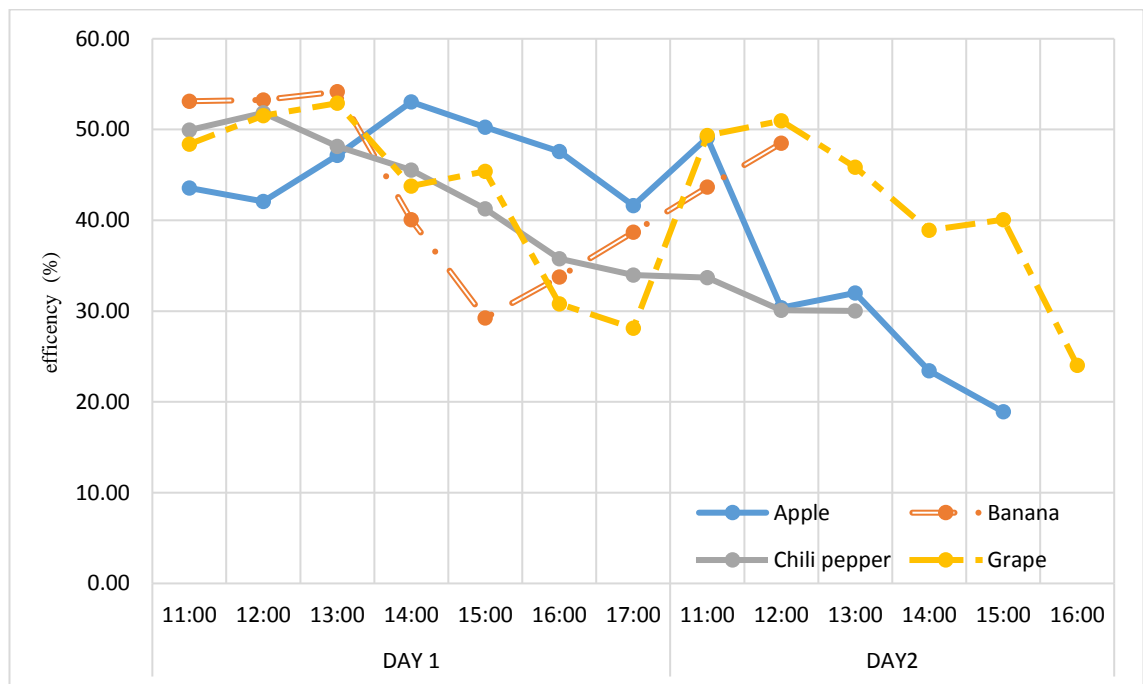


Figure 5.9: Hourly efficiency

The efficiency of the solar collector plays a vital role in the drying time. Most heat transferred to the drying air is gain from the solar collector. So the total system efficiency is most like to be low if the efficiency of the collector used if poor. The drying system in this study has a drying efficiency ranging from 30 % - 40 %. The figure above shows the drying efficiency of the solar drying chamber. The pickup

efficiency of the drying air increases at the starting of drying and then decreases continuously as the drying time increases. The efficiency of the drying chamber also depends on the drying specimen. The average efficiency during the test period of apple, banana, chili pepper and grapes are 38.01 %, 43.84 %, 40.03 % and 42.13 % respectively. Table 5.1 show the experimental summary.

5.7 Uncertainty analysis

Uncertainty analysis is necessary to prove the accuracy of the experimental results.

The result w_R is calculated as a function of the independent variables $x_1, x_2, x_3, \dots, x_n$

and $w_1, w_2, w_3, \dots, w_n$ represents the uncertainties in the independent variables.

In the developed experimental rig, 3 sensor locations were used for determining the

$T_1, T_2, T_3, RH_1, RH_2$ and RH_3 of the ambient, inlet and outlet of the drying chamber.

