A SOLAR CROP DRYER FOR RURAL AREAS

by

TATENDA BLESSING RUNGANGA

Thesis submitted in fulfilment of the requirements for the degree

Master of Engineering: Mechanical Engineering

in the

Faculty of Engineering

at the

Cape Peninsula University of Technology

Supervisor: Dr K Kanyarusoke

Bellville Campus

2019

DECLARATION

I, **Tatenda Blessing Runganga**, declare that the contents of this dissertation/thesis represent my own unaided work and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Runganga

02/10/2019

Signed

Date

ABSTRACT

In most rural areas, food waste is a problem experienced by farmers during the post-harvest period. The main reason for the losses is the degradation of foods during the postharvest period due to high moisture content and poor initial moisture control in these foods. Farm drying methods often compound this problem by contaminating the produce with foreign matter. The losses have a huge impact on farmers, agricultural industry, consumers and on the global economy in general. With famine and frequent droughts due to inadequate rainfall, preserving the available food reserves plays an important role. With the high solar potential levels of South Africa and the rest of the continent, this research assumes the problem of how post-harvest food and moisture content can be addressed if suitable solar dryers are availed to the region. Open sun drying is the main traditional method used for drying crops and fruits in Africa. Its disadvantages include contamination (exposure to dust), infestation (exposure to animals and insects) and exposure to rain due to no enclosures in the system. In effect, moisture control is difficult. This project, therefore, describes a 'design, construct, test and cost' approach to tackling the problem at a rural farm level. The basic assumption is rural farmers desire to reduce postharvest losses hence need to adopt affordable low cost, low technology methods in controllably drying their produce. It was decided that enclosed solar crop drying was feasible due to the high solar radiation levels during harvest times. Therefore, two different dryers designs with $1.5m^2$ and $2m^2$ glazing area were designed, constructed, tested and direct costs estimated. Key design variables were identified whilst different fruit and vegetable products were tested against a control open-air drying system with solar radiation, temperatures and moisture losses monitored. In addition, a modification of the dryer to give a simple automatic indication of readiness of particular foods is given. This characteristic distinguishes it from other designs attempted elsewhere. Both designs reduced drying times to less than one day at the beginning of Cape Town's winter season while open-air drying was problematic, lasting up to one week. The direct cost of each dryer was under ZAR2000. After tests, it was therefore concluded that the designs are feasible and are now ready for redevelopment for commercial purposes.

ACKNOWLEDGEMENTS

I wish to thank:

- God the Almighty for granting me this opportunity and insight in pursuing my studies.

- My supervisor Dr Kant Kanyarusoke for the supervision, advice and encouragement. I am truly thankful for the knowledge you have imparted to me.

- The CPUT Mechanical Engineering Department, staff and undergraduate students who were part of the project for their assistance during this period.

- My mom (Mrs C Runganga), sisters (Lucy, Lorraine and Lynn) and brother Kudzai for their love, support and sacrifices they always made to ensure I achieved my goals.

- My colleagues and friends Caroline Tyavambiza, Luyanda Meyers, Busiswa Jantjies Nteka Elizabeth, Ada Engohang Djamila, Peter Jeremia and Netshifhefhe Bonnie.

- The part financial assistance of the Progressive Africa Solar Engineering Pty. Ltd. towards this research is acknowledged.

DEDICATION

To God the Almighty

and

My late father Kenneth Runganga, wish you could have been here to witness my accomplishment

TABLE OF CONTENTS

LIST OF FIGURES

Chapter 2

Chapter 3

Chapter 4

Chapter 5

LIST OF TABLES

Chapter 3

Chapter 4

Chapter 5

GLOSSARY

Crop drying - the process of removal of water from crops by the application of thermal energy

Dehydration or desiccation – the process of preserving food by removal of moisture

Drying rate – measurement of how quickly material can dry depending on the rate of heat transfer between the material being dried and its surroundings

Drying time – the time taken for a material to lose water or volatile substances to the required moisture content

Moisture content - the ratio of the mass of water in a sample to the mass of solids in the sample

Open air drying – a process to dry a substance by placing or exposing it to the open air

Postharvest - the period after harvesting is done and completed

Renewable energy - energy from a source that is not depleted when used

Rural areas - a geographic area that is located outside towns and cities

Shelf life - It is a period of how long a food product can retain its quality before degrading

Solar radiation – radiant energy emitted by the sun

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATION	DEFINITION
$G_{b'}$	Incident beam radiation on a tilted surface,
G_b	Incident beam radiation on a horizontal surface
θ_i	Beam radiation incident angle.
θ_z	Zenith angle
ΔT	Temperature difference
A	Area
D	Day of the month
d.b	Dry basis
DoE	Department of Energy
FAO	Food and Agricultural Organisation
H_2O	Water
k	Thermal conductivity
m	Mass
R_b	Geometric factor
T	Temperature
t	Thickness
w.b	Wet basis
c	Specific heat capacity
L	Latitude
δ	Declination angle
ω	Hour angle
β	Tilt angle

CHAPTER 1: INTRODUCTION

This chapter gives a brief introduction to solar crop drying together with the project background, aims and objectives.

1.1 Background

Due to the short life spans of most fresh farm produces, large amounts of foods are lost as a result of rotting and/or natural degradation (Rawat, 2015). These processes are mostly catalysed by the action of microorganisms and the enzymes present in the fresh food (Fellows, 2009). Both processes are stimulated by high water content in the food; this provides suitable environmental conditions for microbial growth and the associated biochemical reactions (Gram *et al*., 2002). Reducing the water content in the food either on the market or shelves results in an increase in the food's life spans. This can be achieved by drying the food without compromising the food quality and texture. In most rural areas, farmers incur losses due to food degradation after post-harvest which eventually leads to food scarcity and starvation (Othman *et al*., 2006). The main reason for the losses can be accounted for by the decomposition of foods during post-harvesting, in storage or during transportation to the markets (Beretta *et al.,* 2013). These losses have a huge impact on the farmers, the agriculture industry, consumers and the global economy at large (Kiaya, 2014).

Sun drying is one of the old traditional methods used for the drying of crops and fruits. This system has been used for many years dating back for many centuries and is popular among the methods used for drying agricultural produce (Basunia and Abe, 2001). The process works by placing the crops or fruits to be dried on a flat surface or on the ground where they are exposed to the direct sunlight for the process to begin. Although open sun drying is one of the common drying methods used, it does come with its own disadvantages and negative drawbacks (Ong, 1999). The problems brought about by this method include product contamination, infestation and exposure to different weather conditions due to no enclosures in the drying mechanism (Akoy *et al*., 2006). These factors can result in the degradation of food which in turn decreases the food quality and quantity (Gross *et al*., 2002). Crop drying involves the use of either a renewable or non-renewable energy sources to dry up the air used in the drying process. Use of non-renewable energy means high energy costs for the farmers and more CO_2 emissions and pollution into the atmosphere (Chel and Kaushik, 2011 & Carlsson-Kanyama, 1998). Hence this research will provide a design solution that will ensure incorporation of the following: reduction in food loses in rural areas, allowing food to dry in a well-controlled environment (free from animals and harsh weather conditions), the prolonged life span of agricultural produces whilst using a clean renewable energy source (Aulakh *et al.,* 2013). This can be achieved by use of a solar crop dryer.

Food or crop drying is actually feasible in South Africa due to the good solar radiation levels in the region. Solar radiation levels can range from between 4.5KWh/m^2 and 6.5KWh/m^2 per day (DoE, 2015). The purpose of most food dryers is to ensure that the shelf life of fresh foods is increased by removing the water from the food. This is irrespective of the type of energy source used for the drying process. Food drying also plays an important role for the seasonal crops and fruits which will be made available all year round (Akoy *et al*., 2006). Food deterioration and spoilage are mainly caused by the growth of microorganisms (microbes) and the action of enzymes on food items. These are natural life processes that occur within any type of food (Gross et al., 2002). The conditions that promote the microbial growth which in turn triggers enzyme action leading to food spoilage include a suitable temperature, moisture (H_2O) and food (Rawat, 2015). Spoiled food is characterised by mainly a change in taste, texture, appearance and smell. This makes the food inedible and unsuitable for human consumption (Gross et al., 2002).

Large amounts of foods especially fresh produce are lost every year as they are discarded due spoilage after the post-harvest period. According to the Food and Agricultural Organization (FAO, 1991), the estimates of fruits and vegetables for market and export for 1990 from third world countries were approximately 341.9 million metric tons. These figures are low compared to the current yearly loses and food waste statistics. FAO (2011) reports that approximately 670 million tonnes are lost or wasted in high-income countries whilst the figures are slightly lower in the middle to low range countries (630 million tonnes). In total, this constitutes to about a third of the world’s available edible food. Sahdev (2014) further emphasises on an estimated 30 – 40% loss and whilst (SPORE, 2011) emphasises on 40-50% loss on mostly fruits and vegetables in developing countries due to rotting and decaying. Most of these foods have high moisture content and are highly likely to decay or rot if they are not preserved well (Stancu *et al.,* 2016). The demand for fruits and vegetable products for the market continues to grow with the increase in populations hence it is important to ensure the shelf life of these products is increased to prevent further food losses (Rosa, 2006).

Due to hunger and food crisis in the world - especially in the third world developing countries - it is important to analyse issues regarding food losses (FAO, 2013). The driving factor is mainly to ensure food security and reduce hunger in poverty-stricken areas (Godfray *et al.,* 2010 & Alexandratos and Bruinsma, 2012). For most communities especially in the rural areas, food losses are associated with struggles in food security, losses of capital and income mostly for the small scale farmers (Rawat (2015); Chaboud & Daviron (2017)). Affordability and access to food is the main priority for the low producing consumer hence measures have to be taken in order to reduce the loss of food for the small producing farms. According to the research by Rawat (2015) and Gustafsson et al., (2011), the worldwide postharvest loss of fruits and vegetables are approximately between 30 and 40% (Foley *et al.,* 2011). With the increase in population and the high demand for resources, measures have to be taken to reduce overproduction and save on the food quantities produced (UN, 2011). Overproduction with poor preservation methods does not only result in greenhouse gases which are a threat to the environment but also escalates the loss of the produced food (Kitinoja and Kader, 2015).

1.2 Problem statement

The increase in the economic growth of South Africa and the rest of Africa tends to show an increase in energy usage, energy demand and food requirements. This continuous growth implies that more food reserves are required to ensure food sustainability within most of the communities. Post-harvest losses due to inefficient preservation methods are the factor driving the project. Most rural and small scale farmers rely on their products for food and income. However, due to the short life span of most fresh farm produces, large amounts of foods are lost as a result of rotting. The fresh farm produces need to be preserved in their dried form to ensure their continual use. Due to their limited resources, most small scale farmers dry their produces using open sun drying method. Unfortunately, open sun drying exposes the food to contamination (exposure to dust), infestation (exposure to insects/animals) and various weather changes (rain, wind etc.).

1.3 Limits and constraints

The following were the boundaries and limitations of this research:

- The study was done based on the weather conditions in Cape Town (CPUT Bellville Campus Site)
- Food grade materials were used to ensure the food dried was safe for consumption
- The crop dryer was light and easily operated by any user
- The crop dryer could be moved easily and be secured at any position if required

1.4 Aim of the research

The aim of the research is to provide a solution for the post-harvest losses and poor drying methods by implementing solar crop drying. A ‘design, construct, test and cost’ approach was used in solving the food loss problem. In the process, the technical requirements and functionality tests were assessed on three different drying setups i.e. open sun drying, natural ventilation drying and forced extraction to determine the effectiveness of the dryer setups.

1.5 Research questions

- What is the best solar technology for rural crop drying?
- What solar crop dryer design can be implemented in rural setups?
- How do you test the functionality of a solar crop dryer?
- What indicator can be used in determining if the food has completely dried?

1.6 Research objectives

For this project to be successful, it was necessary to investigate various key objectives. In order to support the research statement titled **“*A Solar crop dryer for rural areas*”** and to showcase that the application and implementation of a crop dryer can yield benefits to the target rural setup, the following objectives were to be achieved in the evaluation of the problem:

- Determine a low cost, low technology solar drying technology suitable for a rural area setup
- Estimate the possible impact (quantitative) on food reduction by the introduction of crop dryers in rural setups based on current research
- Design, build and implement a functional solar crop drying system suitable for a rural area setup
- Test the functionality and drying effects of the different solar crop dryer setups using different fruits and vegetables.
- Include a modification of the dryer that gives a simple automatic indication of readiness

1.7 Significance of the research

As the government is focusing on and supporting the use of adequate and affordable clean energy in the communities, renewable energy technologies are the leading alternative sources. In doing so the renewable energy sector is developed and the energy sources are utilised to realise their potential. Solar crop drying assists in preventing post-harvest losses. As crops are more susceptible to attack by pests and weather conditions whilst in the fields, crop drying provides even and better drying rates which ensure the crops are at low risk to these attacks. Use of solar energy reduces energy costs hence also reducing the drying costs for the farmers. Effective utilisation of the suns’ energy in the drying and preservation of food is significant in ensuring reduction of food losses either during post harvesting and storage thus increasing the sustainability of the farmers and the surrounding communities. Although much of the drying is done with small equipment, there are potential opportunities to invest in drying technologies in South Africa. As most dried products can be used as powders, whole pieces, segments and slices, this gives a wide range in which the products can be used which can be beneficial to the growing food industries. The solar crop drying project is significant and valuable to the rural communities and the country at large since it brings the use of a renewable energy source, ensuring sustainability among communities, reduction in food losses whilst ensuring the food availability for the people all season either for personal consumption or sale to the market if in excess. Since the project is focused on the use of renewable energy, it supports environmental sustainability by reducing carbon emissions and is also beneficial to off-grid rural areas with scarce or no access to electricity. It is important to tap into this energy source due to the fact that it is available throughout the year though at different intensities. Reduction in post-harvest losses means a reduction in carbon emissions and also more food supplies available for consumption and export. Experimental data acquired during the testing phase will be used to determine how effective solar crop dryers can be in food preservation.

1.8 Thesis organisation

The thesis comprises of six chapters, each one specifically allocated to a certain topic for discussion and structured as follows:

Chapter 1 is a brief introduction to solar crop drying together with the project background, objectives and aims.

Chapter 2 is an overview of the overall literature and theory on solar crop drying technologies.

Chapter 3 introduces the design and construction of the solar crop dryer focusing on component selection, concepts, detailed designs and manufacturing processes.

Chapter 4 deals with the experimental setup and methodologies implemented in the project. This includes the methodology, data collection techniques, experimental setup, testing procedures and instrumentation.

Chapter 5 deals with testing and performance evaluation of the designed solar crop dryer. Discussions on results, key performance indicators, measurements and calculations are presented in this section.

Chapter 6 concludes all the results, findings, analysis on all the work covered and gives an overall summary and recommendations.

CHAPTER 2: LITERATURE REVIEW

This chapter gives an overview of the theoretical knowledge and literature on solar crop drying technologies.

2.1 Food preservation

In these modern days, there are many ways used in the preservation of food. One important aspect of food preservation is to maintain the nutritional value, texture and flavour of the food (Gross *et al.,* 2002). These factors determine the type of preservation method to be used for a particular food product – usually based on the required procedure to be applied and food quality requirements (Kiaya, 2014). Through the application of these methods, the growth of microbes is prevented or reduced, visual deterioration is slowed and the shelf life of food increased. Among the types of food preservation methods are sugaring, drying, canning, salting, curing, smoking, freezing etc. (Gram *et al*., 2002). These different preservation methods are applicable to different foods and the ways of the application can differ hence giving different results. Some of the methods can be used in conjunction with other methods in ensuring the food is well preserved. For example in the preservation of some vegetables, it is required first to boil them (blanch) before allowing the drying process to proceed. In all these preservation methods the main objective is to ensure the food lasts longer by achieving one or more of the following: reduction of moisture content, prevention of growth of microbes and prevention of recontamination (by sealing off or airtight containers) (Fellows, 2009). Producers and farmers dry and process their produces for prolonged storage whilst reducing post-harvest losses as evident in the study by Ndukwu *et al.,* (2017) in which cocoyam was dried and processed into flour for easier storage and export to other countries.

2.2 Drying

In general, drying is a thermal process of removing water from a product to produce a solid or semi-solid final product usually triggered by mass and heat transfer within the food substance. Drying has been used as a means of preserving food way before recorded history, mostly for meats, fish and other products (Belessiotis and Delyannis, 2011). It is one of the common methods of food preservation used up to date. Drying reduces the rate of activities of microbes in the food, preventing the food from spoil quickly. This process is used in food preservation by increasing the shelf life and making the food lighter. Research by Tiwari (2016) emphasises that a reliable energy source and air flow are essential in ensuring proper, even drying and ease of removal of moisture from the system. The energy source must be sufficient to provide the heat needed to evaporate the moisture from the food and with the aid of suction fans or conventional air flow, the evaporated moisture is removed from the system.

An energy source - renewable or non-renewable - can be used in the drying depending on the application and design of the drying system. Drying involves the removal of water from the food, a process that is accompanied by the vaporisation of water within the food (Belessiotis and Delyannis, 2011). The latent heat of vaporisation is required for the removal of the water from within the food. This is the minimum heat energy required for phase change from liquid water to water vapour without any temperature change (Aravindh and Sreekumar, 2015). To completely dry any food item, the food has to undergo two distinct processes namely (i) transfer of heat to provide the necessary latent heat of vaporization and (ii) movement of water or moisture within the food before evaporation into the atmosphere (Ekechukwu, 1999). There are different types of drying namely freeze drying, microwave/vacuum drying, spray drying, infrared drying and air and contact drying. The latter was used in this project as it is applicable and more focused on the project objectives. In air and contact drying, heat is transferred through the food either from heated air or from heated surfaces. The water vapour is removed with the air.

2.2.1 Drying process

Heat and mass transfer are the critical aspects that drive the process of food drying. Two processes are involved in food drying. Firstly, heat energy is supplied to provide the latent heat of vaporisation required for the phase change from the liquid to the vapour of water within the food (Sharma *et al.,* 2009). This latent heat of vaporisation is the energy required per kilogram for phase change. It must be supplied to vaporise the water at any given condition and is highly dependent on the temperature. This process is associated with the movement of the moisture from within the food particle to its surface. Heat energy is introduced to the drying system at a temperature higher than that of the product (Chen *et al*., 2005). Due to the temperature gradient between the food product and the air in the dryer, heat transfer from the surrounding dryer area to the food product will occur. This absorbed heat is essential in breaking the bonds between the water and food particles within the product, hence triggering moisture movement to the product surface (Prakash and Kumar, 2012). The next process involves the movement of water within the food to the food surface until it evaporates to the surrounding air around the dryer. This process also requires heat energy to evaporate the moisture before it is extracted from the system. The heat transfer between the surroundings and the food product can occur as a result of convection, conduction, radiation or a combination of both (Chen *et al*.,2005). Due to the different drying rates and properties of food products, different foods will require different energy to completely dry. Overdrying should be prevented as it will compromise the food quality and destroy the food structure (Ekechukwu and Norton, 1999). The following parameters are essential in determining the drying process of any food substances: material to be dried, temperature, volume to be dried, air flow and desired moisture content for the foods i.e. initial and final moisture content.

Solar crop dryers are classified according to the temperature operating range and sizes (Ekechukwu and Norton, 1999). The most applicable for rural area setups used for this project are the low-temperature drying systems which have average to long processing times and can accommodate almost all grain types. Temperature rises of between 30°C and 85°C are sufficient to minimise or stop the growth of the fungi (Farkas, 2013) and be able to completely dry the crops. In general, higher airflow rates, higher air temperatures and lower relative humidity increase the drying rate of food. Any increase in the temperature increases the ability of the air to absorb moisture and decrease the relative humidity (Atanda et al., 2011). The difference between the moisture content of the drying air and the crop moisture play a vital role in the drying rate. In general, the movement of moisture is rapid from the crop (at high moisture concentration) to the air (at lower relative humidity). In contrast, if the air is at high relative humidity it will be difficult for the moisture to move from the food due to the low concentration gradient between the two media. Air flow rate is dependent on the fan size and design, which allows the circulation of air in the system (Ekechukwu and Norton, 1999).

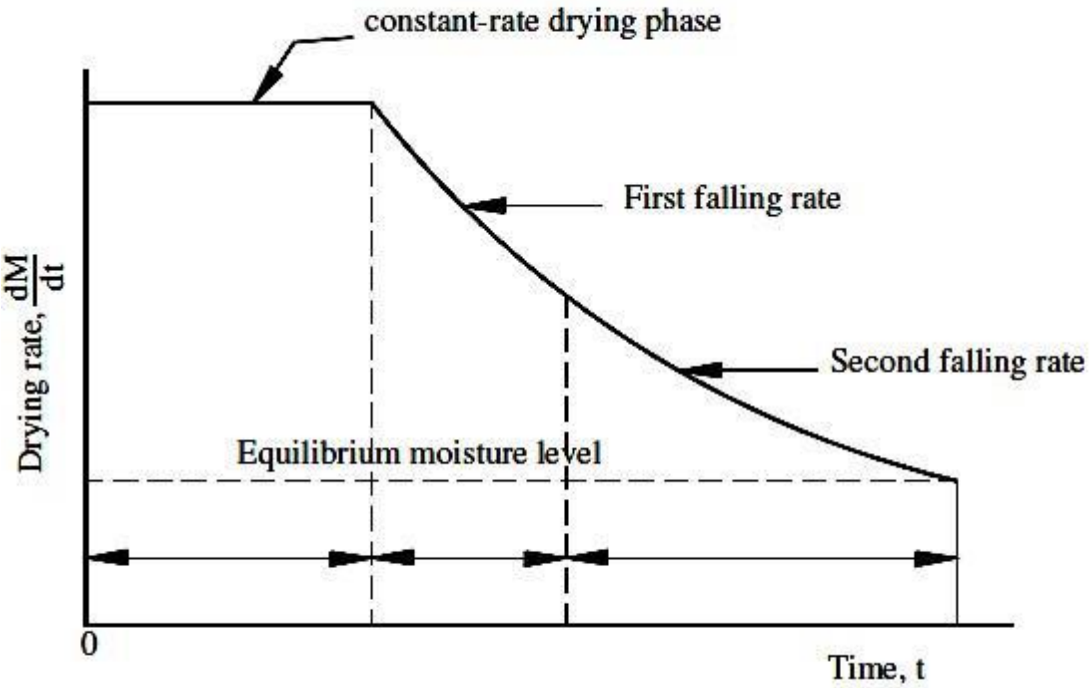


Figure 2.1: Drying rate vs Time graph for the moisture removal process of food samples

(Source: https://tinyurl.com/ya9ecd8v)

Figure 2.1 shows the trend for the drying process of both hygroscopic and non-hygroscopic materials. From the graph, it can be noted that there is an initial constant drying rate phase which is applicable and similar to both the hygroscopic and non-hygroscopic materials (Gallagher *et al*., 1998). The difference will be in the falling period's rates as it will decrease to zero in the non-hygroscopic materials, which is different to the hygroscopic materials as they are capable of retaining the unbound moisture that cannot be completely removed by the drying process. During the drying process, the initial phase of constant drying is usually quicker in comparison to the falling rate period. The latter stage is the one critical as it determines the rate of drying and moisture removal within a material due to diffusion (Gallagher *et al*., 1998).

2.3 Energy sources and crisis

Of the available energy sources that the world is using, approximately 14% of the demand is supplied by renewable energy sources (Panwar *et al.,* 2011) with an expected significant increase in the future. In most developing countries, the increase in populations and growth of the nation triggers the increase in use of the fossil fuels as the countries need to keep up with the demand (Alexandratos and Bruinsma, 2012). The increase in usage of fossil fuels has an impact on the depletion of resources as well as a negative impact on the environment which affects climatic changes and posing health risks (Koyuncu, 2006). Hence it is critical to venture into the use of renewable energy sources to reduce some of these problems. Use of renewable energy sources results in reduced pollution, reduced carbon emissions, conservation of nature whilst ensuring the use of a clean and environment-friendly energy source (Carlsson-Kanyama, 1998). A study by Kravola *et al.,* (2010) on the use of renewable energy shows a trend in the increase of use of these resources. In the study for projections up to 2040, the trends show figures at 13.6% in 2001, 16.6% in 2010, with projected estimates of 23.6% in 2020, 34.7% in 2030 and approximately 47.7% by 2040. In these projects, the figures show that solar energy plays a critical role in providing thermal energy used mostly in solar drying systems, solar home systems, solar cooking and also in the generation of electricity generation.

2.3.1 Renewable energy

Renewable energies are natural occurring and replenishing energy sources that can be used to produce energy continuously without depletion as compared to non-renewable sources (Godfray *et al.,* 2010 & Omer, 2012). Examples of renewable energy sources include solar, wind, biomass and hydro-energy etc. These sources do not allow carbon emissions into the atmosphere i.e. greenhouse gases and any pollutants. Solar energy is the most abundant energy sources available and can be used either directly or indirectly depending on the application ranging from solar drying, cooking, water heating and power generation (Mekhilef *et al*., 2013). Renewable energy sources are gaining attention and are on the rise as alternative energy sources due to their numerous benefits to the environment as well as the consumers. The growth of economies and increases in world populations has resulted in depletion of most energy resources available mostly due to human use, hence for future purposes, most countries are investing in renewable energy sources (Alexandratos and Bruinsma, 2012).

South Africa and most parts of Africa have good solar radiation levels which are beneficial and boost the solar energy use. Majority of the populations are located in the rural areas where the access to electricity is limited or not available to the communities (Koyuncu, 2006). Most people in these areas use firewood, charcoal and other non-renewable energy sources for daily use which gives rise to negative health impact on the society (Munzhedzi & Sebitosi, 2009). Most rural areas and arable farming land are located in these areas making it the high producers of the agriculture products. Besides transporting products to the markets, some percentage needs to be preserved either for consumption or selling to the markets in the offseason. This requires reliable energy sources (Kibria, 2015).

2.3.2 Solar energy

The sun provides a vast amount of energy, which is the source of life on this planet. The sun's energy reaches the earth's atmosphere in form of radiation which can be harnessed by designed systems for different purposes. The sun radiates huge amounts of energy on a daily basis, which is used to sustain life on the planet earth (Munzhedzi & Sebitosi, 2009). Of all the emitted radiation from the sun, only a small fraction reaches the earth. Most of the energy is absorbed and reflected by particles in the atmosphere: water vapour, carbon dioxide and a small percentage of oxygen included (Belessioti & Delyannis, 2011). The sun continuously emits solar radiation through the nuclear fusion that occurs in its inner core, hence making it a good and reliable renewable energy source. The energy produced by the sun is more than 10 000 times the normal requirements needed on earth.

The application of the harnessed energy ranges from direct conversion to electricity, thermal applications inclusive of solar drying and solar air heating. In Southern Africa, South Africa has one of the best solar profiles with solar energy radiation levels ranging from between 4.5KWh/m^2 and 6.5KWh/m^2 per day (DoE, 2015) and over 2 500 hours of sunshine a year (Munzhedzi *& Sebitosi,* 2009). This makes it a good energy source that can be applied for our day to day use. Figure 2.2 depicts the overall solar irradiance levels of most countries in Africa. It can be shown that South Africa has good irradiation levels both for the global and direct irradiation levels.

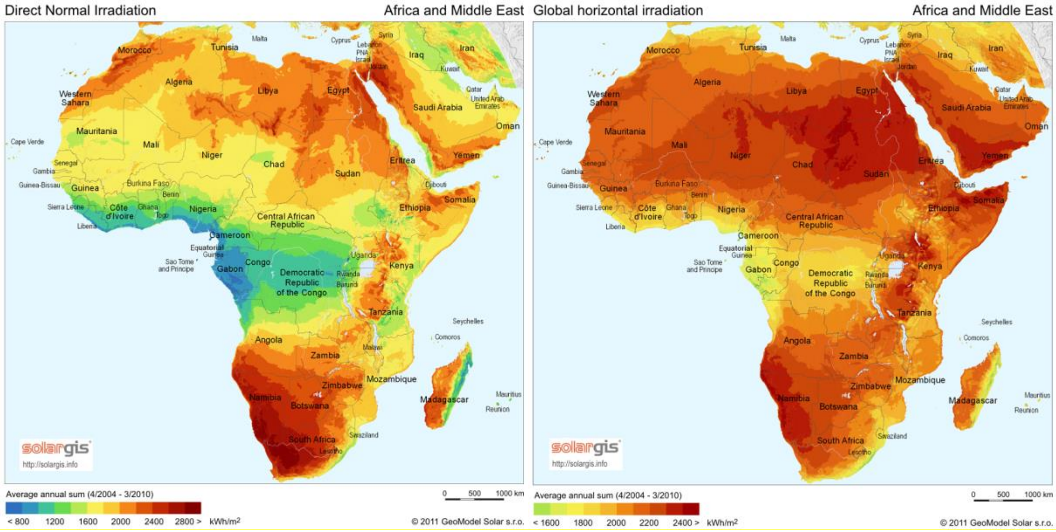


Figure 2.2: Illustration of solar radiation levels in Africa

(SolarGis, 2015)

The use of renewable energy is continuously increasing, hence making it a viable option to maximise the energy sources in designed projects. Solar energy is attractive due to its numerous advantages: renewable, clean energy source, environmentally friendly, free and availability throughout the year though at different intensities (Dhurve *et al.,* 2017). The use of solar energy reduces the strain on the other over exhausted energy sources (mostly non-renewable sources). Solar crop dryers are more beneficial to the rural setups where electricity is scarce or no other fuel sources are available. This means lower transportation costs of food to the markets, increase in food preservation and reduction in food losses for the rural communities (Beretta *et al.,* 2013).

2.4 Crop dryers

Crop dryers can be classified in different ways depending on the type and direction of air flow and also the source of energy used. Some typical examples of crop dryers include low and high-temperature natural dryers, continuous flow, batch dryers etc. (Sadeghi *et al*., 2012). All these different types of dryers have a similar working principle in drying crops that require a combination of heat and airflow in the system. Drying requires air movement and heat for the removal process of moisture. The basic principle is that warm or hot air has the potential of absorbing more moisture than cold air (Sharma *et al.,* 2009). Hence increasing the temperatures in the crop dryers allows the moisture to evaporate quickly and easily be removed from the system by the air flow. The rate of drying of the crops is influenced by the air flow and the heat i.e. increasing the air flow or temperature results in shorter drying time and vice versa. The energy sources used vary depending on the design and functionality of the system (Dhurve *et al.,* 2017).

2.4.1 Solar crop dryers

Solar dryers are devices that are used to dry crops or food substances using solar as the energy source. They can be classified as either (i) direct solar dryer where the food product is exposed to direct sunlight or (ii) indirect solar dryer where air heated by a different source is exposed to the products to be dried. Solar crop dryers are basically an upgrade of the normal open sun drying. Hence they prevent mass loss and reduce drying times in comparison to open sun drying (Sharma *et al.,* 2009) due to the enclosures in the system. This allows improvement in food quality, protection of food from dust, rain, animals etc. Use of solar energy as a heat source proves to be feasible mostly for domestic crop drying as compared to the commercial industry. This is due to limitations of the grain depth. Thicker layers provide too much resistance to the air that cannot be overcome by the small forces created by the thermal solar energy (Sadeghi *et al*., 2012). For the basic working principle of solar crop dryers, the sun shines on the dryer allowing the glazing to absorb and trap the solar radiation. This will increase the interior temperatures, providing the heat energy required in evaporating moisture in the food. An air flow either by natural or forced convection will remove the moist air out of the system allowing the crops to dry (Kibria, 2015).

2.4.1.1 Types of solar crop dryer systems

Solar crop dryers can be classified based on the type of energy source used, the design and the type of airflow used in the system. The two main categories for the solar dryers are the natural and fixed convection. Fixed convection dryers use fans to pump heated air in the system whilst the natural convection uses the natural flow of air at different densities.

2.4.1.2 Open Sun drying

Also commonly known as open sun dryers, these dryers work by placing the food products directly under solar radiation and ambient temperature with no enclosures. This is one of the traditional old ways used in the drying of crops and fruits and is still being practised in many regions (Sahu *et al.,* 2016). Heat losses are high in this type of system since there are no enclosures and it is prone to dust, infestation by animals and insects. In this type of drying it is not easy to control and continuously monitor the products and its conditions due to no enclosures (El-Sebaii & Shalaby, 2012).

In tropical and subtropical countries open sun drying is a traditional method used to preserve agricultural products or crops and is a very simple and easily accessible method to everyone (Abdellatif, 2010). Non-renewable energy and off-grid electricity sources are usually expensive or not accessible to most rural area setups in developing African countries, making open sun drying very attractive. The short and long wavelength radiation is essential in the solar crop drying process. Solar radiation (shortwave) originates from the sun (with a wavelength between 0.3μm and 3μm) for both the beam and diffuse components. The longwave radiation originates from sources at temperatures near the ambient surroundings usually emitted by the atmosphere, collectors or a body at ordinary temperatures. For the longwave radiation, the wavelength (λ) is greater than 3μm. Heat transfer by convection from the surrounding air to the crops occurs, allowing the crops to absorb the heat for the drying process to commence (Janjai and Bala, 2012).

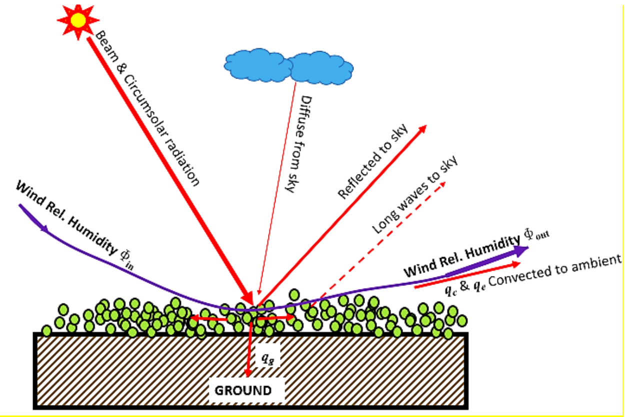


Figure 2.3: Open air sun drying process of crops

Sun drying usually requires very low capital and operating cost in comparison to the other drying methods. It is also dependent on the weather and solar radiation intensity; requires frequent movements of the crops in the cases where the weather changes drastically due to no covers or protection in the system (Jain & Tiwari, 2003).

Drying is a phenomenon governed by both the heat and mass transfer as illustrated by Fick's law of diffusion (Ravindram, 2014), Arrhenius law of chemical kinetics (Sheridan *et al.,* 2012) and the laws of Thermodynamics. As shown in Figure 2.3, the operational principles of the open sun drying can be explained as follows. Solar radiation reaches the crop as $\boldsymbol{I_T}$, the total irradiance on a horizontal plane. A fraction $\boldsymbol{\rho_c I_T}$ is reflected back; some is absorbed to heat up the crop, which in turn conducts part of what it absorbs to the ground. Water in the crop is heated, and some of that at the surface evaporates and is carried away either by a blowing wind if any, or by buoyancy forces in the layer of air atop the crop. This creates a capillary effect in the body of the crop, and by Fick's law, migration of interior molecules to the surface ensues (Runganga and Kanyarusoke, 2018). The process continues and its speed is determined by the nature of the crop, the amount of water remaining in the crop in accordance with equation (2.1);

$$\frac{\partial m_w}{\partial t} = \nabla\left(D\nabla m_w\right) \tag{2.1}$$

D is the diffusivity of water molecules through the crop. It is both crop and temperature-dependent in line with Arrhenius equation (2.2).

$$D = D_0 \exp\left(-E_a / RT\right) \tag{2.2}$$

Here, E_a is the activation energy for the crop, i.e. the threshold energy absorption required to initiate water migration. R is the gas constant for water. (If using molar quantities, then $R = R_u$ = 8.314 J/mol.K)

2.4.1.3 Direct solar dryers

The working principle of direct solar dryers involves placing the materials to be dried in an enclosure drying unit with a transparent cover. The incorporation of enclosures on the system gives the direct solar dryer a huge advantage over the open sun drying system. These include retaining heat in the system, protection against contaminants, animals and weather conditions (Kummu et al., 2012). This has an effect of preserving and maintaining the food quality better. Heat energy from the absorption of direct solar radiation in the drying system is absorbed by the food particles and the interior wall of the dryer. This retains heat in the system, hence ensuring a quick process in the drying of the food. The heat provided is indirectly proportional to the intensity of the solar radiation absorbed by the dryer (Jain and Tiwari, 2003). In indirect solar dryers, the drying products are placed in a designed, well-insulated enclosure that is capable of absorbing solar radiation. The insulation helps in reducing the heat loses to the surroundings.

This design type utilises a transparent top cover that allows the solar radiation to be absorbed by the drying unit with the aid of an absorber plate. Absorber plates have high absorptivity and can retain heat in the system which is essential for the drying process to be efficient (Ekechukwu and Norton, 1999). The absorbed heat increases the temperature within the dryer aiding in the evaporation of moisture within the food. Performance of dryers varies depending on the type of design, size, cost-effectiveness and ease to construct (El-Sebaii & Shalaby, 2012). In general, direct sun dryers are a modification of the open solar drying system. Due to the numerous disadvantages of the open sun drying system, direct systems work much better by eliminating these problems due to their design and efficiency.

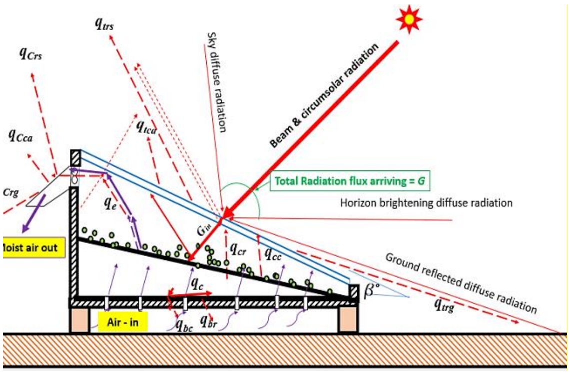


Figure 2.4: An enclosed direct solar crop dryer and its energy transfers

It is practically not possible to drive all water out of the crop by normal drying. This is best illustrated by the Arrhenius equation which leads to the definition of a moisture ratio parameter κ at any one drying time defined by equation (2.3).

$$\kappa(t) = \frac{m_w(t) - m_w(end)}{m_w(0) - m_w(end)} \tag{2.3}$$

where m_w is the mass of water in the crop at beginning of drying (0), time (t) and end of drying period (marked by lack of changes of moisture content within a specified drying period)

In enclosed drying, the processes are similar except that wind has less effect on the product. Figure 2.4 shows the energy transfers in such a dryer. In either the closed or the open systems, water migration from the crop transfers thermal energy from the crop in form of both sensible and latent but the latter is more significant because of change of phase. The vapour increases the humidity of the air in contact with the crop. If this air contacts a surface with a temperature below its dew point, condensation ensues. This can happen on glazing surfaces of enclosed crop dryers (Runganga and Kanyarusoke, 2018). Hence, it is important to keep these surfaces hot – e.g. by use of multi-glazing – or to suction the air out, using fans. In the current work, the three cases of open air, enclosed natural suction and enclosed forced suction are reported. Commercially, they are all important, first, because of different financial and technical skills requirements to acquire and operate them, and secondly, because of productivities and quality of finished products from them (Ekechukwu, 1999).

The design of direct solar radiation dryers consists of protection covers, absorbing plate, insulation and a transparent cover at the top to trap the longwave radiation. The shortwave radiation from the sun penetrates through the transparent covers while a portion is reflected back into the atmosphere. Inside the dryer, the long wave radiation is trapped hence cause an increase in the temperatures in the dryer (Duffie and Beckman, 2013). The black coated absorber plate and the side covers help in absorbing and retaining of the high temperatures within the dryer. In order to prevent rapid heat losses to the surrounding the dryer is completely insulated. It also has double glazing with an air gap of approximately 2 to 5 mm allowable to minimize heat losses by conduction and convection on the upper covers. The high temperatures in the dryer - approximately more than 15°C above the ambient temperature - are sufficient for the drying of the crops (Janjai *et al.,* 2008).

Care must be taken in controlling the drying rate so as to prevent too rapid or slow drying that might affect the drying process. Very slow drying might result in the growth of moulds on the crops whilst too rapid drying might prevent the food from completely drying. Typical drying times in solar dryers range from a few hours to a number of days depending on the specific conditions (Abdellatif, 2010). Many variables influence the drying time for any food sample. These factors include the volume of food to be dried, ambient conditions - irradiance intensity, sunshine hours, airspeed, temperature and humidity - drying area in use and design of the dryer.

2.4.1.4 Indirect solar dryers

These types of dryers utilise the air heated by an external source which is then introduced to the drying chamber for the drying process to begin. The energy source does not directly heat the products but is used in heating up the air instead. The heated air is then passed over the products triggering a moisture removal process in the product before exiting the system and can be recycled during the drying process (Simate, 2003). In contrast to direct solar dryers, indirect solar dryers do not need direct incident solar radiation in drying the food grains. Instead, it uses the principle where the air is heated in a solar collector before it is introduced to the drying chamber to for the drying process to commence. Although indirect dryers are less compact when compared to direct solar dryers, they are generally more efficient. Mixed type dryers are a combination of both the direct and indirect dryers. They utilise the direct incident solar radiation as well as the introduction of heated air from an external source to dry the products (Bolaji and Olalusi, 2008).

2.5 Heat transfer

In a solar crop dryer, heat energy is transferred by either one or a combination of the following heat transfer methods: conduction, convection and radiation. Heat transfer is essential in food drying processes. This process is dependent on the temperature difference between two bodies with a general concept of heat flow from higher temperature region to the lower temperature region (Kumar and Tiwari, 2006). The greater the temperature differences between the two surfaces, the greater the heat transfer and vice versa. The rate of heat transfer is determined by the temperature and resistance between the bodies transferring the heat, a process similar to diffusion. If the rate of change in temperatures, during the heat transfer processes is varying, the heat transfer process is in an unsteady state. If the rate of change is constant then steady-state heat transfer will occur. The transfer of heat from the surroundings to the food determines the rate of drying of the food, as this energy is required to provide the latent heat of vaporisation. Heat transfer can occur as either conduction, convection, radiation or a combination of both (Wankhade *et al.,* 2012).

2.5.1 Rate of heat transfer

The heat transfer occurs due to the temperature gradient of the surroundings and the food particle, with the heat transfer proportional to the temperature difference. This principle applies also to the mass transfer of substances within a material (Kumar and Tiwari, 2006). Though the calculations are a bit complicated due to the complex process of movement of moisture from the food to the moist surface, it is critical to consider this process in determining food drying rates. Mass transfer is proportional to the concentration gradient difference (Ndukwu *et al.,* 2017). Hence the movement of food particle is influenced by the difference in the concentration gradient of materials and external surfaces. In general, the heat transfer in a system can be estimated by the following equation (2.4):

$$\mathbf{Q = U_o A_o \Delta T_0} \qquad \textbf{(2.4)}$$

where: **Q** is the rate heat of transfer

U_o is the overall heat transfer coefficient

A_o is the overall cross-sectional area for heat transfer

ΔT_o is the overall temperature difference.

The overall heat transfer coefficient (U) of the surfaces can be calculated by the following equation (2.5):

$$U = \frac{1}{\frac{1}{h_i} + \frac{x}{k} + \frac{1}{h_0}} \qquad \textbf{(2.5)}$$

where x is the wall thickness (m)

k is the thermal conductivity (W/m .k)

h_i is the inside surface conductance (W/m^2.k)

h_0 is the outside surface conductance (W/m^2.k)

For parallel multi-surface plates, the U factor can be calculated by the following equation (2.6):

$$U = \frac{1}{\frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3}} \quad \textbf{(2.6)}$$

where: x_1, x_2 and x_3 are the thickness of material 1, 2, and 3 respectively.

k_1, k_2 and k_3 are the thermal conductivity of material 1, 2 and 3 respectively

2.5.2 Convection

Convection is the common heat transfer method among gases and liquids. It is characterised by the movement of fluids from different sections due to the difference in gradient between the two mediums. A convection flow occurs when a hotter fluid rises above the colder one, as the denser cold air replaces the warm air at the bottom of the apparatus. Convection is essential for the heat and moisture removal process in the crop dryer. Convection does not usually occur on its own but as a combination of combined processes of heat diffusion (conduction) and bulk fluid flow heat transfer known as advection (Simate, 2003).

The basic relationship for convective heat transfer can be summarised by the following equation (2.7):

$$Q = h\,A\,(T_a - T_b) \quad \textbf{(2.7)}$$

where Q is the heat transferred per unit time

A is the area of the object

h is the heat transfer coefficient,

T_a is the object's surface temperature

T_b is the fluid temperature.

The convective heat transfer coefficient is dependent upon the physical properties of the fluid and the physical surrounding conditions the fluid is placed. Convection is the heat transfer method through advection or diffusion that allows the movement of particles within a fluid or gas. It can occur as either natural convection or forced convection. In the forced convection, an external source is used to force the mixing of the gases or liquid, usually a fan in most instances. Natural convection occurs due to the differences in the densities between the two gases or liquids. As the difference in temperatures has an influence on the air’s density, it plays an important role in the convection currents within the drying systems (Basunia and Abe, 2001).

Heat transfer by convection can be calculated using the following equation (2.8):

$$Q = h\,A\,\Delta T \tag{2.8}$$

where: Q is the rate of heat transfer

h is the convective heat transfer coefficient

A is the surface area for heat transfer

ΔT is the temperature difference

Note $\Delta T = (T_a - T_s)$ for air drying *where* T_a is the air temperature and T_s is the temperature of the surface which is drying.

2.5.3 Conduction

Conduction is the transfer of heat through a solid substance (through the vibration of molecules) due to the difference in temperature between the two surfaces. This is critical in the heat transfer between the interior of the dryer and the ambient surrounding due to the fluctuations of temperatures. Properly insulating the dryer with good insulating materials will greatly minimise losses to the surrounding hence improving the dryer efficiency. Conduction involves the transfer of heat by the interaction between adjacent molecules of a material driven by a temperature gradient between the two surfaces (Varalakshmi, 2016). The transfer of heat usually differs from the media involved. Conduction deals mostly with solid materials, radiation deals with solid or fluid materials whilst convection deals with fluid materials. The heat transfer through conduction can be determined by the use of the Fourier's law of conduction, which is applicable to both rectangular shapes and cylinders. For calculation involving conduction the following equation (2.9) can be used:

$$Q = UA\,(T_a - T_s) \text{ for conduction} \tag{2.9}$$

where U is the overall heat transfer coefficient

T_a is the ambient temperature in the dryer

T_s is the surface temperature of the food

A is the surface area

2.5.4 Radiation

Radiation is the transfer of heat through space/vacuum due to electromagnetic waves. Alternatively, it is a process in which energy is given off by matter in the form of high-speed particles. All bodies emit electromagnetic radiation that arises due to the temperature of a body. The emissions are proportional to the temperature i.e. the higher the temperature the higher the energy is emitted by the body and vice versa. Heat transfer by radiation does not need a medium for the process to occur. This is because all the materials with temperatures above the absolute zero do emit radiant energy to their surroundings. Due to the temperature of a body, it is able to emit radiant energy. The sun is the major source of radiant energy that we use as an energy source on this earth (Tiwari, 2006). Black bodies are good emitters and absorbers of radiation energy. As materials have different properties like rates of absorption and reflection, it is important to choose materials that correspond to the design requirements and criteria for the drying component to be efficient. In the drying unit, heat transfer by radiation occurs mostly on the double glazing to allow the radiation to be absorbed into the system. The trapped air in the double glazing and the different thickness of the glazing materials help in minimising the heat losses from the system (Duffie and Beckman, 2013).

Heat transfer due to radiation can be determined using the following equation (2.10)

$$Q = \sigma A \, \Delta \, T^4 \qquad \textbf{(2.10)}$$

where: Q = heat transfer rate

σ = Stefan-Boltzman constant

A = surface area

Δ T = temperature = $(T_2^4 - T_1^4)$

In a crop dryer, these heat transfer modes are combined in series. The heat transfer showing the overall heat transfer coefficient as a combination of these modes can be summarised as follows by equations 2.11 and 2.12.

$$q_{total} = q_{conduction} + q_{radiation\ in} - q_{convection} - q_{radiation\ out} \qquad \textbf{(2.11)}$$

which can further be expressed as

$$q_{total} = \mathrm{kA}\left(\frac{\Delta \mathrm{T}}{\Delta \mathrm{x}}\right) + \alpha\, A\sigma(T_o^4) - hA(\Delta T) - \varepsilon\, A\sigma(T_s^4) \qquad \textbf{(2.12)}$$

2.6 Solar crop dryer system components

Solar crop dryers come in different designs, shapes and sizes. But nevertheless, all these dryers have some common features in place. Typically a solar crop dryer consists of the following main components: the drying chamber, the extraction system, a mounting stand and monitoring or controlling systems. The following section explains some of the major components of a solar crop dryer.

- **Drying chamber or unit**

  This is the core component of the dryer in which all the drying process occurs. It is made from common materials like metal, wood, concrete or bricks and is used to protect the dried food from insects, contamination and weather conditions in an enclosed system. The sub-components of a drying unit include glazing, absorber plate, structural frame, covers and insulation. All of these assist in absorbing and retaining the useful heat needed for the drying process.

- **Frame**
  The frame forms the overall structure that supports the drying unit. It gives the rigidity of the dryer hence making it critical to select the correct materials to suit the design. Different materials can be used to make the crop dryer frame e.g. wood, steel and bricks.

- **Glazing**
  This transparent material allows short wave solar radiation to penetrate into the drying chamber but blocks most long waves. Hence the long wavelength radiation waves generated by the heated product in the dryer are trapped causing an increase in the interior dryer temperatures and facilitating drying.

- **Absorber plate**
  The absorber plate helps to absorb solar radiation from the sun. It is generally a material with a high conductivity like aluminium. A black coating can be applied to improve the absorptivity of the material.

- **Covers**
  The covers protect the insulation material and also give an outward appearance of the crop dryer.

- **Insulation**
  Insulation is used to prevent heat losses from the system. It must be tightly secured on the sides and bottom of the dryer to minimise heat losses and improve the overall efficiency of the dryer.

- **Moisture extraction system**
  This is used to circulate the air in the system and also assist in the moisture removal process of the water extracted from the dried crops. The use of fans is common in the forced extraction systems whilst natural convection can also be used. Inefficient air circulation may result in the moisture being retained in the system which might cause contamination and moulding of the food.

- **Mounting frame or stand**

  This is used to secure the drying unit in position especially at the required inclination angle when it is mounted. It has movable castor wheels to allow easy transportation and movement when required.

- **Moisture detector and indicator**

  This is used to check levels of moisture during the food drying process hence making it easy to determine and monitor the drying times of different food products.

- **Loading and unloading trays**

  Drying trays are used to load and offload food products. They can be black coated thermoplastic trays that maximise the absorption of solar radiation or a fine wire mesh that allows the air to circulate easily through the food during the drying process.

2.7 Solar irradiance

Solar radiation is radiant energy emitted by the sun, in form of short wave electromagnetic or infrared energy. It is measured by a device called a pyranometer, which can be set to measure either the total global solar radiation (a total of direct radiation, diffuse radiation and reflected radiation) or the beam radiation separately. Direct or beam radiation is the component of the global radiation on the surface normal to the sun's rays (or parallel to the sun). The component of the radiation that is scattered or reflected from any surface is called the diffuse radiation. Some calculations involve the use of the total global radiation which the sum of direct and diffuse and direct radiation.

2.8 Moisture content

The bulk weight of most living organisms is mostly made up of water. This water constitutes approximately 90% by weight in fruits and vegetables and almost 70% in other natural foods. The water in the food can be in form of free water or bound water (Prakash and Kumar, 2012). Free water is the water that can be easily removed from the food by methods like squeezing, drying and pressing. The other form of water that is available in the food that cannot be easily extracted is known as bound/adsorbed water. For each particular food, the bound water differs depending on the method used in measuring the water and the way it is measured. These bonds require more energy to be broken as the water molecules are firmly held by the food elements (Sharma *et al.,* 2009). This is because bound water has more structural bonding than free water, is not free to act as a solvent especially in presence of sugars and salts and also usually has a greater density than free water as the water molecules are closely packed. The water content of most food substances does not reach zero even upon dehydration as the food will still contain bound water.

Table 2.1 shows the typical acceptable moisture content for most of the common dried products (Coles *et al.,* 2003). As seen in the table, the initial moisture in the food is usually very high for most products with the maximum allowable temperatures in the range between 50°C and 75°C (Sahdev, 2014).

Table 2.1: Typical moisture contents and drying temperature for various agricultural produces

Crop	Initial Moisture content(% w.b)	Final Moisture content(% w.b)	Maximum allowable temperature (^{o}C)
Maize	35	15	60
Corn	24	14	50
Green peas	80	5	65
Onions	80	4	55
Cabbage	80	4	55
Sweet Potatoes	75	7	75
Potatoes	75	13	75
Apples	80	24	70
Bananas	80	15	70
Tomatoes	96	10	60

Direct or indirect methods can be used in the determination of moisture content of any food item. The choice of determining the method to use lies mainly on the accuracy of the results required, the samples to be used (size and number) as well as the purpose of the application. Direct methods utilise the actual components of the sample i.e. measuring the direct weight of the samples whilst indirect methods involve the use of a parameter that will correlate to the loss in weight of the product i.e. use of either voltage or electrical resistance to correlate the loss of weight of a sample. For most laboratory experiments the direct methods are used as the actual readings required will be critical. The process involves heating up the samples and determining the difference in weight between the initial sample and the dried sample. The difference in the weight between the two samples is used to find the water loss from the sample by the standard procedures used.

CHAPTER 3: DESIGN AND CONSTRUCTION OF A CROP DRYER

This chapter introduces the design and construction of the solar crop dryer focusing on component selection, concepts, detailed designs and manufacturing processes.

3.1 Introduction

In the design of a crop dryer system, certain factors have to been taken into account in order to meet the needs and produce a quality product for the relevant use. Amongst the many influential factors climatic conditions, cost, material availability and ease to manufacture are some of the critical and driving parameters that influence the design and setup of solar crop dryers. Solar crop dryers consist of basically three major components namely the drying unit, extraction system and mounting stand. Each of these components was sized and designed according to specifications which will be described in the following sections of the report.

3.2 System components

3.2.1 Drying unit

The drying unit is the most fundamental component of the entire crop drying system. It is most critical in ensuring that the maximum solar radiation is absorbed from the sun whilst retaining the heat in the system. Figure 3.1 shows a typical design of the solar drying unit used in the project. The drying unit can be made from many common materials like wood, metal, bricks etc. depending on the user's preference. The drying unit further protects the dried products from any insects, bad weather conditions, moisture and contamination due to the enclosures, unlike the open sun drying. The drying unit consists of a rectangular box with an absorber material and transparent glazing material to absorb the solar radiation. The 30° angle is the angle of inclination for maximum solar radiation for crop dryers in Cape Town – as determined by Kanyarusoke *et al*., (2016) (Applied Energy paper).

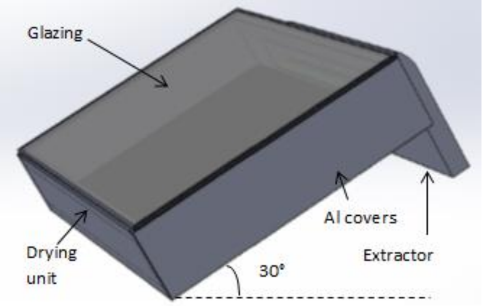


Figure 3.1: An illustration of a solar crop dryer design

Figure 3.2 further shows the exploded view of the drying unit showing the other subcomponents. The sub-components of a drying unit include glazing, absorber plate, structural frame, covers and insulation. The function and parameters of each section will be explained in detail in the sections that follow.

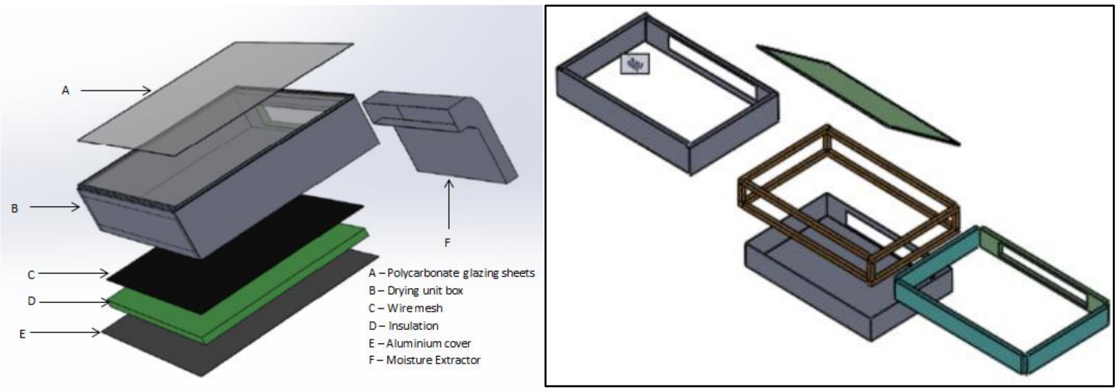


Figure 3.2: Exploded views of the solar crop dryer components

3.2.2 Glazing

Glazing material is important in the determination of the thermal properties of solar crop dryers. Properties like materials transmissivity, reflectivity and absorptivity determine how well the material can be able to absorb and retain heat, hence determining the dryer’s efficiency.

3.2.2.1 Material selection

Glass is the most common material used as glazing in most dryers due to its good properties. Glass is available in different thickness ranging up to 5mm and allows visible light (approx. 88 –90%) and solar radiation (approx. 77 – 86%) to penetrate (Pulker and Pulker, 1999). These parameters make glass the most preferred material for most crop dryers and greenhouses. Glazing is one of the essential components that have an effect on the working principle of a solar crop dryer. It does govern the heat flow in the crop dryer system hence it is critical to ensure that the correct glazing material is used. A good choice of glazing ensures the crop dryer works efficiently and effectively for the user (Benhammou and Draoui, 2013). Different glazing materials are available on the market, with different parameters and applications. Glass and polycarbonate are among the top used glazing materials used for solar crop dryers and greenhouses.

Ultraviolet-protected polycarbonate sheets were used for the glazing of the dryers Polycarbonate was preferred over glass since it is light, flexible, can absorb up to 90% of light whilst withstanding temperatures of up to 270ºC without distorting. It has high transmittance and is virtually unbreakable, unlike glass which is brittle, denser and costly in replacements and cannot withstand high temperatures (Duffie and Beckman, 2013). Double glazing with a 5mm air gap was used with 2mm and 3mm thick polycarbonate sheets for the exterior and interior sides respectively (Table 3.1).

Table 3.1: Glazing parameters for the crop dryer

Item	Length (m)	Width (m)	Thickness (m)
Exterior glazing (Polycarbonate)	1.5	1.0	0.002
Interior glazing (Polycarbonate)	1.5	1.0	0.003

3.2.2.2 Double glazing

Despite the type of glazing material used, double glazing improves the efficiency of the glazing. Double glazing consists of two glazing sheets with an air gap in between. Similar materials of different thickness are used in the making of the double glazing sheet since they are usually exposed to different temperatures during operation. The air gap in-between the sheeting acts as an insulator. The air gap minimises the heat losses to the surrounding by radiation and conduction whilst still allowing solar radiation to be absorbed into the system (Benhammou and Draoui, 2013). Since air is a poor conductor of heat, the rate of heat transfer is reduced as the convective currents at the top of the dryer are reduced hence reducing heat losses by convection. Although double glazing is a bit expensive compared to single glazing, it does improve the effectiveness of the crop dryer. In single glazing more heat escapes into the surroundings compared to double glazing.

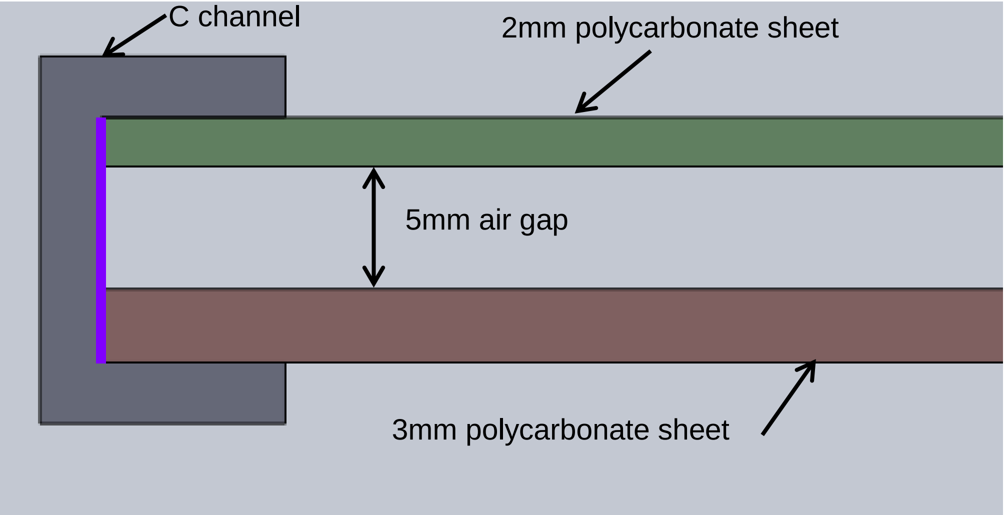


Figure 3.3: Double glazing

The C channel ensures that the glazing sheets are well aligned and properly supported when making the double glazing sheet. A 15mm x10mm x 2.5mm thick C-channel was used for the double glazing in this project. The length and width of the C-channels were 1.5m and 1m respectively. The temperatures inside the dryer are most often very high inside the dryer due to the trapped long wavelength radiation; hence a thicker glazing material has to be used. As seen in Figure 3.3, the 3mm thick glazing is placed on the interior surface of the dryer to ensure that it can withstand the high temperatures in the dryer. Double glazing with a 5mm air gap was used with 2mm and 3mm thick polycarbonate sheets for the exterior and interior sides respectively.

3.2.3 Absorber plate

In a crop dryer, the absorber plate assists in the absorption of solar radiation and retaining of the useful heat that is used in the drying of the products. A good absorber plate must be able to absorb and retain as much heat as possible; hence a material with the appropriate parameters must be determined and selected. The most common materials used for the absorber plate include aluminium, steel and copper due to their high absorptivity rates coefficients, good thermal conductivities and low emittance factors. The lower the emittance factors of the material the less the material emit energy to the surroundings. The absorber plate material must be stable at high temperatures and must not be corrosive as it will affect the final quality of the dried products. Black or dark coloured coatings are usually used as they are very good absorbers of heat.

Table 3.2: Common properties of absorber plate materials

Item	Thermal conductivity	Specific heat capacity(J/gmK)	Density(kg/m^3)
Copper	385	0.4	8940
Aluminium	205	0.9	2712
Steel	50.2	0.46	7850

Table 3.2 shows the typical parameters of the most common materials used as an absorber plate. It can be noted that aluminium has very good properties that make it suitable to be an absorber plate. Hence aluminium sheeting with a coat of food grade black paint was used as the absorber plate due to its good thermal properties in relation to its weight, making it more favourable than copper and steel (El Sebaii and Shalaby, 2012). In comparison to steel and copper, the use of aluminium proved to be cheaper and also material availability and ease to work with also made aluminium a better option. The use of food grade paint does not only assists in the absorption of the solar radiation but also ensures that the food placed in the drier is not contaminated by the paint hence making it safe for human consumption. The dimensions of the absorber plate are shown in Table 3.3.

Table 3.3: Absorber plate

Item	Length (m)	Width (m)	Thickness (m)
Absorber plate	1.5	1.0	0.002

3.2.4 Dying box frame

Availability of materials, cost, manufacturing process were some of the parameters considered in the determination of box frame material. Amongst the available materials, wood was selected as the best material for the structural frame as it gives strong and robust support for the drying unit.

Properties of wood

The properties of wood make it very suitable to fit in the design as it is easily available locally and is easy to work with in comparison to materials like steel. Wood is light and strong hence meets the requirements of the project i.e. to have a light, cheap and strong crop dryer. One disadvantage of wood is that it can be prone to weather conditions like rain and attacks from insects if it is not treated. Treatment of the wood with wood sealant ensures prevention from insect attacks and water damage. Table 3.4 shows the overall dimensions and components used in the assembling of the drying unit frame whilst Figure 3.4 shows the assembled wooden frame for the solar crop dryer. The overall dimensions of the frame are 1.5m x 1.0m x 0.2m.

Table 3.4: Crop dryer wooden frame

Item	Quantity	Length (m)	Width (m)	Thickness (m)
Wooden block 1	4	0.12	0.04	0.04
Wooden block 2	4	1.0	0.04	0.04
Wooden block 3	4	1.42	0.04	0.04
Steel L plates	8	0.02	0.02	0.005

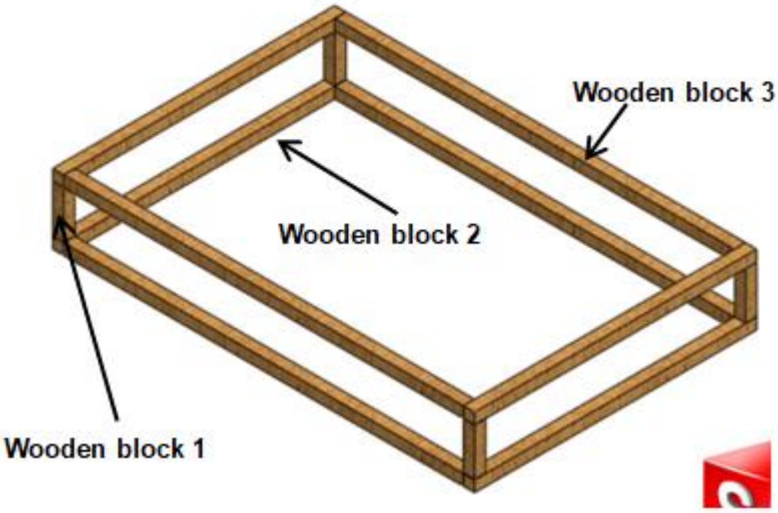


Figure 3.4: Structural frame of the crop dryer drying unit

Steel L plates and screws were used in assembling the wooden pieces together. Once the structural frame was assembled, the drying unit box frame was constructed. This consists of a sheet metal aluminium box frame unit as shown in Figure 3.5.

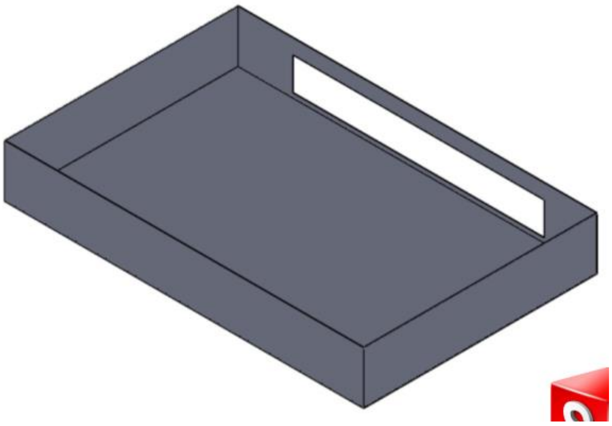


Figure 3.5: Box frame for the crop dryer drying unit

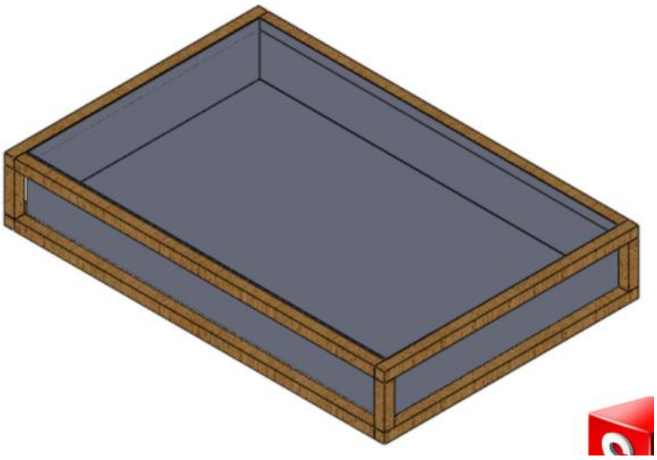


Figure 3.6: Structural frame of the crop dryer drying unit

3.2.5 Frame cover

Aluminium sheeting was used as the covering for the dryer unit. Due to its shiny exterior, it provides a good appearance of the crop dryer which is good for the users. For the joining methods, screws were used to mount the covers onto the wooden frame as shown in the illustration. The sheet material used was approximately 1 to 2mm hence relatively making the system light. The combination of the wooden frame and the aluminium sheets ensured that the drying box would be strong.

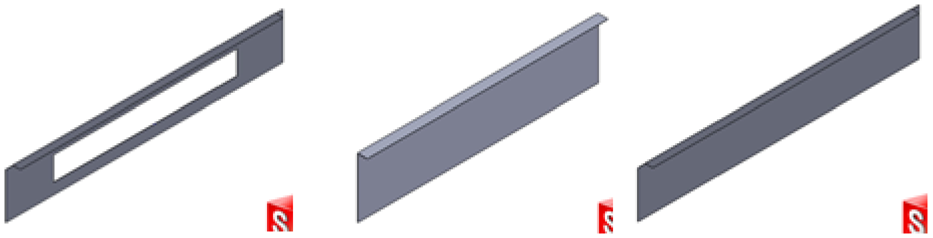


Figure 3.7: (a) back (b) side and (c) front cover for the solar crop dryer

Table 3.5: Frame covers dimensions

Item	Length (m)	Width (m)	Thickness (m)
Side 1	1	0.2	0.002
Side 2	1	0.2	0.002
Back	1.5	0.2	0.002
Front	1.5	0.2	0.002
Bottom	1.5	1.0	0.0025

3.2.6 Insulation

To ensure that there is minimal loss of heat from the crop dryer to the surroundings, the crop dryer has to be well insulated. The lesser the heat lost from the system the better and higher the heat transfer between the dryer interior and the food samples. The crop dryer must be able to retain as much heat as possible in order for the drying process to be effective and also improve the dryer efficiency. The crop dryer was properly insulated on all sides and bottom to minimize the heat loses whilst the top side the double glazing was used.

Among the available insulation materials expanded polystyrene was used. The value of the thermal conductivity (K) ranges between 0.038W/mK and 0.033W/mK depending on the thickness and the density chosen (mostly between 1.5 kg/m^3 and 2.0 kg/m^3). It has a thermal conductivity of 0.037W/mK and can withstand temperatures of up to 70°C. Expanded polystyrene has numerous advantages compared to most of the other insulation materials. It is cost effective, light, easy to install, energy efficient, strong, has a good R-value and does not degrade easily.

Table 3.6: Insulation dimensions (expanded polystyrene)

Item	Length (m)	Width (m)	Thickness (m)
Side 1	0.92	0.12	0.002
Side 2	0.92	0.12	0.002
Back	0.5	0.12	0.002
Front	1.42	0.12	0.002
Bottom	1.42	0.92	0.0025

3.2.7 Moisture extractor

Due to the increase in the relative humidity during the drying process, a system is required to remove this excess moisture. Hence a moisture extraction system was put in place. This ensured a continuous flow of air in and out of the system hence allowing all the moisture released by the food to be taken out of the dryer. In doing so, the process helped in preventing condensation of moisture within the dryer which can highly cause moulding and allow growth of microorganisms on the food. The extraction system consisted of a channel to direct the moisture or air flow out of the system. In this section, the hot extracted air condenses when it gets in contact with the surface of the channel. Depending on the dryer design, fans can be incorporated if drying requires forced extraction systems whilst no fans are required in a natural ventilation system. Use of fans in one of the dryers required the use of an external energy source to supply the power.

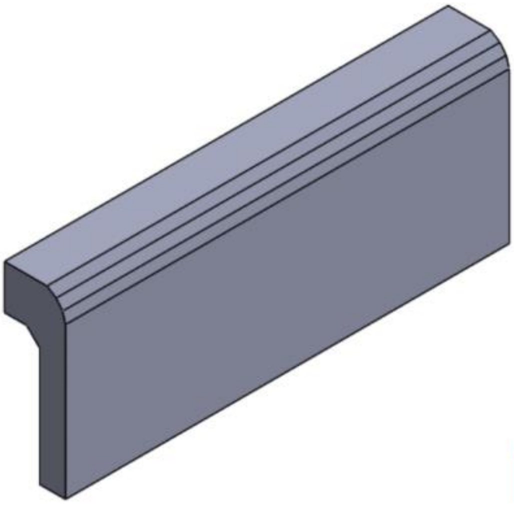
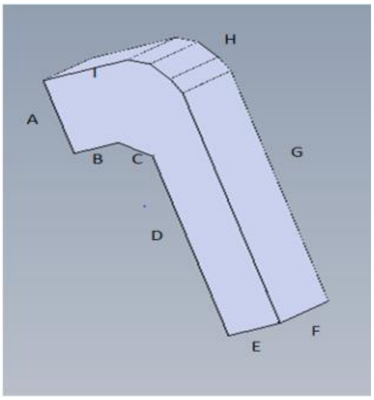


Figure 3.8: Moisture extraction unit

Aluminium was used as the material of choice for the channel section of the extractor. The material was easy to work with hence it was chosen for use on this component. Shown in Table 3.7 are the overall dimensions of the moisture extraction unit for the crop dryer. Four extraction fans were used to move the air through the dryer and also draw out the hot moist air from the system. The extraction fans used in the project are shown in Figure 3.9.

Table 3.7: Dimensions for the moisture extraction unit

Side	Dimension (m)	Side	Dimension (m)
A	0.13	F	1.0
B	0.06	G	0.41
C	0.05	H	0.03
D	0.32	I	0.115
E	0.07		



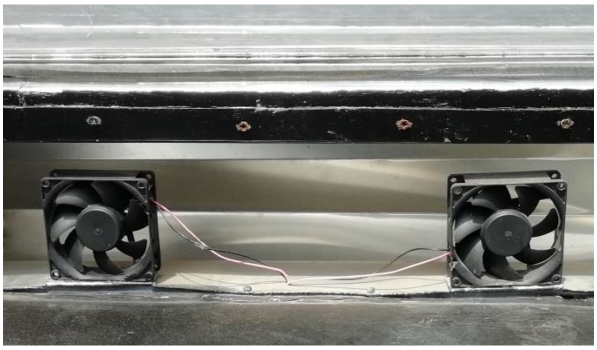


Figure 3.9: Extraction fans

3.2.8 Support frame

The support frame gives the structural aspect which holds the drying unit in the required position for easy operation by the user. Angle iron was used in the construction of the frame as it is strong and can withstand the weight of the dryer both in the loaded or unloaded state. Table 3.8 summarises the dimensions of the components used in the support frame.

Table 3.8: Dimensions for the support frame (40x40mm L plate)

Item	Length (m)	Thickness (m)	Quantity
Side 1	1.0	0.003	2
Side 2	1.5	0.003	2
Short legs	0.7	0.003	2
Long legs	1.1	0.003	2

A 30º angle was chosen as the angle of inclination of solar dryers for Cape Town area, for all year round testing. For this project, a fixed angle supporting frame (not adjustable) was used. This was in line with Kanyarusoke *et al*., (2016) recommendation on maximising annual incident power on a fixed inclined surface. For this project, a fixed angle supporting frame (not adjustable) was used for the testing. If the crop dryer has to be used in other area, frame adjustments will be taken into consideration. Castor wheels were also placed on the frame for easy manoeuvring.

3.2.9 Extras

To prevent the system from theft or attacks by animals or being blown off by wind, a locking system was put into place. This is a simple system easy to operate, cheap to install and replace if need be. The dryer also has drying trays which can be used for easy loading and unloading of the food products in the dryer. Alternatively, a wire mesh can also be used in the drying of the food.

3.2.10 Overall dryer parameters

In the testing of the dryers, different dryer setups were used and a comparison done on the overall effectiveness of each. Figure 3.10 shows the different dryer designs that were used for the testing of the project. (a) shows the designed 2m^2 natural convection dryer whilst (b) shows the 1.5m^2 forced extraction drying unit. Only the design for the 1.5m^2 dryer is shown and explained in this section. The 2m^2 was used only for comparison as it was designed prior to this on a separate project.

Table 3.9 further shows the specifications of these two dryer designs highlighting the key parameters whilst Table 3.10 summarises the overall cost of the dryers.

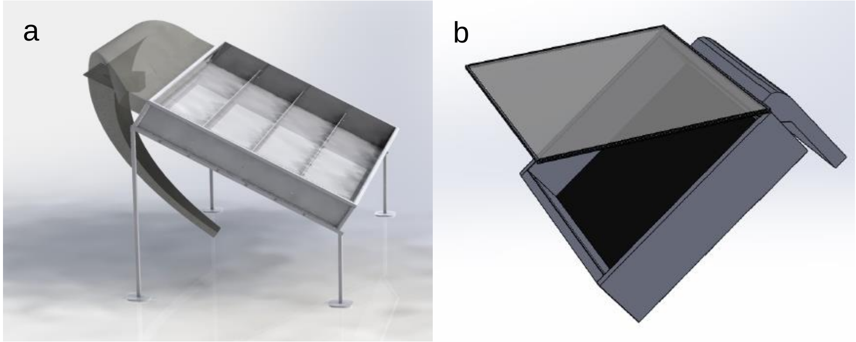


Figure 3.10: (a) 2m^2 crop dryer and (b) 1.5m^2 crop dryer design

Table 3.9: Overall specifications of the crop dryers

Parameter	2m^2 dryer	1.5m^2 dryer
Length	2m	1.5m
Width	1m	1m
Depth	0.2m	0.15m
Area	2m^2	1.5m^2
Drying unit covers	Mild steel (UPVC)	Plywood (Aluminium)
Extractor	Steel channel	Aluminium channel
Glazing	Polycarbonate	Polycarbonate
Tilt angle	34º	30º
Absorber	Steel	Aluminium
Surface finish	Black paint	Black paint
Glazing	Double	Double
Insulation	Polystyrene (20mm)	Polystyrene (20mm)

Figure 3.11: Overall dryer design and setup

Table 3.10: Costing for the 1.5m^2 and 2m^2 solar crop dryers

Materials	1.5 m^2 Dryer	2 m^2 Dryer
Polycarbonate sheets	R470.00	R530.00
Aluminium C sections	R250.00	R200.00
Aluminium sheets	R250.00	R250.00
Wooden blocks	R100.00	X
Extractor sheets(Al/steel)	R300.00	R250.00
Silicone, paint, rubber strips, rivets,	R50.00	R50.00
Extraction fan	R100.00	X
Steel tubing, angle brackets	R200.00	R200.00
Castor wheels, nuts, bolts	R120.00	R70.00
Insulation	R100.00	R100.00
Filler foam	X	R50.00
Gas lift shocks	X	R200.00
Total expected cost	**R1,940.00**	**R1,900.00**

CHAPTER 4: EXPERIMENTAL SETUP AND METHODOLOGY

This chapter covers the experimental setup and methodologies implemented in the project. This includes the methodology, data collection techniques, experimental setup, testing procedures and instrumentation.

4.1 Experimental setup and methodology

This chapter describes the methodology and experimental setup used in obtaining the data and parameters for the solar crop dryers. The focus was mainly on the testing procedures, instrumentation used, derived and calculated parameters as well as experimental setups for the different tests conducted on the crop dryer setups. The crop dryer design, construction, testing and project commission was done in Cape Town at the CPUT Mechanical Engineering department. The experiments were carried out in the months from May to July, close to the Cape Town winter season, in order to determine the effectiveness of the crop dryer setups.

4.2 Model testing procedures

The crop dryer project was implemented and tested under the atmospheric conditions at CPUT Bellville Campus, Mechanical Engineering Department compound area. This is located at a latitude of 33.93° S and longitude 18.64° E. It was ensured that the dryer testing was done between hours of 0900hrs and 1700hrs on the selected testing days. This was to ensure that the products were exposed to the solar radiation for the maximum time possible i.e. at least six to eight hours.

4.3 Testing site ambient conditions

At the testing site, the conditions monitored during the experimentation stage included the following: ambient temperature, airspeed, radiation levels and relative humidity. Average ambient temperatures on the testing days ranged between 15°C and up to 30°C, as the tests were conducted close to the winter season in the months of May, June and July. The average wind velocity at the site fluctuated between 0m/s and 6m/s. On average the daily sunshine hours were between six and eight, and each experiment conducted specifies the number of hours for the testing that was required. The relative humidity varied also depending on the changes in temperatures recorded on the respective testing days. Ranges of between 30% and 80% were noticeable due to the differences in temperatures recorded on these days.

4.4 Instrumentation and parameter setting for data measuring

For the crop dryer experiments, the ambient conditions played a vital role in determining the efficient working principle of the crop drying system. The ambient conditions measured during the test included wind speed, solar irradiance intensity, relative humidity and ambient temperature. These parameters were obtained from the weather station situated at the top of the mechanical building, the site where the project was implemented.

4.5 Weather station

The installed Campbell scientific weather station consists of various equipment and instrumentation to measure different ambient conditions at the testing site. These include a cup anemometer, two distinct pyranometers for the total and diffuse radiation, temperature sensors and a data logger. Figure 4.1 shows the typical setup of the weather station which will be explained in the sections that follow.

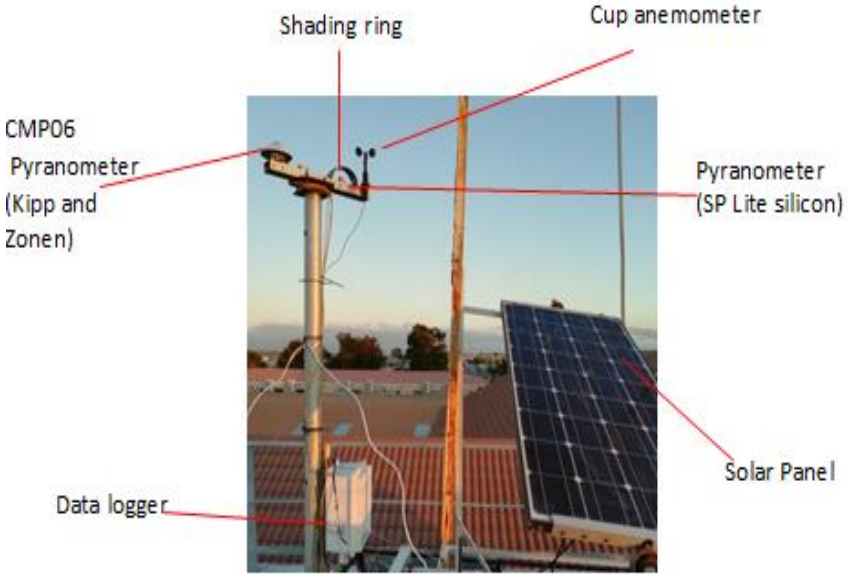


Figure 4.1: Weather station

4.6 Solar irradiance

Two distinctive pyranometers were used for the weather station to measure and record the total incident irradiance as well as the diffused irradiation.

4.6.1 Total solar irradiance

The CMP6 pyranometer was used to measure the total solar radiation i.e. (diffuse and beam radiation) on level and plane surface. It consists of thermocouple sensing elements connected in series, coated with a high stable spectral absorbing carbon-based non-organic coating. The improved performance of the pyranometer is due to the increased thermal mass and the double glass dome construction, which is ideal for cost-effectiveness, good quality and accurate measurements. The pyranometer does not require any power source and it supplies a low voltage of between 0 to 20mV in relation to the amount of incoming radiation. Figure 4.2 shows the typical setup of the CMP6 thermocouple. The signal produced by the pyranometer is measured and recorded on the data logger. Refer to Table 4.1 for technical specifications of the pyranometer.

Figure 4.2: CMP6 pyranometer: Kipp and Zonen

Table 4.1: Specifications of CMP6 pyranometer https://tinyurl.com/yb6nc9g2

Spectral range (50% points)	285 to 2800 nm
Sensitivity	5 to 20 µV/W/m²
Response time	18 s
Zero offset A	< 10 W/m²
Zero offset B	< 4 W/m²
Directional response (up to 80° with 1000 W/m² beam)	< 20 W/m²
Temperature dependence of sensitivity (-10 ºC to +40 ºC)	< 4 %
Operational temperature range	-40 °C to +80 °C
Maximum solar irradiance	2000 W/m²
Field of view	180 °

4.6.2 Diffuse radiation

The Kipp and Zonen SP Lite2 pyranometer shown in Figure 4.3 was used for measuring solar radiation and works well under any weather conditions. It is essential for measuring energy available for use in solar energy applications. It can easily be used and connected to a data logger to give direct readings of the solar radiation levels obtained in W/m^2. SP Lite2 uses a photodiode detector, which creates a voltage output that is proportional to the incoming radiation. Also due to the unique design of the diffuser, its sensitivity is proportional to the cosine of the angle of incidence of the incoming radiation, allowing for accurate and consistent measurements. Refer to Table 4.2 for technical specifications of the pyranometer.

Figure 4.3: SP Lite2 pyranometer

Table 4.2: Specifications SP Lite2 https://tinyurl.com/y8t9ppuh

Spectral range (overall)	400 to 1100 nm
Sensitivity	60 to 100 µV/W/m²
Response time SP Lite2 (95%)	< 500 ns
Directional response (up to 80° with 1000 W/m² beam)	< 10 W/m²
Temperature response	< -0.15 %
Operational temperature range	-40 °C to +80 °C
Maximum solar irradiance	2000 W/m²
Field of view	180 °

4.6.3 Shadow Ring

The shadow ring shown in Figure 4.4 was used in conjunction with the Kipp and Zonen pyranometer to shield the instrument from direct radiation. The purpose of combining a shadow ring and a global measuring instrument was to provide a solution for measuring the diffuse radiation from the sky. Minor adjustments on the ring were done to suit the current conditions at the testing site and ensuring that the pyranometer dome was completely covered by the ring. The aluminium shading ring was placed in such a way that it shades the thermopile element from the direct sunlight (beam radiation) hence the diffuse radiation can be measured.

Figure 4.4: CM121B/C Shadow Ring

4.6.4 Radiation levels

The data of the radiation levels recorded at the testing site, Mechanical department in the previous year is shown in the figures below. Figure 4.5 shows the average monthly total radiation levels whilst Figure 4.6 shows the average diffuse radiation at the same testing site. The trends show peak radiation values between months of October to April i.e. the summer season with maximum values ranging between 350W/m^2 and 550/m^2 (total radiation) and 60W/m^2 and 120W/m^2 (diffuse radiation). The mean values for the radiation usually obtained in the winter season show values of around (200 – 250) W/m^2 and (30 - 50) W/m^2 for the total and diffuse radiation respectively.

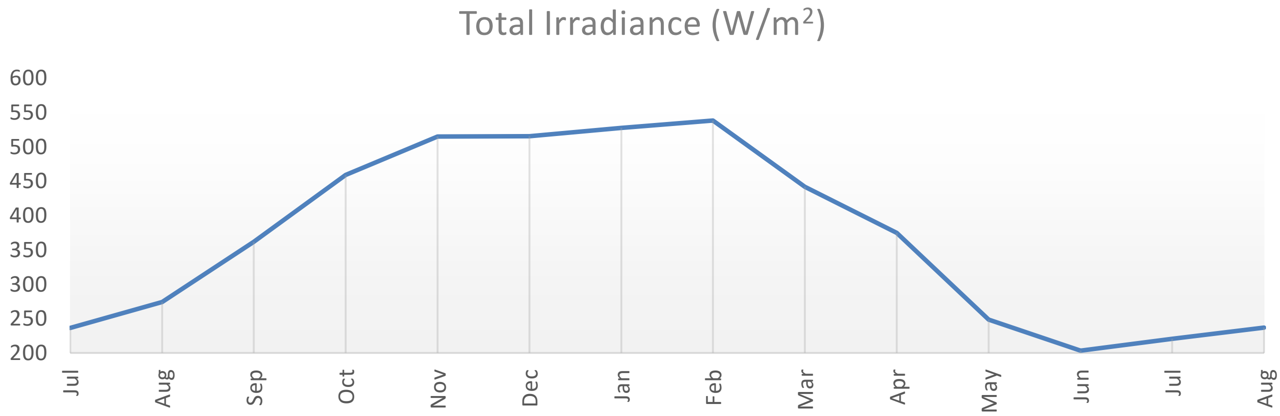


Figure 4.5: Average monthly total radiation levels at CPUT Bellville weather station

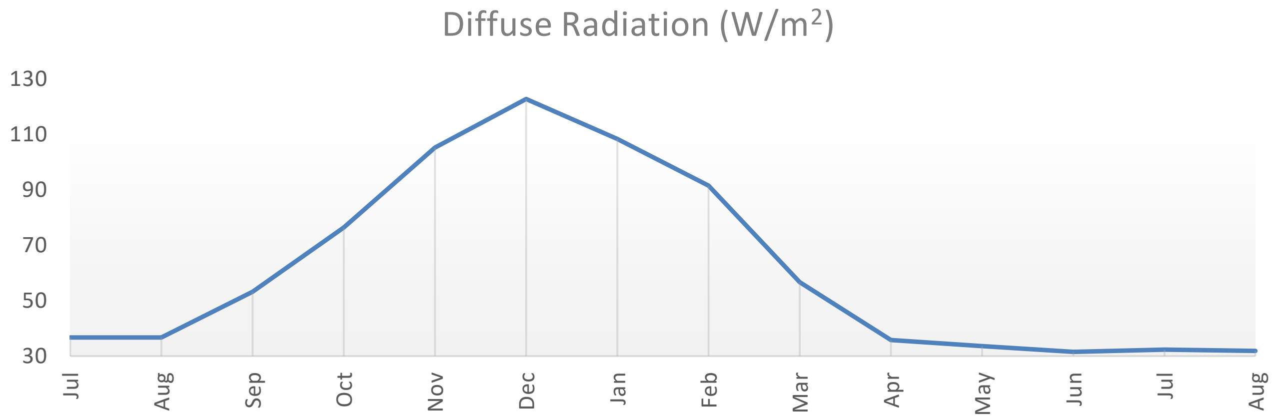


Figure 4.6: Average monthly diffuse radiation levels at CPUT Bellville weather station

4.7 Temperature measurements

Calculations to determine the drying rates, insulation etc. required temperature measurements in the crop drying systems. Temperature played a major role and influenced most of the parameters in the project hence it was measured and recorded during the testing. The operational temperatures of the dryer were determined during the testing to enable the proper setting of the thermocouples. Thermocouples are electrical devices that can produce a temperature dependent voltage - due to the thermoelectric effect - which can be interpreted to measure temperature hence the reason they can be used as temperature sensors. Thermocouples can be limited on the accuracy depending on the actual system of installation. For the solar crop dryer, the temperature accuracy limitations which are sufficient for the testing of the food samples were chosen.