Then, uncertainty w_R is expressed as (Ozgen et al., 2009, Buker et al., 2014):

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \left(\frac{\partial R}{\partial x_3} w_3 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \quad 5.1$$

Experiments were conducted by using following instruments: Thermocouples with the

maximum deviation of $\pm 0.4^\circ\text{C}$ for temperature and $\pm 3\%$ for relative humidity while

the voltmeter use to measure the voltage in the pyranometer was $\pm 3.3\%$

It is obtained from the equation (3.16), the efficiency (η) is the function of T, RH and

I (solar intensity) measured in charging and discharging cycles, each subject to

uncertainty:

$$\eta = f(T_1, T_2, T_3, RH_1, RH_2, RH_3, I) \quad 5.2$$

Total uncertainty for overall system efficiency can be expressed as;

$$w_R = \left[\left(\frac{\partial \eta}{\partial T_1} w_{T_1} \right)^2 + \left(\frac{\partial \eta}{\partial T_2} w_{T_2} \right)^2 + \left(\frac{\partial \eta}{\partial T_3} w_{T_3} \right)^2 + \left(\frac{\partial \eta}{\partial RH_1} w_{RH_1} \right)^2 + \left(\frac{\partial \eta}{\partial RH_2} w_{RH_2} \right)^2 + \left(\frac{\partial \eta}{\partial RH_3} w_{RH_3} \right)^2 + \left(\frac{\partial \eta}{\partial I} w_{I_3} \right)^2 \right]^{1/2} \quad 5.3$$

Total uncertainty rate affecting the efficiency of the drying chamber was computed by using Equations 5.1 – 5.3. The estimation implies that total uncertainty in calculation of the η is found to be 3.51%.

Table 5.1: Experiment summary

Specimen	APPLE	BANANA	GRAPE	CHILLI PEPPER
Drying start date	29th June 2017	3rd July 2017	10th July 2017	6th July 2017
Drying end date	30th June 2017	4th July 2017	11th July 2017	7th July 2017
Start Weight (kg)	0.96	1.19	0.87	0.60
End Weight (kg)	0.05	0.29	0.17	0.01
Drying time (hrs.)	12.00	9.00	13.00	10.00
Average RH1 (%)	28.25	20.17	11.31	21.80
Average RH2 (%)	16.62	11.12	6.26	12.50
Average RH3 (%)	30.08	22.94	14.88	24.85
Average T1 (°C)	32.10	35.03	34.36	32.32
Average T2 (°C)	41.59	45.96	45.38	42.67
Average T3 (°C)	44.26	48.59	51.04	46.01
Average power utilizes (W)	77.20	88.62	87.04	81.44
Average power supplied (W)	202.68	199.71	201.02	201.98
Efficiency of drying chamber (%)	38.10	43.84	42.13	40.03
Energy consumption rate for drying (kwh/ton)	2670.33	1997.10	3733.23	3423.39
Energy consumption rate for fan (kwh)	7.20	5.4	7.8	6

5.8 Simulation for the drying chamber using EES

The mathematical modeling for a Mix-mode solar dryer was constructed and solved using engineering equation solver software (EES). Some underlying assumption was made to enable simplicity of the system:

1. The system operates under steady state condition.
2. The constant specific heat of the air.
3. Average inlet humidity of 50 %.

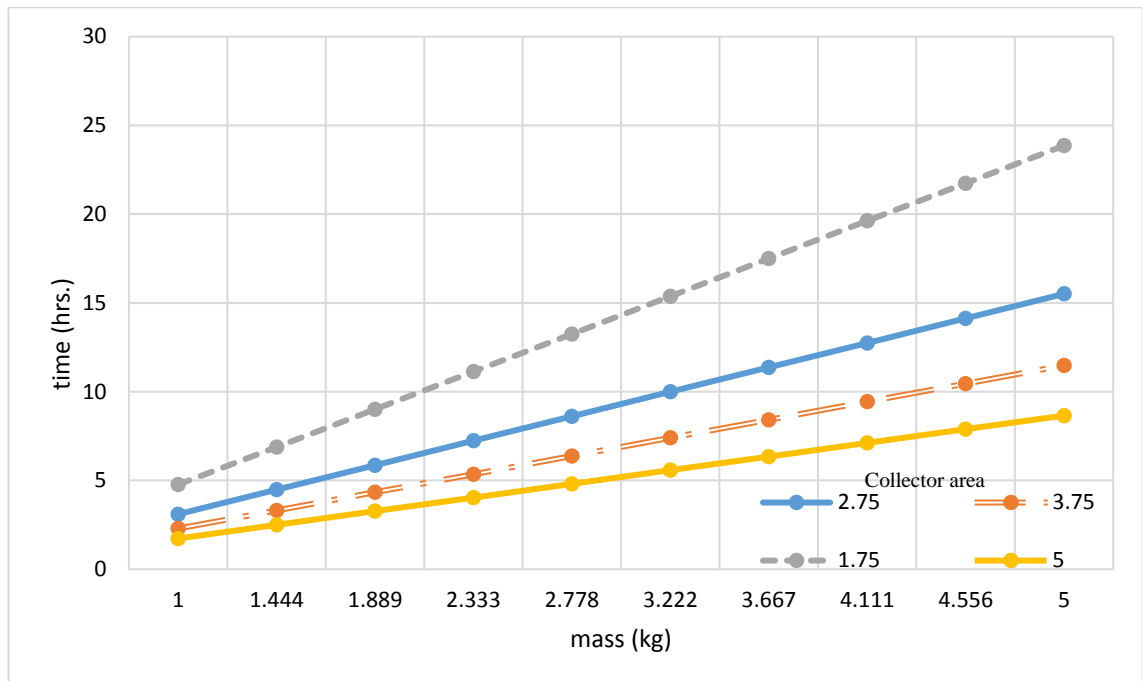


Figure 5.10: Time required to evaporated various masses of water for different collector area.

The collector area plays a significant role in the drying time of a specimen. Figure 5.6 shows the drying time at different moisture content under a particular collector area. From the graph, the time required evaporating 1kg of moisture from a specimen using a collector area of 1.75 m² was about 5 hrs. Though this simulated result contradicts with the experiment data like in the case of apple drying about 0.91 kg of moisture was a loss from the apple with a drying time of 12 hrs. The reason behind this gap is the

heat loss from the system which was not accounted for in the simulated design, some basic assumption. Also from the figure above, an increase in the collector area in turn reduces the drying time.

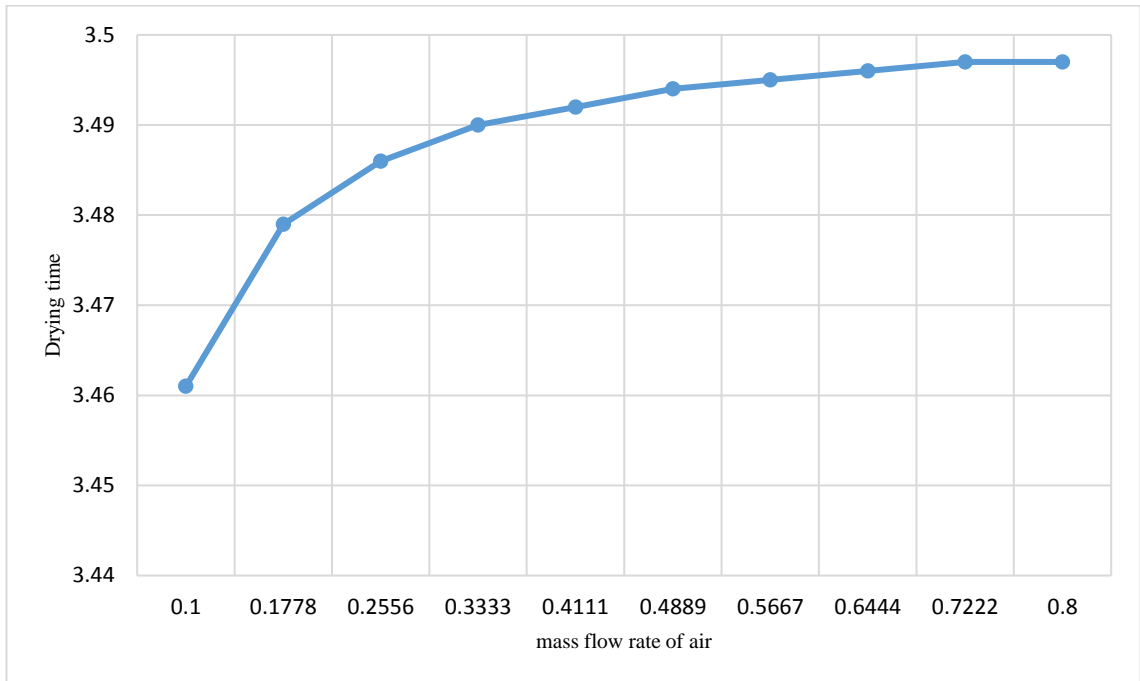


Figure 5.11: Effect of mass flow rate of air on the drying time

From equation 3.9, increase in \dot{m} (mass flow rate of air) will cause a decrease in the exit temperature of the collector. As discussed in the design section, the exit air temperature of the collector happens to be the inlet air to the chamber. Low temperature air entering the chamber means relative humidity is high and the ability of the air to accommodate more water is reduced. Figure 5.9 shows the drying time relation with the mass flow rate of air over 2 kg moisture content and a collector area of 5 m².