The K type thermocouples were used in measuring the ambient temperature and the other dryer interior temperatures (T_{air}, $T_{product}$, T_{plate} etc.). A separate thermocouple connected to the data logger at the weather station was used to measure the ambient temperature at regular set intervals of 10 minutes. The product and interior dryer temperatures were measured using a temperature logger that measured the different temperature sensors installed in the crop dryer. The temperatures were measured in 1-hour intervals. Figure 4.7 shows the typical thermocouples and temperature data logger used in the experiment. The K type thermocouple is a common general-purpose thermocouple made from chromel - alumel alloy with probes that can record temperature range on −200 °C to +1350 °C. Refer to Appendix A for detailed specifications of the type K thermocouple (www.omega.com)

Figure 4.7: Temperature data logger and a K type thermocouple

(https://tinyurl.com/yaz2m4a9)

Figure 4.8 shows the typical average monthly values recorded at the CPUT Bellville weather station for the previous year. Similarly to the trend of radiation levels, it can be noted the average monthly temperature was high during the summer months from October to April (18 to 28°C) and low in the winter months from May to August (14 to 20°C). It is important to do the testing during these months to have the best results. For maximum performance of the dryer, the testing has to be done on clear sunny days were the irradiation exposure is high preferably in the summer.

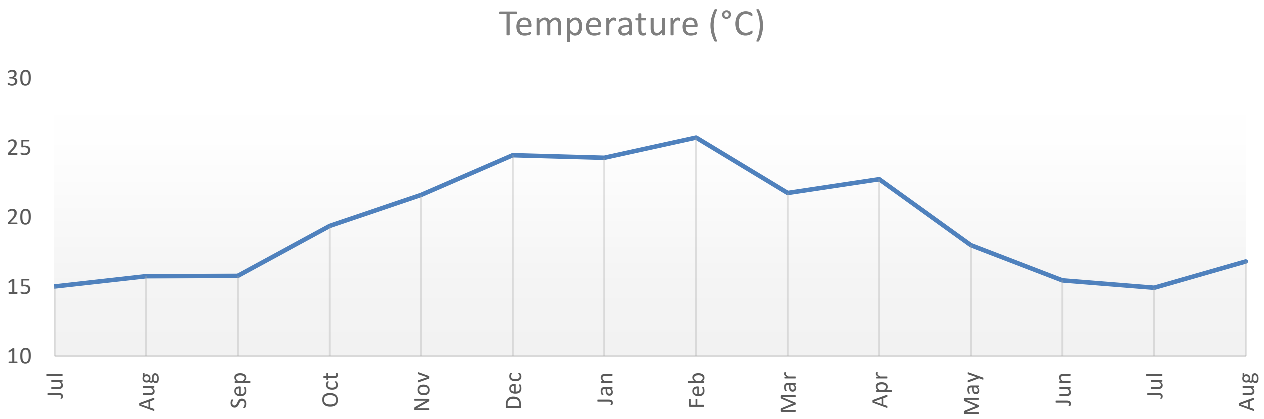


Figure 4.8: Average monthly ambient temperature at CPUT Bellville weather station

4.8 Humidity

Besides the effect of temperature in the crop drying system, humidity also played a role in the product drying process. Humidity is associated with the amount of water vapour present in the air which is influenced and dependent on the temperature of the surroundings. The higher the humidity of the air, the difficult it is for the air to absorb and retain moisture. The amount of water vapour that is needed to achieve saturation increases as the temperature increases. Hence as the temperature of the air decreases, the less water it will hold to reach a saturation point and vice versa. A humidity sensor was used to determine the humidity in the system and it was also coupled with a temperature sensor to record the corresponding temperatures. This was used also as an indicator to aide in checking the readiness of the products by monitoring the moisture levels in the dryer. This setup was used both to monitor the readings manually using a simple interface as well as populating results on the computer whilst the program was running.

4.9 Wind speed measurements

The air flow has an impact on the moisture removal process. As the food samples lose water to the surroundings, the heated air removes the water through convection and disposes it out via the extraction system. This ambient air speed has much influence on the open sun drying system whilst the air speed inside the dryer is determined by the set fan speed or natural airflow. The surrounding airspeeds were measured by the 03101 R.M Young three cup anemometer installed at the weather station shown in Figure 4.9. It is connected to a data logger to record the airspeed in meters per second (m/s) at a regular set interval. The working range for the cup anemometer is between 0 and 50m/s. Refer to Appendix B for shows the technical specifications of the cup anemometer used for airspeed measurements (www.campbellsci.com).

Figure 4.9: A 03101 R.M Young three cup anemometer

Figure 4.10 shows the average monthly airspeed values recorded at the CPUT Bellville weather station for the previous year. Average monthly wind speeds recorded ranged between 2m/s and 4m/s. It has to be noted that some of the days the airspeeds will exceed 4m/s and can even be 0m/s in some instances.

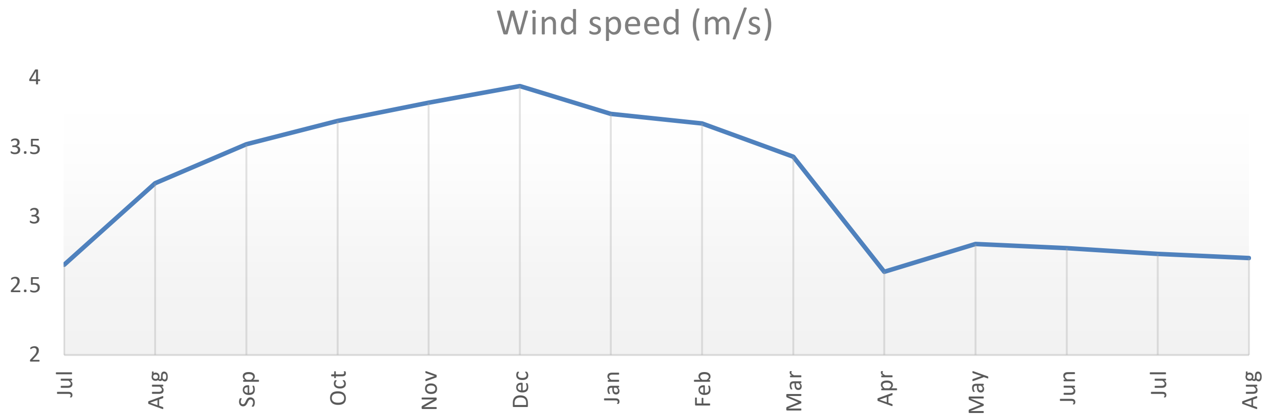


Figure 4.10: Average monthly wind velocity at CPUT Bellville weather station

.

4.10 Data recording instruments

The Campbell scientific CR1000 model data logger was used as the data acquisition system to process and record all the sensors measurements used for the crop drying system. The data logger was set to record ambient conditions i.e. ambient temperature, airspeed, radiation levels and relative humidity at regular intervals of 15 minutes throughout the testing period. The CR1000 operates for extended time periods using a rechargeable battery due to its low power consumption. Figure 4.11 shows a typical CR1000 model data logger used for the project.

Figure 4.11: Campbell scientific CR1000 data logger

4.11 Solar panel

The weather station has a solar panel installed that was used to the run the fans that are on the crop dryer Figure 4.12. This panel utilised the solar energy and ensured that the fans were running during the testing period hence assisting with the moisture removal process. A 90W solar panel with a rated voltage (V_{mp}) of 18.40V and rated current (I_{mp}) of 4.90A was used. The open circuit voltage (V_{oc}) and short circuit current (I_{sc}) was 22.40V and 5.5A respectively at the standard conditions of 25°C and radiation of 1000W/m^2. This battery was used to run the four 3W AC fans connected to the crop dryer system.

Figure 4.12: Solar panel

4.12 Experimental setup

The solar crop dryer setup consisted of a drying unit mounted on a stand. The working principle of the solar crop dryer involved placing of the food products to be dried in the drying trays which were then placed in the drying unit. The food samples were cut to the required specifications and placed in the right quantities during the drying process. Once the drying process started, the moisture was removed from the food and extracted from the dryer system with the aid of installed fans or natural ventilation. Before placing the test samples, all the required measuring instrumentation was put in place and secured on the dryer.

For the testing of the crop dryer, two different crop dryers were tested together with control to determine the effectiveness of the drying setups in drying the food. The model setup and working principle of the two dryers are generally the same with only minor differences explained in the following sections. The test model consisted of a solar crop dyer with different instruments for measuring different parameters. The typical solar crop dryer setup used for the testing is shown in Figure 4.15 with the respective points were the sensory devices were placed in the system. For Cape Town area test conditions, the drying unit was mounted on a frame inclined 30 degrees to the horizontal, facing the north direction to maximize all year incident radiation on a fixed plane as recommended by Kanyarusoke *et al.*, (2016).

Before the testing commenced all the components and testing equipment for the experiment were cleaned to remove any impurities. For the project, two products were tested to check the effectiveness of the dryers i.e. one fruit (banana) and a vegetable (cabbage) which are more likely to be preserved in the rural communities for use in the post-harvest periods. It has to be noted that the crop dryer can be used to dry any food product as it is not limited to only the products tested during the experiments. The drying trays and wire mesh were cleaned to ensure that no contamination of the dried products would occur. For accurate measurements and prevention of any shading on the measuring instruments, the weather station was mounted high above the roof on a mounting pole approximately 2m clear of the surroundings. Figure 4.13(a) shows the arrangements of the testing model whilst Figure 4.13 (b) shows the weather station equipment on the mounting frame. Figure 4.13(c) shows the back view of one of the crop dryer setups.

.

Figure 4.13: (a) Front view of the solar crop dryer model and (b) the weather station (c): Back view of the solar crop dryer

4.13 Solar radiation estimation and calculations

For the solar measurements and calculation for the experiment, a method was devised to get the incident radiation on the solar crop dryer setups. Calculations were done to check the energy and heat transfer in crop dryers. The total incident energy on the dryer was determined together with the heat loses in the crop dryers to have the overall useful energy in the system. The amount of energy entering the atmosphere is known as the solar constant ($\mathbf{I_{sc}}$). It is the energy from the sun per unit time received on a unit area on a surface perpendicular to the direction of propagation of radiation at the mean earth-sun distance outside the atmosphere. This is measured in W/m^2 and is averagely around 1367W/m^2 (Duffie and Beckman, 2013). The energy, however, is dissipated before it reaches the earth's surface as it is influenced by the weather, location, seasons and time of the day. The data collected from the Campbell Scientific weather station shows the solar radiation measured on a horizontal surface. For tilted surfaces, the total incident solar radiation ($\mathbf{I_T}$) is obtained by summing the beam radiation ($\mathbf{I_{T,b}}$), the diffuse radiation ($\mathbf{I_{T,d}}$) and the reflected radiation on the surface ($\mathbf{I_{T,reflected}}$). This can be expressed as following:

$$\mathbf{I_T = I_{T,b} + I_{T,d} + I_{T,reflected}} \qquad \textbf{(4-1)}$$

The beam radiation in this instance reaches the crop dryer surface area directly; the diffuse radiation reaches the crop dryer surface indirectly after being deflected by the clouds whilst the reflected radiation reached the surface after being reflected off the ground and other surrounding surfaces as illustrated in Figure 4.14.

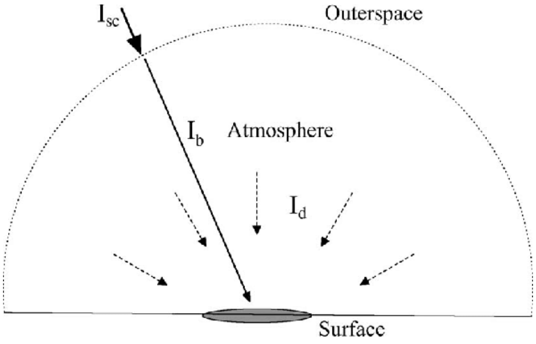


Figure 4.14: Solar radiation illustration on a crop dryer surface

The extra-terrestrial radiation i.e. the radiation that is received in the absence of the atmosphere can be given by the following equation depending on the variation with time of year

$$\boldsymbol{Ioa = Isc\left(1 + 0.033\,cos\frac{360n}{365}\right)} \qquad \textbf{(4-2)}$$

where $\boldsymbol{Ioa}$ is the extra-terrestrial radiation incident to the plane perpendicular to the radiation on the nth day of the year.

This can further be expressed as

$$I_{0a} = I_0 \left[\cos\delta \cos\left(\frac{t}{4}\right)^o \cos L + \sin\delta \sin L \right] \left[1 + 0.03 \cos\left(\frac{360n}{365}\right) \right] \qquad \textbf{(4-3)}$$

with **L** as the latitude for the particular location

δ as the declination

t as the solar time of day from noon

The latitude is defined as the angular location North or South of the equator. The north is perceived as positive (degrees) while the south is perceived as negative (degrees) and the equator as zero degrees.

$$-90^o \leq \text{Latitude (L)} \leq 90^o$$

The angular position of the sun at the solar noon (sun over the meridian) with respect to the plane of the equator known as declination can be calculated by the following equation as obtained from ASHRAE (2009).

$$\delta = 23.45 \sin\left(360 \frac{284+n}{365}\right) \qquad \textbf{(4-4)}$$

With the declination found in a range of $-23.45^o \leq \delta \leq 23.45^o$ and n is the day of the month specified. To determine the value for n for a specific day, Table 4.3 can be used, where D is the day of the month.

Table 4.3: Determination of n for a specific day

Month	Formulae	Month	Formulae
January	D	**July**	181 + D
February	31 + D	**August**	212 + D
March	59 + D	**September**	243 + D
April	90 + D	**October**	273 + D
May	120 + D	**November**	304 + D
June	151 + D	**December**	334 + D

4.13.1 Solar radiation on a tilted surface

In order to determine the incident beam radiation on the crop dryer inclined at an angle from the horizontal, the actual incident horizontal beam radiation on the dryer has to be multiplied with a certain geometric factor. Geometric factor (R_b) is a ratio of beam radiation incident on an inclined surface to the beam radiation on a horizontal surface at a given time. Hence to determine the incident beam radiation on an inclined surface at an angle β to the horizontal, the direct beam horizontal radiation (I_b) is multiplied by the geometric factor as expressed in the following equations:

$$\boldsymbol{I_{b_{inclined\,surface}} = I_b R_b} \tag{4-5}$$

Since R_b is a ratio of the incident inclined radiation to the horizontal radiation it can further be deduced that

$$\boldsymbol{R_b = \frac{I_{b'}}{I_b} = \frac{I_N cos\theta_i}{I_N cos\theta_z} = \frac{cos\theta_i}{cos\theta_z}} \tag{4-6}$$

where:

I_b is the incident beam radiation on a horizontal surface

$I_{b'}$ is the incident beam radiation on a tilted surface

I_N is the beam radiation intensity

$\boldsymbol{\theta_z}$ is the zenith angle i.e. the angle between the vertical and the line of the sun

$\boldsymbol{\theta_i}$ is the incident angle of the beam radiation.

To determine the zenith angle the following equation can be used

$$\boldsymbol{cos\theta_z = cosLcos\delta\cos\omega + sinLsin\delta} \tag{4-7}$$

Similarly, the incident beam angle also can be obtained from this equation

$$\boldsymbol{cos\theta_i = cos(L+\beta)cos\delta\cos\omega + sin(L+\beta)sin\delta} \tag{4-8}$$

where $\boldsymbol{\delta}$ is the sun’s declination angle

$\boldsymbol{L}$ is the latitude of the location, with north positive

$\boldsymbol{\beta}$ is the tilt angle

$\boldsymbol{\omega}$ is the hour angle

For the tilt angle i.e. the angle between the plane of a surface and the horizontal.

$$0° \le \beta \le 180°$$

If β > 90º => downward facing component

If β = 90º => vertical surface
If β = 0º => horizontal surface

The hour angle is given by the following

$$\boldsymbol{\omega = 15(t - t_{noon})} \qquad \textbf{(4-9)}$$

with $\boldsymbol{t}$ is the local time and $\boldsymbol{t_{noon}}$ is solar noon
$\boldsymbol{\omega}$ is positive for afternoon hours and negative before noon

Since the geometric factor is given by equation (4-6) and $\boldsymbol{cos\theta_i}$ and $\boldsymbol{cos\theta_z}$ known the following expressions can be derived to calculare R**b**

$$\boldsymbol{R_b = \frac{cos\theta_i}{cos\theta_z}} \qquad \textbf{(4-10)}$$

With $\boldsymbol{cos\theta_i}$ and $\boldsymbol{cos\theta_z}$ known

$$\boldsymbol{R_b = \frac{cos\theta_i}{cos\theta_z}}$$

$$= \boldsymbol{\frac{cos(L+\beta)cos\delta\cos\omega + sin(L+\beta)sin\delta}{cosLcos\delta\cos\omega + sinLsin\delta}} \qquad \textbf{(4-11)}$$

4.13.2 Diffuse radiation

On an inclined surface, however, the Perez equation was used to determine the incident radiation on the crop dryers (Perez *et al.,* (1990). Hence the total incident radiation on the tilted surface (I_{panel}), can be obtained as follows

$$I_{panel} = I_{bh}R_b + I_d(1 - F_1)\left(\frac{1+\cos(\beta)^\circ}{2}\right) + I_dF_1\frac{a}{b} + I_dF_2\sin(\beta^\circ) + I_h\rho_g\left(\frac{1-\cos(\beta^\circ)}{2}\right) \qquad \textbf{(4-12)}$$

where I_{bh} is the horizontal incident beam flux
β is the panel slope
R_b is the panel to horizontal incident beam flux ratio
ρ_g is ground reflectivity
b is dependent on zenith angle
a is dependent on the incident angle at the panel
I_d is general incident diffuse flux

I_h is total horizontal incident radiation flux

F_1, F_2 circumsolar horizontal incident radiation flux

For the project, three different tests were done before the overall conclusion of the effectiveness of the solar crop dryer was concluded. These are (i) the dry run or no load tests (ii) the sample thickness test and (iii) the full load test. For all these tests the same procedure was used with only different parameters measured in each of the tests for analysis purposes. The same weather station was used for the ambient conditions as the tests were done on the same testing site.

4.14 Control sample test

The control sample test was used as a way to measure the effects of the parameters in the normal way without any variables altered. This normally demonstrates what is usually expected from the drying process without any independent variables changed. For this test, the open air sun drying was used as the control test, in which all the tests were conducted based on the ambient test site conditions.

For the control sample, the weather conditions used for the testing site were from the weather station. The critical conditions noted included the ambient temperature, airspeed, irradiance levels and relative humidity. For the control samples, the readings were taken anywhere within the proximity of the testing site as the control sample has no boundaries. The outside testing conditions are generally the same hence implying the same readings for all the parameters taken. During testing, the food samples were placed anywhere on the testing area for analysis (as long as they are exposed to the same conditions as the main tested dryer). The testing area covers a huge area but all the ambient conditions in that space will be the same. Hence for the control sample, only the ambient temperature was recorded for analysis as the conditions were uniform. For the crop dryer, with a controlled area for drying the food, more temperature measurements were required for performance analysis of the crop dryer.

4.15 Drying test procedures

- **Solar irradiance and wind speed**

During the no-load test, no product was placed in the dryer during the testing period. The ambient conditions – temperature, solar irradiance (both the total and diffuse) and wind speed were measured and recorded during the test period using the weather station. The data were recorded every 15 minutes for the full day on the data logger. But for analysis and calculations, only data during the sunshine hour's i.e.0900hrs to 1700hrs was used.

- **Temperature measurements and humidity**

For the interior of the dryer different temperature measurements were measured and recorded for the heat transfer analysis and heat distribution in the crop dryer. K type thermocouples were used to measure the various temperatures within the dryer (Figure 4.15). The following temperatures were measured in the crop dryer for the no-load test:

- Dryer air temperature ($T_{air\ \mathrm{dryer}}$)
- Dryer relative humidity ($RH_{\mathrm{air\ dryer}}$)
- Absorber plate temperature (T_{plate})
- Left side temperature (T_{left})
- Right side temperature (T_{right})
- Bottom side temperature (T_{bottom})
- Ambient temperature (T_a) from the weather station

The illustration on Figure 4.15 shows the respective positions and arrangements of the thermocouples on the crop dryer.

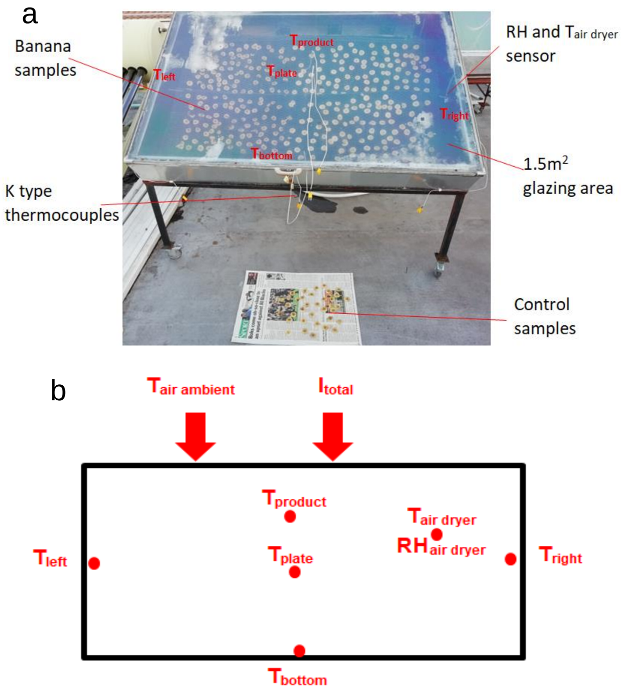


Figure 4.15: a) Thermocouples distribution in the crop dryer b) schematic top view of the positions of the thermocouples on the crop dryer

The solar crop dryer system is a closed system with fixed boundaries. Depending on the size of the dryer and its effective area, some functionalities of the dryer are limited. In contrast to the control test (open sun drying) in which the temperatures are uniform, for the temperatures of the closed system had to be taken at different sections within the dryer. Figure 4.15 shows the arrangements of the different sensors on the solar crop dryer used to measure different temperatures, relative humidity and airspeed. Due to the fixed nature of the drying space within the dryer different measurements had to be taken.

A thermocouple was installed on the weather station to measure the ambient temperature (T_a) of the testing site. This temperature is uniform and can be used for analysis in both the tested dryers and control tests. Another temperature sensor was installed on the dryer to measure the $T_{air\ \mathrm{dryer}}$ i.e. the dryer air temperature with the respective air dryer relative humidity ($RH_{\mathrm{air\ dryer}}$). This was the temperature for the heated air in the dryer due to the absorbed solar radiation. It is critical in the drying of the food product and has an impact on determining how quickly the food can dry. For each $T_{air\ \mathrm{dryer},}$ a corresponding $RH_{\mathrm{air\ dryer}}$ is also given. A different thermocouple was placed to record the T_{plate} i.e. the absorber plate temperature of the crop dryer. This temperature is determined by the intensity of the solar radiation absorbed by the glazing and also influences the air temperature within the dryer used in drying the products.

In order to check the uniformity of the temperatures within the dryer three other different sensors were put into place. These thermocouples were to record the following temperatures: left side temperature of the dryer (T_{left}), right side temperature of the dryer (T_{right}) and bottom side temperature of the dryer (T_{bottom}) as shown in Figure 4.15. Unlike in the control test where the ambient temperatures are uniform throughout the test site, in the crop dryer the scenario is slightly different. Due to the boundaries of the crop dryer, the temperatures on the different sides of the dryer may differ due to a number of factors. The direction of air flow, the direction of exposure of solar irradiance, shading and dryer orientation may cause slight differences in the temperatures within the dryer. These will also be used for analysis of heat gain, heat loss and effectiveness of insulation within the dryer. During the result analysis, the impact of these temperatures will be explained in detail.

Similarly to the dry run or no load test, the experiments were done to determine the correct sample thickness for the product testing. The noticeable difference was that in the no-load test no products were placed in the dryer to test, but only the experimental results were measured, monitored and recorded. Small samples and different thickness sizes of the test product were cut and placed in the dryer for testing. After this, the full load test was done with specifically known weight samples dried in the different dryer setups. Other parameters like weight loss and product quality were checked in these tests and used in determining the outcome of the test results.

4.16 Determination of moisture content

Determination of moisture and weight loss, together with the rate of drying was one important aspect to note in this project. With good irradiation levels on sunny days, good dry rates of food products were attainable. Test samples were weighed before and after drying to determine the weight difference hence determine also the moisture loss per food item. Direct weighing was used for measuring the direct weight loss for the test samples. Sample weighing method uses the direct measurement of the difference in weight of a test sample before and after. Although not 100% accurate as compared to the oven drying, due to the different temperatures the samples are subjected to during the moisture removal process, it still provides conclusive results to determine the drying effects of the test samples.

Loss of weight on drying samples is used in determining and calculating the moisture content and other soluble substance in the food product. Samples are dried until a constant mass is reached resulting in the moisture content of the food samples being the difference between the starting and final weight. Other parameters noted during the drying process included time, temperature, sample preparation methods and effects of heat applied. In order to get conclusive results, the tested samples were sent to a laboratory to check the actual moisture content for comparison with the weight loss method. The samples are tested using the oven drying method. In this method, the test samples are heated under specified and monitored conditions, after which the weight loss can be used to determine the moisture loss from each tested product.

The moisture content (MC) for the tested products can be obtained by the following equation (Nielsen, 2010):

$$Moisture\ content\ = \frac{M_{initial} - M_{final}}{M_{initial}} \times 100 \qquad \textbf{(4-13)}$$

were $M_{initial}$ is the initial mass of the tested product

M_{final} is the final mass of the dried product

The drying rate (R_d) of the samples can also be calculated using the following equation

$$Drying\ rate\ = \frac{M_{initial} - M_{final}}{t} \qquad \textbf{(4-14)}$$

were *t* is the time taken to dry the products

The moisture ratio can be calculated as follows

$$Moisture\ ratio\ = \frac{M - M_e}{M_{initial} - M_e} \tag{4-15}$$

were M is the equilibrium moisture

M_e is the moisture content at anytime

Moisture content to be removed from a wet sample to a safe storage level in a specified time is obtained as follows:

$$Moisture\ content\ to\ remove\ = \frac{M_{initial} - M_{final}}{100 - M_{final}} \times M_{product} \tag{4-16}$$

were $M_{product}$ is the mass of the wet product

The moisture content can be expressed as either wet basis (w.b) or dry basis (d.b). In wet basis, the percentage moisture is expressed as a ratio of the overall weight of the sample (water and dry component) whilst in dry basis, the percentage moisture is expressed as a ratio of the dry component only. In the calculations done it is specified if the results obtained are in d.b or w.b. This is important in determining actual moisture loss from the food samples based on correct calculation parameters. The following equations show how the moisture content is calculated on wet basis and dry basis.

$$\%\, Mc\ w.b = \frac{Ww - Wd}{Ww} \times 100 \tag{4-17}$$

$$\%\, Mc\ d.b = \frac{Ww - Wd}{Wd} \times 100 \tag{4-18}$$

were W_w is the weight of the wet product

W_d is the weight of the dried product

Moisture content conversion from wet basis (w.b) to dry basis (d.b)

$$Mc\ wb = \frac{Mc\ db}{1 + Mc\ db} \tag{4-19}$$

$$Mc\ db = \frac{Mc\ wb}{1 - Mc\ wb} \tag{4-20}$$

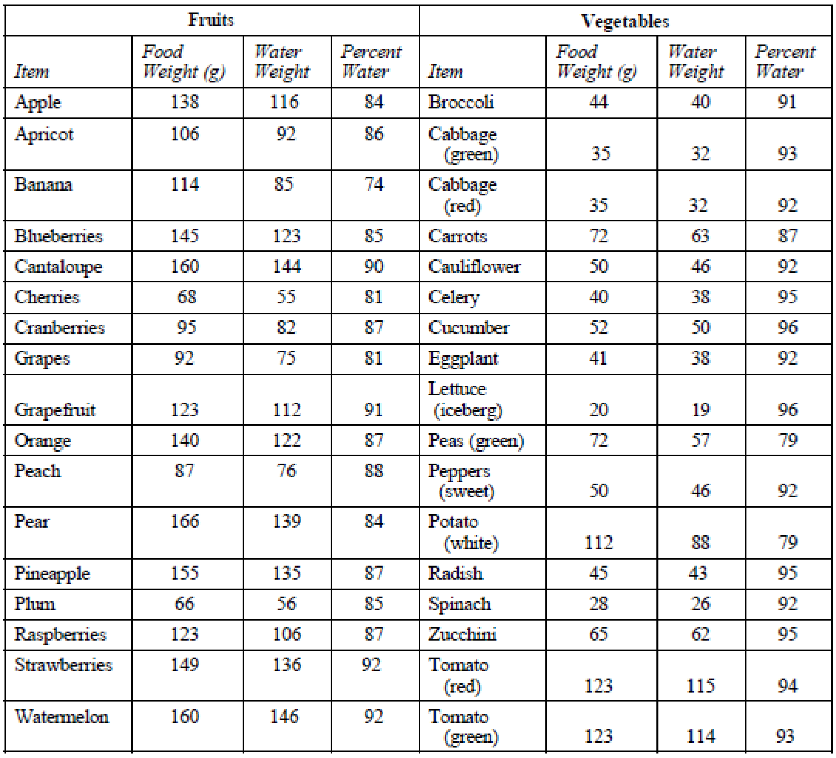
To obtain accurate measurements of the moisture content or total solids of food using evaporation methods, it is necessary to remove all of the water molecules that were originally present in the food, without changing the mass of the food matrix.

$$\%\,Total\ solids\ =\ 100 - \%\,Moisture \qquad \textbf{(4-21)}$$

4.16.1 Moisture content

Table 4.4 shows examples of different moisture contents of fruits, vegetables and meat products obtained from research. As seen in the table most food products have very high initial moisture content ranging up to 96% which results in high degradation rates of these products after harvesting. Hence crop drying addresses these issue by reducing the moisture content to between 15% and 25% for safe drying of most of the produces (Bradley, 2010).

Table 4.4: Moisture content of different fruit and vegetables



Fruits				Vegetables			
Item	*Food Weight (g)*	*Water Weight*	*Percent Water*	*Item*	*Food Weight (g)*	*Water Weight*	*Percent Water*
Apple	138	116	84	Broccoli	44	40	91
Apricot	106	92	86	Cabbage (green)	35	32	93
Banana	114	85	74	Cabbage (red)	35	32	92
Blueberries	145	123	85	Carrots	72	63	87
Cantaloupe	160	144	90	Cauliflower	50	46	92
Cherries	68	55	81	Celery	40	38	95
Cranberries	95	82	87	Cucumber	52	50	96
Grapes	92	75	81	Eggplant	41	38	92
Grapefruit	123	112	91	Lettuce (iceberg)	20	19	96
Orange	140	122	87	Peas (green)	72	57	79
Peach	87	76	88	Peppers (sweet)	50	46	92
Pear	166	139	84	Potato (white)	112	88	79
Pineapple	155	135	87	Radish	45	43	95
Plum	66	56	85	Spinach	28	26	92
Raspberries	123	106	87	Zucchini	65	62	95
Strawberries	149	136	92	Tomato (red)	123	115	94
Watermelon	160	146	92	Tomato (green)	123	114	93

Although drying is a food preservative method, it can be associated with decomposition if proper care and handling are not done. Nielsen (2010), states that the loss of moisture in food is a function of temperature and time. Hence a balance between the two is required to prevent decomposition. Decomposition of food is prone to happen when the moisture content is high. Storage of food at too high moisture levels may result in the risk of mould growth as the moisture content in food is influenced by drying time, temperature and food condition.

4.16.2 Limits of drying

Although drying preserves food and gives long shelf life, caution has to be taken to preserve the nutrients and quality of the food. Drying does not improve the food quality hence ripe food samples were used. Drying is fairly a slow process depending on the type of foods to be dried. It can also be associated with moulding if the samples are not dried or stored properly. It also involves the change of the physical state of the food depending on the exposure periods of the food to solar radiation. Minimizing exposure of the samples to the atmosphere, preserve and prevents any moisture gain or loss to the surroundings which might result in inaccuracies in the readings obtained.

4.16.3 Samples to be tested

With the project target areas being the rural setups, products that would cater to the needs of the people and sustain the communities were chosen. Although any product can be tested in the dryer, for this project one fruit and one vegetable product were selected for testing. Availability, affordability and ease of obtaining the food products were some of the factors taken into consideration for the choices of the testing products. Bananas were selected as they contain many essential nutrients like vitamin B-6, manganese, vitamin C and potassium and are important as a source of food in many rural communities. Vegetables form an important part of the dietary and fibre foods to people on a daily basis. Hence cabbage was used as a test sample.

- **Sample parameters**

Certain parameters were determined for each product being tested to ensure an effective and efficient drying pattern to ensure a good working principle of the crop dryer. Hence parameters like sample thickness, sample size and sample depth had to be determined. Thicker samples tend to take more time and energy is required to completely dry whilst thinner sample easily crumble and stick to the surface. Hence for this testing, the correct depth or thickness samples had to be determined first.

- **Sample preparation**

Preparation and storage of food samples must be handled so as not to cause any moisture loss or absorption from the surroundings. To secure and store food samples, airtight containers or foil paper were used to prevent moisture loss or gain during the testing period. Hence a balance is required to determine the effective, economic and best way of drying the food samples. The thicker and bigger the samples are, the more time is required to dry them. A proper thickness was selected to maintain the quality of the samples, without crumbles and discolouring. The volume of the samples was also determined which was sufficient to cover the drying trays with a thin layer of product.

Drying does not interfere with the ripeness of the food samples. Hence all samples dried were ripe and use of less ripe or overripe food samples was avoided. For hygiene purpose, all food samples and drying equipment were cleaned prior to the testing to prevent any impurities in the system. Any cuts in the samples were removed to prevent any moulding during drying. Thinly sliced samples were used to ensure even and uniform drying of the samples using the determined thicknesses and depths calculated for this experiment. Pre-treatments may be used (if necessary) to stop any enzyme activities that might cause the decomposition of the crops. It is mostly used if colour and flavour need to be retained in food sample to be dried like for example in the blanching of cabbage. One layer of the dried product was evenly spread on the surface hence allowing even exposure of sunlight and air flow to the contents. For small scale production, the dryer is loaded and products only removed after the drying is complete for easy and simple operation.

Properties of samples before testing:
Initial moisture content of the samples, Initial wet sample weights, Initial texture of the samples, Initial taste of the samples

Properties of samples after testing:
Final moisture content of the samples**,** final dry sample weights**,** final texture of the samples**,** final taste of the samples, water loss weight and percentage

Conditions before testing and after testing (data logger recording)

- Ambient temperature
- Temperatures within the dryer
- Wind speed
- Relative humidity
- Solar irradiance

- **Equipment required**

Weighing scale (accurate to 0.01g), moisture content recorder, timer, cutting utensils for the samples, temperature recorder

- **Parameters to be calculated**

Moisture loss for the samples, mass loss/water loss, drying time, the moisture content of the samples (before and after), sample readiness indicator, heat calculations

Changing variables in the dryer

  - Relative humidity decreases
  - Air temperature increases
  - Velocity of air varies
  - Product moisture content during the drying phase

- **Placement of drying samples**

  In order not to interfere with the even drying of the product, it is essential to avoid making lumps when placing samples in trays and avoiding too thick samples. Allow even placing of samples over the drying surface of the tray. The samples should be placed in the drying trays fast to avoid evaporation or absorbing moisture from the atmosphere.

- **Factors to note during the drying process**
  - Ensure that all samples to be dried are ripe; avoid using less ripe and overripe food samples.
  - No impurities on the samples hence ensure they are well cleaned before the drying process.
  - Ensure that any scars or cuts in the samples are removed as they can easily cause moulds and affect the drying process.
  - Thinly sliced/cut samples should be used to ensure even and uniform drying of the samples. Apply the determined thicknesses and depths calculated for this experiment.
  - Pre-treatments may be used (if necessary) to stop any enzyme activities that might cause the decomposition of the crops. Mostly used if you need to retain the colour and flavour of the food sample to be dried.
  - Use food grade plastic, spray or trays to ensure the dried samples do not stick to the surface of the dryer
  - Ensure one layer of contents evenly spread on the surface - to allow even exposure of sunlight and air flow to the contents
  - Small scale production - load dryer and only remove the contents after the drying is complete (easy and simple operation design)

4.17 Heat transfer calculations

From the total solar radiation incident on a surface, only a fraction reaches the food product as some portions are reflected or lost to the atmosphere due to conduction, radiation and convection. Figure 4.16 illustrates the general distribution of the incident solar radiation on a glazing material (glass). From the total 100% incoming incident radiation on the glazing, approximately 80 to 84% is transmitted into the solar dryer (Ahmed *et al.,* 2017). Up to 8% of the incident radiation is reflected on the glazing surface and can also increase if double glazing is used. Heat losses due to convection and conduction are also noticeable hence it is recommended to use proper insulation to reduce the heat losses in the system.

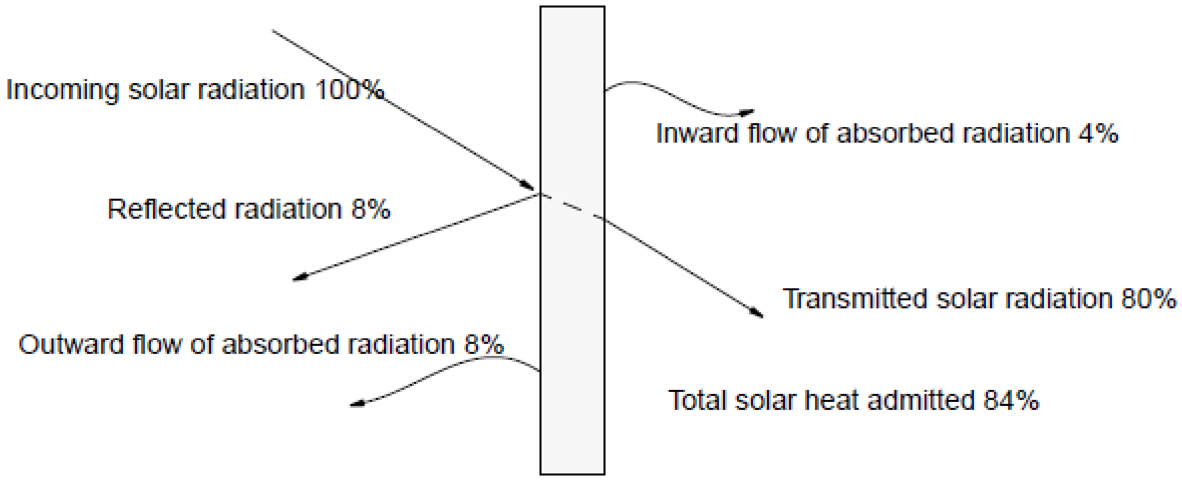


Figure 4.16: Solar radiation distribution on a glazing material (glass)

(Adapted from Ahmed *et al.*, 2017)

Figure 4.17 shows the typical heat transfer system that occurs in a crop dryer. In order to determine the overall useful heat energy required in drying the food, all the energy gains and losses in the systems had to be calculated.

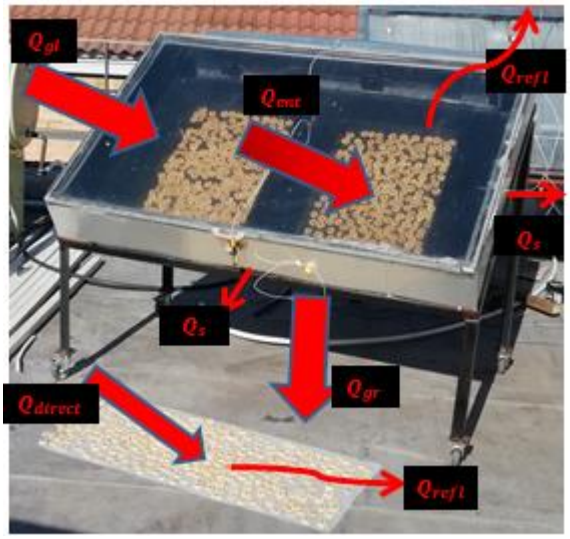


Figure 4.17: Heat transfer in a crop dryer system

Total heat gain in the system can be expressed by the following equation:

$$I \times A_C = Q_{in} + Q_{conduction} + Q_{convection} + Q_{radition} + Q_{reflected} \tag{4-22}$$

were Q is the respective heat energy in the system

A_c is the collector glazing area

I is the incident solar radiation

The total heat energy incident on the glazing surface ($Q_{glazing}$) can be obtained from the following equation:

$$Q_{glazing} = \int I_{glazing} \times A \times \Delta t \tag{4-23}$$

were $I_{glazing}$ is the incident solar radiation on the glazing surface

A is the overall glazing area

Δt is the change in time

Since a percentage of the incident radiation on the glazing is reflected, the total heat energy inside the dryer (Q_{in}) has to be obtained using the incident radiation inside the dryer. Hence the following equation was obtained:

$$Q_{in} = \int I_{in} \times A \times \Delta t \tag{4-24}$$

were I_{in} is the incident solar radiation inside the dryer

hence the optical efficiency of the dryer can be obtained as follows

$$Optical\ efficiency = \frac{Incident\ energy\ in\ the\ dryer}{Incident\ energy\ on\ the\ glazing} = \frac{Q_{in}}{Q_{glazing}} \tag{4-25}$$

The heat energy required to drive out or evaporate the water from the food product (Q_{evap}):

$$Q_{evap} = m_{w\ lost} \times h_{fg} + m_{crop} \times C_{crop} \times \Delta T_{crop} \tag{4-26}$$

were $m_{w\ lost}$ is the mass of moisture lost from crop

h_{fg} is the latent heat of vaporization

m_{crop} is the total mass of crop to be dried

C_{crop} is the specific heat capacity of the crop

ΔT_{crop} is the temperature difference in the crop i.e. $T_{max} - T_{min}$

The experimental heat transfer in a crop dryer can be summarised as follows:

$$Q_{experimentally} = Q_{in} - Q_{crop} \tag{4-27}$$

were $Q_{crop} = mC\Delta T_{crop}$

Henceforth the heat energy lost from the system can be summarised as follows:

$$Q_{lost\ experimentally} = \int I_{in} \times A \times \Delta T - Q_{evap} \tag{4-28}$$

The heat energy lost in the system can be in the form of conduction, radiation or convection. To minimise heat losses by convection double glazing with an air gap of 5mm was used at the top of the dryer whilst the heat loss by conduction on the sides was minimised by use of insulation. Heat lost from the system can be calculated as follows:

$$Q_{lost\,=}\ Q_{rad\ top} + Q_{conv\ top} + Q_{ground} + Q_{side} \tag{4-29}$$

$$Q_{ground} = \frac{T_{air\ inside} - T_{ground}}{R_{t\ ground}} \tag{4-30}$$

The thermal resistance (R_t) of a certain material can be obtained by the following equation:

$$R_t = \frac{t}{Ak} + \frac{1}{h_{r+c}A} \tag{4-31}$$

were h_{r+c} is the conductive heat coefficient

A is the area in m^2

k is the thermal conductivity of the material in W/m.K

t is the material's thickness in meters

The overall dryer efficiency can be obtained as follows

$$Dryer\ energy\ efficiency = \frac{Energy\ required\ to\ dry\ crop}{Incident\ energy\ on\ the\ crop\ dryer}$$

$$= \frac{Q_{crop}}{Q_{in}} \tag{4-32}$$

4.18 Temperature and humidity detection system

4.18.1 System components

Different foods have different drying temperatures and humidity levels required to maintain their nutritional value after drying (Al-Amri, 1997). It is important to be able to determine the temperature and humidity levels of the interior of the dryer to ensure the drying process occurs in the required way. Some of the basic components incorporated in the design include the Arduino Uno, Arduino BLUE LCD 16x2 I2C screen, temperature and humidity sensor (DH122) and a 9V rechargeable battery (for testing purposes).

4.18.2 Arduino Uno

This is a microcontroller board comprised of 14 digital input and output pins, a USB connector, power jack and other analogue inputs. All the components needed to support the microcontroller are integrated into the system. It can be powered by a USB cable connected to a computer, an AC-DC adapter or a suitable battery. Different versions of UNO exist and are consistently upgraded to improve the performance of the system.

4.19 Technical Specifications

Table 4.5: Arduino Uno Technical Specifications

Item	Specifications
Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage (recommended)	7-9V
Input Voltage (limits)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328) (0.5 KB used by bootloader)
SRAM	2 KB (ATmega328)
EEPROM	1 KB (ATmega328)
Clock Speed	16 MHz

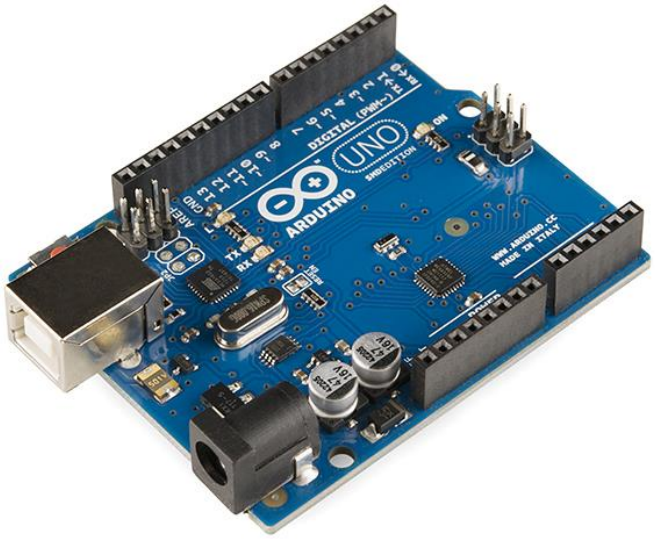


Figure 4.18: Arduino Uno (Sparkfun.com 2017)

4.19.1 Power

The power source of an Arduino Uno can be selected automatically by the system itself, either by a USB connection or external power supply (AC to DC adapter or battery). A 2.1mm centre positive plug is used to connect the adapter to the board's power jack. For the battery connection, the battery leads can be inserted in the ground pins (GND) and VIN headers in the power connector. External power sources of voltage from 6V to 20V (Al-Amri, 1997) are recommended and can be used to power the system. The board may be unstable if voltage supplies of less than 7V are used and a voltage regulator must be used if voltage >12V is used to prevent any damage to the board and overheating.

The available power pins are as follows:

VIN - Input voltage can be supplied through this pin if the Arduino board is using an external source of power or also use this pin for supplying voltage if using a power jack.

5V - The regulated power supply used to power the microcontroller and other components on the board. This can come either from VIN via an onboard regulator, or be supplied by USB or another regulated 5V supply.

3V3 - 3.3-volt supply generated by the onboard regulator. Maximum current draw is 50 mA.

GND - Ground pins

4.19.2 Programming

The Arduino Uno has to be programmed for it to be able to record the required temperature and humidity values and display them. The sensor can be programmed in two ways (i) to populate the results on the computer where the program is running or (ii) display the results on a display screen that can be used to monitor the readings manually. For the project, both methods were used. The manual reading is important for the users as it gives a simple and user-friendly interface.

4.19.3 USB Overcurrent Protection

It is worthy to note that for the system to perform well, it must be protected from any short-circuiting. A resettable polyfuse is incorporated to protect the system at all times especially when plug to the power source. In cases of too high voltage in the system, the fuse will break the connection to protect the system.

4.19.4 Physical Characteristics

The dimensions of the UNO PCB are approximately 68 x 53mm excluding the protruding power jack and the USB connector. These dimensions make it fairly easy to fit the system on the dryer as it will easily be placed. The board is attachable to any surface using the screw holes on each corner of the board.

Figure 4.19: I2C 16X2 LCD Blue Board for Arduino UNO

Table 4.6: Board Functions & Features

Item	**Specification**
Construction	COB(Chip-on-Board)
Display Format	16x2 Characters
Display Type	STN, Transflective, Positive, Y-G
Controller	SPLC780D1 or equivalent controller
Interface	8-bit parallel interface
Backlight	yellow-green\bottom lights
Viewing Direction	6 O’clock
Driving Scheme	1/16 Duty Cycle, 1/5 Bias
Power Supply Voltage	5.0 V

VLCD Adjustable For Best Contrast	5.0 V (VOP.)
Operation temperature	-10℃ to +60℃
Storage temperature	-20℃ to +70℃

4.19.5 Safety Instruction

Safety guide instructions to follow when installing and using I2C LCD Blue Board:

- It is important to handle carefully the I2C LCD Blue Board during installation and ensure it is placed on an insulation surface to prevent any damage if it falls
- The board must be kept in dust free and low humidity areas to prevent any contamination of the components
- Do not expose to rain or water
- Do not block or cover the openings to prevent any overheating of the board
- Never use I2C LCD Blue Board has been damaged

4.19.5 Connecting I2C LCD Blue Board for Arduino

Connect this I2C LCD Blue Board to your Arduino Uno motherboard with I2C bus cable

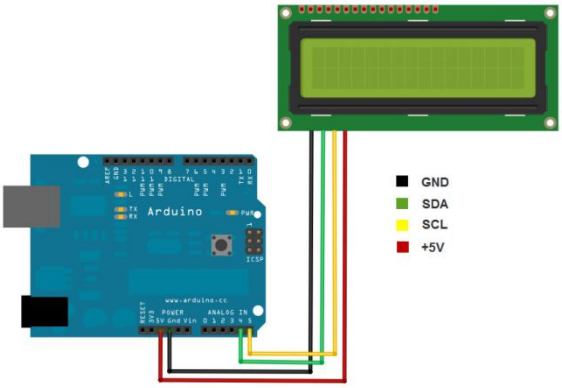


Figure 4.20: Connecting I2C LCD Blue Board for Arduino

4.19.6 Diagram of I2C Module:

Figure 4.20 shows the arrangement of the I2C module when connected to the display screen. The module has four pins: 2 used for the voltage and ground while the other 2 are the I2C connections. The other features of the board also allow for controlling the backlight and adjusting the LCD contrast. Some of the features are labelled in Figure 4.21 as shown.

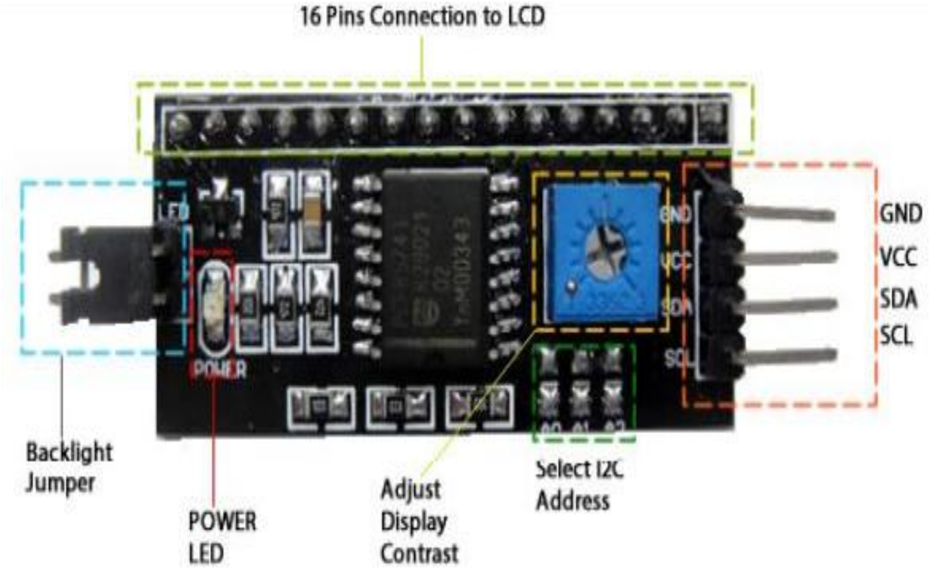


Figure 4.21: Diagram of I2C Module

4.20 AM2303 Temperature and humidity

The AM2303 sensor is programmed to sense and measure the temperature and humidity. This module is calibrated to display the digital output signal of the temperature and relative humidity on the display screen using the sensors. The incorporated technology allows for stability, accuracy and precision of the measurements to be obtained. The temperature and humidity sensor features make it attractive for use in this project. These include fast responses to the environment when taking readings, easy and quick to use, low power consumption and highly (portable).

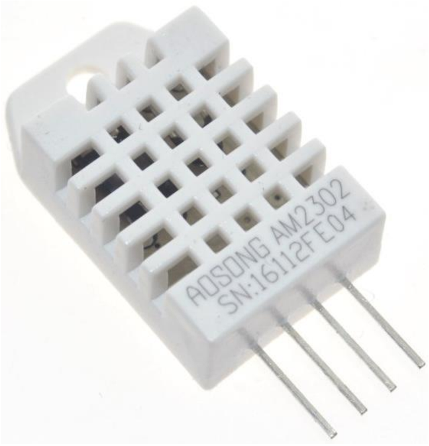


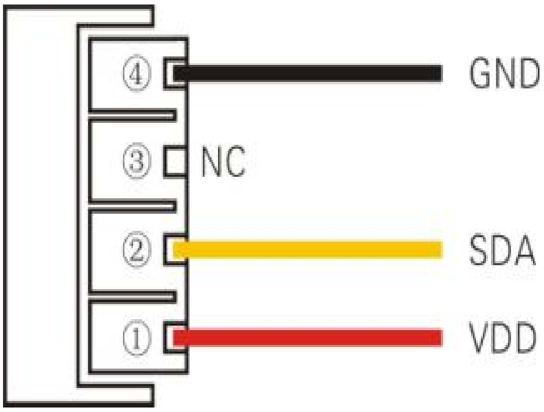
Figure 4.22: AM2303 Temperature and humidity

(AliExpress.com)

This sensor has vast applications where it can be used to check the humidity and temperature conditions. The critical aspects involved are controlling and monitoring systems through data logging, measurement and running tests.

AM2302 Pins Arrangement

Pin	Name	Description
①	VDD	Power (3.3V–5.5V)
②	SDA	Serial data, bi directional port
③	NC	Empty
④	GND	Ground



Determination of the temperature and humidity inside the dryer is critical in the drying process. Hence an Arduino system was designed to check and monitor the temperature and relative humidity within the dryer. This was used also as an indicator to aide in checking the readiness of the products by monitoring the moisture levels in the dryer. This setup was used both to monitor the readings manually as well as populating results on the computer whilst the program was running. Using this setup was easy as it has a simple user friendly interface which anyone can read at any time. The display shows the temperature reading as well as the relative humidity recorded by the sensor placed in the dryer. This was used as a simple indicator to check the readiness of the dried products in the dryer. This indicator was mostly used during the testing period to get the results for this study.

CHAPTER 5: RESULTS AND DISCUSSION

This chapter focuses on the testing *and performance evaluations of the designed solar crop dryer focusing on results, key performance indicators, measurements and calculations.*

5.1 Introduction

This chapter discusses the results obtained during the testing done on the designed solar crop dryers. The results presented along with the environmental conditions at the testing site, shows the comparison of the different drying setups in terms of drying times, effectiveness and efficiencies. For this project, banana and cabbage samples were tested to verify the functionality of the dryer setups. It has to be noted that the tested products are not limited to banana and cabbages only but other agricultural products can be dried also. For this project the products were tested under three different drying conditions stated below:

a. Open sun drying under ambient conditions (*Control sample*)
b. Forced extraction drying (*Dryer 1*)
c. Natural ventilation drying (*Dryer 2*)

The primary objectives drawn from the data analysis were the determination of the different income level dryers for rural farm level users in terms of product drying time, food hygiene and effectiveness in product drying. From these outcomes, it was possible to present the different options for the user on the dryer choice based on drying times, hygiene levels and associated costs.

5.2 Testing conditions

The testing of the solar crop dryers was conducted between the months of May and July, close to the winter season in Cape Town. Since the ambient conditions played a role in determining the testing days for the project, sunny day periods with minimal cloud cover and no rain were chosen for testing. Performances of solar dryers are more favourable in the summer season due to high solar radiation levels and very high temperatures unlike in the winter season were these parameters are low.

5.3 Ambient conditions

Prior to the testing, the weather conditions for the testing site were measured and recorded to show variations during the day. The daily obtained weather conditions for ambient temperature, wind speed and solar irradiation levels at the testing site were measured and recorded. From the weather station, the total irradiance levels during the test days ranged between 120W/m^2 and 600W/m^2, with diffuse radiation ranging between 10W/m^2 and

40W/m^2. The variation of the wind speed was between 0m/s and 6m/s whilst ambient temperatures fluctuated between 15°C and 30°C. The given ambient conditions are an average on the testing days; the actual daily conditions for each specific test will be presented during the result analysis.

5.4 Dryer conditions

The illustration in Figure 5.1 shows the tested solar drying setups used for the project. From the illustration shown, Figure 5.1(a) shows the constructed 1.5m^2 direct solar crop dryer with a forced extraction system (solar powered fans) which will be referred to as *Dryer 1.* Figure 5.1(b) shows the constructed 2m^2 natural ventilation system with no fans in the extraction system referred to as *Dryer 2.* Figure 5.1(c) shows the open sun drying system referred to as the control sample. The test on the different drying setups was done with the same product (bananas and cabbages) under the same conditions of the testing site. The amount of sunlight reflected by a surface without being absorbed differs between materials. This is known as the albedo. This value is around 10 – 25% for green grass and 15 – 25% for concrete. From this it can be noted that the reflected radiation from these surfaces is almost similar hence not having a huge impact on the radiation levels in the crop dryer.

Figure 5.1: Solar crop dryer setup (a) forced extraction dryer (b) natural ventilated dryer and (c) open sun drying

5.5 Dry run tests

5.5.1 Dryer 1

For the dry run test, the crop dryers were tested with no food products inside and the relevant parameters recorded. The temperature was a critical parameter that had to be determined as it played a role in the drying of the food products. In Figure 5.2, the comparison between the ambient conditions and interior air temperatures from dryer 1 on the 5th, 6th and 7th of June is shown. Ambient temperatures between 18°C and 28°C were reached on the test days with a maximum of 28.5°C achieved during midday hours (13:00) on test day 1. On the other hand, dryer air temperatures of between 30°C and 65°C are achieved for the corresponding ambient temperatures. The obtained air temperatures in the dryer were almost 15°C greater than the surrounding temperature in the morning hours

(09:00) with the difference increasing up to 30/35°C during midday hours (13:00). The high temperatures achieved implied high incident energy on the dryer which allowed the tested product to dry faster compared to the control samples with the low ambient temperatures.

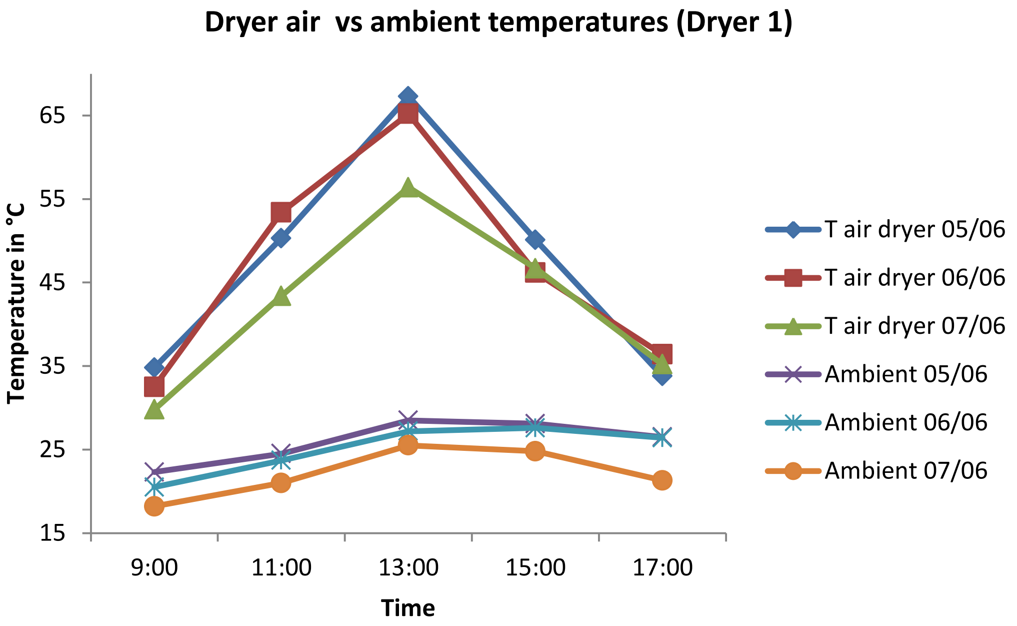


Figure 5.2: Comparison of dryer air temperature and ambient temperature from the 5th to the 7th of June for dryer 1.

During the test, the absorber plate temperatures and the inside wall temperatures were also recorded. The plate temperatures achieved were high ranging above 30°C in the morning to a maximum of 80°C on day 1 of testing.

Figure 5.3 shows the trend of absorber plate temperatures on the 5^{th}, 6^{th} and 7^{th} of June. The wall temperatures were also comparatively high reaching up to 65°C during the test. From the trends, it can be seen that the maximum temperatures are reached mostly during the midday hours around 13:00. In the morning the temperatures were fairly low and gradually increased to a maximum then decreased towards the end of the day. This trend is similar to that of the irradiance levels on the dryer depicting the energy absorbed by the dryer at different time intervals of the day. The temperatures on the sides of the dryer were also recorded i.e. T_{right}, T_{left} and T_{bottom}. The temperatures on these 3 sides did not vary much throughout the test hence for analysis T_{wall} was used, which is average of T_{right}, T_{left} and T_{bottom}.

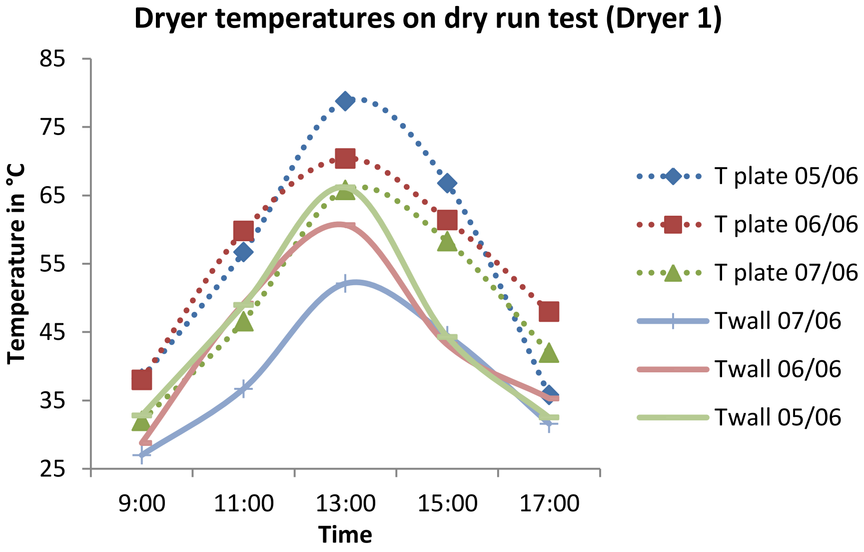


Figure 5.3: Absorber plate and dryer wall temperatures from the 5th to the 7th of June for dryer 1

5.5.2 Dryer 2

For dryer 2 test run, a similar trend to dryer 1 was observed on the results obtained especially the temperatures. Though the temperatures for dryer 2 are a bit lower compared to dryer 1, they were still higher than the ambient temperature. For the test (5^{th} - 7^{th} June), the ambient temperatures were the same for both dryers i.e. between 18°C and 28°C. However, the dryer air temperatures obtained were between 25°C and 60°C as shown in Figure 5.4. The maximum temperatures achieved from dryer differed by approximately 7°C from dryer 1 during this test period.

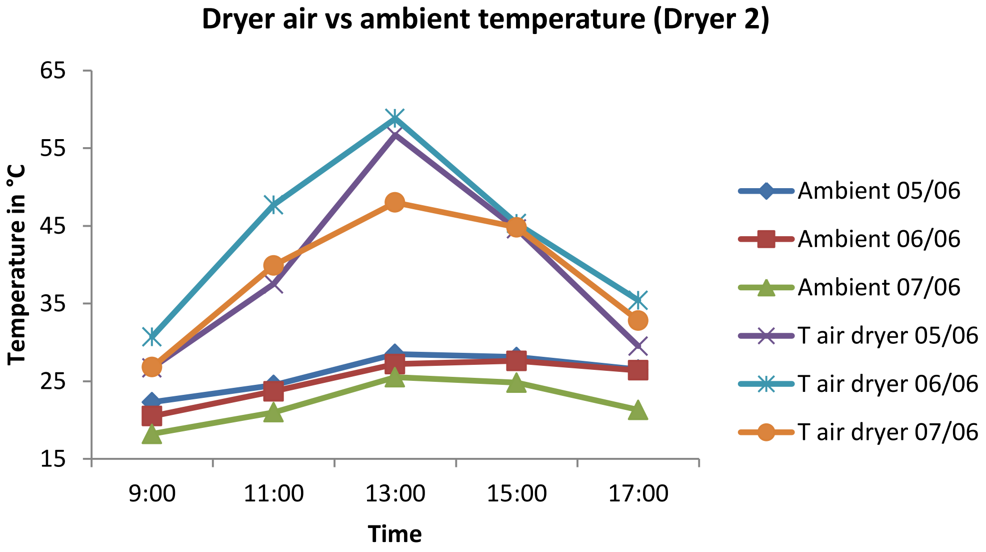


Figure 5.4: Comparison of dryer air temperature and ambient temperature from the 5th to the 7th of June for dryer 2.

Figure 5.5 shows the trend of the absorber plate temperatures obtained from dryer 2 (5th - 7th June). The maximum achieved temperature was approximately 67°C on day 1 of the test. The **T$_{wall}$** for these days was fairly high between 23°C and 51°C.

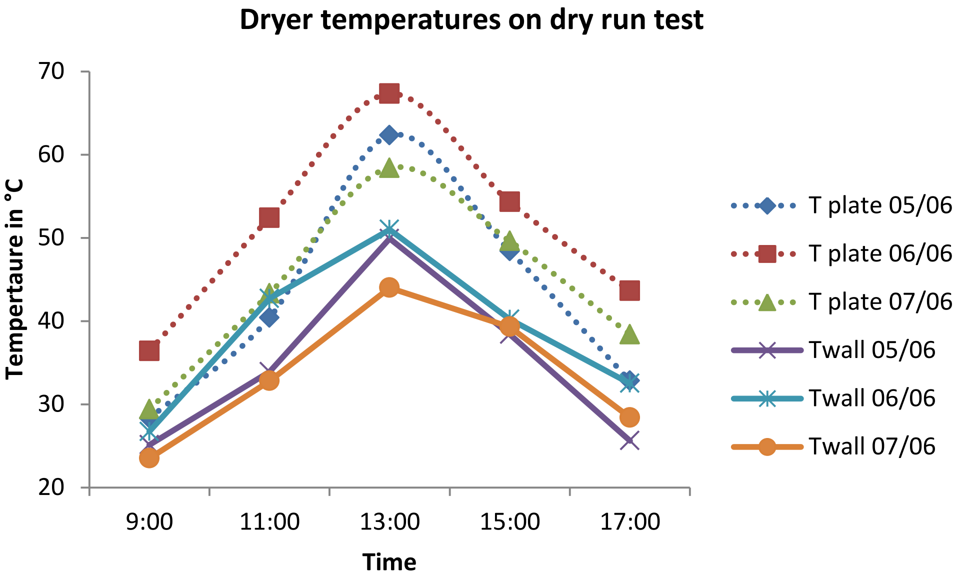
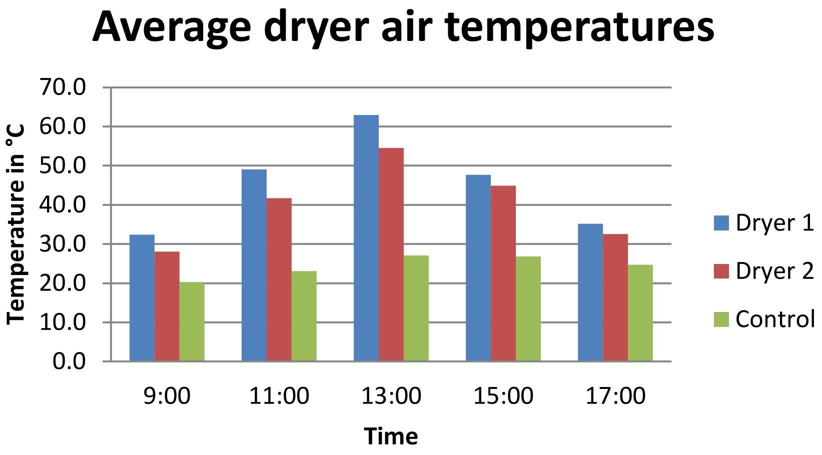


Figure 5.5: Absorber plate and dryer wall temperatures from the 5th to the 7th of June 2018 for dryer 2.

5.5.3 Control sample

As shown in Figure 5.5 during the same test period (5th - 7th June), the ambient temperature remains the same i.e. 18°C and 28°C. A similar trend is seen for the recorded data for the average monthly temperatures shown in Figure 4.8. These are the temperatures that impact the drying of the control sample i.e. open sun drying. The ambient temperatures are fairly low compared to the air temperatures obtained in the other two drying setups explained above. These low temperatures in the open sun drying mean more time is required in drying the food product. Figure 5.6 shows a comparison of the average air temperatures of the 3 drying setups over the 3 day testing period whilst the minimum and maximum air temperatures obtained are shown in table insert on the graph.

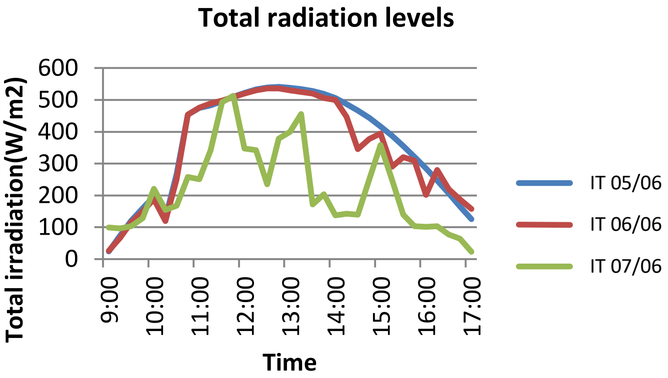


	Max	Min
Dryer 1	67.2	29.4
Dryer 2	59.8	27.4
Control	28.5	18.2

Figure 5.6: Average air temperatures for dryer 1, dryer 2 and control over the testing period from the 5th to the 7th of June and maximum and minimum air temperatures obtained

5.6 Solar irradiation levels

The solar radiation levels from the 5th - 7th of June shown (Figure 5.7) summaries both the total incident radiation as well as the diffuse radiation measured on the respective days. The trends obtained on the radiation levels still resembles and are almost similar to the other dates recorded when the dryers were tested with different products. These values show a resemblance with the recorded data in Figure 4.5 and Figure 4.6 for the average monthly total radiation and average monthly diffuse radiation respectively.



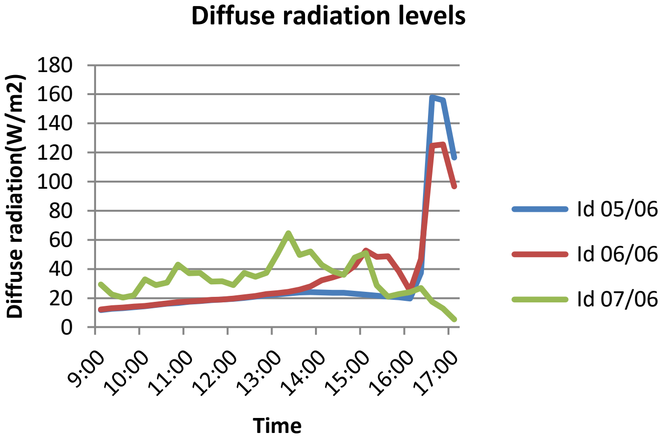


Figure 5.7: Total and diffuse irradiation levels on the 5th to 7th of June

5.7 Wind speeds

The graph below (Figure 5.8) shows the wind speeds variation measured during the dryer testing from the 5th to the 7th of June. These values obtained on these days correspond to the recorded average monthly wind speed shown in Figure 4.10.

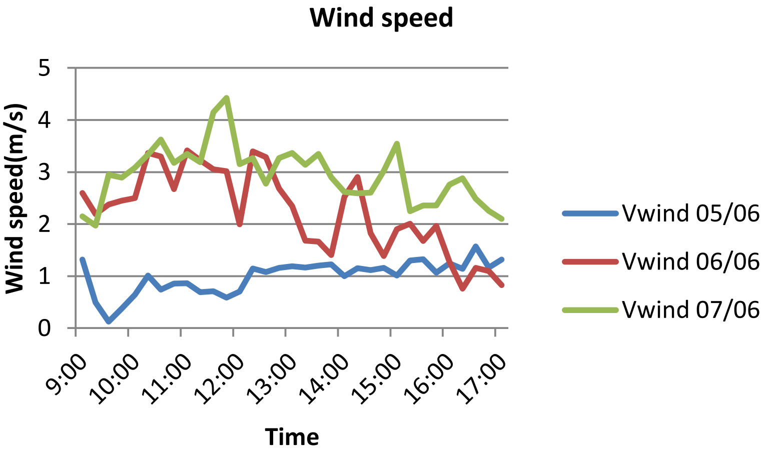


Figure 5.8: Wind speed variations from the 5th to the 7th of June

5.8 Heat gain and loss calculations

Based on the calculations in Appendix D, the incident radiation levels on the solar crop dryers were calculated. Both the incident radiation on the glazing as well as the radiation inside the dryers was calculated. Figure 5.9 summarises some of the heat calculations on one of the testing days.

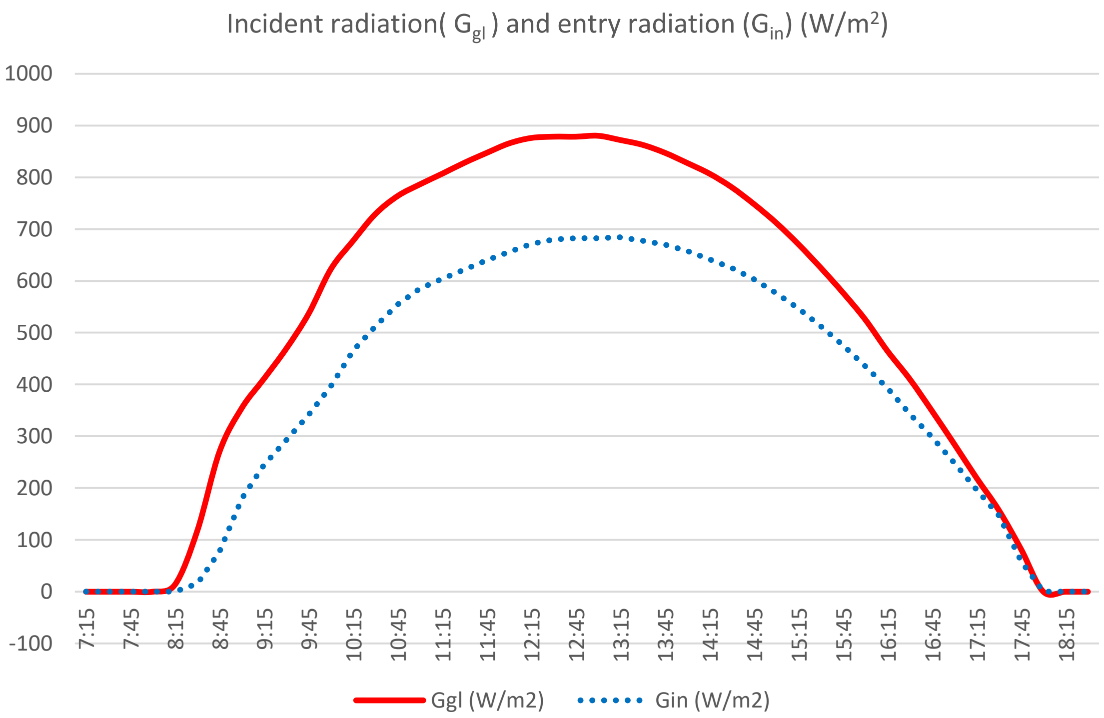


Figure 5.9: Calculated incident and entry irradiation on the glazing

The total incident radiation energy on the glazing material was obtained using the integral of the total radiation on the polycarbonate surface. Figure 5.9 shows the variation of the total incident radiation levels with time on the polycarbonate sheet (glazing) as well as the total radiation inside the crop dryer. Hence from the given trends the total energy the dryer receives at each specific time can be obtained. Using the trapezium rule the total incident radiation on the crop dryers can be obtained as follows:

Hence the total incident radiation in megajoules (MJ) can be obtained as follows

$$\frac{x}{2} \times \left[(h_0 + h_n) + 2\left(\sum h_1 \ldots h_{n-1} \right) \right] \times A_c \times 10^{-6}$$

Where x is the time interval between the h values selected

h denotes the radiation value at a specific time

A_c is the collector area

Given a time interval of 15 minutes which is 900 seconds

Total incident energy (MJ) using G$_{gl}$= $\frac{x}{2} \times [(h_0 + h_n) + 2(\sum h_1 \ldots h_{n-1})] \times A_c \times 10^{-6}$

= $\frac{900}{2} \times [(13.7173 + 81.8863) + 2(\sum 117.3399 + 270.375 + \cdots + 157.893)] \times 1.5 \times 10^{-6}$

= 63.1 MJ

Total entry energy (MJ) using G_{in} = $\frac{x}{2} \times [(h_0 + h_n) + 2(\sum h_1 \dots h_{n-1})] \times A_c \times 10^{-6}$

= $\frac{900}{2} \times [(13.7173 + 81.8863) + 2(\sum 117.3399 + 270.375 + \cdots + 157.893)] \times 1.5 \times 10^{-6}$

= 47.6MJ

5.9 Performance analysis

Given the total entry energy and the total incident energy, the optical efficiency of the dryer can be determined

$$Optical\ efficiency = \frac{Incident\ energy\ in\ the\ dryer}{Incident\ energy\ on\ the\ glazing}$$

$$= \frac{Q_{in}}{Q_{glazing}}$$

$$= \frac{47.6\ MJ}{63.1\ MJ} \times 100$$

= 75.44%

Since the optical efficiency is 75.44% it can be noted that the dryer can convert at least three-quarters of the incident radiation into useful energy in the dryer. Hence the 24.56% of the total incident radiation is reflected by the glazing and lost to the surroundings.

5.10 Sample thickness analysis

5.10.1 Thickness determination

Determination of the appropriate thickness of the banana samples to use was necessary for this test. Figure 5.10 shows the different banana sample thicknesses tested to determine the appropriate and effective size to use in drying including the samples before and after drying. The different thickness sizes (2mm, 4mm, 6mm and 8 mm) were tested and the drying times and final sample textures measured.

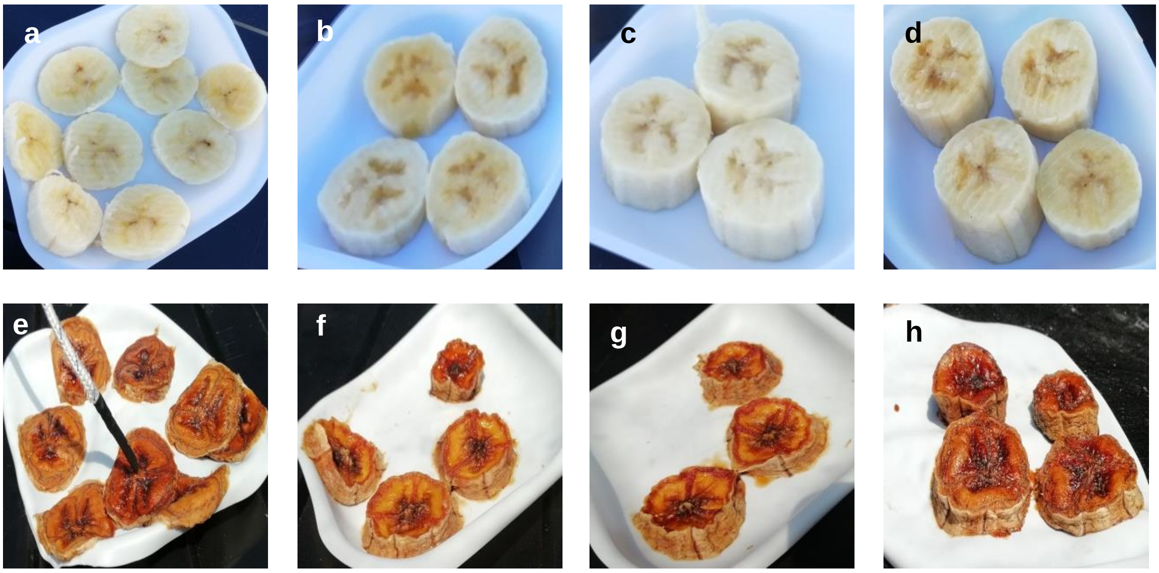


Figure 5.10: Different thickness of banana samples before drying (a-d) and after drying (e-h)

Different thickness sizes of bananas were placed in the solar crop dryer whilst the drying times and final product appearance were monitored. The tested samples (a-d) all recorded losses between 70.59% and 72.02% of their moisture content by the end of the testing day as illustrated in Figure 5.11. The 2mm samples dried fairly quicker than the rest of the samples whilst the 8mm samples took the longest time to dry. Although the 2mm samples dried fast, they crumbled and stuck on the surface of the testing plates. On the other hand, the 8mm samples dried at fairly a slow rate requiring more drying time whilst the 6mm and 4mm samples had an average drying time without crumbling. From the drying trend, it can be seen that all the samples exhibited a similar drying curve with the 2mm samples having a sharper decrease in comparison to the others. Although all samples significantly decreased in weight, the 6mm thick samples proved to provide a better drying time and desirable final outcome of the dried product, hence the thickness (6mm) was chosen for testing done.

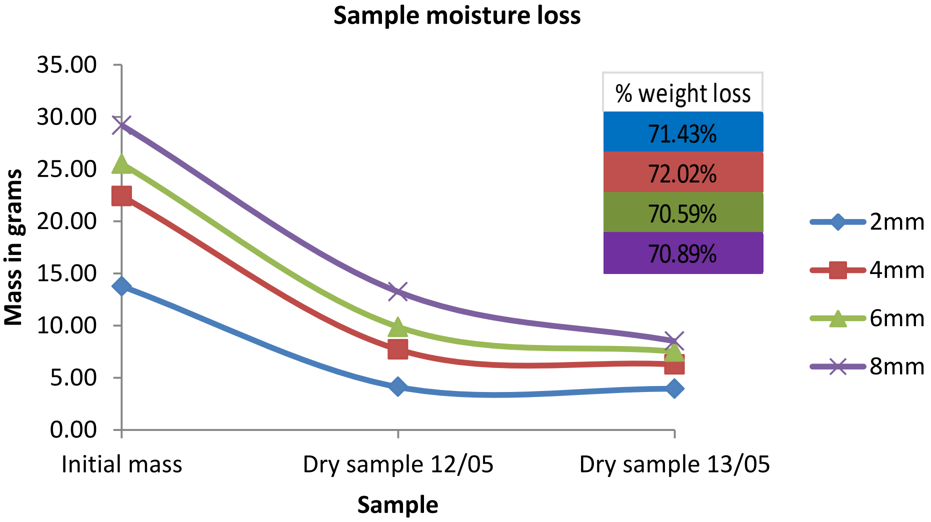


Figure 5.11: Effect of sample thickness on drying

5.10.2 Interior dryer conditions

During the testing phase, the interior and exterior dryer parameters were monitored and recorded. Interior dryer temperatures obtained were high on sunny days with maximum temperatures of up to 80ºC achieved from the dryer. Figure 5.12 and Figure 5.13 shows the average interior dryer temperatures (**T_{plate}, T_{food}, T_{air}, T_{wall}**) obtained on the 14th and 15th of May during an 8 hour test period using the forced extraction dryer 1. In comparison, these interior temperatures ranging between 30°C and 85°C are very high compared to the ambient temperature obtained on the same days (Figure 5.14). Ambient temperatures averaging between 15°C and 28°C have less effect on the drying of the crops (control sample) as compared to the high temperatures reached in the dryers. The very high temperatures obtained on the 14th and 15th of May can be accounted for by the fact that the fan system was not operational. As there is no air flow circulation in the dryer, the setup tends to reach its stagnation point where the temperatures reached will be maximum. Hence to minimise these stagnation temperatures, an airflow system was used to regulate the temperatures and distribute the heat energy in the system as well as assisting in the heat removal process.

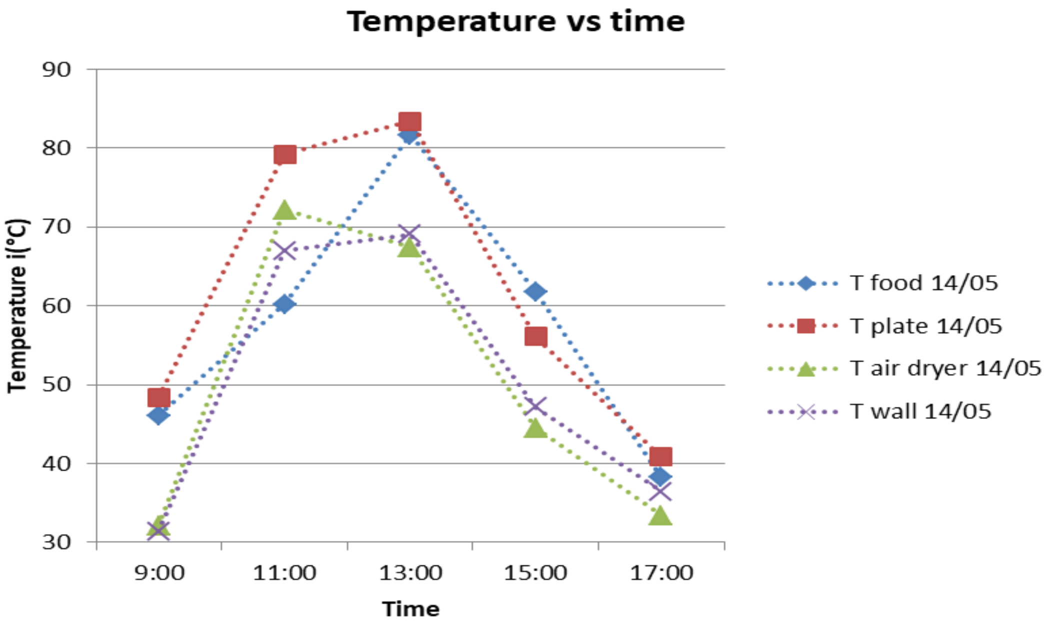


Figure 5.12: Operating interior temperatures of the crop dryer on the 14th May

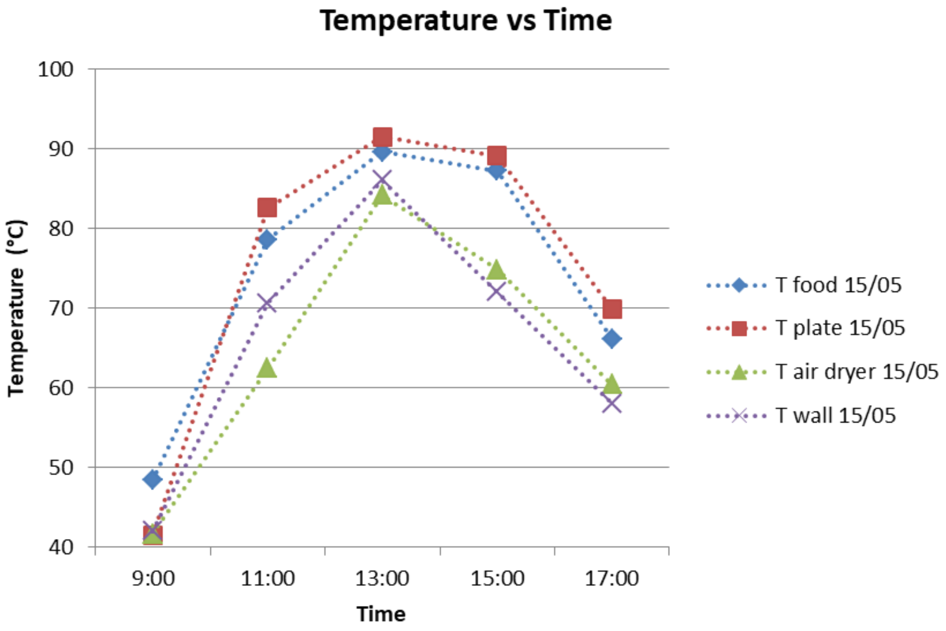


Figure 5.13: Operating interior temperatures of the crop dryer on the 15th May

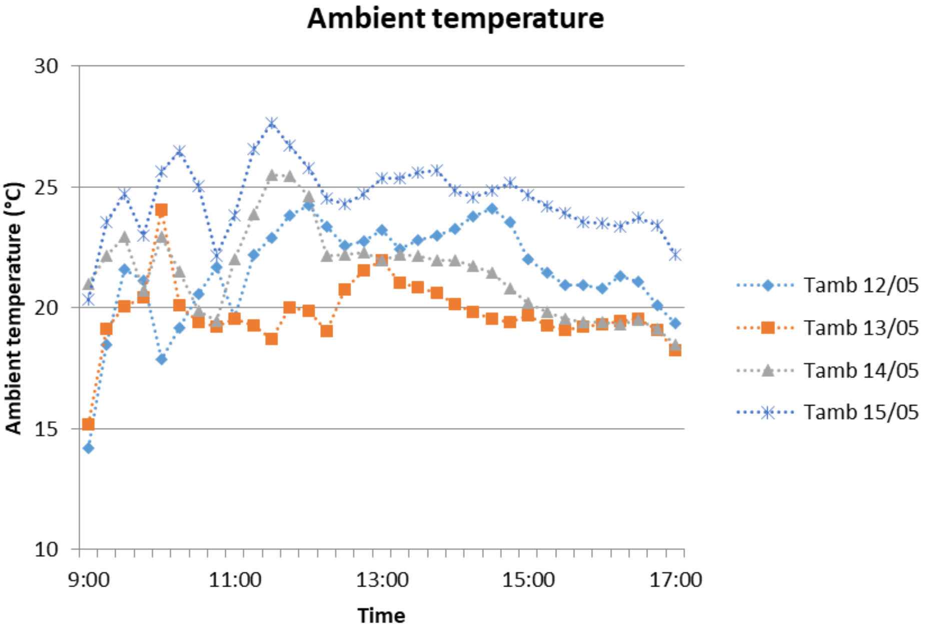


Figure 5.14: Ambient temperature from the weather station during the testing period from the 12th to the 15th of May

The variations of the wind speeds on the same days are shown in Figure 5.15. Maximum wind speeds of around 5m/s were reached on the 13th of May. On some of the days it can be noted that wind speed was very low (even 0m/s) during the early hours of the day. These wind speeds have a direct effect mostly on the open sun drying control sample.