5.9 Product quality

In the course of processing, many elements can affect the dietary value of the products and might cause nutrition degradation. What influences the degradation of different vitamins vary, but typically excessive temperature and the time exposed to the excessive temperature is vital. Additionally, oxygen and light are critical elements about nutrition degradation. The balance these factors must be considered properly before processing. In this study, the color of the specimen during apple and banana drying was taking into proper considering by cleaning the specimen with 1 % of citric acid before drying process.



Figure 5.12: Drying sample at the end of each day during banana drying

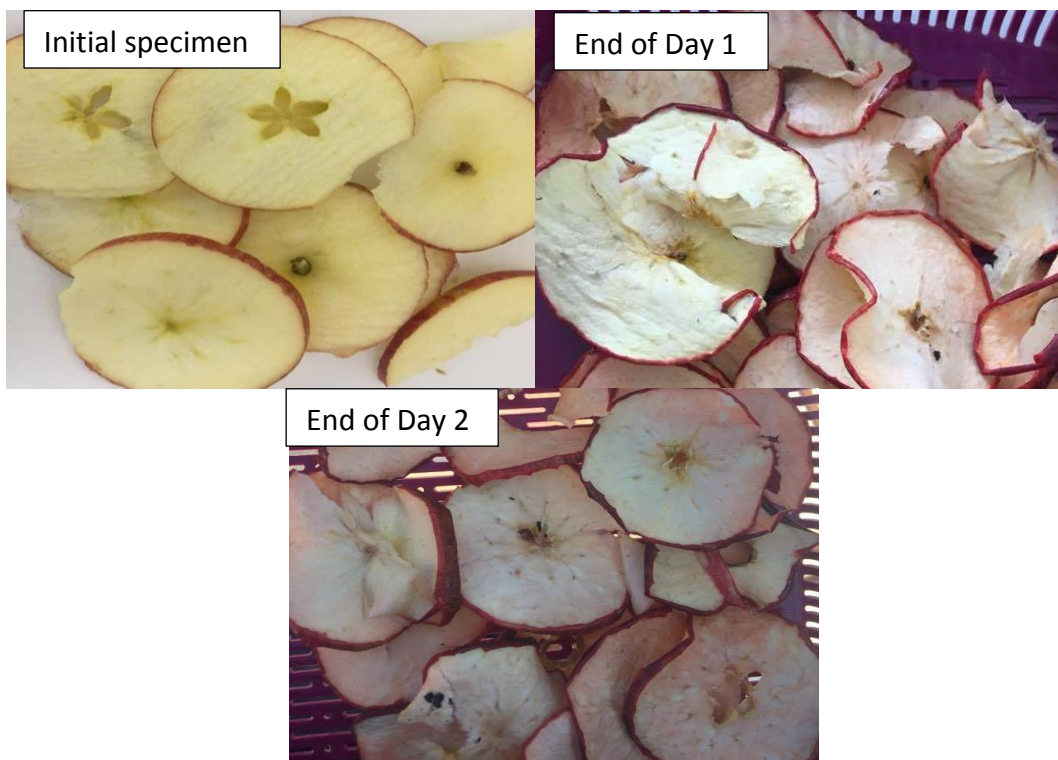


Figure 5.13: Drying sample at the end of each day during apple drying

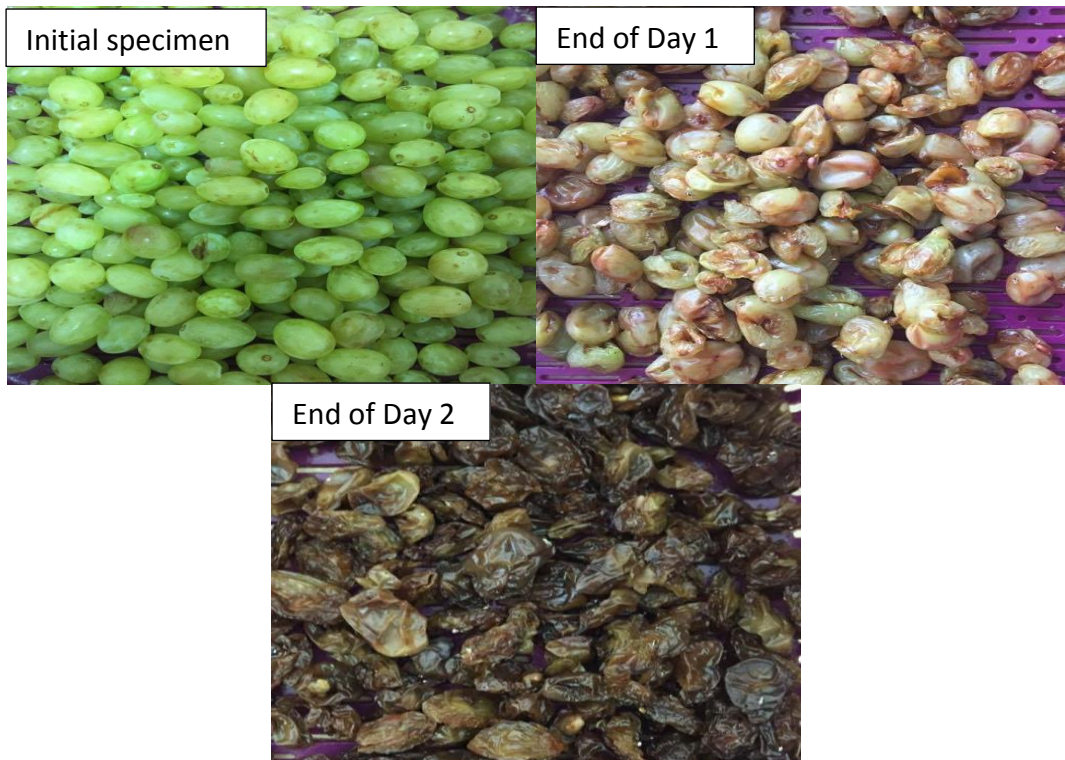


Figure 5.14: Drying sample at the end of each day during grape drying



Figure 5.15: Drying sample at the end of each day during chill pepper drying

The Color and appearance is an important term to consider for the dried products. Figure 5.11-5.14 shows a photograph of the solar-dried banana, apple, grape and chili pepper. Visual inspection of the fruit was conducted by comparing it with the available ones in the market to determine its commercial value. Finally, the products are suitable for commercial consumption.

5.10 Drying cost analysis

The cost of drying different specimen varies with the amount of moisture present in the product. The energy cost related with drying apple, banana, grape and chili pepper using solar energy is very low. In this cost analysis, 1tonne of each material will be considered to be dry yearly of 10 years. The prototype dryer which uses only solar energy will be compared with dryers that use electricity and heat pump (with COP 4).

The cost of our prototype dryer will be the fan cost while the energy required to evaporate the need moisture would be considered for the other energy sources. From the graph below, the solar dryer has proven to be a cost effective dryer though it's low efficiency when compared with the electric and heat pump dryer. The drying cost of using solar energy over a period of 10 years for drying apple, banana, grape and chili pepper is lower than 35 tl. For the heat pump and electric dryer, it is capital intensive.