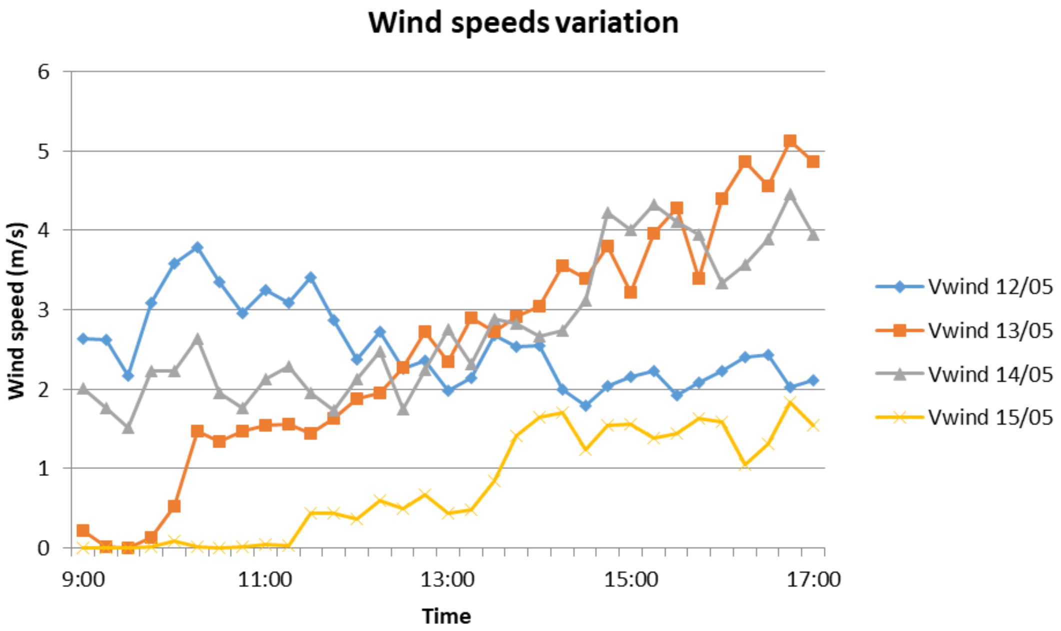


Figure 5.15: Air speeds from the weather station during the testing period from the 12th to the 15th of May

Other testing conditions monitored include the dryer air temperatures and the relative humidity. A temperature and humidity sensor installed on the crop dryer was used to measure the respective parameters. Figure 5.16(a) shows the dryer air temperatures with the corresponding relative humidities shown in Figure 5.16(b). The high temperature obtained in the dryer and the associated low relative humidities present good conditions for the drying of the food products in the dryer. Low relative humidity ensures that the air can hold more moisture lost from the food products before being extracted from the dryer. There is a sharp increase in the ambient temperature on day 2 which indicates a sharp increase also in the air temperatures recorded. The testing was done with the fans not running on these days hence the high temperatures recorded since the air flow in the system was minimal. Corresponding humidity levels were very low i.e. mostly less than 30%, which are preferable as they allow the air to absorb more moisture from the drying products.

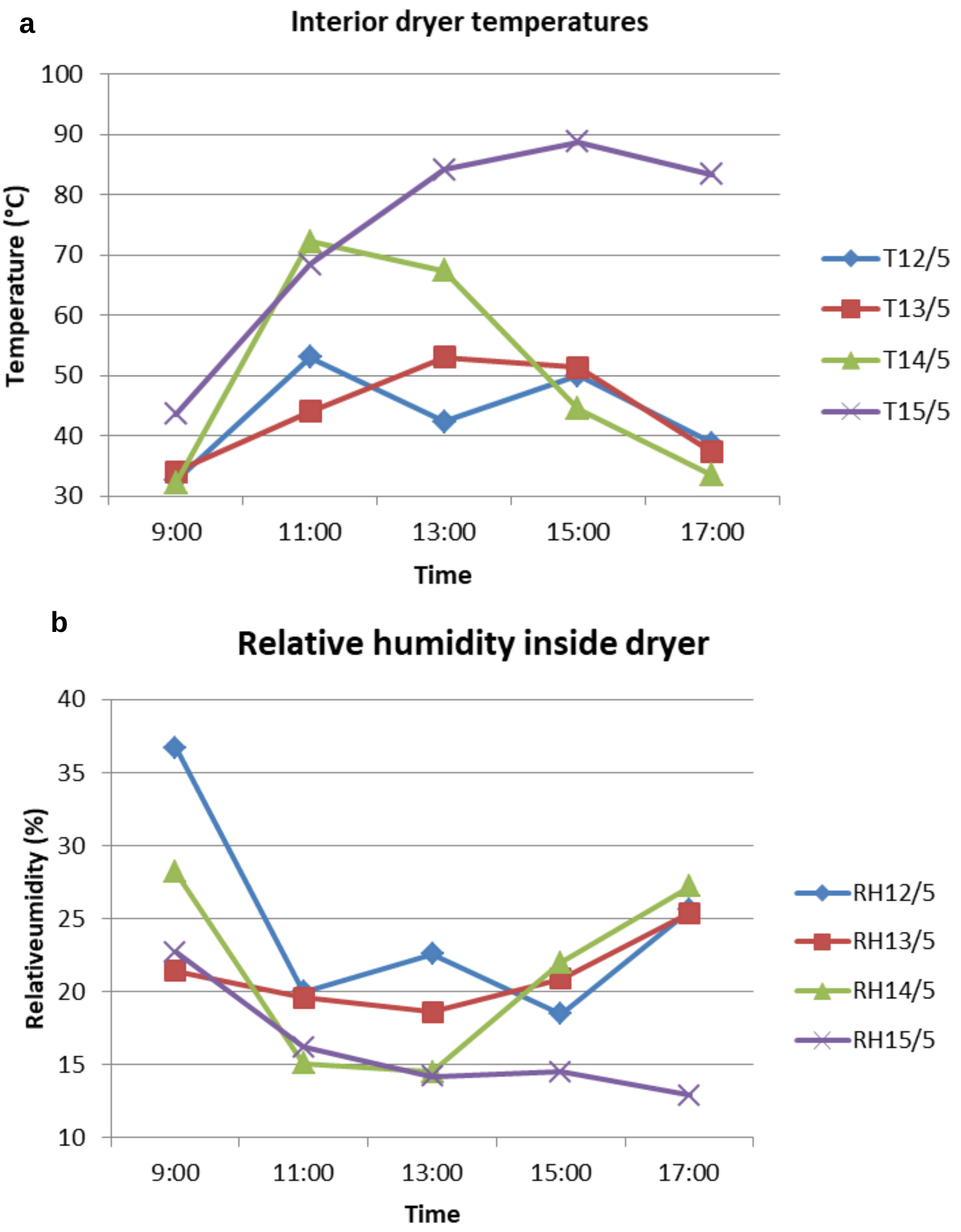


Figure 5.16: (a) Interior dryer air temperatures and (b) relative humidity measured during the testing period from the 12th to the 15th of May

5.10.3 Solar radiation

The solar irradiation levels on the testing days from the 12th to the 15th of May are shown in Figure 5.17 and Figure 5.18.

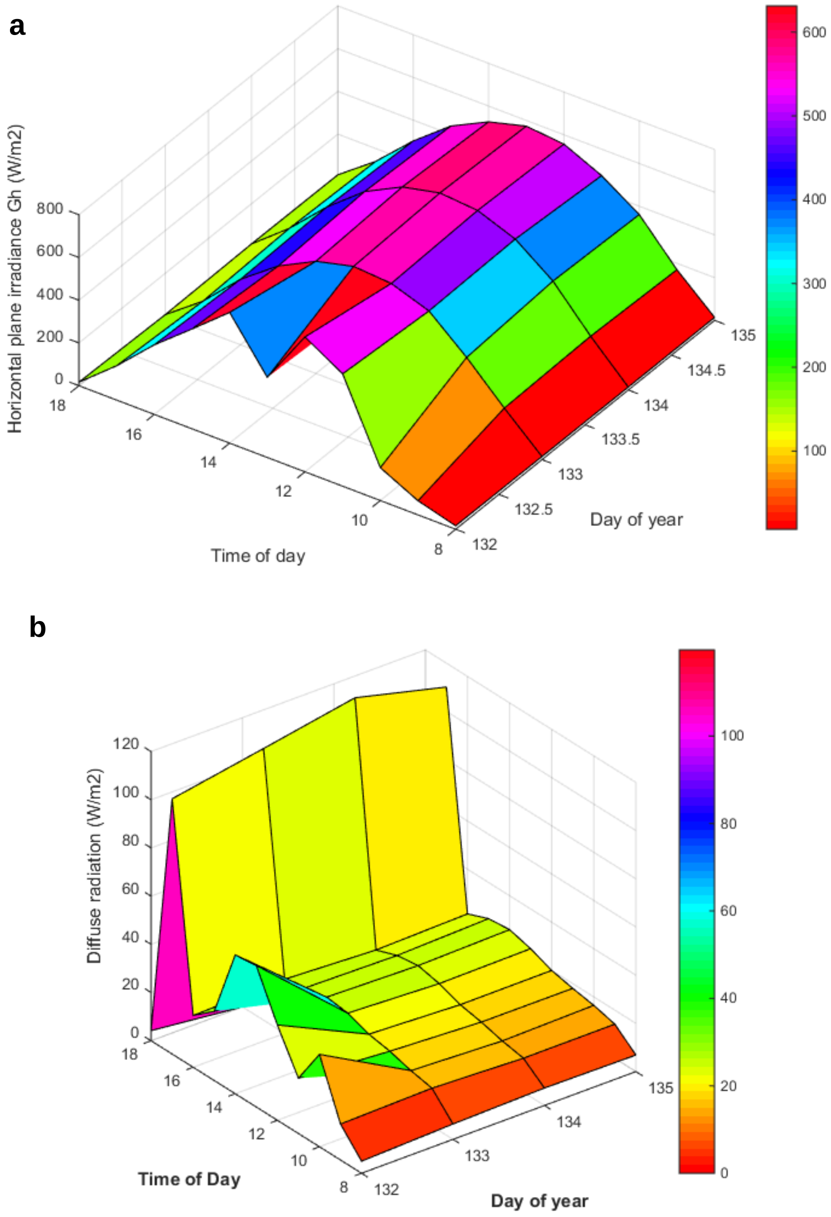


Figure 5.17: (a) Horizontal plane irradiance (Gh) and (b) diffuse radiation measurements obtained during the testing period from the 12th to the 15th of May

The horizontal incident radiation levels produced a similar trend to the temperature curves obtained. As shown in Figure 5.17(a), low irradiation levels values are obtained in the morning and evening periods with peak values during the midday hours. The values of the irradiance ranged between 0W/m^2 and 120W/m^2 during the testing days. The diffuse radiation reaching the solar crop dryer at the testing site is shown in Figure 5.17(b). Same as the incident radiation the morning and evening hours have low radiation levels whilst gradual increases are noticeable during the day hours. The diffuse radiation levels range between 20W/m^2 and 100W/m^2.

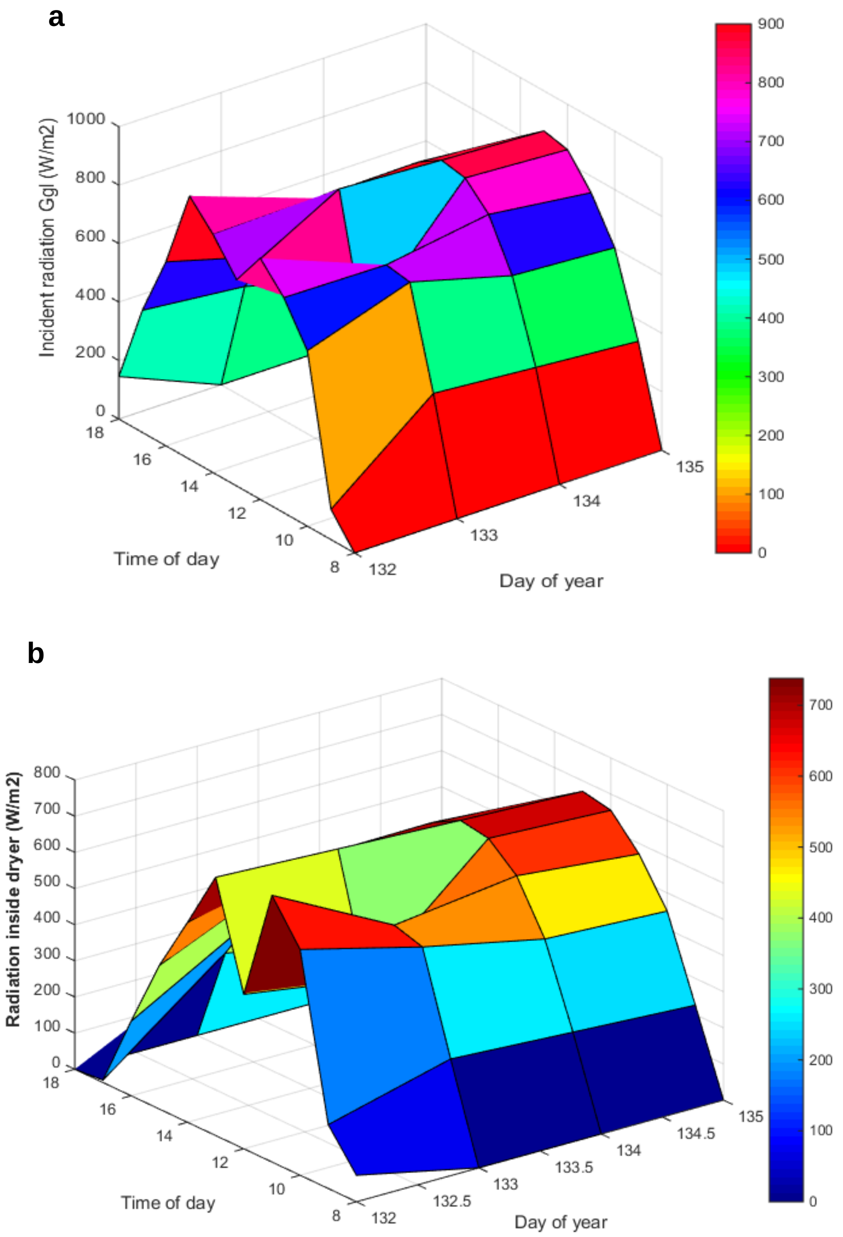


Figure 5.18: (a) Incident radiation (Ggl) measurements obtained and (b) irradiance levels obtained inside the dryer during the testing period from the 12th to the 15th of May

Incident radiation on the glazing for the testing period is shown in Figure 5.18(a) with obtained values up to 800W/m^2 achievable during the testing days. Similarly, incident radiation levels in the dryer of up to 600W/m^2 (Figure 5.18(b)) were obtained inside the crop dryers. There is a resemblance to the radiation trends on all the testing days. From the analysis of the irradiation levels, it can be seen that the testing days had good radiation levels suitable for testing the product.

Furthermore, on the 15th of May, different random samples of bananas were weighed and placed in crop dryer 1 to determine the average weight loss. Different banana samples ranging between 20g and 41g were dried in dryer 1. The samples were allowed to dry from

0900 to 1700 before the dried samples weights were recorded. The loss in weight for each sample is shown in Table 5.1 together with the respective percentage weight losses. There was a significant loss in weight for almost all the samples ranging between 70.1% and 76.86% with an average loss of 74.19%. From the overall wet samples mass (221.8g), a final mass of 58.067g was obtained meaning a 163.733g (73.82%) weight loss. Based on the tests done it was noticed that the weight loss from the banana was usually between 70 and 77%.

Table 5.1: Weight loss of banana samples on the 15th of May

Sample	Wet sample mass	Dry sample mass	Weight loss	% loss (w.b)
1	20.600	5.200	15.400	74.76%
2	21.967	5.833	16.133	73.44%
3	31.533	7.733	23.800	75.48%
4	30.767	7.733	23.033	74.86%
5	20.400	4.733	15.667	76.80%
6	23.700	5.667	18.033	76.09%
7	40.900	12.200	28.700	70.17%
8	31.933	8.967	22.967	71.92%
Overall	221.800	58.067	163.733	73.82%

5.11 Preliminary banana 1kg test using dryer 1

Figure 5.19: Banana samples dried using a forced extraction crop dryer

On the 29th of May, a preliminary test was done to determine the drying parameters and weight loss of a 1kg of bananas using dryer 1 as shown in Figure 5.19. An overall sample weight of 1.0772kg was placed in the crop dryer and dried. During the test time from 09:00 to 17:00 the samples were then reweighed, dried again until a constant mass of the products was reached. At the end of testing day 1, the dry sample weight obtained was 0.2948kg - indicating a weight loss of 0.7824kg over the 8 hour testing period (Figure 5.20). This showed a wet basis weight loss of 72.63%. On average the drying rate for the banana sample was approximately 0.097kg/hr (0.027167kg/s). The control sample during this experiment was blown away by the wind since there were no supports placed on the testing surface. Hence no data is available for the control sample.

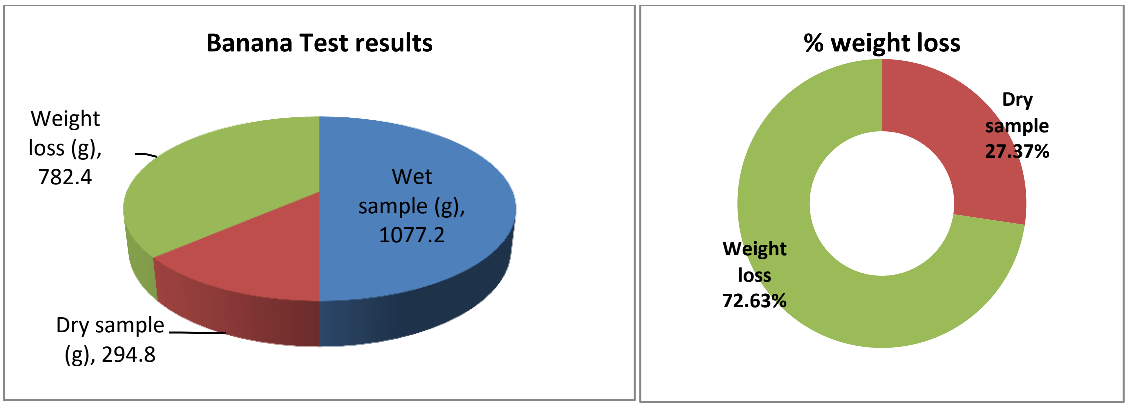


Figure 5.20: Weight losses analysis of the banana samples

Minimum constant mass of bananas achieved at 70% implies that for the tested sample (0.7 x 1.0772kg) = 0.754kg was lost. For the maximum weight loss at 77% implies that a total weight of (0.77 x 1.0772kg) = 0.829kg were lost. Average weight loss based on the measured parameters is (0.7419 x 1.0772kg) = 0.7992kg. Hence from this analysis, it can be seen that the actually achieved water loss from the bananas ranges between 0.754kg and 0.829kg i.e. 70% and 77% losses as the lower and upper limits respectively.

5.12 Banana samples testing - 2kg test

The 6mm thickness was used as the standard for the testing of the bananas in the 3 dryer setups. 2kg samples of bananas were tested in both dryer 1 and 2 whilst a control sample of 1kg was used. For dryer 1 and 2 the same sample mass was used since the setups are closed systems within a controlled space. Due to the enclosures in the dryers, the conditions inside the dryers vary depending on the conditions the dryers are exposed to. Having the same samples makes it easy to assess the impact of the different parameters of the two dryers. As for the control sample, since it is an open system and the ambient conditions are the same on the whole testing area, any sample mass can be used for testing as long as the sample areas size correlates i.e. the ratio of area covered is similar. Figure 5.21 shows the dryer setup used for testing the bananas from the 11th of June. As shown (Figure 5.21), the comparison was done for the banana samples under the same conditions at the testing site.

The dryer 1 depicts the forced air drying system in which the air is circulated in the system by the solar powered fans. It consists of 4 small fans that extract the air out of the system aiding in the moisture removal process and air circulation. The control samples can be seen in Figure 5.21(a) next to dryer 1. Typical in rural setups the products can be placed directly on the ground, pavements or makeshift trays. For this project, the bananas are placed on a plastic surface to allow ease of carrying the products for weighing. The dryer 2 Figure 5.21(b) shows the natural convection dryer (with no fan system). The amount of sunlight reflected by a surface without being absorbed differs with the material. This is known as the albedo. This value is around 10 – 25% for green grass and 15 – 25% for concrete. From this it can be noted that the reflected radiation from these surfaces is almost similar hence not having a huge impact on the radiation levels in the crop dryer.

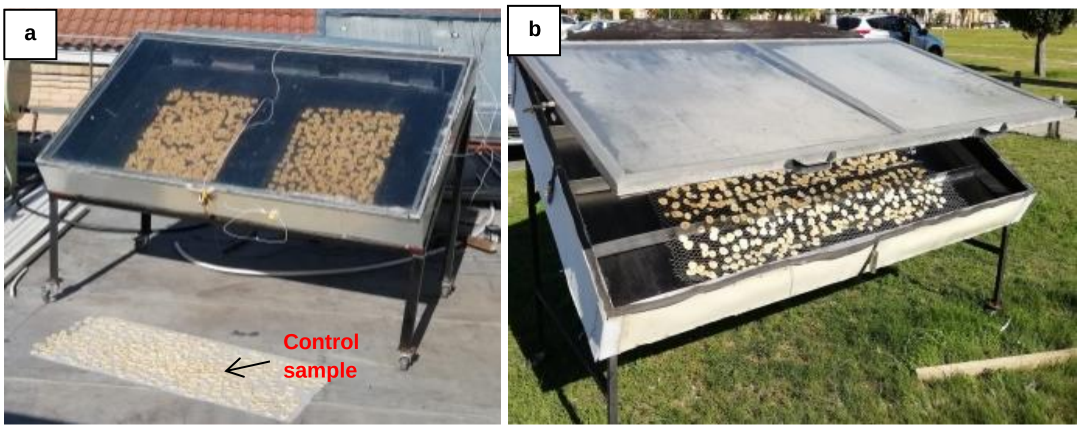


Figure 5.21: Dryer setups for the tested banana sample (a) 1.5m^2 forced convention dryer, open-air sun drying control sample (b) 2m^2 natural convection dryer.

The weight loss from the three different dryer setups was recorded over a 7 day test period. The testing was conducted until a constant mass was reached for each testing sample. From the test, the weight loses obtained from the different samples are shown in Figure 5.22. For dryer 1, a weight loss of 1.1582kg was recorded on the first day with a further loss of 0.2904kg on the second day. For the remainder of the days, a constant mass was observed for the samples. For the dryer 2, the mass loss was 0.8192kg on day 1, 0.3828kg and 0.2234kg on day 2 and 3 respectively. A further decrease in the weight of 0.0209kg was observed on day 4 before the mass became constant. For the control samples, a 1kg sample was used. On day 1, a weight loss of 0.3368kg with a further loss of 0.1759kg and 0.1075kg on day 2 and 3 respectively. The testing continued for a further few days in which significant weight losses can be seen from the samples. Weight losses of 0.0622kg and 0.0342kg are recorded on day 4 and 5 of the testing.

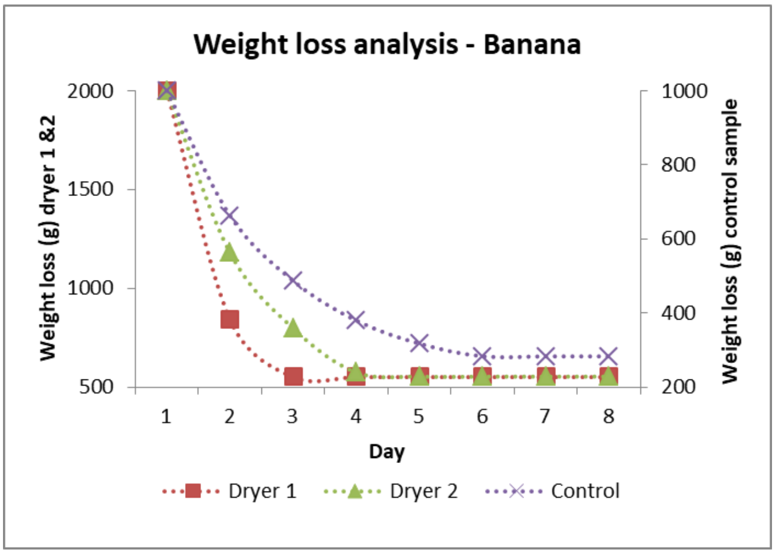


Figure 5.22: Weight loss for banana drying from the 11th to the 15th of June

A similar trend is observed in the drying pattern of the different samples. In both tests, the bulk of the weight decrease of the samples is noticed in the first 2 test days. On day 1, weight losses of between 33.68% and 57.91% are recorded for the drying setups. Figure 5.23 also summarises the daily percentage weight loss from each dryer setup after testing.

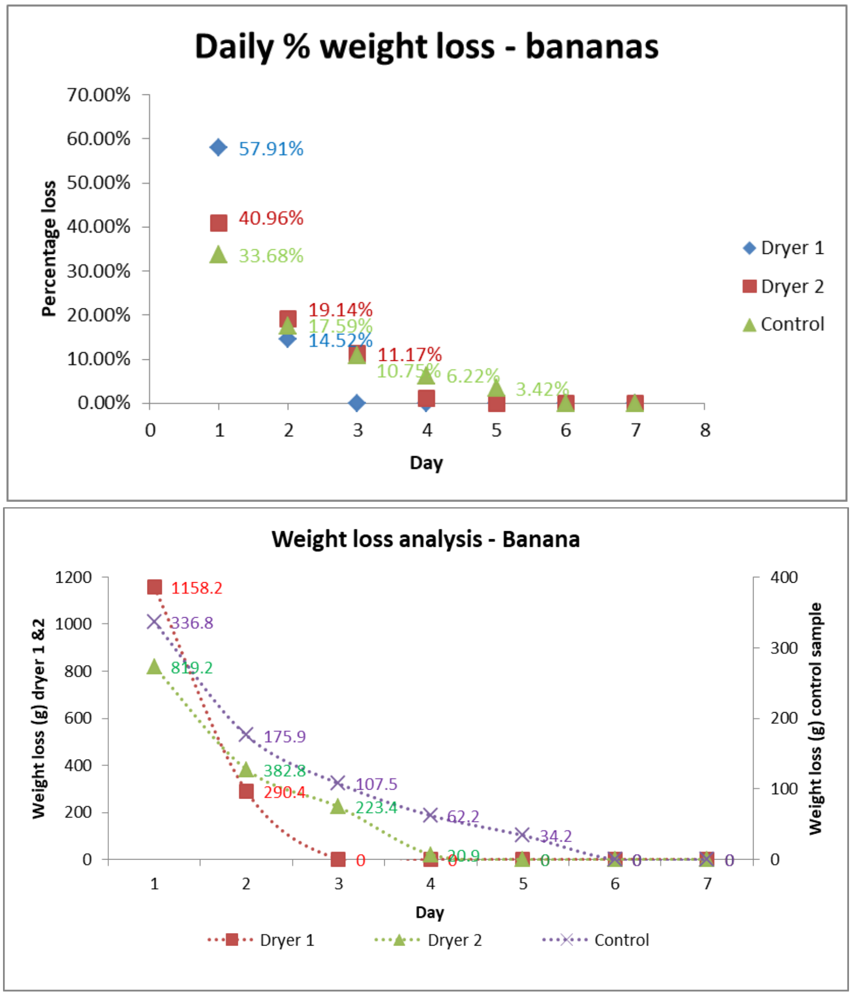


Figure 5.23: Daily percentage and actual weight loss of test for drying bananas during test period 11th to 15th June

From the results obtained, it can be seen that the banana dried quickly in dryer 1 (forced extraction system), followed by dryer 2 (natural ventilated system) then lastly the control sample (open sun drying). On day 1 the weight loss for dryer 1 was 57.91% compared to 40.96% and 33.68% for dryer 2 and the control respectively. Based on the losses for the day 1 i.e. over an 8 hour period of drying, the average drying rates for the dryer setups were as follows: 0.1448kg/hr for the forced extraction drying, 0.1024kg/hr for natural ventilation drying and 0.0421kg/hr for the open sun drying. Furthermore by day 2 the dry rates had decreased to 0.0363kg/h, 0.04785kg/hr and 0.021.9875kg/hr for the 3 systems respectively. The forced extraction drying dried the bananas within just over a day; whilst the natural ventilation required at most two days and the open sun drying prolonged the process even after the 4 testing days. The prolonged drying for the open sun drying can be on account of weather and also reabsorption of moisture by the product at night periods due to no enclosure in the system. The recorded temperatures on the testing days are summarised in Table 5.2.

Table 5.2: Temperatures recorded during the banana tests

11-Jun	**Dryer 1 - 1.5m^2**			**Dryer 2 - 2m^2**			**Control**	
Time	T_{food}	T_{plate}	$T_{air\ dryer}$	T_{food}	T_{plate}	$T_{air\ dryer}$	$T_{ambient}$	T_{food}
9:00	28.5	44.5	36	30.4	38.5	34.5	22.4	21.5
11:00	53.7	65.5	56	36.4	44.5	42	25.9	24.7
13:00	46.5	60.6	52.7	42.4	48	45.6	29.8	29.3
15:00	43.5	52.4	44.8	36	40.2	37.4	27.5	27.3
17:00	27	32.5	30.5	29.3	30.3	28.3	23.4	24.2
12-Jun	**Dryer 1 - 1.5m^2**			**Dryer 2 - 2m^2**			**Control**	
Time	T_{food}	T_{plate}	$T_{air\ dryer}$	T_{food}	T_{plate}	$T_{air\ dryer}$	$T_{ambient}$	T_{food}
9:00	31.4	39.6	33.7	39.6	34.6	32.3	20.7	19.6
11:00	42.6	44.8	42.7	36.8	42.8	39.6	23.1	17.3
13:00	66.4	60.2	51.8	40.6	48.9	44.3	28.7	31.4
15:00	44	41.1	42.6	36.6	41.4	38.7	27.8	24.4
17:00	35	32.3	31.4	29.4	31.2	30.8	26.4	23.8

5.13 Cabbage trial test

After testing the banana samples, new samples of vegetables were tested in the same dryers used for the previous test. Cabbage was used as a test sample as it is easily available and is mostly used in many dietary requirements. For the sample run, two cabbage samples were dried using the same procedure used for the bananas using dryer 1(forced ventilation). The same test procedure was used in which a known weight sample is placed in the dryer and the final constant weight determined whilst the interior and exterior dryer conditions were monitored.

A test was conducted with cabbage sample, one that was not blanched and the other which was blanched cabbage samples. This was to compare the difference in the drying of the two as well as the final product produced. Water blanching was used in which the samples were boiled in hot water for approximately 5 mins before being rapidly cooled to stop the enzyme activities in the food samples. Once the process was completed both samples (blanched and unblanched) were placed in the crop dryer and monitored during the testing period. An unblanched cabbage sample mass of 0.3344kg and a 0.3512kg blanched cabbage sample were both placed in drying trays. For the blanched sample, 0.3388kg of cabbage was boiled for 5 minutes before rapidly cooled. The samples were placed in the dryer at 1130 and the following weights were obtained at the end of the testing day by 1600: unblanched samples 0.0683kg and blanched cabbage 0.0297kg.

From the dried samples obtained it was noted that the weight loss on day 1 for the blanched cabbage was 91.54% whilst that of the unblanched cabbage was 79.58%. A further 10.2% was noticed on the unblanched cabbage on day 2 whilst the blanched cabbage maintained a constant weight. Figure 5.24 shows the trend in the weight loss of the tested cabbage samples. The percentage water content of cabbage is around 92%. From the results obtained it can be noted that the blanched sample completely dried on day 1 whilst the unblanched sample required a section of day 2.

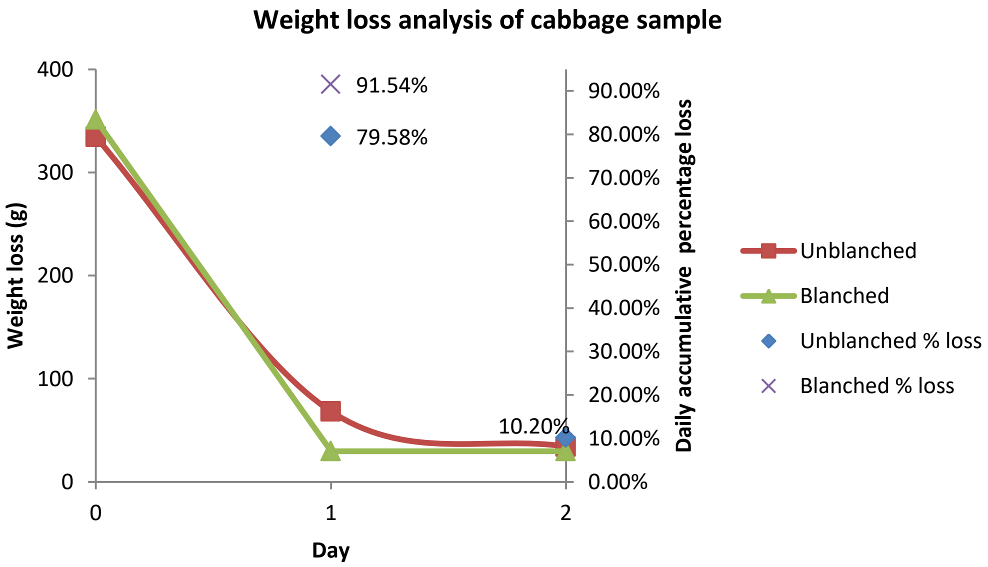


Figure 5.24: Weight loss of tested blanched and unblanched cabbage samples

On average the drying rate for the cabbage samples was approximately 0.07144kg/hr and 0.05913kg/hr for the blanched and unblanched samples respectively over the 4.5 hour testing period. As seen from this analysis it can be seen that the blanched cabbage dries at a faster rate compared to the unblanched sampled. The texture and quality of the final products obtained is a bit different as the unblanched sample did maintain its greenish cabbage colour. The corresponding dryer temperatures can be seen in Figure 5.25. The temperature in the dryer ranged between 39.5°C and 64.4°C for the interior dryer temperatures measured.

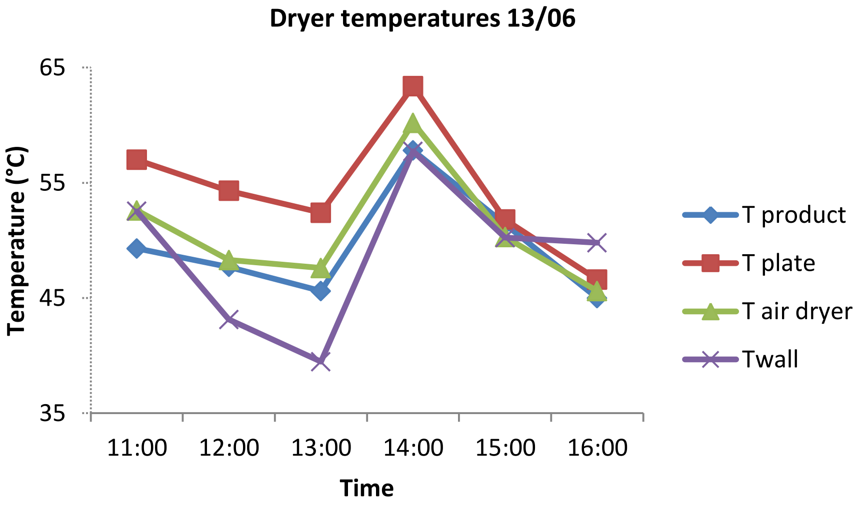


Figure 5.25: Temperature variations in dryer 1 for cabbage test on 13/06

5.14 Cabbage Test

For the cabbage test, the same procedure used in the testing of the bananas was used. The cabbage samples were tested in the three different drying setups i.e. natural ventilated closed dryer (Dryer 2), forced extraction closed dryer (Dryer 1) and open sun drying system (control). For the samples tested both the blanched and unblanched cabbage were used. For each test done a cabbage head cut in half was used as a sample size and the average weight for each was around 0.610kg ± 0.005kg. The sample size was made similar only for testing purpose to ensure that equal sample sizes were used for easier and fair analysis of the results. The cabbage test samples weight losses from the three different dryer setups are shown in the following figures over a 7 day testing period. The testing was conducted until a constant mass was reached for each of the samples tested.

5.14.1 Unblanched cabbage sample

Figure 5.26 shows the measured and recorded weight loss of the cabbage samples (unblanched). The sample sizes used for the testing were 0.610kg ± 0.005kg and the actual weights used for each sample are shown in Table 5.3. The weight losses trend of the tested samples is shown in Figure 5.27 for the unblanched cabbage. The samples from dryer 1 dried fairly faster compared to the rest of the samples. For dryer 1 the initial recorded wet mass was 0.6068kg. At the end of day 1, a weight loss of 0.3978kg was observed on the cabbage samples with a further decrease of 0.1623kg on day 2. For dryer 2 the samples exhibited almost a similar trend. Weight losses of 0.1862kg, 0.2293kg,0.1304kg and 0.0159kg were recorded on day 1,2,3 and 4 respectively before a constant mass was reached. As for the control sample (wet mass 0.6055kg), a slightly different trend was noted. Weight losses of 0.2215kg, 0.1313kg, 0.1024kg and 0.0531kg were recorded on the first 4 testing days and a slight decrease in weight was noticed in the further 3 days.

Table 5.3: Moisture loss analyses of dried cabbage samples

Day	0	1	2	3	4	5	6	7
Dryer 1	606.8	209	46.7	46.7	46.7	46.7	46.7	46.7
Dryer 2	610	423.8	194.5	64.1	48.2	48.2	48.2	48.2
Control	605.5	384	252.7	150.3	97.2	63.4	55.4	49.3

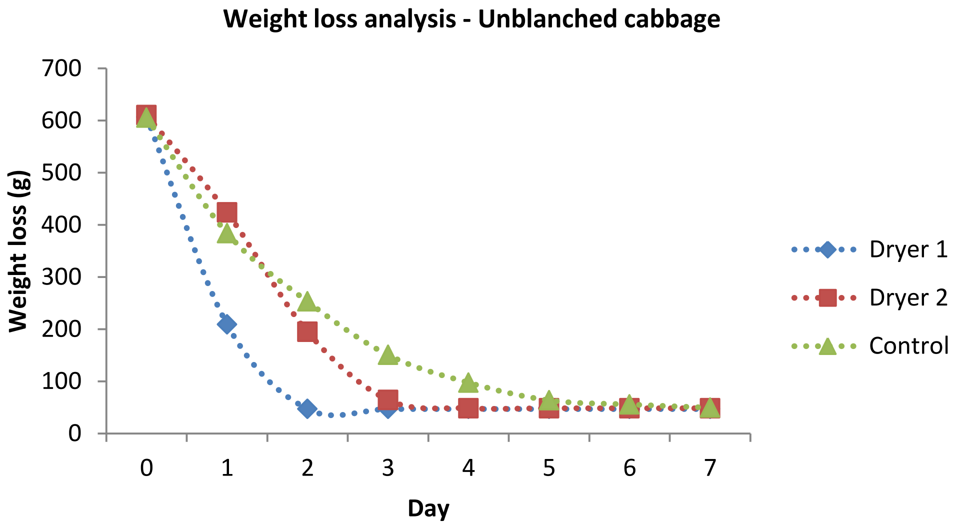


Figure 5.26: Unblanched cabbage weight lost from test days 4th to the 10th of July

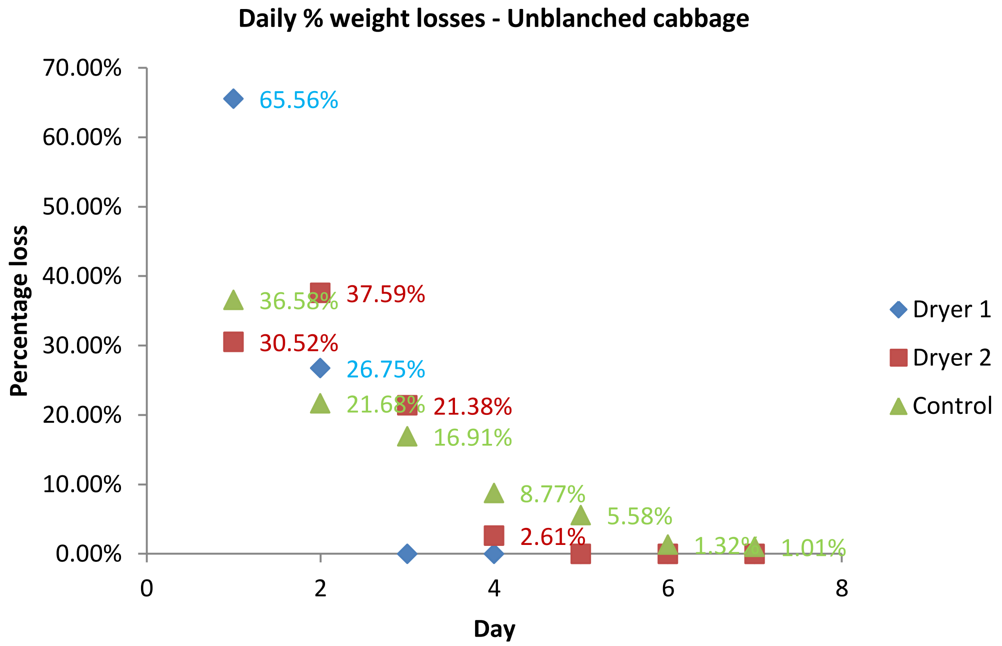


Figure 5.27: Unblanched cabbage daily percentage weight lost from test days 4th to the 10th of July

5.14.2 Blanched cabbage sample

Figure 5.28 shows the daily percentage loss of the samples during the test period. From the analyses the dryer 1 sample dried in at least 2 days, for dryer 2 the sample dried in less than 4 days whilst the control sample took up to 7 days to dry. Dryer 1 shows high percentage weight loss on the first 2 days (65.65% and 26%) showcasing high drying rates of the samples on the respective days. Dryer 2 showed fairly consistent weight loss over the first 3 days. The control sample dried gradually at a slow rate during the testing days. This was accounted for by the reabsorption of the moisture by the samples during the morning period as they were no enclosures in the system. These samples varied with the previous one in the pre-treatment method done before drying. The same drying procedure was used and the following results were obtained. Shown in Figure 5.28 is the weight losses recorded for the tested samples. Dryer 1 sample had a weight loss of 0.467kg and 0.0965kg in the first two days of drying compared to 0.2595kg, 0.2078kg and 0.0964kg for the samples in dryer 2 in the first 3 testing days. For the control samples, the weight losses of 0.2441kg, 0.1478kg, 0.1424kg and 0.0211kg were noticeable on the tested days. Further small noticeable changes were still observed on the control samples in the further 3 to 4 days.

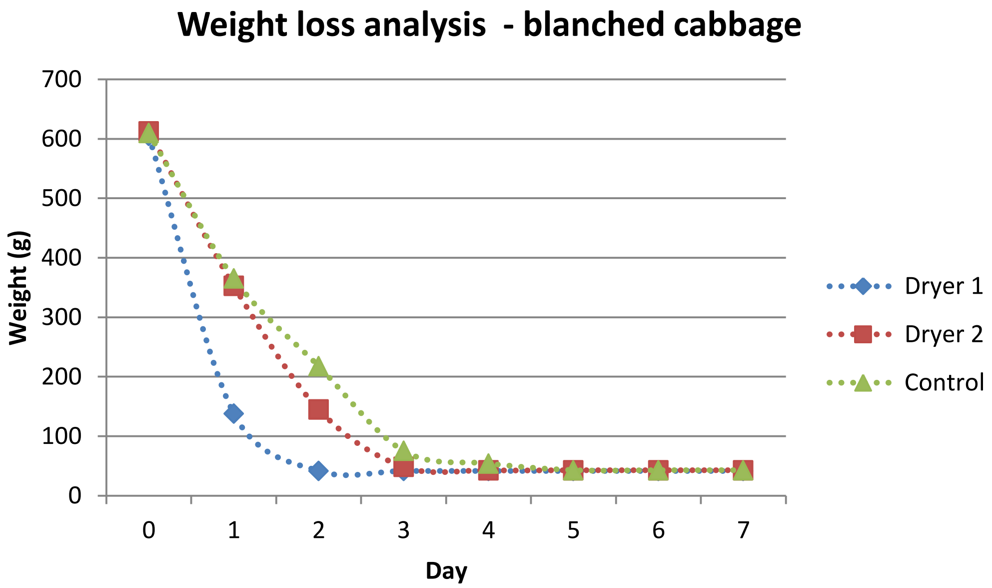


Figure 5.28: Blanched cabbage weight lost from test days 4th to the 10th of July

Similarly to the unblanched cabbage samples, it can still be noticed that the dryer 1 has the highest and fastest drying rates as compared to the dryer 2 and control samples.

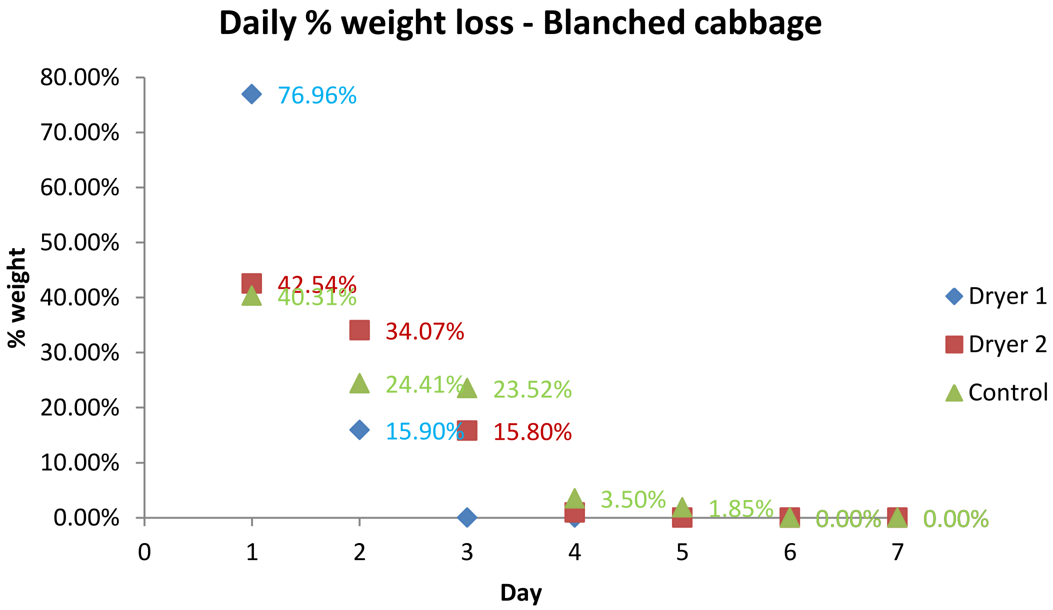


Figure 5.29: Blanched cabbage daily percentage weight lost from test days 4th to the 10th of July

The same drying pattern noticed from the unblanched samples can be seen from the blanched samples also. The major noticeable difference is that the blanched sample dried at a very high rate compared to to the unblanched samples due to the difference in the pre-treatment procedures. Figure 5.29 shows the daily weight losses obtained from the actual dried samples over the test period from the 4^{th} to the 10^{th} of July.

5.14.3 Interior dryer conditions

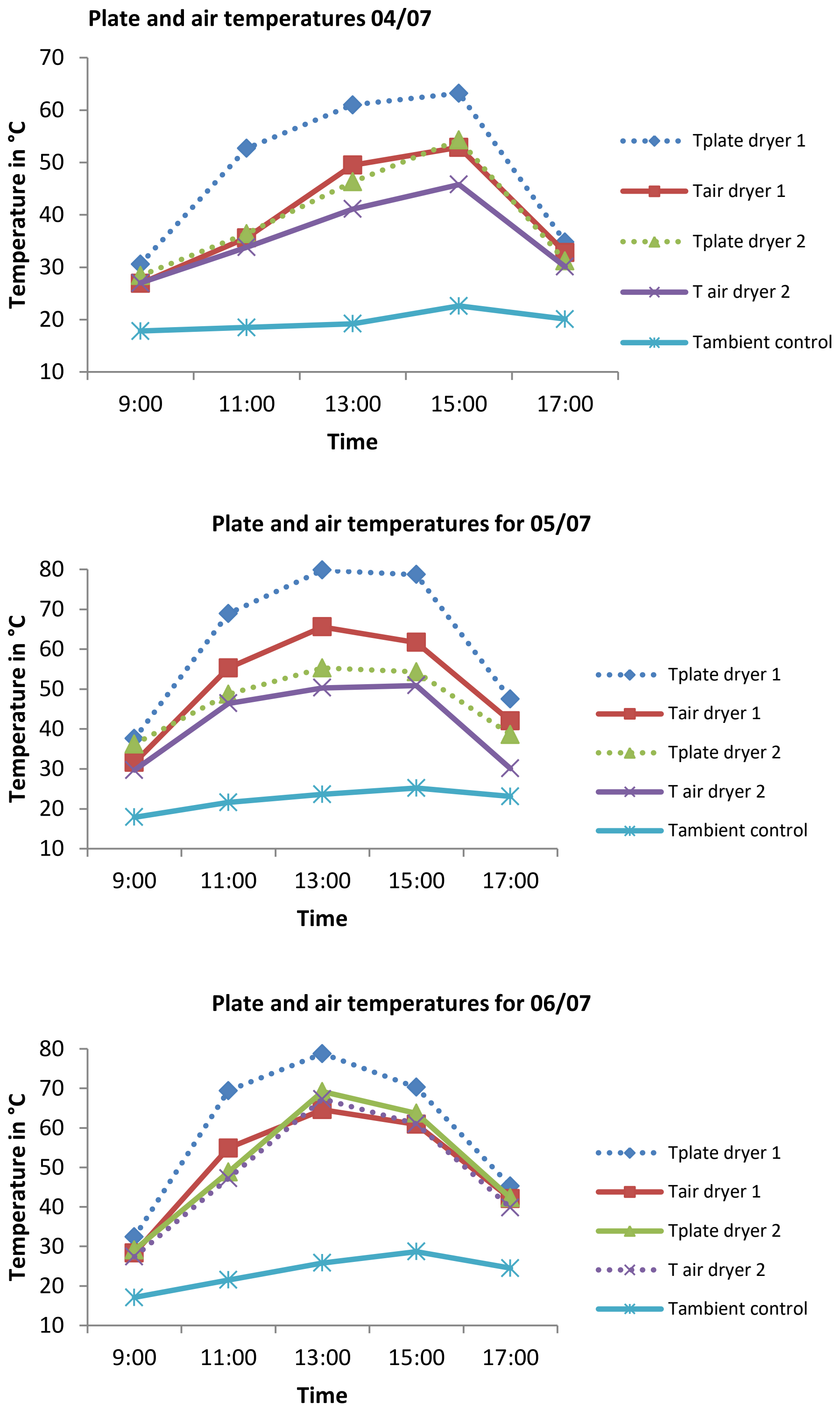


Figure 5.30: Plate and air temperatures for the dryers on from the 4th to the 6th of July

From the analysis of the weather condition at the testing site, it can be noted that the obtained interior temperatures in the dryer surpass the ambient temperatures. For the 3 testing days shown in Figure 5.30, it can be noted that the temperatures obtained are low ranging between 17°C and 28°C. The average temperature over the days is around 21.8°C.

The high plate temperatures in the dryer influence the high air temperatures obtained in the dryer and Figure 5.30 shows the typical temperatures achievable in the dryers. For the forced ventilation dryer 1 temperature ranges are between 30°C and 80°C whilst the ones obtained in dryer 2 ranging between 28°C and 69°C for the plate temperatures. These plate temperatures correspond to the high air temperatures obtained for the air temperatures respectively hence ensuring the fast drying of the products in dryer 1 and 2 compared to the open sun drying control samples.

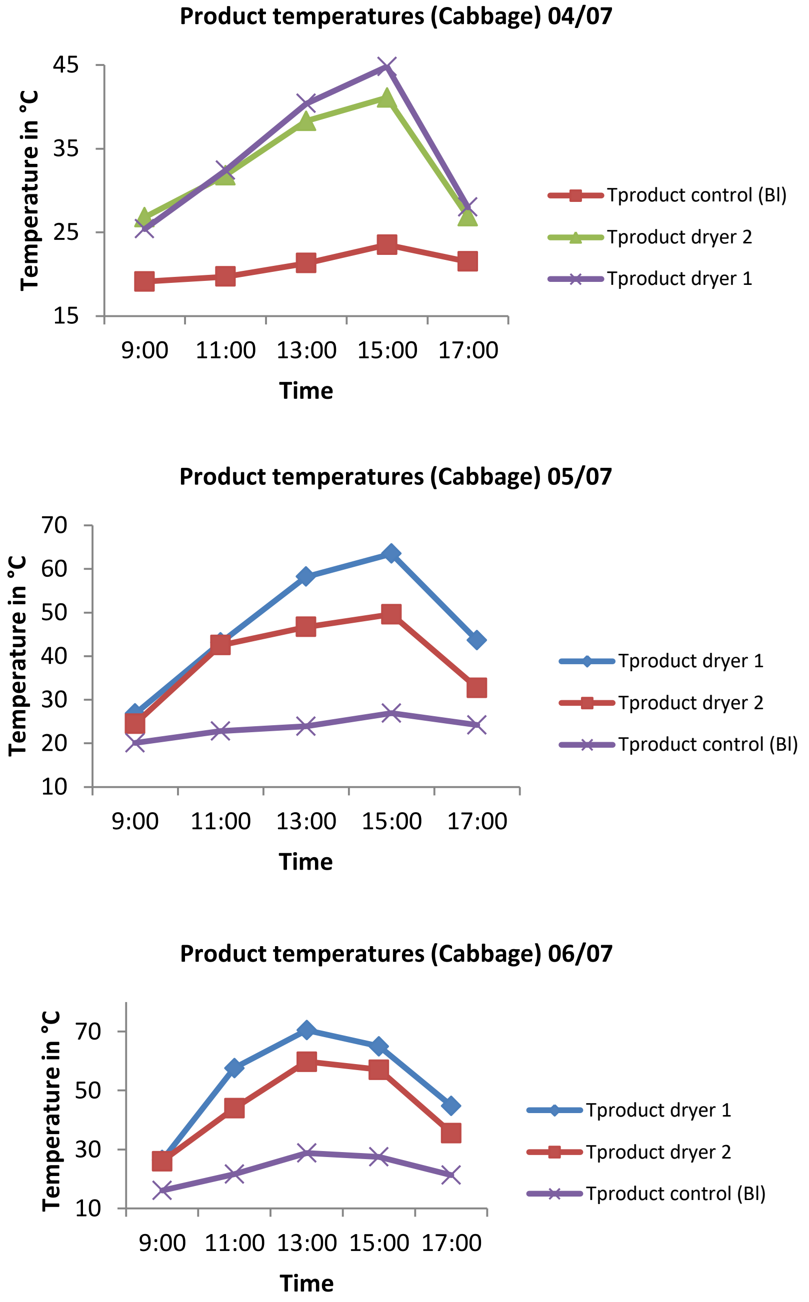


Figure 5.31: Product (cabbage) temperatures in the dryers on from the 4th to the 6th of July

Throughout the testing period for the cabbage samples, similar trends for the temperatures curves were observed during the testing days. Similarly, high crop temperatures were obtained in dryer 1 followed by dryer 2 then lastly control samples as in the previous tests done. High temperatures indicated that high thermal energy was available which was absorbed by the food and is critical in the drying process. As shown in Figure 5.31, the crop temperatures, especially for the control samples, are very low whilst high temperatures were recorded for the dryer 1 and 2. The temperatures for the blanched and unblanched samples are usually almost similar showing a slight temperature difference though the temperatures are still low compared to the products in the enclosed dryers.

5.14.4 Tested samples

From the tests done on the cabbage with the different drying setups, the samples were taken before and after the drying process was complete. Figure 5.32 shows the tested samples from Dryer 1 whilst Figure 5.33 and Figure 5.34 show the tested samples for Dryer 2 and the control sample respectively.

Figure 5.32: Tested sample products of cabbage from Dryer 1

Figure 5.33: Tested sample products of cabbage from Dryer 2

Figure 5.34: Tested sample products of cabbage from control sample

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Summary

Natural degradation is common among most fresh farm produces in causing loss of food during post-harvest. This can be accounted for by the high moisture content in most of these food sources hence causing a short life span of these foods. Drying can be used as a preservation method to reduce the water content without compromising the texture and overall quality of the food. Although many different preservation methods exist to improve the shelf life of the food, solar crop drying brings numerous advantages especially to the rural communities which assist in tackling issues of energy and food security.

This research focused mainly on ways to reduce the food losses that occur during the post-harvest period and increase the shelf life of food by introducing solar crop drying. In doing so, the amount of preserved food can be increased and can be made available in the off season periods. Hence a solar crop dryer was designed, built and tested to determine the effectiveness in reducing drying times of the food. Three different drying setups were put into test by comparing the drying times of the products, product quality as well as the related cost in constructing the dryers. The three dryer setups tested were forced extraction, natural ventilation and open-air sun drying. The dryer setups were tested using Cape Town weather conditions between the months of May and July. In literature, parameters and factors relating to solar crop drying were investigated to check their impact of the drying method. To determine and analyse the performance of the dryers, a series of experiments were conducted and data collected (solar radiation, ambient temperature, wind speed etc.) from the testing site.

6.2 Conclusions

Based on the results obtained from the tests done in this project the following conclusions were drawn. Overall, two solar crop dryers were designed and tested together with a control open-air sun drying. Both designed crop dryer worked satisfactorily during the testing period in reducing the moisture content in the food samples. From the experiments done, it was noted that solar crop drying is feasible and effective in the drying of the food produces. Based on the tested products forced extraction achieved drying in one winter day whilst the natural ventilated needed a second day to complete the drying. Open air drying of similar samples could not achieve the drying even after 7 days, i.e. 3 days after the reported work.

Although the tests were conducted towards the Cape Town winter season, the radiation levels were favourable for the drying process. The available solar radiation levels were significant in the drying process hence had an influence on the thermal properties useful in drying the crops. The experiments also show that the temperatures in the designed crop dryers were higher than the outside ambient temperature due to the glazing material. Hence the high drying rates and quicker drying times of the products compared to the open sun drying. Notably forced extraction drying is preferably the best to use as it reduces the drying process to at most a day based on the tested products followed by the natural ventilation drying. Open sun drying takes the longest time and is problematic in the drying of the food due to its numerous disadvantages. As seen from the tests done, open sun drying took long, up to a week in drying the product and the food quality was not that too good. For this project, banana and cabbage samples were used as testing samples to verify the functionality of the dryer setups. Among the factors tested the product drying time, associated dryer costs and food quality were the most critical.

Average ambient temperatures ranging between 18°C and 28°C were reached on the test days whilst interior dryer air temperatures of ranged between 30°C and 65°C were achieved. It was noticeable that the high temperatures were reached mostly during the midday hours around 13:00 with low temperatures in the early and late hours of the day. Most noticeably dryer 1 had high temperatures compared to dryer 2 with a marginal noticeable difference. Based on the calculations done the optical efficiency obtained was 75.44%. Different thickness sizes (2mm, 4mm, 6mm and 8 mm) were tested and the drying times and final sample textures measured. From the sample run done on the thickness for banana samples, the 6mm was chosen as it proved to give a better drying time and desirable final outcome of the dried product. Hence this thickness was used and is recommended for the banana testing. The dryers were also used in the drying of different cabbage samples and the results were very satisfactory. Hence it was shown that the different dryer setups can be used effectively to dry different food products.

The materials costs were just within the targeted ZAR 2000 per unit. Hence this shows that a low cost, low technology dryer can be built and implemented in a rural setup using a reasonable budget. If the work were to be commercialised, this cost could further be reduced owing to bulk purchases. In that case, it would probably be possible to provide a 2m^2 dryer at a consumer price perhaps below ZAR 3000. This would most likely be commercially attractive since the dryer could be used to dry different products over a long period of time.

6.3 Recommendations for future research

- To use an indirect solar heating system to improve the quality of the food as there will not be direct heating which at times cause discolouring of the food products.

- To also include a water collection system that will be used to prevent the loss of water into the environment.

- To improve the indicator for readiness that will easily be incorporated on the crop dryer setup.

REFERENCES

- Abdellatif, S.M., Yousef, A.T., Ghada, M and Mosad, A. 2010. Utilization of solar tunnel greenhouse as a solar drier for drying seedless grapes, Thermal performance analysis of solar drier. *Journal of Soil Sciences and Agricultural Engineering*. 4: 363-377.

- Ahmed, A.A., Khalid, C.A., Ahmed, E.B and Mohsin, G.S. 2017. Impact of solar radiation on building envelope using energyplus software.

- Akoy, E.O., Ismail, M.A., Ahmed, E.A and Luecke, W. 2006. Design and Construction of A Solar Dryer for Mango Slices. In Tropentag 2006 Prosperity and poverty in a globalised world: Challenges for Agriculture Research. Bonn, Germany, 11-13 October 2006.

- Al-Amri A.M.S. 1997. Thermal performance tests of solar dryer under hot and humid climatic conditions. *AMA*. 28(3): 56-60.

- Alexandratos, N and Bruinsma, J. 2012. *World agriculture towards 2030/2050: the 2012 revision.* 12(3). FAO, Rome: ESA Working paper.

- Aravindh, M.A and Sreekumar, A. 2015. Solar drying—a sustainable way of food processing. In *Energy sustainability through green energy.* 27-46.

- ASHRAE: American Society of Heating, Refrigeration and Air conditioning Engineers 2009. *ASHRAE Handbook Fundamentals*, Chapter 14.

- Atanda, S.A., Pessu P. O., Agoda S., Isong I. U and Ikotun. 2011. The concepts and problems of post-harvest food losses in perishable crops. *African Journal of Food Science.* 5(11): 603-6013.

- Aulakh, J., Regmi, A., Fulton, J and Alexander, C. 2013. Food losses: Developing a consistent global estimation framework. In *Agricultural and applied economics association annual meeting.* 4-6.

- Basunia, M.A. and Abe, T. 2001. Thin-layer solar drying characteristics of rough rice under natural convection. *Journal of food engineering*. *47*(4): 295-301.

- Belessiotis, V and Delyannis, E. 2011. Solar drying. *Solar Energy.* 85:1665–1691.

- Benhammou, M. and Draoui, B. 2013. Effect of double glazing on the thermal performances of a solar still coupled to a condenser. *ISESCO Journal of science and Technology*. 9(15): 2-8.

- Beretta, C., Stoessel, F., Baier, U and Hellweg, S. 2013. Quantifying food losses and the potential for reduction in Switzerland. *Waste management*. *33*(3): 764-773.

- Bolaji, B.O and A. P. Olalusi, A.P. 2008. Performance evaluation of a mixed-mode solar dryer. *AU Journal of Technology*. 11(4): 225–231.

- Bradley, R.L. 2010. Moisture and total solids analysis. *Food analysis.* 85-104.

- Campbell Scientific. 03101 R.M Young Anemometer https://s.campbellsci.com/documents/cn/manuals/03001.pdf [Accessed 12/09/2018].

- Carlsson-Kanyama, A. 1998. Climate change and dietary choices—how can emissions of greenhouse gases from food consumption be reduced? *Food policy*. *23*(3-4): 277-293.

- Chaboud, G and Daviron, B. 2017. Food losses and waste: navigating the inconsistencies. *Global Food Security*, *12*, pp.1-7.
- Chel, A. and Kaushik, G. 2011. Renewable energy for sustainable agriculture. *Agronomy for Sustainable Development*. *31*(1): 91-118.
- Chen, H.H., Hernandez, C.E and Huang, T.C. 2005. A study of the drying effect on lemon slices using a closed-type solar dryer. *Solar Energy*. 78: 97-103.
- Coles, R., McDowell, D and Kirwan, M.J. 2003. *Food packaging technology* (Vol. 5). CRC Press.
- Department of energy (DOE), 2015. State of Renewable Energy in South Africa 2015: 109-111.
- Dhurve, B. Gupta, V and Singh, A.K. 2017. Experiment Analysis of Open, Simple and Modified Greenhouse Dryers for Drying Tomato Flakes. *International Journal of Research and Scientific Innovation (IJRSI*). 4: 128 -131.
- Duffie, J.A and Beckman,W.A. 2013. *Solar Engineering of Thermal Processes*. New Jersey, Canada: Wiley & Son. 236-240.
- Ekechukwu, O.V and Norton, B. 1999. Review of solar-energy drying systems III: low temperature air-heating solar collectors for crop drying applications. *Energy Convers Manage*. 40: 657-667
- Ekechukwu, O.V. 1999. Review of solar-energy drying systems I: an overview of drying principles and theory. *Energy Convers Manage*, 40: 593-613.
- El-Sebaii, A.A and Shalaby, S.M. 2012. Solar drying of agricultural products: A review. *Renewable and Sustainable Energy Reviews.* 16: 37– 43.
- FAO, 2013. Food wastage footprint: Impacts on natural resources.
- Farkas, I. 2013. Integrated use of solar energy for crop drying. Drying technology. 31(8): 866-871.
- Fellows, P.J. 2009. *Food processing technology: principles and practice*. Elsevier.
- Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C and Balzer, C. 2011. Solutions for a cultivated planet. *Nature*. *478*(7369): 337.
- Food and Agricultural Organization of the United Nations (FAO). 1991. FAO year book. Rome: FAO Yearbook Production. 44–125.
- Food and Agriculture Organisation (FAO). 2011. Global food losses and food waste – Extent, causes and prevention. Rome
- Gallagher, P.K., Brown, M.E and Kemp, R.B. 1998. Handbook of thermal analysis and calorimetry. New York: Elsevier.
- Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F.,

Pretty, J., Robinson, S., Thomas, S.M and Toulmin, C. 2010. Food security: the challenge of feeding 9 billion people. *Science*. *327*(5967): 812-818.

- Godfray, H.C.J., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Nisbett, N., Pretty, J., Robinson, S., Toulmin, C and Whiteley, R. 2010. The future of the global food system.
- Gram, L., Ravn, L., Rasch, M., Bruhn, J.B., Christensen, A.B and Givskov, M. 2002. Food spoilage—interactions between food spoilage bacteria. *International journal of food microbiology*. *78*(1-2): 79-97.
- Gross, K., Wang, C.Y and Saltveit, M.E. 2002. The commercial storage of fruit, vegetables and florist and nursery stocks. USDA Agr Handb. 66 (http://www.ba.ars.usda.gov/hb66/ index.html)
- Gustafsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R and Meybeck, A. 2011. Global food losses and food waste: extent, causes and prevention. Food and Agriculture Organisation of the United Nations (FAO). Rome. 29.
- Jain, D. and Tiwari, G.N. 2003. Thermal aspects of open sun drying of various crops. *Energy*. 28(1): 37-54.
- Janjai, S and Bala, B.K.2012. Solar drying technology. *Food Engineering Reviews*. 4:16–54.
- Janjai, S., Srisittipokakun, N and Bala, B.K. 2008. Experimental and modelling performances of a roof-integrated solar drying system for drying herbs and spices. *Energy*. 33(1): 91–103.
- Kanyarusoke, K.E., Gryzagoridis, J. and Oliver G. 2016. Re-mapping sub-Sahara Africa for equipment selection to photo electrify energy poor homes. *Applied Energy* [Online] *175*: 240-250.
- Kiaya, V. 2014. Post-harvest losses and strategies to reduce them. *Technical Paper on Postharvest Losses, Action Contre la Faim (ACF)*.
- Kibria, G. 2015. Sustainable Energy for Rural Development in Developing Countries-Economic, Social, and Environmental Benefits of Renewable Energy. A Case Study.
- Kipp & Zonen CMP06 Pyranometer, http://www.ames.si/files/attachments/ KippZonen_Brochure_Pyranometers.pdf [Accessed 23/10/2018].
- Kipp & Zonen SP-LITE silicon pyranometer. http://s.campbellsci.com/documents/ us/manuals/sp-lite.pdf. [Accessed 23/10/2018].
- Kitinoja, L and Kader, A.A. 2015. Measuring postharvest losses of fresh fruits and vegetables in developing countries. *The Postharvest Education Foundation (PEF White Paper 15-02)*.
- Koyuncu, T. 2006. Performance of various designs of solar air heaters for crop drying applications. *Renewable energy*. *31*(7): 1073-1088.
- Kralova, I and Sjöblom, J. 2010. Biofuels–renewable energy sources: a review. *Journal of Dispersion Science and Technology*, *31*(3): 409-425.

- Kumar, A and Tiwari, G.N. 2006. Effect of mass on convective heat transfer coefficient during onion flakes drying. *American Journal of Food Technology.* 1(1): 1- 18.

- Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O and Ward, P.J. 2012. Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Science of the total environment*. *438*: 477-489.

- Mekhilef, S., Faramarzi, S.Z., Saidur, R and Salam, Z. 2013. The application of solar technologies for sustainable development of agricultural sector. *Renewable and sustainable energy reviews*.*18*: 583-594.

- Munzhedzi, R and Sebitosi, A.B. 2009. Redrawing the solar map of South Africa for photovoltaic applications. *Renewable Energy*.34: 165-169.

- Ndukwu, M.C., Dirioha, C., Abam, F.I and Ihediwa, V.E. 2017. Heat and mass transfer parameters in the drying of cocoyam slice. Case Studies in Thermal Engineering. *Science Direct* [Online]. 9: 62-71. Available at https://doi.org/10.1016/j.csite.2016.12.003

- Nielsen, S.S. 2010. Determination of moisture content. In *Food Analysis Laboratory Manual*. 17-27. Springer, Boston, MA.

- Omega. Revised Thermocouple Reference Tables Type K. https://www.omega.com/techref/pdf/z204-206.pdf [Accessed 14/09/2018].

- Omer, A.M. 2012. Built environment: Relating the benefits of renewable energy technologies. *International Journal of Automotive and Mechanical Engineering*. 5: 561-75.

- Ong KS.1999. Solar dryers in Asia-Pacific region. *Renewable Energy*.16: 779–84.

- Othman, M.Y.H, Sopian, K., Yatim, B and Daud, W.R.W. 2006. Development of advanced solar assisted drying systems. *Renewable Energy*. 31: 703–709.

- Panwar, N.L., Kaushik, S.C and Kothari, S. 2011. Role of renewable energy sources in environmental protection: a review. *Renewable and Sustainable Energy Reviews*. *15*(3): 1513-1524.

- Perez, R., Ineichen, P., Seals, R and Zalenka, A. 1990. Making full use of the clearness index for parameterising hourly insolation conditions. *Solar Energy.* 45: 111-4

- Prakash, O and Kumar, A. 2012. Historical review and recent trends in solar drying systems *International Journal of Green Energy*. 10(7): 690-738.

- Pulker, H and Pulker, H.K. 1999. Coatings on glass (Vol. 20). Elsevier.

- Ravindran, P. 2014. Diffusion and Fick's law, Lecture notes, Physics Dept. Central University of Tamil, India. Available at: http://folk.uio.no/ravi/PMAT2013

- Rawat, S. 2015. Food Spoilage: Microorganisms and their prevention. Asian Journal of Plant Science and Research, 5(4): 47-56.

- Rosa Rolle S. 2006. Postharvest management of fruit and vegetables in the Asia-

Pacific region. Asian Productivity Organization, Tokyo, Japan.

- Runganga, T.B and Kanyarusoke, K.E. 2018. A solar crop dryer for rural area. Presented at The August 2018 ICUE Conference (Cape Town, South Africa).

- Sadeghi, G., Taheri, O and Mobadersani, F. 2012. New technologies of solar drying systems for agricultural and marine products. In *The 1st Middle-East Drying Conference (MEDC2012), Mahshar, Iran*.

- Sahdev, R.K. 2014. Open sun and greenhouse drying of agricultural and food products: a review. *International Journal of Engineering Research and Technology*, *3*(3): 1053-1066.

- Sahu, T.K., Gupta, V and Singh, A.K. 2016. Experimental Analysis of Open, Simple and Modified Greenhouse Dryers for Drying Potato Flakes under Forced Convection. *International Journal of Engineering Research and Applications*. 6(7): 56-60.

- Sharma, A., Chen, C.R and Vu Lan, N. 2009. Solar-energy drying systems: A review. *Renewable and Sustainable Energy Reviews*. 13: 1185–1210.

- Sheridan, C., Petersen, J and Rohwer, J. 2012. On modifying the Arrhenius equation to compensate for temperature changes for reactions with biological systems. *Water SA.* 38(1): 149-151.

- Simate, N. 2003. Optimization of mixed-mode and indirect-mode natural convection solar dryers. *Renewable Energy*. 28(3): 435–453, 2003.

- SolarGis. 2015. *Global Horizontal Irradiation (GHI), South Africa* [ONLINE]. Available at: http://solargis.info/doc/_pics/freemaps/1000px/ghi/SolarGIS-Solar-map-South-Africa-en.png [Accessed 29 May 17].

- SPORE, 2011. Post-harvest management. Adding value to crops. The magazine for agricultural and rural development in ACP countries. N° 152. http://spore.cta.int.

- Stancu, V., Haugaard, P and Lähteenmäki, L. 2016. Determinants of consumer food waste behaviour: Two routes to food waste. *Appetite*. *96*: 7-17.

- Tiwari, A. 2016. A Review on Solar Drying of Agricultural Produce. *Journal of Food Process Technology.* 7(9): 1-12.

- Tiwari, G.N. 2006. Solar Energy Technology Advances. New York: Nova Science Publishers, Inc.

- UN World population prospects: the 2010 revision. Population division of the Department of Economic and Social Affairs of the United Nations (UN) Secretariat (2011).

- Varalakshmi, K. 2016. Role of conventional energy in rural development in India: feasibility analysis of solar drying technology. *International Journal of Energy and Environmental Engineering. 7*(3): 321-327.

- Wankhade, P.K., Sapkal, R.S and Sapkal, V.S. 2012. “Drying characteristics of okra slices using different drying methods by comparative evaluation,” in *Proceedings of the world congress on engineering and computer science.* WCECS. San Francisco. 24-26.

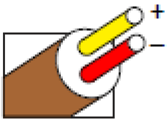
APPENDIX A: SPECIFICATION SHEET FOR A K-TYPE THERMOCOUPLE

MAXIMUM TEMPERATURE RANGE
Thermocouple Grade
– 328 to 2282°F
– 200 to 1250°C
Extension Grade
32 to 392°F
0 to 200°C

LIMITS OF ERROR
(whichever is greater)
Standard: 2.2°C or 0.75% Above 0°C
2.2°C or 2.0% Below 0°C
Special: 1.1°C or 0.4%

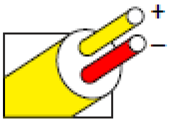
COMMENTS, BARE WIRE ENVIRONMENT:
Clean Oxidizing and Inert; Limited Use in Vacuum or Reducing; Wide Temperature Range; Most Popular Calibration

TEMPERATURE IN DEGREES °C
REFERENCE JUNCTION AT 0°C



Thermocouple Grade

Nickel-Chromium
vs.
Nickel-Aluminum



Extension Grade

Revised Thermocouple Reference Tables

TYPE K

Reference Tables
N.I.S.T. Monograph 175
Revised to ITS-90

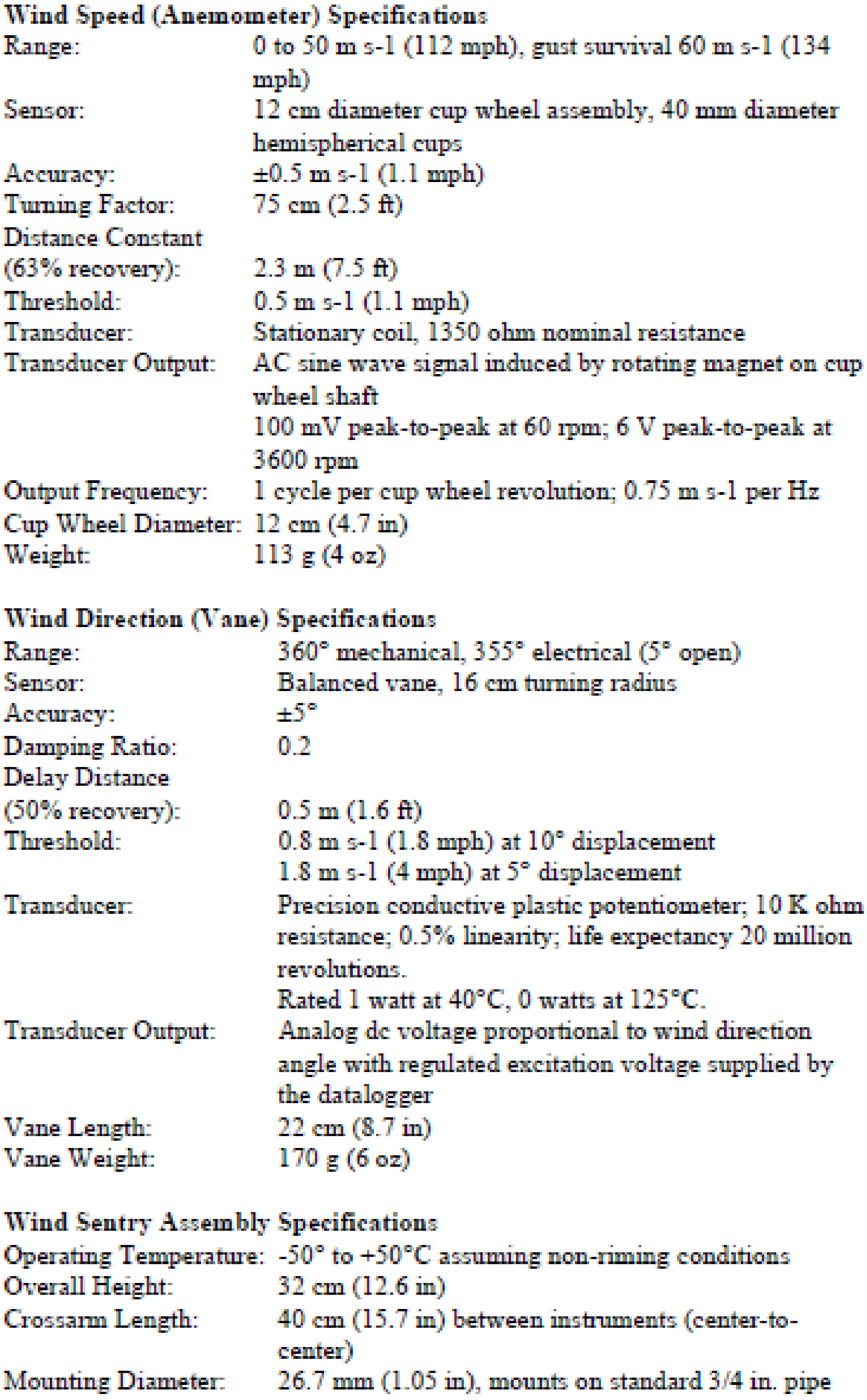
Thermoelectric Voltage in Millivolts

°C	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	°C
-260	-6.458	-6.457	-6.456	-6.455	-6.453	-6.452	-6.450	-6.448	-6.446	-6.444	-6.441	-260
-250	-6.441	-6.438	-6.435	-6.432	-6.429	-6.425	-6.421	-6.417	-6.413	-6.408	-6.404	-250
-240	-6.404	-6.399	-6.393	-6.388	-6.382	-6.377	-6.370	-6.364	-6.358	-6.351	-6.344	-240
-230	-6.344	-6.337	-6.329	-6.322	-6.314	-6.306	-6.297	-6.289	-6.280	-6.271	-6.262	-230
-220	-6.262	-6.252	-6.243	-6.233	-6.223	-6.213	-6.202	-6.192	-6.181	-6.170	-6.158	-220
-210	-6.158	-6.147	-6.135	-6.123	-6.111	-6.099	-6.087	-6.074	-6.061	-6.048	-6.035	-210
-200	-6.035	-6.021	-6.007	-5.994	-5.980	-5.965	-5.951	-5.936	-5.922	-5.907	-5.891	-200
-190	-5.891	-5.876	-5.861	-5.845	-5.829	-5.813	-5.797	-5.780	-5.763	-5.747	-5.730	-190
-180	-5.730	-5.713	-5.695	-5.678	-5.660	-5.642	-5.624	-5.606	-5.588	-5.569	-5.550	-180
-170	-5.550	-5.531	-5.512	-5.493	-5.474	-5.454	-5.435	-5.415	-5.395	-5.374	-5.354	-170
-160	-5.354	-5.333	-5.313	-5.292	-5.271	-5.250	-5.228	-5.207	-5.185	-5.163	-5.141	-160
-150	-5.141	-5.119	-5.097	-5.074	-5.052	-5.029	-5.006	-4.983	-4.960	-4.936	-4.913	-150
-140	-4.913	-4.889	-4.865	-4.841	-4.817	-4.793	-4.768	-4.744	-4.719	-4.694	-4.669	-140
-130	-4.669	-4.644	-4.618	-4.593	-4.567	-4.542	-4.516	-4.490	-4.463	-4.437	-4.411	-130
-120	-4.411	-4.384	-4.357	-4.330	-4.303	-4.276	-4.249	-4.221	-4.194	-4.166	-4.138	-120
-110	-4.138	-4.110	-4.082	-4.054	-4.025	-3.997	-3.968	-3.939	-3.911	-3.882	-3.852	-110
-100	-3.852	-3.823	-3.794	-3.764	-3.734	-3.705	-3.675	-3.645	-3.614	-3.584	-3.554	-100
-90	-3.554	-3.523	-3.492	-3.462	-3.431	-3.400	-3.368	-3.337	-3.306	-3.274	-3.243	-90
-80	-3.243	-3.211	-3.179	-3.147	-3.115	-3.083	-3.050	-3.018	-2.986	-2.953	-2.920	-80
-70	-2.920	-2.887	-2.854	-2.821	-2.788	-2.755	-2.721	-2.688	-2.654	-2.620	-2.587	-70
-60	-2.587	-2.553	-2.519	-2.485	-2.450	-2.416	-2.382	-2.347	-2.312	-2.278	-2.243	-60
-50	-2.243	-2.208	-2.173	-2.138	-2.103	-2.067	-2.032	-1.996	-1.961	-1.925	-1.889	-50
-40	-1.889	-1.854	-1.818	-1.782	-1.745	-1.709	-1.673	-1.637	-1.600	-1.564	-1.527	-40
-30	-1.527	-1.490	-1.453	-1.417	-1.380	-1.343	-1.305	-1.268	-1.231	-1.194	-1.156	-30
-20	-1.156	-1.119	-1.081	-1.043	-1.006	-0.968	-0.930	-0.892	-0.854	-0.816	-0.778	-20
-10	-0.778	-0.739	-0.701	-0.663	-0.624	-0.586	-0.547	-0.508	-0.470	-0.431	-0.392	-10
0	-0.392	-0.353	-0.314	-0.275	-0.236	-0.197	-0.157	-0.118	-0.079	-0.039	0.000	0

°C	0	1	2	3	4	5	6	7	8	9	10	°C
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397	0
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798	10
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203	20
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612	30
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023	40
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436	50
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851	60
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267	70
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682	80
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096	90
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509	100
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920	110
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328	120
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735	130
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138	140
150	6.138	6.179	6.219	6.259	6.299	6.339	6.380	6.420	6.460	6.500	6.540	150
160	6.540	6.580	6.620	6.660	6.701	6.741	6.781	6.821	6.861	6.901	6.941	160
170	6.941	6.981	7.021	7.060	7.100	7.140	7.180	7.220	7.260	7.300	7.340	170
180	7.340	7.380	7.420	7.460	7.500	7.540	7.579	7.619	7.659	7.699	7.739	180
190	7.739	7.779	7.819	7.859	7.899	7.939	7.979	8.019	8.059	8.099	8.138	190
200	8.138	8.178	8.218	8.258	8.298	8.338	8.378	8.418	8.458	8.499	8.539	200
210	8.539	8.579	8.619	8.659	8.699	8.739	8.779	8.819	8.860	8.900	8.940	210
220	8.940	8.980	9.020	9.061	9.101	9.141	9.181	9.222	9.262	9.302	9.343	220
230	9.343	9.383	9.423	9.464	9.504	9.545	9.585	9.626	9.666	9.707	9.747	230
240	9.747	9.788	9.828	9.869	9.909	9.950	9.991	10.031	10.072	10.113	10.153	240
°C	0	1	2	3	4	5	6	7	8	9	10	°C