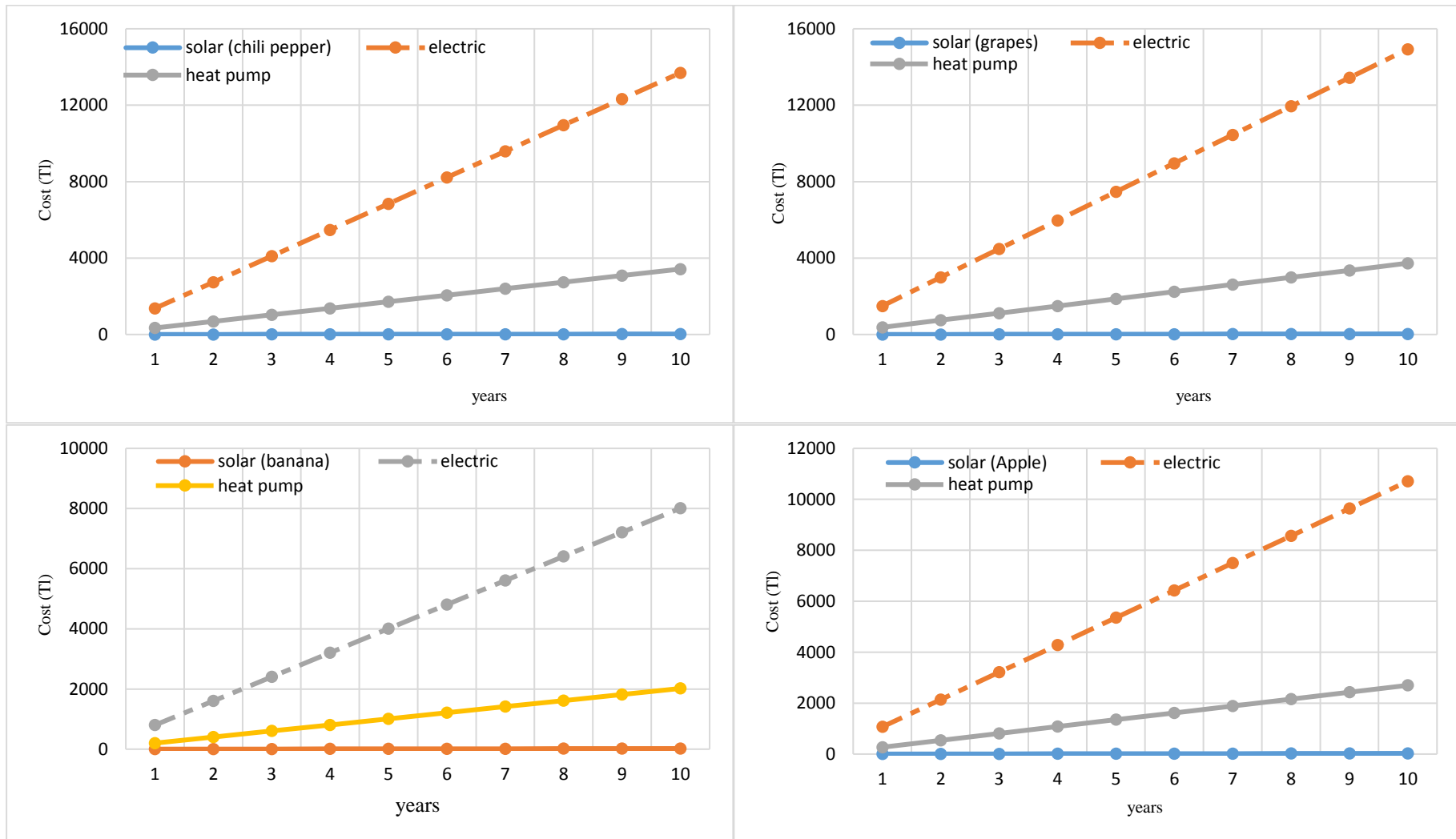


Figure 5.16: Drying cost for four specimen considering different energy sources.

Chapter 6

CONCLUSION

A mix mode solar dryer with different drying chamber module was designed and constructed. The performance of the solar dryer was evaluated in Northern Cyprus (35.125°N and 33.95°E). Numerical analysis using EES was carried out to enable evaluate the dryer based on different condition like a change in collector area and change in mass flow rate of air.

Experiment was perform on the mix-mode dryer using four specimens: apple, banana, chili pepper and grape with an initial weight of 0.96 kg, 1.16 kg, 0.6 kg and 0.87 kg. each test was conducted for two days under different loading batch. The average inlet air temperature and the relative humidity for various test range from 32 °C – 35 °C and 11 %-28 % respectively. While the exit temperature and the relative humidity ranges from 44 °C – 51°C and 14 %-30 % respectively.

The efficiency of the drying chamber depends on the drying specimen and the solar radiation. For apples, the drying time was twelve sunshine hours and the efficiency of the drying chamber was recorded to be 38.1 %. Testing the efficiency of the chamber using banana, the drying period was 9hrs and the chamber has an efficiency of 43.84 %.While the efficiency of the chamber and the drying time of chili pepper and grape during are 40.03 %, 42.12 % and 13 hrs, 10 hrs respectively.

Simulating the dryer for using EES was carried out. The larger disagreement between the numerical work and experiment work can be generated from the following reasons:

- Thermal properties of all the materials that are employed for manufacturing the collector and the drying chamber should be investigated in detail to avoid mishap between the actual properties and those used for the simulation.
- In the measurement of the temperature and mostly the relative humidity of the inlet and exit air, a more accurate equipment should be employed.

6.1 Future works

Several suggestions for the development of the current solar dryer design are mentioned here. Those potential trends are detailed and discussed in this document to provide a foundation for continuing the improvement of the contemporary prototype. These proposed changes are meant to enhance the prototype regarding the drying effectiveness, efficiency, and throughput.

The current prototype consisted of 2 modules and was applied in drying grapes, banana, apple and chili pepper for less the 15 hrs. A larger system can be developed to process more fruit in the same period by increasing the module concerning the collector area. It is also expected that the drying time could be reduced by using a heat exchanger at the exit of the drying chamber to recover waste heat as seen in the figure below. Also a photovoltaic power source can be introduce to the system to reduce the solar drying cost to zero.

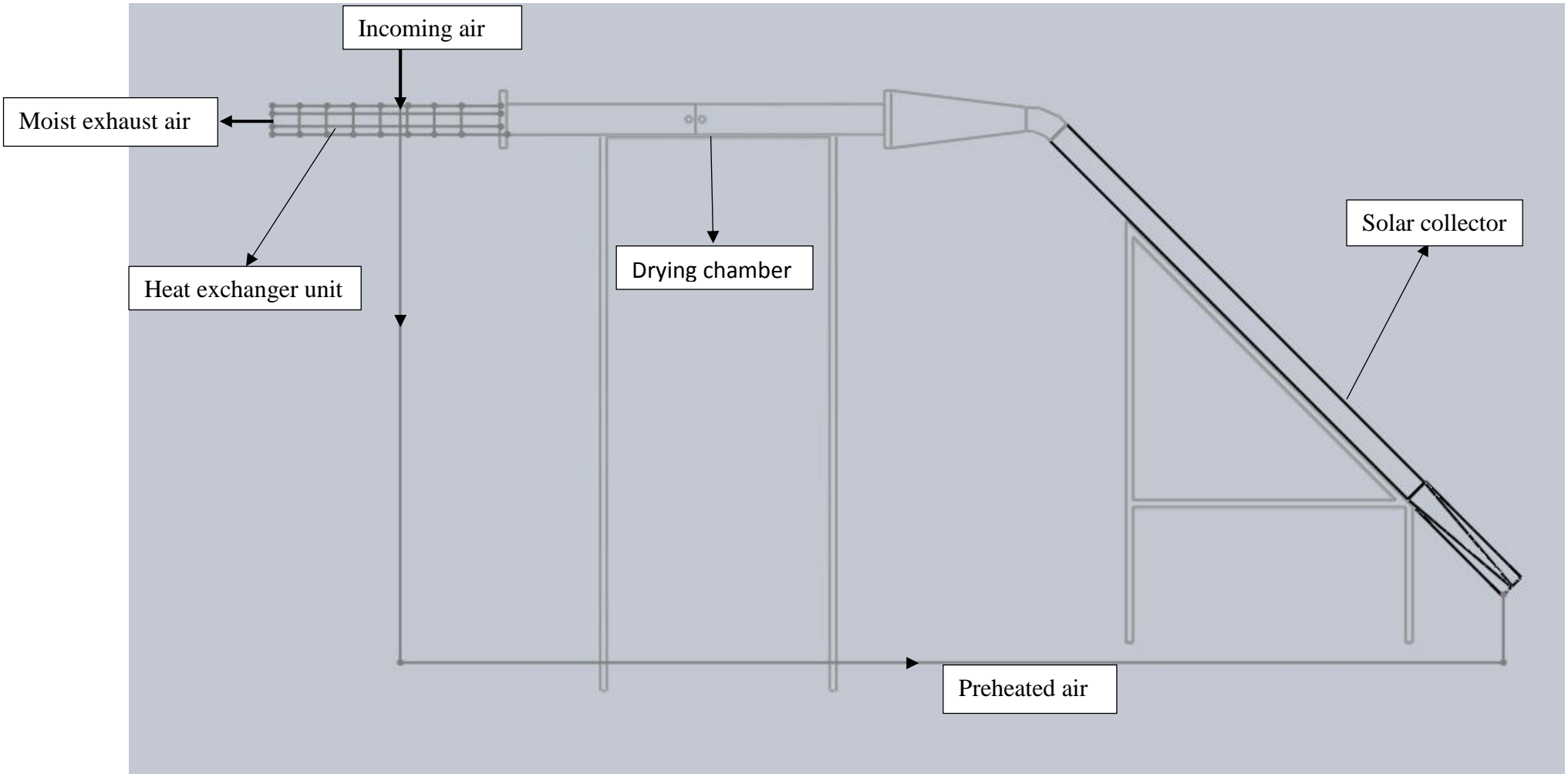


Figure 6.1: Schematic of future work

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APPENDICES

Appendix A: Experimental results

Banana testing

	time	RH1	RH2	RH3	T1	T2	T3	I (HORI)	I (SURFACE)
DAY1	11:00	25.5	14.08	31	35.5	44.28	45.13	795.24	823.81
	12:00	20.5	12.32	28	35.51	45.08	47.13	876.19	842.86
	13:00	20	11.46	26	36.58	47.17	49.65	923.81	809.52
	14:00	17	9.317	18.5	36.98	48.48	51.23	909.52	709.52
	15:00	15.5	8.518	14	36.45	47.85	50.75	833.33	576.19
	16:00	17	9.188	17	37.55	49.38	49.78	704.76	371.43
	17:00	18	10.12	22	31.6	42.15	44.33	538.09	171.43
DAY2	11:00	25.5	13.337	23.5	32.55	44.53	49.45	833.33	852.38
	12:00	22.5	11.7	26.5	32.59	44.73	49.88	919.05	876.19

Chili pepper testing

	time	RH1	RH2	RH3	T1	T2	T3	I (HORI)	I (SURFACE)
DAY1	11:00	26	13.24	27.5	30.35	42.68	45.4	842.86	861.9
	12:00	24.5	12.7	27.5	31.35	43.43	46.3	876.19	861.9
	13:00	23.5	12.34	26.5	32.28	44.2	46.8	909.52	809.52
	14:00	20.5	11.54	26	32.78	43.4	45.65	900	700
	15:00	20.5	12.9	26	32.73	41.23	43.38	823.81	561.9
	16:00	22.5	16.29	27.5	31.95	37.78	39.78	719.05	390.48
	17:00	24	16	31.5	32.08	39.45	41.55	516.91	185.71
DAY2	11:00	23.5	11.96	24.5	30.93	43.33	49.6	809.52	823.81
	12:00	19.5	10.43	17.5	33.53	45.2	50.1	895.24	847.61
	13:00	13.5	7.599	14	35.18	46	51.5	947.62	838.09

Grape testing

	time	RH1	RH2	RH3	T1	T2	T3	I(HORI)	I (SURFACE)
DAY1	11:00	14.5	7.6	21.5	33.1	45.25	48.43	833.33	842.86
	12:00	11.5	6.2	19	34.43	46.13	50.23	923.81	885.71