°C	0	1	2	3	4	5	6	7	8	9	10	°C
250	10.153	10.194	10.235	10.276	10.316	10.357	10.398	10.439	10.480	10.520	10.561	250
260	10.561	10.602	10.643	10.684	10.725	10.766	10.807	10.848	10.889	10.930	10.971	260
270	10.971	11.012	11.053	11.094	11.135	11.176	11.217	11.259	11.300	11.341	11.382	270
280	11.382	11.423	11.465	11.506	11.547	11.588	11.630	11.671	11.712	11.753	11.795	280
290	11.795	11.836	11.877	11.919	11.960	12.001	12.043	12.084	12.126	12.167	12.209	290
300	12.209	12.250	12.291	12.333	12.374	12.416	12.457	12.499	12.540	12.582	12.624	300
310	12.624	12.665	12.707	12.748	12.790	12.831	12.873	12.915	12.956	12.998	13.040	310
320	13.040	13.081	13.123	13.165	13.206	13.248	13.290	13.331	13.373	13.415	13.457	320
330	13.457	13.498	13.540	13.582	13.624	13.665	13.707	13.749	13.791	13.833	13.874	330
340	13.874	13.916	13.958	14.000	14.042	14.084	14.126	14.167	14.209	14.251	14.293	340
350	14.293	14.335	14.377	14.419	14.461	14.503	14.545	14.587	14.629	14.671	14.713	350
360	14.713	14.755	14.797	14.839	14.881	14.923	14.965	15.007	15.049	15.091	15.133	360
370	15.133	15.175	15.217	15.259	15.301	15.343	15.385	15.427	15.469	15.511	15.554	370
380	15.554	15.596	15.638	15.680	15.722	15.764	15.806	15.849	15.891	15.933	15.975	380
390	15.975	16.017	16.059	16.102	16.144	16.186	16.228	16.270	16.313	16.355	16.397	390
400	16.397	16.439	16.482	16.524	16.566	16.608	16.651	16.693	16.735	16.778	16.820	400
410	16.820	16.862	16.904	16.947	16.989	17.031	17.074	17.116	17.158	17.201	17.243	410
420	17.243	17.285	17.328	17.370	17.413	17.455	17.497	17.540	17.582	17.624	17.667	420
430	17.667	17.709	17.752	17.794	17.837	17.879	17.921	17.964	18.006	18.049	18.091	430
440	18.091	18.134	18.176	18.218	18.261	18.303	18.346	18.388	18.431	18.473	18.516	440
450	18.516	18.558	18.601	18.643	18.686	18.728	18.771	18.813	18.856	18.898	18.941	450
460	18.941	18.983	19.026	19.068	19.111	19.154	19.196	19.239	19.281	19.324	19.366	460
470	19.366	19.409	19.451	19.494	19.537	19.579	19.622	19.664	19.707	19.750	19.792	470
480	19.792	19.835	19.877	19.920	19.962	20.005	20.048	20.090	20.133	20.175	20.218	480
490	20.218	20.261	20.303	20.346	20.389	20.431	20.474	20.516	20.559	20.602	20.644	490
500	20.644	20.687	20.730	20.772	20.815	20.857	20.900	20.943	20.985	21.028	21.071	500
510	21.071	21.113	21.156	21.199	21.241	21.284	21.326	21.369	21.412	21.454	21.497	510
520	21.497	21.540	21.582	21.625	21.668	21.710	21.753	21.796	21.838	21.881	21.924	520
530	21.924	21.966	22.009	22.052	22.094	22.137	22.179	22.222	22.265	22.307	22.350	530
540	22.350	22.393	22.435	22.478	22.521	22.563	22.606	22.649	22.691	22.734	22.776	540
550	22.776	22.819	22.862	22.904	22.947	22.990	23.032	23.075	23.117	23.160	23.203	550
560	23.203	23.245	23.288	23.331	23.373	23.416	23.458	23.501	23.544	23.586	23.629	560
570	23.629	23.671	23.714	23.757	23.799	23.842	23.884	23.927	23.970	24.012	24.055	570
580	24.055	24.097	24.140	24.182	24.225	24.267	24.310	24.353	24.395	24.438	24.480	580
590	24.480	24.523	24.565	24.608	24.650	24.693	24.735	24.778	24.820	24.863	24.905	590
600	24.905	24.948	24.990	25.033	25.075	25.118	25.160	25.203	25.245	25.288	25.330	600
610	25.330	25.373	25.415	25.458	25.500	25.543	25.585	25.627	25.670	25.712	25.755	610
620	25.755	25.797	25.840	25.882	25.924	25.967	26.009	26.052	26.094	26.136	26.179	620
630	26.179	26.221	26.263	26.306	26.348	26.390	26.433	26.475	26.517	26.560	26.602	630
640	26.602	26.644	26.687	26.729	26.771	26.814	26.856	26.898	26.940	26.983	27.025	640
650	27.025	27.067	27.109	27.152	27.194	27.236	27.278	27.320	27.363	27.405	27.447	650
660	27.447	27.489	27.531	27.574	27.616	27.658	27.700	27.742	27.784	27.826	27.869	660
670	27.869	27.911	27.953	27.995	28.037	28.079	28.121	28.163	28.205	28.247	28.289	670
680	28.289	28.332	28.374	28.416	28.458	28.500	28.542	28.584	28.626	28.668	28.710	680
690	28.710	28.752	28.794	28.835	28.877	28.919	28.961	29.003	29.045	29.087	29.129	690
700	29.129	29.171	29.213	29.255	29.297	29.338	29.380	29.422	29.464	29.506	29.548	700
710	29.548	29.589	29.631	29.673	29.715	29.757	29.798	29.840	29.882	29.924	29.965	710
720	29.965	30.007	30.049	30.090	30.132	30.174	30.216	30.257	30.299	30.341	30.382	720
730	30.382	30.424	30.466	30.507	30.549	30.590	30.632	30.674	30.715	30.757	30.798	730
740	30.798	30.840	30.881	30.923	30.964	31.006	31.047	31.089	31.130	31.172	31.213	740
750	31.213	31.255	31.296	31.338	31.379	31.421	31.462	31.504	31.545	31.586	31.628	750
760	31.628	31.669	31.710	31.752	31.793	31.834	31.876	31.917	31.958	32.000	32.041	760
770	32.041	32.082	32.124	32.165	32.206	32.247	32.289	32.330	32.371	32.412	32.453	770
780	32.453	32.495	32.536	32.577	32.618	32.659	32.700	32.742	32.783	32.824	32.865	780
790	32.865	32.906	32.947	32.988	33.029	33.070	33.111	33.152	33.193	33.234	33.275	790
°C	0	1	2	3	4	5	6	7	8	9	10	°C

APPENDIX B: SPECIFICATIONS FOR 03101 R.M YOUNG CUP ANEMOMETER



Wind Speed (Anemometer) Specifications

Range:	0 to 50 m s-1 (112 mph), gust survival 60 m s-1 (134 mph)
Sensor:	12 cm diameter cup wheel assembly, 40 mm diameter hemispherical cups
Accuracy:	±0.5 m s-1 (1.1 mph)
Turning Factor:	75 cm (2.5 ft)
Distance Constant (63% recovery):	2.3 m (7.5 ft)
Threshold:	0.5 m s-1 (1.1 mph)
Transducer:	Stationary coil, 1350 ohm nominal resistance
Transducer Output:	AC sine wave signal induced by rotating magnet on cup wheel shaft 100 mV peak-to-peak at 60 rpm; 6 V peak-to-peak at 3600 rpm
Output Frequency:	1 cycle per cup wheel revolution; 0.75 m s-1 per Hz
Cup Wheel Diameter:	12 cm (4.7 in)
Weight:	113 g (4 oz)

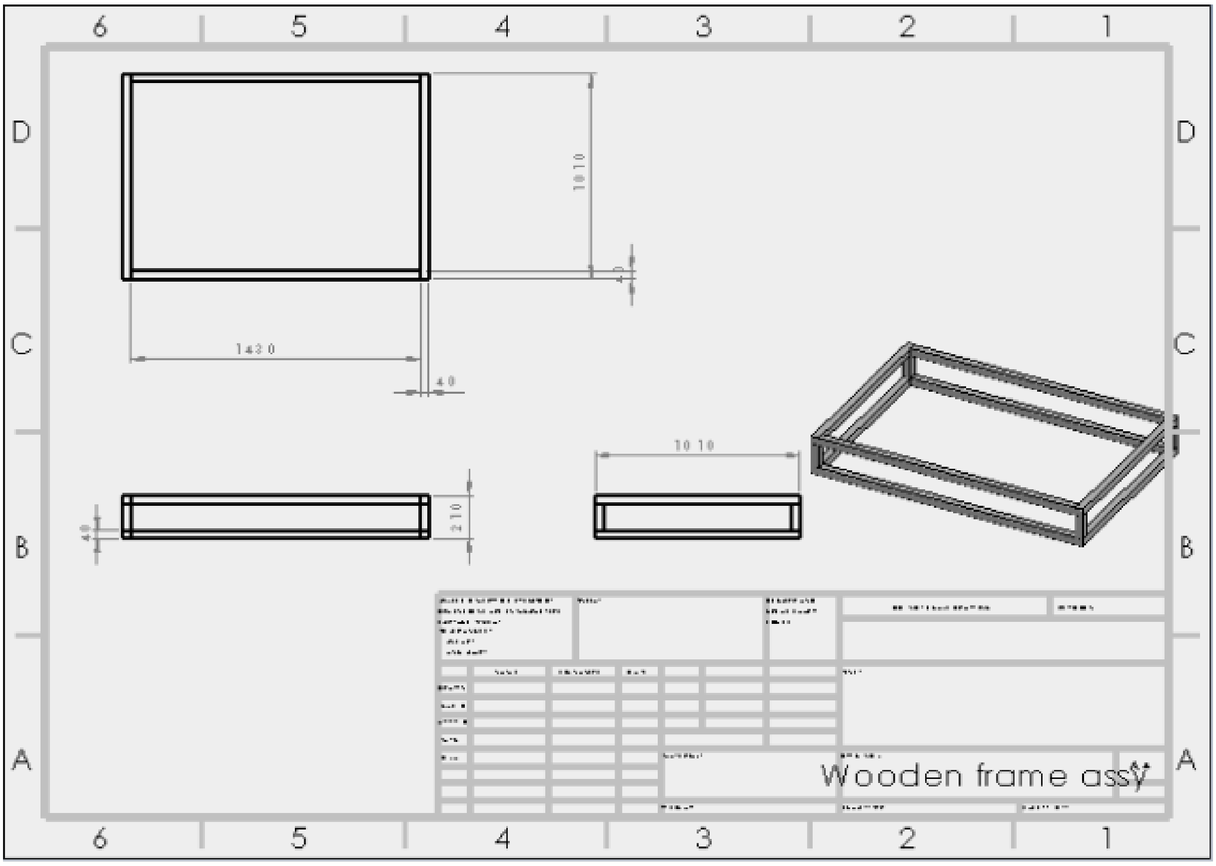
Wind Direction (Vane) Specifications

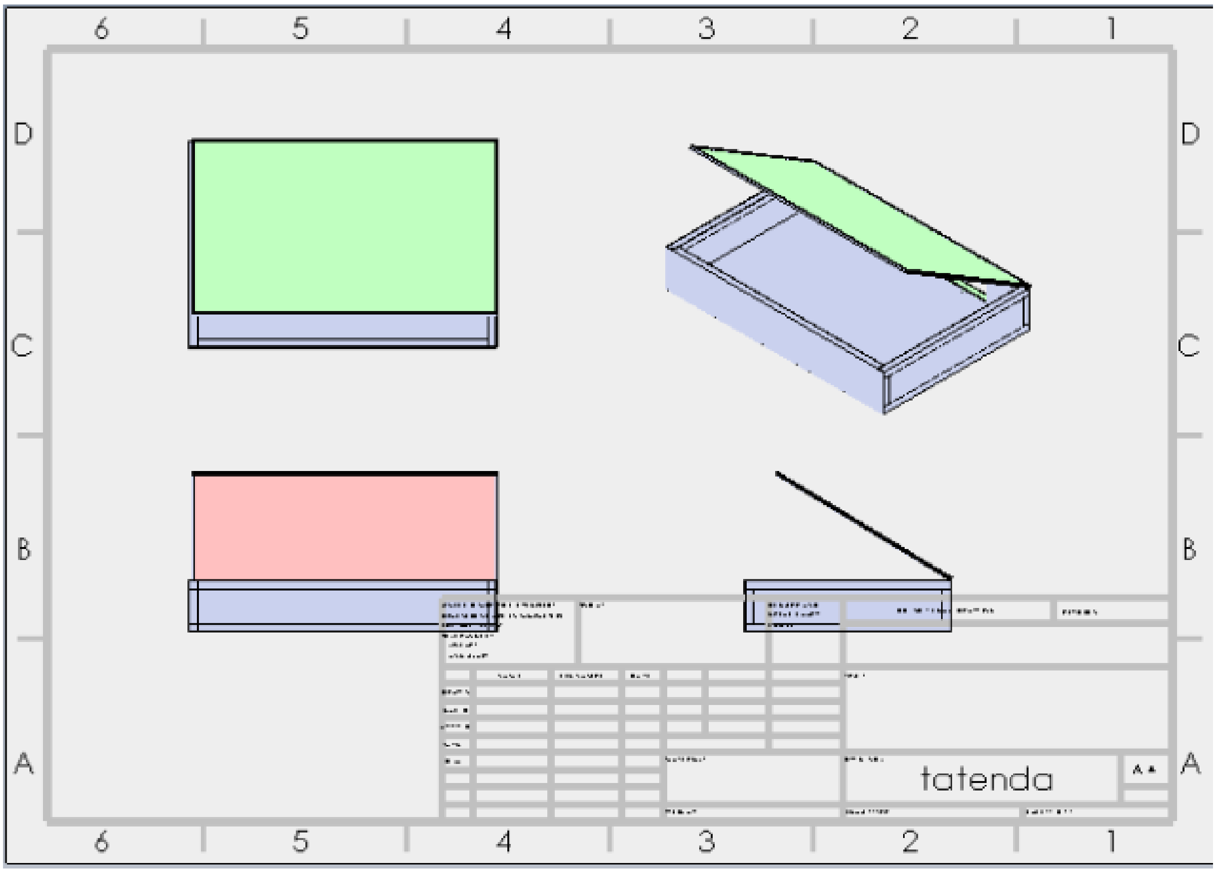
Range:	360° mechanical, 355° electrical (5° open)
Sensor:	Balanced vane, 16 cm turning radius
Accuracy:	±5°
Damping Ratio:	0.2
Delay Distance (50% recovery):	0.5 m (1.6 ft)
Threshold:	0.8 m s-1 (1.8 mph) at 10° displacement 1.8 m s-1 (4 mph) at 5° displacement
Transducer:	Precision conductive plastic potentiometer; 10 K ohm resistance; 0.5% linearity; life expectancy 20 million revolutions. Rated 1 watt at 40°C, 0 watts at 125°C.
Transducer Output:	Analog dc voltage proportional to wind direction angle with regulated excitation voltage supplied by the datalogger
Vane Length:	22 cm (8.7 in)
Vane Weight:	170 g (6 oz)

Wind Sentry Assembly Specifications

Operating Temperature:	-50° to +50°C assuming non-riming conditions
Overall Height:	32 cm (12.6 in)
Crossarm Length:	40 cm (15.7 in) between instruments (center-to-center)
Mounting Diameter:	26.7 mm (1.05 in), mounts on standard 3/4 in. pipe

APPENDIX C: TECHNICAL DRAWINGS





APPENDIX D: CALCULATIONS

The following calculations show the different calculated parameters at the testing site on the different test days. Calculations will be done for the first testing day (12th May 2018) whilst for the remaining days the values will be tabulated (using the same formulae as for the first day).

Incident solar radiation on transparent cover

Day: May 12 2018

Latitude: = -33.93°	Longitude: =18.46° (CPUT Bellville campus)
Cover inclination angle: β=30°	Solar constant: I_{SC}=1367 W/m^2
Reflectance: ρ=0.2	Local time: 12:00(for calculation purposes)

From the measured values at the weather station, the following was obtained:

$\mathbf{I_{d\ measured}}$ at midday = 39.53 W/m^2

$\mathbf{I_{T\ measured}}$ at midday = 631.3 W/m^2

$\mathbf{I_{b\ calculated}}$ at midday: I_T - I_d = 591.77W/m^2

Solar angles

Declination angle: $\delta\ = 23.45\ \sin\left(360\ \frac{284+n}{365}\right)$ from equation 4.4

For the 12th of May the value of n for the specific day can be obtained from Table 4.1

n = 120 + d = 120 + 12 = 132 hence δ for the 12th of May is

δ = 18.04°

Hour angle: ω= 15(t - t_{noon})

For these calculation t=12.0h was used whilst the other calculations for the other days are shown in the table below

t_{noon} =720+4 x longitude- equation of time

Equation of time = 9.87 sin 2B -7.53 cos B -1.5 sin B

B=360 x (n-81)/365 = 360 x (132 -81)/365

B= 50.3014°

Therefore,

Equation of time = 9.87 x sin (2x50.3014) – 7.53 x cos (50.3014) -1.5 sin (50.3014)

Equation of time= 3.7375

From this t_{noon} can be obtained as follows

t_{noon} =720+4 x longitude- equation of time

= 720 + (4 x 18.64) – 3.7375

= 790.824 minutes

= 13.1804 hours

ω = 15 (12.0 - 13.1804) = -17.706°

Table D1: Summarised calculation of the parameters for the other testing days

Day	n	δ	B	ω	EOT	t_{noon}
May 12 to 15	132	18.04	50.30	-17.71	3.74	13.18
	133	18.30	51.29	-17.70	3.75	13.18
	134	18.55	52.27	-17.70	3.76	13.18
	135	18.79	53.26	-17.70	3.76	13.18
June 5 to 7	156	22.54	73.97	-18.21	1.72	13.21
	157	22.65	74.96	-18.25	1.54	13.22
	158	22.75	75.95	-18.30	1.37	13.22
June 11 to 15	162	23.09	79.89	-18.49	0.61	13.23
	163	23.15	80.88	-18.54	0.42	13.24
	164	23.21	81.86	-18.59	0.22	13.24
	165	23.27	82.85	-18.64	0.01	13.24
	166	23.31	83.84	-18.69	-0.19	13.25
July 4 to 10	185	22.89	102.58	-19.64	-4.02	13.31
	186	22.80	103.56	-19.69	-4.19	13.31
	187	22.70	104.55	-19.73	-4.36	13.32
	188	22.59	105.53	-19.77	-4.52	13.32
	189	22.48	106.52	-19.81	-4.68	13.32
	190	22.36	107.51	-19.85	-4.83	13.32
	191	22.24	108.49	-19.88	-4.97	13.33

Incident angle of beam radiation:

$\theta_i = \cos^{-1} [\cos (L+\beta) \times \cos \delta \times \cos \omega + \sin (L+\beta) \times \sin \delta]$

$= \cos^{-1} [\cos (-33.93+ 30) \times \cos 18.04 \times \cos (-17.706) + \sin (-33.93 + 30) \times \sin 18.04]$

$= 28.06°$

Zenith angle:

$\boldsymbol{\theta}_z = \cos^{-1} [\cos L \times \cos \delta \times \cos \omega + \sin L \times \sin \delta]$

$= \cos^{-1} [\cos (-33.93) \times \cos 18.04 \times \cos (-17.706) + \sin (-33.93) \times \sin 18.04]$

$= 54.64°$

<u>Beam radiation calculation</u>

$I_{b\ inclined} = R_b \times I_b$

$R_b = \cos \theta_i / \cos \theta_z = \cos (28.06) / \cos (54.64)$

$R_b = 1.525$

$I_{b\ inclined} = 1.525 \times 591.77$

$I_{b\ inclined} = 902.44\ W/m^2$

<u>Diffuse radiation calculations</u>

In simpler terms, the diffuse radiation at the tilt or inclined surface can be obtained as follows using the equation below

$I_{Td} = I_{T\ diffuse} \times (1 + \cos \beta)/2$

$= 39.53 \times (1- \cos 30)/2$

$I_{Td} = 36.882 W/m^2$

Reflected radiation calculation

$I_{Trefl} = I_{total}\ \rho_g\ (1- \cos\beta)/2$

$= (I_{beam} + I_{diffuse}) \times \rho_g \times (1- \cos\beta)/2$

$= 631.3 \times 0.2 \times (1- \cos30)/2$

$= 8.458\ W/m^2$

Total solar radiation incident on the transparent cover

$I_T = I_{Tb} + I_{Td} + I_{Trefl}$

$I_T = 902.44 + 36.882 + 8.458$

$I_T = 947.78\ W/m^2$.

Heat calculations

The following illustration shows the heat transfer that occurs within a solar crop dryer. The calculations for the heat and energy flow in the system are summarised in the calculations in the section below based on the data collected on one of the testing days i.e. 14 May.

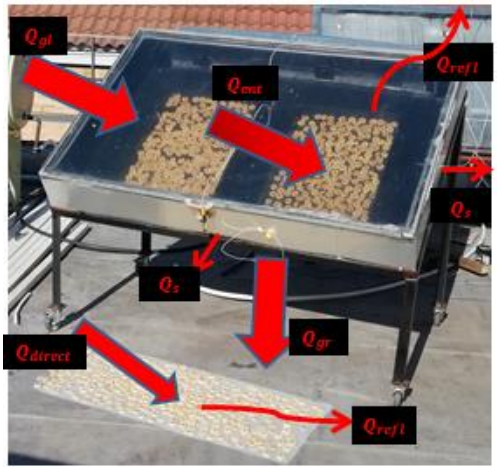


Fig D1: Heat transfer system in a crop dryer

Table D2: Total radiation levels obtained on the glazing and inside the dryer obtained on one of the testing days

Time	G_{gl} (W/m^2)	G_{in} (W/m^2)	Time	G_{gl} (W/m^2)	G_{in} (W/m^2)
7:15	0	0	**13:00**	880.151	682.7
7:30	0	0	**13:15**	871.8998	684.2
7:45	0	0	**13:30**	862.5943	677.7
8:00	0	0	**13:45**	847.3051	670.1
8:15	**13.7173**	0	**14:00**	827.6777	657.7
8:30	117.3399	**15.4**	**14:15**	807.0778	641.7
8:45	270.375	77.4	**14:30**	780.8151	624.8
9:00	354.4772	180.2	**14:45**	748.3092	603.2
9:15	411.3013	245	**15:00**	712.1087	576.5
9:30	469.3311	292.6	**15:15**	670.6354	546.8
9:45	536.5076	341.1	**15:30**	625.2962	512.6
10:00	622.6965	396.4	**15:45**	577.1951	475.3
10:15	677.4325	466	**16:00**	525.3999	435.5
10:30	729.1047	511.8	**16:15**	464.5057	392.7
10:45	763.8394	554.9	**16:30**	410.4361	343
11:00	786.342	584.6	**16:45**	348.7526	298.3
11:15	806.8872	604.3	**17:00**	284.8234	248.2
11:30	828.0743	622.1	**17:15**	219.5723	197.3
11:45	847.1637	640.1	**17:30**	157.2893	147.1
12:00	865.3768	656.1	**17:45**	**81.8862**	**58**
12:15	875.9225	671.2	**18:00**	0	0
12:30	878.3952	680.1	**18:15**	0	0
12:45	878.3318	682.5	**18:30**	0	0

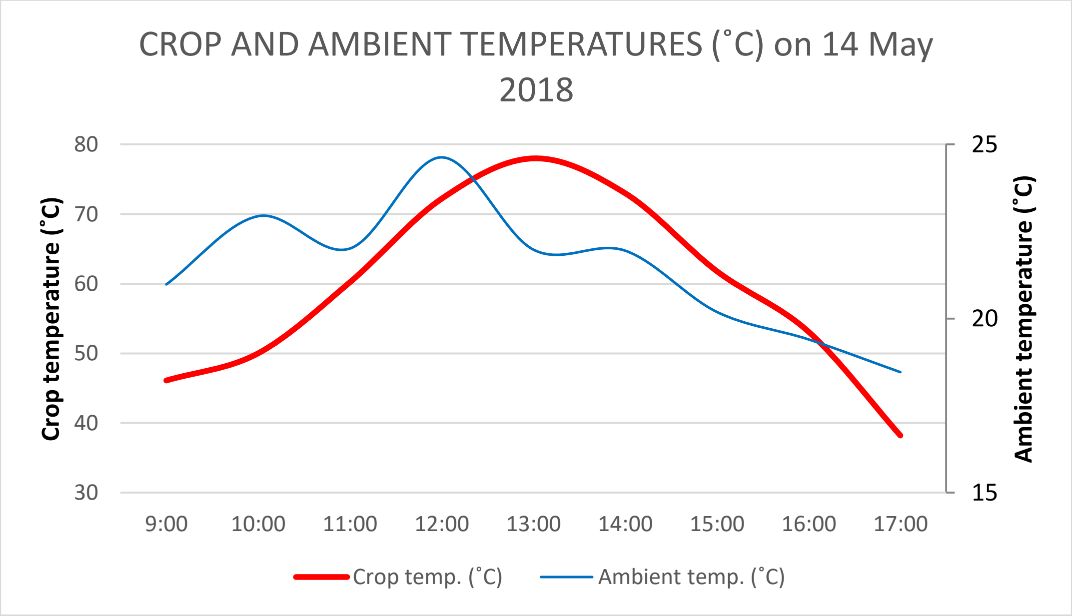


Fig D2: Crop and ambient temperatures

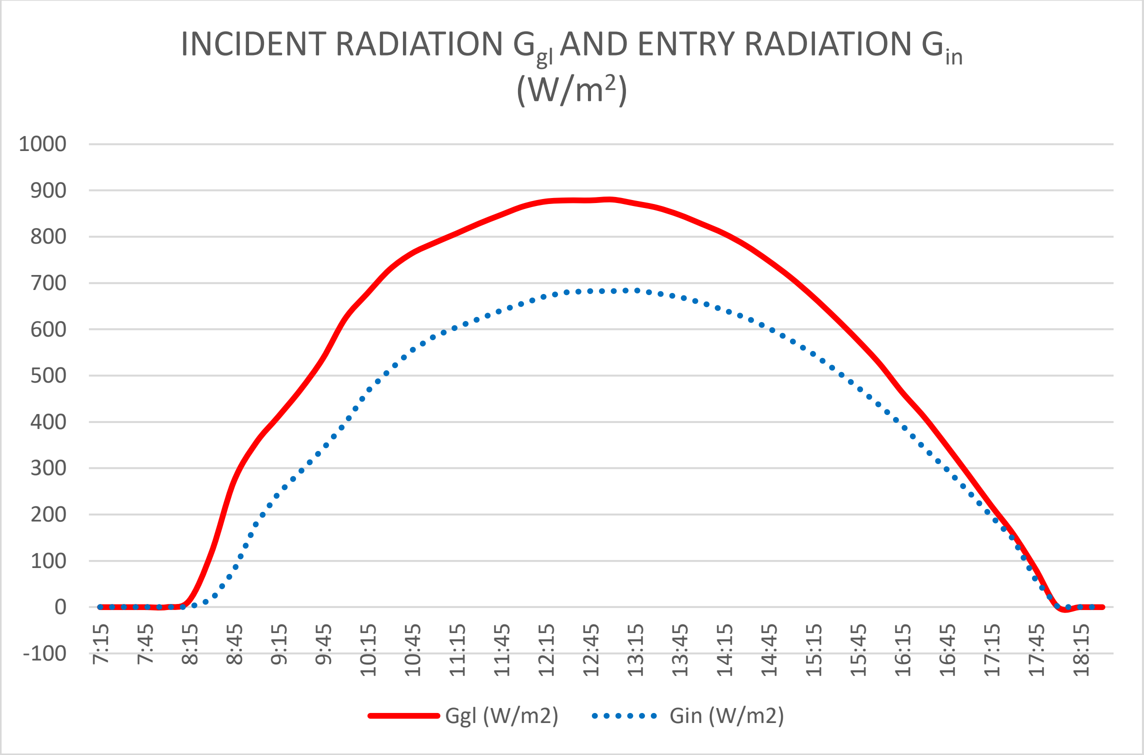


Fig D3: Incident radiation and entry radiation

The total incident radiation energy on the glazing material was obtained using the integral of the total radiation on the polycarbonate surface. The figure above shows the total incident radiation levels on the polycarbonate sheet as well as the total radiation inside the crop dryer. Hence from the given trends the total energy, the dryer receives at each specific time can be obtained. Using the trapezium rule the total incident radiation on the crop dryers can be obtained as follows:

Hence the total incident radiation in megajoules (MJ) can be obtained as follows

$$\frac{x}{2} \times \left[(h_0 + h_n) + 2\left(\sum h_1 \ldots h_{n-1}\right)\right] \times A_c \times 10^{-6}$$

Where x is the time interval between the h values selected

h denotes the radiation value at a specific time

A_c is the collector area

Given a time interval of 15 minutes which is 900 seconds

Total incident energy (MJ) using G_{gl}= $\frac{x}{2} \times [(h_0 + h_n) + 2(\sum h_1 \ldots h_{n-1})] \times A_c \times 10^{-6}$

= $\frac{900}{2} \times [(13.7173 + 81.8863) + 2(\sum 117.3399 + 270.375 + \cdots + 157.893)] \times 1.5 \times 10^{-6}$

= 63.1 MJ

Total entry energy (MJ) using $G_{in} = \frac{x}{2} \times [(h_0 + h_n) + 2(\sum h_1 \ldots h_{n-1})] \times A_c \times 10^{-6}$

$= \frac{900}{2} \times [(13.7173 + 81.8863) + 2(\sum 117.3399 + 270.375 + \cdots + 157.893)] \times 1.5 \times 10^{-6}$

= 47.6MJ

Given the total entry energy and the total incident energy, the optical efficiency of the dryer can be determined

$$Optical\ efficiency = \frac{Incident\ energy\ in\ the\ dryer}{Incident\ energy\ on\ the\ glazing}$$

$$= \frac{Q_{in}}{Q_{glazing}}$$

$$= \frac{47.6\ MJ}{63.1\ MJ} \times 100$$

$$= 75.44\%$$

Since the optical efficiency is 75.44% it can be noted that the dryer can convert at least three-quarters of the incident radiation into useful energy in the dryer. Hence the 24.56% of the total incident radiation is reflected by the glazing and lost to the surroundings.

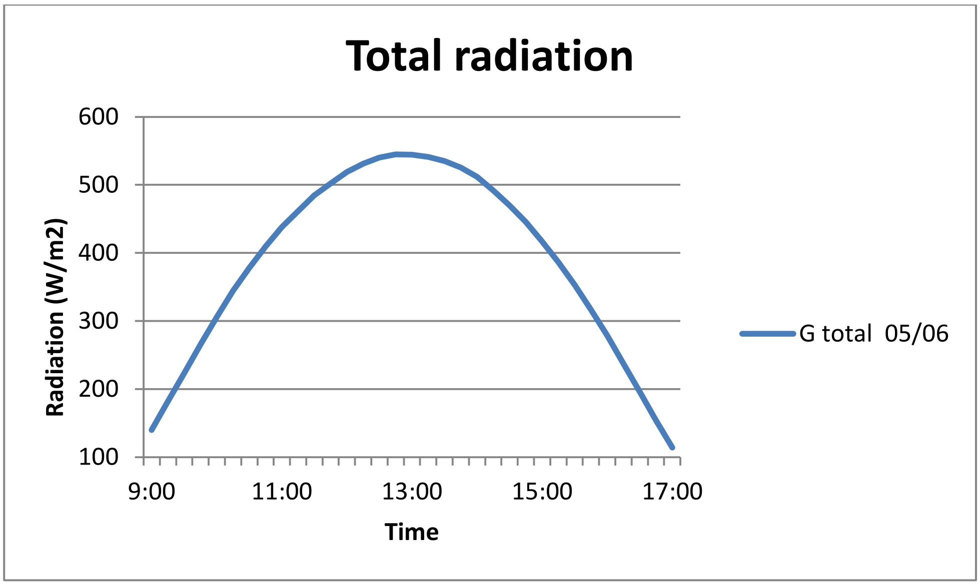


Fig D4: Total radiation

The extra-terrestrial radiation for the different testing days can be summarised by equation 4.3

$$I_{0a} = I_0 \left[\cos\delta \cos\left(\frac{t}{4}\right)^o \cos L + \sin\delta \sin L \right] \left[1 + 0.03 \cos\left(\frac{360n}{365}\right) \right]$$

Given the latitude of the location, declination for the specific day and the solar time the actual extra-terrestrial radiation can be obtained for the respective test days.

APPENDIX E: MEASURED DATA FROM WEATHER STATION

Table E1 - Measured data on 12 May 2018

12-May-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	66.15	14.92	51.23	2.64	13.78	78.12	13.92	0.89	92.93
9:15	232.80	17.09	215.71	2.62	15.23	328.94	15.95	3.12	348.01
9:30	344.00	35.31	308.69	2.17	17.02	470.73	32.94	4.61	508.29
9:45	358.60	52.35	306.25	3.09	16.98	467.01	48.84	4.80	520.66
10:00	153.80	38.32	115.48	3.58	16.22	176.10	35.75	2.06	213.91
10:15	309.00	23.46	285.54	3.78	16.94	435.43	21.89	4.14	461.46
10:30	464.80	20.61	444.19	3.35	19.00	677.36	19.23	6.23	702.82
10:45	488.20	19.90	468.30	2.95	18.70	714.13	18.57	6.54	739.24
11:00	525.70	22.94	502.76	3.25	18.58	766.68	21.40	7.04	795.12
11:15	435.80	27.50	408.30	3.09	19.25	622.63	25.66	5.84	654.13
11:30	543.30	23.47	519.83	3.41	19.18	792.71	21.90	7.28	821.88
11:45	559.50	22.68	536.82	2.87	21.58	818.62	21.16	7.50	847.27
12:00	631.30	39.53	591.77	2.37	22.46	902.41	36.88	8.46	947.75
12:15	548.90	60.12	488.78	2.72	21.88	745.36	56.09	7.35	808.80
12:30	474.60	47.28	427.32	2.26	20.87	651.64	44.11	6.36	702.11
12:45	596.00	56.76	539.24	2.36	20.85	822.31	52.96	7.98	883.25
13:00	374.90	58.68	316.22	1.98	21.20	482.22	54.75	5.02	541.99
13:15	290.10	46.81	243.29	2.14	20.85	371.00	43.67	3.89	418.56
13:30	546.20	49.90	496.30	2.69	21.83	756.83	46.56	7.32	810.70
13:45	597.60	67.82	529.78	2.54	22.98	807.88	63.28	8.01	879.16
14:00	611.80	57.62	554.18	2.55	24.86	845.09	53.76	8.20	907.05
14:15	624.40	61.23	563.17	2.00	26.23	858.80	57.13	8.37	924.29
14:30	591.90	54.44	537.46	1.79	26.74	819.59	50.79	7.93	878.32
14:45	524.00	40.07	483.93	2.04	25.51	737.96	37.39	7.02	782.37
15:00	466.80	28.67	438.13	2.16	23.98	668.12	26.75	6.25	701.12
15:15	432.40	24.49	407.91	2.23	22.88	622.04	22.85	5.79	650.68
15:30	399.30	23.13	376.17	1.92	21.49	573.64	21.58	5.35	600.57
15:45	363.90	22.15	341.75	2.08	21.18	521.15	20.67	4.88	546.69
16:00	325.70	21.48	304.22	2.22	20.78	463.92	20.04	4.36	488.32
16:15	285.10	20.61	264.49	2.41	20.24	403.33	19.23	3.82	426.38
16:30	243.90	19.14	224.76	2.44	19.58	342.74	17.86	3.27	363.87
16:45	202.50	32.08	170.42	2.03	19.19	259.88	29.93	2.71	292.52
17:00	160.40	105.90	54.50	2.11	18.86	83.11	98.81	2.15	184.06

Table E2 - Measured data on 13 May 2018

13-May-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	I $_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	200.00	28.13	171.87	0.22	13.71	263.18	26.25	2.68	292.11
9:15	236.10	29.32	206.78	0.01	15.81	316.64	27.36	3.16	347.16
9:30	236.60	26.27	210.33	0.00	17.38	322.08	24.51	3.17	349.76
9:45	263.40	33.25	230.15	0.13	17.20	352.43	31.02	3.53	386.98
10:00	433.20	39.71	393.49	0.53	18.42	602.55	37.05	5.80	645.40
10:15	372.30	37.49	334.81	1.48	18.51	512.69	34.98	4.99	552.66
10:30	337.10	30.69	306.41	1.34	19.36	469.21	28.63	4.52	502.36
10:45	450.80	44.04	406.76	1.48	18.89	622.87	41.09	6.04	670.00
11:00	472.30	36.32	435.98	1.55	19.46	667.62	33.89	6.33	707.83
11:15	300.60	21.07	279.53	1.55	20.07	428.04	19.66	4.03	451.73
11:30	282.80	20.94	261.86	1.45	19.45	400.99	19.54	3.79	424.31
11:45	540.10	35.36	504.74	1.64	22.08	772.91	32.99	7.24	813.14
12:00	328.10	30.60	297.50	1.88	21.58	455.56	28.55	4.40	488.51
12:15	314.50	26.49	288.01	1.95	19.80	441.03	24.72	4.21	469.96
12:30	617.30	48.34	568.96	2.27	20.35	871.25	45.10	8.27	924.62
12:45	619.90	45.19	574.71	2.73	20.03	880.05	42.16	8.31	930.52
13:00	600.80	35.49	565.31	2.34	20.19	865.66	33.11	8.05	906.82
13:15	585.30	31.34	553.96	2.89	19.87	848.28	29.24	7.84	885.36
13:30	575.10	28.91	546.19	2.72	19.96	836.38	26.97	7.70	871.06
13:45	561.20	27.35	533.85	2.92	20.54	817.48	25.52	7.52	850.52
14:00	545.20	26.69	518.51	3.04	21.29	793.99	24.90	7.30	826.20
14:15	528.80	26.50	502.30	3.56	21.46	769.17	24.72	7.08	800.98
14:30	509.40	25.89	483.51	3.40	21.55	740.40	24.16	6.82	771.38
14:45	485.40	25.13	460.27	3.80	20.82	704.81	23.45	6.50	734.76
15:00	458.80	24.40	434.40	3.21	21.05	665.20	22.77	6.15	694.11
15:15	427.10	23.45	403.65	3.96	19.92	618.11	21.88	5.72	645.71
15:30	395.50	22.17	373.33	4.28	19.04	571.68	20.68	5.30	597.66
15:45	360.20	21.30	338.90	3.39	19.19	518.96	19.87	4.83	543.66
16:00	324.50	20.81	303.69	4.40	19.02	465.04	19.42	4.35	488.80
16:15	305.10	23.27	281.83	4.87	18.50	431.57	21.71	4.09	457.36
16:30	295.30	26.97	268.33	4.56	18.27	410.89	25.16	3.96	440.01
16:45	257.80	46.64	211.16	5.13	18.20	323.35	43.52	3.45	370.32
17:00	199.70	123.50	76.20	4.86	17.88	116.69	115.23	2.68	234.59

Table E3 - Measured data on 14 May 2018

14-May-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	184.60	14.12	170.48	2.01	16.03	262.13	13.17	2.47	277.78
9:15	226.00	14.82	211.18	1.76	17.34	324.71	13.83	3.03	341.57
9:30	268.40	15.38	253.02	1.51	18.72	389.05	14.35	3.60	406.99
9:45	316.20	15.47	300.73	2.23	18.07	462.40	14.43	4.24	481.07
10:00	375.50	15.79	359.71	2.23	18.50	553.09	14.73	5.03	572.86
10:15	416.90	16.44	400.46	2.64	18.91	615.75	15.34	5.59	636.67
10:30	456.20	17.15	439.05	1.95	20.44	675.09	16.00	6.11	697.20
10:45	484.70	17.63	467.07	1.76	20.59	718.17	16.45	6.49	741.11
11:00	504.90	18.11	486.79	2.13	20.36	748.49	16.90	6.76	772.15
11:15	523.10	18.46	504.64	2.29	22.00	775.94	17.22	7.01	800.17
11:30	541.00	18.91	522.09	1.95	22.33	802.77	17.64	7.25	827.66
11:45	556.90	19.40	537.50	1.73	23.68	826.46	18.10	7.46	852.03
12:00	571.60	19.84	551.76	2.13	24.84	848.39	18.51	7.66	874.56
12:15	580.70	20.40	560.30	2.48	23.83	861.52	19.03	7.78	888.33
12:30	583.90	21.35	562.55	1.75	22.55	864.98	19.92	7.82	892.72
12:45	584.80	22.31	562.49	2.24	22.16	864.89	20.82	7.83	893.54
13:00	586.30	23.08	563.22	2.75	21.76	866.01	21.53	7.85	895.40
13:15	580.60	23.87	556.73	2.32	22.05	856.03	22.27	7.78	886.08
13:30	573.60	24.45	549.15	2.89	22.79	844.38	22.81	7.68	874.87
13:45	562.10	24.64	537.46	2.83	23.55	826.40	22.99	7.53	856.92
14:00	547.20	25.05	522.15	2.66	24.10	802.86	23.37	7.33	833.56
14:15	531.10	25.12	505.98	2.73	24.16	778.00	23.44	7.12	808.55
14:30	510.80	24.87	485.93	3.11	23.53	747.17	23.20	6.84	777.22
14:45	486.00	24.40	461.60	4.22	22.07	709.76	22.77	6.51	739.04
15:00	458.40	23.76	434.64	4.01	21.14	668.31	22.17	6.14	696.62
15:15	427.10	22.99	404.11	4.33	20.45	621.36	21.45	5.72	648.53
15:30	393.10	22.15	370.95	4.10	19.69	570.38	20.67	5.27	596.31
15:45	357.20	21.36	335.84	3.94	19.49	516.39	19.93	4.79	541.10
16:00	319.00	20.54	298.46	3.34	19.46	458.91	19.16	4.27	482.35
16:15	275.70	19.64	256.06	3.57	19.21	393.72	18.32	3.69	415.74
16:30	236.60	19.05	217.55	3.88	18.77	334.51	17.77	3.17	355.45
16:45	194.00	45.98	148.02	4.46	18.39	227.60	42.90	2.60	273.10
17:00	151.50	119.70	31.80	3.95	18.12	48.90	111.68	2.03	162.61

Table E4 - Measured data on 15 May 2018

15-May-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	169.90	14.18	155.72	0.00	14.35	240.41	13.23	2.28	255.92
9:15	215.80	14.76	201.04	0.00	16.28	310.38	13.77	2.89	327.04
9:30	259.20	15.43	243.77	0.00	18.13	376.35	14.40	3.47	394.21
9:45	304.50	16.28	288.22	0.01	17.95	444.97	15.19	4.08	464.24
10:00	361.00	16.50	344.50	0.08	18.51	531.86	15.39	4.84	552.09
10:15	410.60	17.07	393.53	0.02	20.61	607.55	15.93	5.50	628.98
10:30	432.20	17.53	414.67	0.00	22.80	640.19	16.36	5.79	662.34
10:45	468.80	18.17	450.63	0.02	23.07	695.71	16.95	6.28	718.94
11:00	476.00	18.04	457.96	0.04	21.41	707.02	16.83	6.38	730.23
11:15	492.20	18.33	473.87	0.03	23.70	731.59	17.10	6.59	755.28
11:30	524.00	18.84	505.16	0.44	23.28	779.89	17.58	7.02	804.49
11:45	543.10	19.19	523.91	0.44	23.94	808.84	17.90	7.28	834.02
12:00	556.30	19.99	536.31	0.37	25.42	827.99	18.65	7.45	854.09
12:15	567.30	20.51	546.79	0.59	27.02	844.16	19.14	7.60	870.90
12:30	574.10	21.08	553.02	0.50	25.94	853.78	19.67	7.69	881.14
12:45	577.50	22.09	555.41	0.67	25.68	857.47	20.61	7.74	885.82
13:00	573.20	23.51	549.69	0.44	28.51	848.64	21.94	7.68	878.26
13:15	572.30	24.34	547.96	0.48	28.34	845.97	22.71	7.67	876.35
13:30	562.50	25.02	537.48	0.84	28.35	829.79	23.34	7.54	860.67
13:45	541.80	25.44	516.36	1.41	28.10	797.19	23.74	7.26	828.18
14:00	526.10	25.91	500.19	1.64	26.53	772.22	24.17	7.05	803.44
14:15	508.00	26.14	481.86	1.70	26.04	743.92	24.39	6.81	775.12
14:30	486.00	26.08	459.92	1.24	26.74	710.05	24.33	6.51	740.89
14:45	464.90	25.61	439.29	1.55	26.61	678.20	23.89	6.23	708.32
15:00	439.40	24.99	414.41	1.56	26.13	639.79	23.32	5.89	668.99
15:15	405.50	24.18	381.32	1.39	25.38	588.70	22.56	5.43	616.70
15:30	376.30	23.55	352.75	1.44	24.27	544.60	21.97	5.04	571.61
15:45	341.20	22.76	318.44	1.63	23.69	491.63	21.24	4.57	517.43
16:00	302.30	21.46	280.84	1.59	23.52	433.58	20.02	4.05	457.65
16:15	258.50	21.25	237.25	1.05	23.15	366.28	19.83	3.46	389.57
16:30	217.20	21.37	195.83	1.32	22.85	302.33	19.94	2.91	325.18
16:45	179.30	53.66	125.64	1.83	22.30	193.97	50.07	2.40	246.44
17:00	139.20	110.10	29.10	1.55	21.70	44.93	102.72	1.86	149.52

Table E5 - Measured data on 05 June 2018

5-Jun-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	23.98	11.73	12.25	1.32	10.22	20.23	10.94	0.32	31.50
9:15	73.27	12.55	60.72	0.49	11.06	100.30	11.71	0.98	112.99
9:30	120.40	13.18	107.22	0.13	12.42	177.10	12.30	1.61	191.01
9:45	159.30	13.66	145.64	0.38	15.38	240.56	12.74	2.13	255.44
10:00	197.00	14.35	182.65	0.65	15.66	301.70	13.39	2.64	317.72
10:15	129.00	15.27	113.73	1.01	17.37	187.86	14.25	1.73	203.83
10:30	267.10	16.10	251.00	0.74	22.06	414.59	15.02	3.58	433.19
10:45	454.20	16.70	437.50	0.86	19.68	722.65	15.58	6.09	744.31
11:00	474.60	17.42	457.18	0.86	22.84	755.15	16.25	6.36	777.77
11:15	483.30	17.99	465.31	0.69	22.39	768.58	16.78	6.47	791.84
11:30	496.50	18.59	477.91	0.71	24.18	789.40	17.34	6.65	813.39
11:45	509.60	18.99	490.61	0.58	28.67	810.37	17.72	6.83	834.92
12:00	522.00	19.49	502.51	0.70	30.06	830.03	18.18	6.99	855.21
12:15	533.40	20.14	513.26	1.15	30.88	847.79	18.79	7.15	873.72
12:30	539.60	21.03	518.57	1.08	31.89	856.56	19.62	7.23	883.41
12:45	541.00	21.86	519.14	1.16	33.33	857.50	20.40	7.25	885.14
13:00	538.20	22.57	515.63	1.19	34.31	851.70	21.06	7.21	879.97
13:15	533.70	23.27	510.43	1.17	33.83	843.11	21.71	7.15	871.97
13:30	528.00	23.81	504.19	1.20	34.95	832.80	22.22	7.07	862.09
13:45	519.20	24.15	495.05	1.23	35.63	817.71	22.53	6.96	847.19
14:00	505.70	23.88	481.82	1.00	35.87	795.85	22.28	6.78	824.91
14:15	487.20	23.67	463.53	1.15	35.12	765.64	22.08	6.53	794.25
14:30	466.80	23.57	443.23	1.12	35.39	732.11	21.99	6.25	760.36
14:45	443.70	23.01	420.69	1.16	35.59	694.88	21.47	5.94	722.29
15:00	417.20	22.40	394.80	1.01	34.20	652.12	20.90	5.59	678.61
15:15	387.50	21.57	365.93	1.30	26.14	604.43	20.13	5.19	629.75
15:30	355.60	20.99	334.61	1.33	23.88	552.70	19.58	4.76	577.05
15:45	321.10	20.50	300.60	1.07	23.24	496.52	19.13	4.30	519.95
16:00	284.90	19.68	265.22	1.24	24.18	438.08	18.36	3.82	460.26
16:15	246.70	37.28	209.42	1.14	23.10	345.91	34.78	3.31	384.00
16:30	206.80	158.00	48.80	1.57	22.06	80.61	147.42	2.77	230.79
16:45	165.60	155.90	9.70	1.16	21.32	16.02	145.46	2.22	163.70
17:00	125.50	116.50	9.00	1.32	20.65	14.87	108.70	1.68	125.24