	13:00	10	5.4	14	34.58	46.25	50.88	947.62	838.09
	14:00	10	5.4	15	34.1	45.78	50.83	923.81	728.57
	15:00	10	5.3	15	33.5	45.27	50.2	866.67	585.71
	16:00	10	5.3	11	31.5	43.03	47.3	761.9	395.5
	17:00	10	5.3	10	30.5	42.11	45.5	557.14	150
DAY2	11:00	17	8.8	14	33.83	46.3	55.68	819.05	871.43
	12:00	12.5	6.5	17	34.63	46.9	55.63	866.67	876.19
	13:00	11	6.2	18	35.8	46.55	53.6	871.43	766.67
	14:00	10.5	6.6	16	37.17	46	50.9	852.38	657.14
	15:00	10	6.2	12	37.23	46.33	53.8	776.19	522.81
	16:00	10	6.6	11	36.3	44.05	50.55	661.9	400

Apple testing

	time	RH1	RH2	RH3	T1	T2	T3	I (HORI)	I (SURFACE)
DAY1	11:00	44	23.74	41	28.48	39.55	40.15	780.95	809.52
	12:00	38	22	38.5	30.05	39.93	41.13	861.9	828.57
	13:00	31.5	17.97	36	30.05	40.2	42.08	904.76	785.71
	14:00	25	14.4	33.5	30.29	40.28	42.68	880.95	690.48
	15:00	20	13.18	29	32.38	39.98	42.75	804.76	542.86
	16:00	26	18.05	29	34.18	40.9	43.6	690.48	357.14
	17:00	29.5	19.72	34	33.5	40.9	43.6	466.67	171.43
DAY2	11:00	31.5	17.17	30	30.68	41.75	44.68	804.76	833.33
	12:00	36.5	19.59	25	31.93	43.4	46.88	900	871.43
	13:00	28	15.61	22.5	32.35	43.13	46.88	942.86	838.09
	14:00	16.5	10.24	23.5	35.55	44.5	48.33	928.57	733.33
	15:00	12.5	7.823	19	35.8	44.6	48.38	842.86	571.4

Appendix B: Cost of drying chamber and collector

Materials	Cost (TL)
Wood	40
Glass	60
Steel sheet	65
Steel pipe	83
Screws	12
Collector Glazing	80
Insulation	48
Labor cost (15% of Labor)	100
TOTAL	488

* Conversion rate of 1 USD = 3.72 TL (As of September – December 2017)