Table E6 - Measured data on 06 June 2018

6-Jun-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	26.05	12.26	13.79	2.60	13.99	22.83	11.44	0.35	34.61
9:15	66.16	13.02	53.14	2.19	14.78	87.96	12.15	0.89	101.00
9:30	115.30	13.59	101.71	2.38	15.88	168.36	12.68	1.54	182.59
9:45	149.70	14.11	135.59	2.45	18.92	224.45	13.16	2.01	239.62
10:00	188.30	14.71	173.59	2.50	19.74	287.35	13.72	2.52	303.60
10:15	119.20	15.58	103.62	3.37	21.27	171.53	14.54	1.60	187.66
10:30	251.10	16.32	234.78	3.30	23.81	388.64	15.23	3.36	407.23
10:45	453.60	17.18	436.42	2.67	22.67	722.42	16.03	6.08	744.52
11:00	476.10	17.69	458.41	3.42	24.72	758.82	16.50	6.38	781.70
11:15	488.80	18.19	470.61	3.22	24.87	779.01	16.97	6.55	802.53
11:30	498.50	18.74	479.76	3.05	26.20	794.16	17.48	6.68	818.32
11:45	508.60	19.13	489.47	3.02	30.33	810.23	17.85	6.81	834.90
12:00	520.00	19.68	500.32	2.00	32.55	828.19	18.36	6.97	853.52
12:15	530.40	20.47	509.93	3.40	32.43	844.10	19.10	7.11	870.31
12:30	536.40	21.47	514.93	3.29	32.20	852.38	20.03	7.19	879.60
12:45	535.70	22.68	513.02	2.69	33.95	849.22	21.16	7.18	877.55
13:00	530.20	23.32	506.88	2.35	36.03	839.05	21.76	7.10	867.91
13:15	525.20	24.31	500.89	1.68	36.96	829.14	22.68	7.04	858.86
13:30	519.80	25.89	493.91	1.67	37.51	817.58	24.16	6.96	848.70
13:45	506.10	28.02	478.08	1.40	37.83	791.38	26.14	6.78	824.30
14:00	499.80	32.33	467.47	2.52	36.55	773.82	30.16	6.70	810.68
14:15	447.30	34.27	413.03	2.91	33.91	683.70	31.97	5.99	721.67
14:30	345.00	36.55	308.45	1.82	31.66	510.59	34.10	4.62	549.31
14:45	377.60	42.05	335.55	1.38	31.59	555.45	39.23	5.06	599.74
15:00	394.70	52.63	342.07	1.90	31.90	566.24	49.10	5.29	620.63
15:15	290.30	48.36	241.94	2.01	27.07	400.49	45.12	3.89	449.50
15:30	320.00	48.66	271.34	1.68	26.25	449.16	45.40	4.29	498.84
15:45	309.10	38.38	270.72	1.96	25.87	448.13	35.81	4.14	488.08
16:00	202.00	24.91	177.09	1.28	25.41	293.14	23.24	2.71	319.09
16:15	280.40	46.70	233.70	0.76	25.65	386.85	43.57	3.76	434.18
16:30	220.30	124.60	95.70	1.16	25.04	158.41	116.25	2.95	277.62
16:45	187.40	125.60	61.80	1.10	24.43	102.30	117.19	2.51	222.00
17:00	157.70	96.80	60.90	0.82	24.03	100.81	90.32	2.11	193.24

Table E7 - Measured data on 07 June 2018

7-Jun-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	99.00	29.34	69.66	2.15	14.40	115.55	27.37	1.33	144.25
9:15	96.70	22.54	74.16	1.97	15.26	123.01	21.03	1.30	145.34
9:30	103.60	20.36	83.24	2.95	16.66	138.07	19.00	1.39	158.45
9:45	128.40	21.87	106.53	2.89	17.44	176.70	20.40	1.72	198.83
10:00	221.30	32.83	188.47	3.08	18.63	312.62	30.63	2.96	346.21
10:15	154.90	28.85	126.05	3.33	19.29	209.08	26.92	2.08	238.07
10:30	168.20	30.76	137.44	3.62	18.54	227.97	28.70	2.25	258.93
10:45	258.20	43.01	215.19	3.17	19.36	356.94	40.13	3.46	400.52
11:00	250.60	37.00	213.60	3.35	19.65	354.30	34.52	3.36	392.18
11:15	341.40	37.23	304.17	3.19	20.61	504.53	34.74	4.57	543.84
11:30	492.70	31.40	461.30	4.15	23.13	765.16	29.30	6.60	801.06
11:45	513.50	31.47	482.03	4.43	25.85	799.55	29.36	6.88	835.79
12:00	347.80	29.02	318.78	3.15	24.62	528.76	27.08	4.66	560.50
12:15	342.10	37.31	304.79	3.27	23.68	505.56	34.81	4.58	544.95
12:30	234.80	34.66	200.14	2.78	22.30	331.97	32.34	3.15	367.46
12:45	378.70	37.21	341.49	3.27	24.34	566.43	34.72	5.07	606.22
13:00	400.10	50.56	349.54	3.37	24.37	579.78	47.17	5.36	632.32
13:15	456.20	64.55	391.65	3.14	25.76	649.63	60.23	6.11	715.97
13:30	171.90	49.72	122.18	3.35	21.24	202.66	46.39	2.30	251.35
13:45	203.80	52.02	151.78	2.90	20.70	251.76	48.54	2.73	303.02
14:00	137.50	42.71	94.79	2.62	20.02	157.23	39.85	1.84	198.92
14:15	142.70	38.48	104.22	2.59	19.73	172.87	35.90	1.91	210.68
14:30	139.90	36.03	103.87	2.61	19.70	172.29	33.62	1.87	207.78
14:45	250.90	47.80	203.10	3.03	20.91	336.88	44.60	3.36	384.84
15:00	358.80	50.93	307.87	3.54	24.37	510.67	47.52	4.81	562.99
15:15	248.80	28.77	220.03	2.25	22.11	364.96	26.84	3.33	395.14
15:30	139.90	20.92	118.98	2.36	21.06	197.35	19.52	1.87	218.75
15:45	103.70	22.76	80.94	2.36	19.91	134.26	21.24	1.39	156.88
16:00	101.60	24.14	77.46	2.76	19.34	128.48	22.52	1.36	152.37
16:15	103.80	26.85	76.95	2.88	19.14	127.64	25.05	1.39	154.08
16:30	76.88	17.51	59.37	2.49	18.92	98.48	16.34	1.03	115.84
16:45	64.78	12.81	51.97	2.25	18.61	86.20	11.95	0.87	99.02
17:00	23.26	5.34	17.92	2.10	18.21	29.73	4.98	0.31	35.02

Table E8 - Measured data on 11 June 2018

11-Jun-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	30.52	15.20	15.32	0.85	9.67	25.59	14.18	0.41	40.18
9:15	36.62	14.18	22.44	0.23	10.67	37.48	13.23	0.49	51.20
9:30	77.06	14.41	62.65	1.60	11.69	104.64	13.44	1.03	119.12
9:45	88.50	14.65	73.85	1.37	14.07	123.35	13.67	1.19	138.20
10:00	132.30	15.66	116.64	0.98	14.79	194.82	14.61	1.77	211.20
10:15	67.17	16.74	50.43	1.07	15.96	84.23	15.62	0.90	100.75
10:30	110.80	17.24	93.56	1.18	20.61	156.27	16.09	1.48	173.84
10:45	407.20	18.16	389.04	1.10	19.51	649.80	16.94	5.46	672.20
11:00	456.60	19.64	436.96	1.01	20.38	729.84	18.32	6.12	754.29
11:15	469.60	20.55	449.05	1.20	21.22	750.04	19.17	6.29	775.50
11:30	484.90	21.22	463.68	1.34	21.94	774.47	19.80	6.50	800.77
11:45	494.60	21.98	472.62	1.08	26.68	789.41	20.51	6.63	816.54
12:00	499.40	23.49	475.91	1.16	28.22	794.90	21.92	6.69	823.51
12:15	496.30	23.24	473.06	1.55	29.04	790.14	21.68	6.65	818.47
12:30	500.20	24.82	475.38	1.24	29.50	794.02	23.16	6.70	823.88
12:45	536.20	29.00	507.20	1.50	30.29	847.16	27.06	7.18	881.41
13:00	548.10	33.11	514.99	1.40	31.57	860.18	30.89	7.34	898.41
13:15	535.60	31.07	504.53	1.54	32.10	842.71	28.99	7.18	878.87
13:30	515.20	27.09	488.11	1.29	32.01	815.28	25.28	6.90	847.46
13:45	470.10	25.11	444.99	1.37	31.72	743.26	23.43	6.30	772.98
14:00	452.90	24.68	428.22	1.96	30.36	715.25	23.03	6.07	744.34
14:15	365.80	21.39	344.41	1.71	29.50	575.26	19.96	4.90	600.12
14:30	429.40	24.33	405.07	2.15	30.28	676.58	22.70	5.75	705.03
14:45	427.80	24.41	403.39	2.18	30.41	673.77	22.77	5.73	702.28
15:00	399.50	22.81	376.69	1.71	30.60	629.18	21.28	5.35	655.81
15:15	366.00	21.59	344.41	1.55	27.92	575.26	20.14	4.90	600.31
15:30	342.40	21.00	321.40	2.05	24.10	536.83	19.59	4.59	561.01
15:45	308.70	20.21	288.49	1.58	21.55	481.86	18.86	4.14	504.85
16:00	272.00	19.58	252.42	1.64	21.42	421.61	18.27	3.64	443.52
16:15	236.80	50.25	186.55	1.52	21.76	311.59	46.88	3.17	361.65
16:30	198.90	169.50	29.40	1.64	20.19	49.11	158.15	2.66	209.92
16:45	159.10	148.20	10.90	1.78	19.33	18.21	138.27	2.13	158.61
17:00	121.50	110.40	11.10	2.04	18.63	18.54	103.00	1.63	123.17

Table E9 - Measured data on 12 June 2018

12-Jun-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{\ reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	27.33	12.99	14.34	2.72	17.76	23.99	12.12	0.37	36.47
9:15	38.10	14.04	24.06	3.07	18.10	40.24	13.10	0.51	53.85
9:30	77.64	14.93	62.71	3.49	18.80	104.89	13.93	1.04	119.86
9:45	85.60	15.65	69.95	4.00	20.47	117.00	14.60	1.15	132.75
10:00	130.60	16.48	114.12	3.74	20.84	190.88	15.38	1.75	208.01
10:15	67.27	17.43	49.84	3.87	21.26	83.37	16.26	0.90	100.53
10:30	115.40	18.28	97.12	4.62	22.94	162.45	17.06	1.55	181.05
10:45	406.60	19.11	387.49	4.56	22.71	648.14	17.83	5.45	671.42
11:00	460.30	20.02	440.28	4.17	23.33	736.44	18.68	6.17	761.29
11:15	470.80	21.23	449.57	4.31	23.96	751.98	19.81	6.31	778.10
11:30	483.00	22.30	460.70	4.49	25.09	770.60	20.81	6.47	797.87
11:45	419.70	22.33	397.37	2.91	27.36	664.67	20.83	5.62	691.12
12:00	383.00	23.43	359.57	2.57	28.10	601.44	21.86	5.13	628.43
12:15	295.40	23.71	271.69	1.46	27.78	454.45	22.12	3.96	480.53
12:30	197.40	31.15	166.25	1.63	25.20	278.08	29.06	2.64	309.79
12:45	347.00	55.88	291.12	2.67	26.35	486.95	52.14	4.65	543.73
13:00	504.30	49.73	454.57	2.25	29.82	760.34	46.40	6.76	813.50
13:15	524.60	50.89	473.71	2.99	30.71	792.36	47.48	7.03	846.87
13:30	485.10	51.98	433.12	3.39	30.49	724.46	48.50	6.50	779.46
13:45	420.00	44.43	375.57	3.82	30.18	628.20	41.45	5.63	675.28
14:00	510.20	40.25	469.95	3.20	32.42	786.07	37.55	6.84	830.46
14:15	475.90	35.11	440.79	3.37	32.86	737.29	32.76	6.38	776.43
14:30	449.90	31.96	417.94	4.24	32.31	699.07	29.82	6.03	734.92
14:45	438.90	30.34	408.56	4.38	32.39	683.38	28.31	5.88	717.57
15:00	399.70	27.82	371.88	4.82	31.57	622.03	25.96	5.35	653.34
15:15	329.70	24.84	304.86	3.61	30.20	509.93	23.18	4.42	537.52
15:30	269.60	21.81	247.79	3.65	28.07	414.47	20.35	3.61	438.43
15:45	325.90	27.76	298.14	3.14	27.18	498.69	25.90	4.37	528.95
16:00	243.20	27.05	216.15	2.94	26.78	361.55	25.24	3.26	390.04
16:15	185.60	40.20	145.40	3.06	26.49	243.21	37.51	2.49	283.20
16:30	220.00	147.90	72.10	2.76	25.90	120.60	137.99	2.95	261.54
16:45	163.50	126.20	37.30	2.06	25.50	62.39	117.75	2.19	182.33
17:00	123.60	97.10	26.50	1.22	24.92	44.33	90.60	1.66	136.58

Table E10 - Measured data on 13 June 2018

13-Jun-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	27.25	12.70	14.55	1.25	17.31	24.37	11.85	0.37	36.58
9:15	35.69	13.78	21.91	1.45	17.90	36.70	12.86	0.48	50.03
9:30	70.78	14.57	56.21	0.76	18.76	94.14	13.59	0.95	108.69
9:45	75.55	15.32	60.23	0.00	21.44	100.88	14.29	1.01	116.18
10:00	119.30	16.23	103.07	0.00	21.05	172.63	15.14	1.60	189.37
10:15	63.66	17.23	46.43	0.65	21.02	77.76	16.08	0.85	94.69
10:30	98.70	17.66	81.04	2.54	23.56	135.73	16.48	1.32	153.53
10:45	382.40	18.44	363.96	1.32	24.36	609.58	17.20	5.12	631.90
11:00	441.00	19.08	421.92	1.52	25.28	706.65	17.80	5.91	730.36
11:15	452.70	19.59	433.11	2.14	25.06	725.39	18.28	6.07	749.73
11:30	464.50	20.07	444.43	2.27	25.39	744.35	18.73	6.22	769.30
11:45	477.80	20.60	457.20	2.15	29.12	765.74	19.22	6.40	791.36
12:00	488.50	21.34	467.16	1.76	31.58	782.42	19.91	6.54	808.87
12:15	499.90	22.04	477.86	1.34	33.29	800.34	20.56	6.70	827.60
12:30	506.70	22.93	483.77	1.85	34.92	810.24	21.39	6.79	838.42
12:45	510.70	23.62	487.08	2.92	33.99	815.78	22.04	6.84	844.66
13:00	512.00	24.18	487.82	4.41	30.48	817.02	22.56	6.86	846.44
13:15	506.70	24.77	481.93	3.64	30.65	807.16	23.11	6.79	837.06
13:30	498.50	25.40	473.10	3.36	31.19	792.37	23.70	6.68	822.74
13:45	488.20	25.69	462.51	3.22	31.78	774.63	23.97	6.54	805.14
14:00	474.40	26.05	448.35	3.13	32.13	750.92	24.30	6.36	781.58
14:15	457.40	26.42	430.98	3.33	32.29	721.82	24.65	6.13	752.60
14:30	437.50	26.08	411.42	3.19	32.52	689.06	24.33	5.86	719.26
14:45	414.20	25.75	388.45	4.14	31.79	650.59	24.03	5.55	680.17
15:00	387.10	24.76	362.34	2.94	32.06	606.86	23.10	5.19	635.15
15:15	359.30	24.12	335.18	3.31	29.97	561.37	22.50	4.81	588.69
15:30	328.60	23.64	304.96	2.83	28.64	510.76	22.06	4.40	537.22
15:45	292.60	23.21	269.39	2.94	26.85	451.19	21.66	3.92	476.76
16:00	256.50	23.19	233.31	2.67	26.77	390.76	21.64	3.44	415.83
16:15	218.50	48.15	170.35	2.46	27.09	285.31	44.92	2.93	333.16
16:30	178.00	137.00	41.00	1.79	25.78	68.67	127.82	2.38	198.88
16:45	138.60	113.30	25.30	1.00	25.20	42.37	105.71	1.86	149.94
17:00	102.30	80.50	21.80	1.03	24.44	36.51	75.11	1.37	112.99

Table E11 - Measured data on 14 June 2018

14-Jun-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	3.36	0.88	2.48	5.68	13.10	4.15	0.82	0.04	5.02
9:15	5.40	1.39	4.01	5.84	13.18	6.72	1.30	0.07	8.10
9:30	9.69	2.70	6.99	6.10	13.21	11.72	2.52	0.13	14.37
9:45	11.92	3.23	8.69	6.49	13.19	14.57	3.01	0.16	17.74
10:00	39.71	9.36	30.35	6.58	13.23	50.89	8.73	0.53	60.16
10:15	60.32	15.66	44.66	6.33	13.40	74.89	14.61	0.81	90.31
10:30	108.40	26.23	82.17	6.88	13.61	137.78	24.47	1.45	163.71
10:45	148.20	37.09	111.11	7.74	14.05	186.31	34.61	1.99	222.90
11:00	115.70	30.01	85.69	7.32	13.99	143.69	28.00	1.55	173.24
11:15	131.50	29.78	101.72	7.38	14.26	170.56	27.79	1.76	200.11
11:30	312.80	44.61	268.19	7.93	15.30	449.70	41.62	4.19	495.51
11:45	337.50	54.02	283.48	8.81	16.23	475.34	50.40	4.52	530.26
12:00	156.50	37.79	118.71	9.24	16.13	199.05	35.26	2.10	236.41
12:15	55.78	15.16	40.62	7.89	14.63	68.11	14.14	0.75	83.00
12:30	146.00	36.30	109.70	7.87	14.89	183.95	33.87	1.96	219.77
12:45	87.40	24.46	62.94	9.65	14.59	105.54	22.82	1.17	129.53
13:00	32.61	8.83	23.78	7.22	13.68	39.87	8.24	0.44	48.55
13:15	52.71	13.48	39.23	8.22	13.49	65.78	12.58	0.71	79.06
13:30	93.20	25.77	67.43	7.56	14.19	113.07	24.04	1.25	138.36
13:45	36.13	9.50	26.63	6.58	14.32	44.65	8.86	0.48	54.00
14:00	39.89	10.41	29.48	6.25	14.54	49.43	9.71	0.53	59.68
14:15	105.90	25.82	80.08	7.11	14.85	134.28	24.09	1.42	159.79
14:30	180.60	33.31	147.29	6.87	15.21	246.98	31.08	2.42	280.47
14:45	371.30	50.45	320.85	6.98	17.21	538.00	47.07	4.97	590.05
15:00	316.30	50.81	265.49	7.03	17.76	445.17	47.41	4.24	496.82
15:15	153.80	32.29	121.51	7.73	16.41	203.75	30.13	2.06	235.94
15:30	56.16	15.38	40.78	6.13	15.23	68.38	14.35	0.75	83.48
15:45	85.90	22.30	63.60	4.69	15.10	106.64	20.81	1.15	128.60
16:00	101.30	30.00	71.30	5.98	15.34	119.56	27.99	1.36	148.90
16:15	52.84	15.59	37.25	5.68	15.07	62.46	14.55	0.71	77.71
16:30	73.37	20.10	53.27	5.21	15.12	89.32	18.75	0.98	109.06
16:45	109.90	63.57	46.33	5.08	14.98	77.69	59.31	1.47	138.47
17:00	32.25	10.39	21.86	5.08	14.29	36.65	9.69	0.43	46.78

Table E12 - Measured data on 15 June 2018

15-Jun-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	44.06	15.05	29.01	2.49	13.57	48.69	14.04	0.59	63.33
9:15	80.80	21.18	59.62	2.83	14.50	100.08	19.76	1.08	120.92
9:30	116.30	23.87	92.43	3.72	15.52	155.15	22.27	1.56	178.98
9:45	146.90	32.35	114.55	4.35	16.76	192.28	30.18	1.97	224.43
10:00	256.10	51.80	204.30	4.08	18.21	342.93	48.33	3.43	394.69
10:15	102.50	27.69	74.81	3.70	16.56	125.57	25.84	1.37	152.78
10:30	148.40	25.63	122.77	3.27	16.67	206.08	23.91	1.99	231.98
10:45	73.50	19.16	54.34	3.98	15.81	91.21	17.88	0.98	110.07
11:00	112.90	28.45	84.45	4.30	13.40	141.75	26.54	1.51	169.81
11:15	196.20	38.84	157.36	2.90	13.68	264.14	36.24	2.63	303.00
11:30	136.40	40.14	96.26	3.35	13.63	161.58	37.45	1.83	200.86
11:45	214.00	36.05	177.95	3.73	13.62	298.70	33.64	2.87	335.20
12:00	458.20	30.95	427.25	3.81	17.18	717.16	28.88	6.14	752.18
12:15	375.50	74.40	301.10	5.23	16.48	505.41	69.42	5.03	579.86
12:30	173.10	45.31	127.79	4.56	15.65	214.50	42.27	2.32	259.10
12:45	157.20	50.63	106.57	3.64	14.91	178.88	47.24	2.11	228.23
13:00	183.20	32.67	150.53	3.38	15.55	252.67	30.48	2.45	285.61
13:15	388.40	23.04	365.36	3.59	19.99	613.28	21.50	5.20	639.98
13:30	487.40	31.30	456.10	4.66	22.41	765.59	29.20	6.53	801.32
13:45	323.70	37.64	286.06	4.58	19.75	480.17	35.12	4.34	519.62
14:00	250.40	44.91	205.49	5.05	19.24	344.93	41.90	3.35	390.18
14:15	194.80	42.20	152.60	5.39	17.26	256.15	39.37	2.61	298.13
14:30	183.00	38.91	144.09	4.18	16.26	241.86	36.30	2.45	280.62
14:45	307.00	52.98	254.02	4.77	18.09	426.39	49.43	4.11	479.93
15:00	315.70	41.25	274.45	4.72	19.01	460.68	38.49	4.23	503.39
15:15	236.00	35.94	200.06	3.88	17.82	335.81	33.53	3.16	372.51
15:30	125.00	25.23	99.77	4.94	16.80	167.47	23.54	1.67	192.68
15:45	39.61	11.52	28.09	4.75	15.09	47.15	10.75	0.53	58.43
16:00	115.90	22.94	92.96	3.41	14.02	156.04	21.40	1.55	178.99
16:15	66.60	18.82	47.78	2.44	13.73	80.20	17.56	0.89	98.65
16:30	24.73	8.43	16.30	2.51	13.33	27.36	7.87	0.33	35.56
16:45	22.98	7.20	15.78	2.89	13.15	26.49	6.72	0.31	33.51
17:00	30.76	13.13	17.63	3.26	12.95	29.59	12.25	0.41	42.26

Table E13 - Measured data on 04 July 2018

4-Jul-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	59.49	20.52	38.97	4.18	16.95	65.02	19.15	0.80	84.96
9:15	104.00	23.75	80.25	4.59	17.23	133.90	22.16	1.39	157.45
9:30	157.10	21.20	135.90	4.91	17.46	226.75	19.78	2.10	248.63
9:45	194.10	27.62	166.48	4.57	19.20	277.77	25.77	2.60	306.14
10:00	239.80	38.39	201.41	5.04	18.72	336.05	35.82	3.21	375.08
10:15	278.50	38.10	240.40	4.78	20.01	401.11	35.55	3.73	440.39
10:30	206.00	43.36	162.64	4.99	21.19	271.37	40.46	2.76	314.58
10:45	399.90	44.33	355.57	4.23	23.07	593.27	41.36	5.36	639.99
11:00	488.60	41.51	447.09	4.49	23.60	745.97	38.73	6.55	791.25
11:15	498.10	50.25	447.85	5.55	24.23	747.24	46.88	6.67	800.80
11:30	399.30	56.87	342.43	5.59	25.10	571.35	53.06	5.35	629.76
11:45	378.00	48.16	329.84	5.68	25.76	550.34	44.93	5.06	600.34
12:00	368.40	31.87	336.53	6.13	26.93	561.50	29.74	4.94	596.17
12:15	351.00	24.11	326.89	6.40	26.31	545.42	22.49	4.70	572.62
12:30	517.50	21.00	496.50	0.68	32.46	828.41	19.59	6.93	854.94
12:45	512.70	21.57	491.13	0.04	33.94	819.45	20.13	6.87	846.45
13:00	508.40	22.16	486.24	0.25	33.78	811.29	20.68	6.81	838.78
13:15	505.40	22.75	482.65	0.28	34.12	805.30	21.23	6.77	833.30
13:30	503.50	23.73	479.77	0.25	34.61	800.50	22.14	6.75	829.38
13:45	499.30	24.82	474.48	0.05	35.84	791.67	23.16	6.69	821.52
14:00	501.80	25.53	476.27	0.85	33.90	794.66	23.82	6.72	825.20
14:15	450.90	23.76	427.14	0.31	35.35	712.69	22.17	6.04	740.89
14:30	432.80	24.20	408.60	0.91	33.24	681.75	22.58	5.80	710.13
14:45	423.50	24.57	398.93	0.56	32.13	665.62	22.92	5.67	694.21
15:00	405.60	24.64	380.96	0.17	32.68	635.63	22.99	5.43	664.06
15:15	378.90	24.75	354.15	0.62	30.55	590.90	23.09	5.08	619.07
15:30	347.80	25.43	322.37	1.16	26.03	537.88	23.73	4.66	566.26
15:45	328.10	27.75	300.35	0.77	21.91	501.14	25.89	4.40	531.42
16:00	306.00	28.78	277.22	0.84	20.46	462.54	26.85	4.10	493.49
16:30	244.10	144.90	99.20	1.39	22.25	165.52	135.19	3.27	303.98
16:45	195.00	114.80	80.20	1.56	20.54	133.81	107.11	2.61	243.54
17:00	73.08	25.77	47.31	1.17	17.90	78.94	24.04	0.98	103.96

Table E14 - Measured data on 05 July 2018

5-Jul-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	24.61	10.68	13.93	0.13	9.83	23.20	9.96	0.33	33.50
9:15	39.37	11.44	27.93	0.00	10.56	46.52	10.67	0.53	57.72
9:30	103.50	11.61	91.89	0.00	11.71	153.06	10.83	1.39	165.28
9:45	95.50	12.36	83.14	0.00	16.14	138.49	11.53	1.28	151.30
10:00	187.30	13.42	173.88	0.12	15.38	289.64	12.52	2.51	304.67
10:15	122.50	14.30	108.20	0.31	14.59	180.23	13.34	1.64	195.21
10:30	130.70	15.33	115.37	0.00	21.95	192.17	14.30	1.75	208.23
10:45	377.60	15.94	361.66	0.03	20.73	602.43	14.87	5.06	622.36
11:00	453.30	16.57	436.73	0.13	23.54	727.47	15.46	6.07	749.00
11:15	465.30	17.19	448.11	0.19	22.97	746.43	16.04	6.23	768.70
11:30	469.40	17.60	451.80	0.46	21.64	752.57	16.42	6.29	775.28
11:45	480.50	18.75	461.75	0.07	28.01	769.15	17.49	6.44	793.08
12:00	488.20	19.43	468.77	0.57	30.54	780.84	18.13	6.54	805.51
12:15	509.20	19.49	489.71	0.55	31.93	815.72	18.18	6.82	840.73
12:30	519.50	20.25	499.25	0.49	33.76	831.61	18.89	6.96	857.47
12:45	520.80	21.33	499.47	0.46	34.04	831.98	19.90	6.98	858.86
13:00	520.40	22.25	498.15	0.60	34.43	829.78	20.76	6.97	857.51
13:15	517.30	23.06	494.24	1.08	33.98	823.27	21.52	6.93	851.71
13:30	509.30	23.85	485.45	1.15	34.15	808.63	22.25	6.82	837.70
13:45	502.60	24.16	478.44	1.07	34.86	796.95	22.54	6.73	826.22
14:00	490.80	24.51	466.29	0.92	35.62	776.71	22.87	6.58	806.15
14:15	477.40	24.58	452.82	0.92	37.16	754.27	22.93	6.40	783.60
14:30	451.10	24.65	426.45	1.22	35.37	710.35	23.00	6.04	739.39
14:45	440.50	25.02	415.48	0.75	36.47	692.08	23.34	5.90	721.32
15:00	411.10	23.81	387.29	1.27	34.20	645.12	22.22	5.51	672.84
15:15	359.00	21.74	337.26	1.00	31.17	561.78	20.28	4.81	586.88
15:30	346.50	21.96	324.54	0.33	28.31	540.59	20.49	4.64	565.73
15:45	317.80	21.26	296.54	0.59	24.02	493.95	19.84	4.26	518.05
16:00	288.00	20.54	267.46	0.79	22.18	445.51	19.16	3.86	468.54
16:15	252.00	23.12	228.88	1.31	23.18	381.25	21.57	3.38	406.20
16:30	213.50	111.30	102.20	1.55	23.46	170.24	103.84	2.86	276.94
16:45	174.70	161.00	13.70	1.48	20.86	22.82	150.22	2.34	175.38
17:00	137.40	124.90	12.50	1.65	18.82	20.82	116.53	1.84	139.20

Table E15 - Measured data on 06 July 2018

6-Jul-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	23.57	11.67	11.90	1.78	10.88	19.79	10.89	0.32	30.99
9:15	37.43	12.51	24.92	1.74	11.70	41.44	11.67	0.50	53.61
9:30	107.90	13.19	94.71	1.51	12.82	157.48	12.31	1.45	171.23
9:45	100.90	13.77	87.13	1.49	17.09	144.87	12.85	1.35	159.07
10:00	199.00	14.35	184.65	1.83	16.15	307.02	13.39	2.67	323.08
10:15	132.00	15.14	116.86	1.85	16.30	194.31	14.13	1.77	210.20
10:30	145.10	15.79	129.31	1.88	22.89	215.01	14.73	1.94	231.68
10:45	401.20	16.57	384.63	1.66	22.20	639.54	15.46	5.38	660.37
11:00	466.30	17.17	449.13	1.67	24.69	746.78	16.02	6.25	769.05
11:15	474.80	17.67	457.13	1.50	23.36	760.09	16.49	6.36	782.93
11:30	485.00	18.22	466.78	1.54	23.77	776.13	17.00	6.50	799.63
11:45	501.00	18.63	482.37	1.94	29.40	802.05	17.38	6.71	826.15
12:00	515.20	19.09	496.11	2.02	30.91	824.90	17.81	6.90	849.61
12:15	526.80	19.74	507.06	2.49	30.87	843.11	18.42	7.06	868.58
12:30	535.30	20.62	514.68	1.48	32.20	855.78	19.24	7.17	882.19
12:45	538.60	21.46	517.14	1.52	32.73	859.87	20.02	7.22	887.10
13:00	537.80	22.16	515.64	1.67	33.17	857.37	20.68	7.21	885.25
13:15	535.00	22.69	512.31	2.22	32.44	851.83	21.17	7.17	880.17
13:30	528.30	23.20	505.10	2.68	32.34	839.85	21.65	7.08	868.57
13:45	520.60	23.67	496.93	1.88	34.01	826.26	22.08	6.97	855.32
14:00	507.60	24.00	483.60	1.96	34.08	804.10	22.39	6.80	833.29
14:15	493.10	24.15	468.95	1.76	35.44	779.74	22.53	6.61	808.88
14:30	474.00	23.85	450.15	2.30	34.36	748.48	22.25	6.35	777.08
14:45	451.70	23.62	428.08	2.02	34.78	711.78	22.04	6.05	739.87
15:00	425.70	22.99	402.71	2.07	33.82	669.60	21.45	5.70	696.75
15:15	399.30	22.35	376.95	2.58	30.05	626.77	20.85	5.35	652.97
15:30	366.50	21.57	344.93	2.87	26.17	573.53	20.13	4.91	598.56
15:45	331.80	21.18	310.62	2.26	24.39	516.48	19.76	4.45	540.68
16:00	299.50	20.60	278.90	2.13	24.21	463.74	19.22	4.01	486.97
16:15	260.70	22.69	238.01	2.21	25.27	395.75	21.17	3.49	420.41
16:30	219.90	103.20	116.70	2.30	25.99	194.04	96.29	2.95	293.27
16:45	180.70	164.40	16.30	1.65	23.37	27.10	153.39	2.42	182.91
17:00	141.70	126.60	15.10	1.20	22.44	25.11	118.12	1.90	145.13

Table E16 - Measured data on 07 July 2018

7-Jul-18	Measured parameters					Calculated parameters			
Time	**I_T (W/m2)**	**I_d (W/m2)**	**I_b (W/m2)**	**Vw_{ind} (m/s)**	**$T_{ambient}$ (°C)**	**I_b inclined (W/m2)**	**$I_{diffuse}$ inclined (W/m2)**	**$I_{reflected}$ (W/m2)**	**I_{Total} inclined (W/m2)**
9:00	35.72	14.78	20.94	1.67	12.20	34.75	13.79	0.48	49.02
9:15	53.84	16.32	37.52	1.54	12.93	62.27	15.23	0.72	78.21
9:30	118.80	17.53	101.27	1.66	13.59	168.06	16.36	1.59	186.01
9:45	119.10	18.27	100.83	1.81	16.91	167.33	17.05	1.60	185.97
10:00	205.50	18.85	186.65	1.68	16.88	309.75	17.59	2.75	330.09
10:15	156.20	19.50	136.70	1.53	18.19	226.86	18.19	2.09	247.14
10:30	175.80	20.19	155.61	2.02	25.46	258.24	18.84	2.36	279.43
10:45	388.90	20.82	368.08	2.39	24.26	610.84	19.43	5.21	635.48
11:00	443.80	21.27	422.53	2.16	24.89	701.20	19.85	5.95	726.99
11:15	457.90	21.70	436.20	2.78	23.66	723.89	20.25	6.13	750.27
11:30	470.60	22.20	448.40	3.68	24.96	744.14	20.71	6.30	771.15
11:45	484.90	22.59	462.31	3.11	28.56	767.22	21.08	6.50	794.79
12:00	497.20	22.82	474.38	3.01	29.81	787.25	21.29	6.66	815.20
12:15	510.90	23.35	487.55	2.77	31.47	809.11	21.79	6.84	837.74
12:30	516.80	24.00	492.80	2.43	32.85	817.82	22.39	6.92	847.14
12:45	522.10	24.89	497.21	2.03	34.26	825.14	23.22	6.99	855.36
13:00	522.50	25.52	496.98	2.10	34.55	824.76	23.81	7.00	855.57
13:15	519.50	26.01	493.49	1.77	35.42	818.96	24.27	6.96	850.19
13:30	512.10	26.47	485.63	1.01	38.47	805.92	24.70	6.86	837.48
13:45	500.40	26.78	473.62	1.20	38.33	785.99	24.99	6.70	817.68
14:00	487.30	27.16	460.14	0.96	39.90	763.62	25.34	6.53	795.49
14:15	475.70	27.47	448.23	1.01	41.15	743.85	25.63	6.37	775.86
14:30	455.40	27.09	428.31	1.38	40.32	710.80	25.28	6.10	742.17
14:45	428.20	26.56	401.64	1.64	37.19	666.54	24.78	5.74	697.05
15:00	404.80	26.23	378.57	2.21	35.88	628.25	24.47	5.42	658.15
15:15	373.30	25.67	347.63	2.68	32.08	576.90	23.95	5.00	605.86
15:30	343.90	24.82	319.08	2.47	27.43	529.52	23.16	4.61	557.29
15:45	313.60	24.05	289.55	2.01	25.45	480.52	22.44	4.20	507.16
16:00	279.50	23.42	256.08	2.16	24.50	424.97	21.85	3.74	450.57
16:15	241.90	24.42	217.48	2.03	25.38	360.92	22.78	3.24	386.94
16:30	204.00	85.40	118.60	1.96	26.19	196.82	79.68	2.73	279.23
16:45	165.80	139.10	26.70	1.19	23.53	44.31	129.78	2.22	176.31
17:00	127.50	106.30	21.20	0.26	22.19	35.18	99.18	1.71	136.07

Table E17 - Measured data on 08 July 2018

8-Jul-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	29.40	13.07	16.33	1.67	12.12	27.04	12.19	0.39	39.63
9:15	51.23	14.15	37.08	1.57	12.78	61.41	13.20	0.69	75.30
9:30	125.80	15.04	110.76	1.47	14.31	183.43	14.03	1.69	199.15
9:45	124.20	15.61	108.59	0.88	20.23	179.84	14.56	1.66	196.07
10:00	215.60	16.23	199.37	1.40	19.55	330.18	15.14	2.89	348.22
10:15	170.60	17.04	153.56	0.98	19.32	254.32	15.90	2.29	272.50
10:30	192.90	17.68	175.22	1.34	27.63	290.19	16.50	2.58	309.27
10:45	403.20	18.37	384.83	1.85	25.43	637.33	17.14	5.40	659.87
11:00	452.90	19.02	433.88	2.69	24.13	718.56	17.75	6.07	742.38
11:15	465.60	19.56	446.04	2.59	23.71	738.70	18.25	6.24	763.19
11:30	477.10	20.08	457.02	2.27	26.49	756.89	18.73	6.39	782.01
11:45	490.20	20.55	469.65	1.51	32.94	777.80	19.17	6.57	803.55
12:00	500.00	20.99	479.01	1.21	36.55	793.31	19.58	6.70	819.59
12:15	510.20	21.54	488.66	0.82	37.89	809.29	20.10	6.84	836.22
12:30	519.50	22.45	497.05	1.42	38.15	823.18	20.95	6.96	851.09
12:45	522.20	23.14	499.06	1.71	37.41	826.51	21.59	7.00	855.10
13:00	524.10	23.85	500.25	1.85	37.07	828.48	22.25	7.02	857.76
13:15	522.30	24.34	497.96	2.66	34.82	824.69	22.71	7.00	854.40
13:30	517.50	24.82	492.68	2.93	34.42	815.95	23.16	6.93	846.04
13:45	509.20	25.16	484.04	3.23	33.71	801.64	23.47	6.82	831.93
14:00	496.50	25.46	471.04	2.36	35.59	780.11	23.75	6.65	810.51
14:15	482.60	25.58	457.02	2.93	35.25	756.89	23.87	6.47	787.22
14:30	465.10	25.14	439.96	3.17	34.32	728.63	23.46	6.23	758.32
14:45	441.30	24.79	416.51	2.98	34.99	689.80	23.13	5.91	718.84
15:00	414.10	23.99	390.11	2.56	33.92	646.08	22.38	5.55	674.01
15:15	385.50	23.34	362.16	2.11	32.67	599.79	21.78	5.16	626.73
15:30	355.50	22.67	332.83	1.97	27.57	551.21	21.15	4.76	577.13
15:45	323.10	22.22	300.88	1.87	26.09	498.30	20.73	4.33	523.36
16:00	287.90	21.65	266.25	1.84	25.66	440.95	20.20	3.86	465.00
16:15	251.40	22.35	229.05	1.27	26.98	379.34	20.85	3.37	403.56
16:30	213.80	81.30	132.50	1.95	27.48	219.44	75.85	2.86	298.16
16:45	175.40	154.00	21.40	1.68	24.48	35.44	143.68	2.35	181.48
17:00	136.60	121.20	15.40	2.33	23.63	25.50	113.08	1.83	140.42

Table E18 - Measured data on 09 July 2018

9-Jul-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	23.79	11.76	12.03	3.32	15.44	19.88	10.97	0.32	31.17
9:15	52.07	12.51	39.56	3.37	16.18	65.37	11.67	0.70	77.74
9:30	135.40	13.21	122.19	3.28	17.05	201.92	12.33	1.81	216.06
9:45	135.60	13.79	121.81	3.89	20.25	201.30	12.87	1.82	215.98
10:00	233.00	14.35	218.65	4.29	19.76	361.33	13.39	3.12	377.84
10:15	192.60	15.18	177.42	3.31	20.29	293.19	14.16	2.58	309.94
10:30	223.30	15.98	207.32	3.45	25.33	342.60	14.91	2.99	360.51
10:45	411.80	16.56	395.24	2.20	26.20	653.15	15.45	5.52	674.12
11:00	453.00	17.23	435.77	2.44	24.67	720.13	16.08	6.07	742.27
11:15	464.10	17.77	446.33	2.10	24.54	737.58	16.58	6.22	760.38
11:30	471.60	18.36	453.24	1.98	28.21	749.00	17.13	6.32	772.45
11:45	487.10	18.77	468.33	2.83	30.88	773.93	17.51	6.53	797.97
12:00	499.20	19.12	480.08	2.49	32.31	793.35	17.84	6.69	817.88
12:15	511.00	19.67	491.33	2.53	33.39	811.94	18.35	6.85	837.14
12:30	516.30	20.42	495.88	2.06	35.53	819.46	19.05	6.92	845.43
12:45	518.40	21.45	496.95	1.87	37.97	821.23	20.01	6.95	848.19
13:00	517.80	22.09	495.71	1.98	38.35	819.18	20.61	6.94	846.73
13:15	514.30	22.60	491.70	1.75	38.07	812.55	21.09	6.89	840.53
13:30	511.50	23.13	488.37	2.66	37.72	807.05	21.58	6.85	835.48
13:45	502.80	23.57	479.23	3.33	37.10	791.95	21.99	6.74	820.67
14:00	491.70	23.66	468.04	3.47	36.68	773.45	22.08	6.59	802.12
14:15	479.00	23.57	455.43	3.26	36.78	752.62	21.99	6.42	781.02
14:30	461.60	23.18	438.42	3.05	36.97	724.51	21.63	6.18	752.32
14:45	439.60	22.81	416.79	2.74	37.11	688.76	21.28	5.89	715.93
15:00	414.70	22.06	392.64	2.25	35.61	648.85	20.58	5.56	674.99
15:15	384.90	21.48	363.42	1.97	33.89	600.57	20.04	5.16	625.76
15:30	354.40	21.00	333.40	1.97	27.86	550.96	19.59	4.75	575.30
15:45	323.80	20.36	303.44	2.71	25.77	501.45	19.00	4.34	524.78
16:00	290.30	19.68	270.62	2.68	25.23	447.21	18.36	3.89	469.46
16:15	253.20	19.87	233.33	2.53	26.05	385.59	18.54	3.39	407.52
16:30	213.80	71.52	142.28	2.40	27.36	235.12	66.73	2.86	304.72
16:45	174.30	153.80	20.50	2.58	24.04	33.88	143.50	2.34	179.71
17:00	134.30	120.60	13.70	2.32	22.96	22.64	112.52	1.80	136.96

Table E19 - Measured data on 10 July 2018

10-Jul-18	Measured parameters					Calculated parameters			
Time	I_T (W/m2)	I_d (W/m2)	I_b (W/m2)	Vw_{ind} (m/s)	$T_{ambient}$ (˚C)	I_b inclined (W/m2)	$I_{diffuse}$ inclined (W/m2)	$I_{reflected}$ (W/m2)	I_{Total} inclined (W/m2)
9:00	57.28	17.23	40.05	0.47	14.12	66.03	16.08	0.77	82.88
9:15	77.85	21.95	55.90	0.05	14.96	92.17	20.48	1.04	113.69
9:30	84.70	22.97	61.73	0.13	14.94	101.78	21.43	1.13	124.34
9:45	127.40	31.97	95.43	0.27	15.53	157.34	29.83	1.71	188.88
10:00	204.50	41.40	163.10	0.00	17.40	268.91	38.63	2.74	310.28
10:15	207.40	28.81	178.59	0.00	18.63	294.45	26.88	2.78	324.11
10:30	220.10	21.21	198.89	0.04	24.69	327.92	19.79	2.95	350.66
10:45	332.00	21.68	310.32	0.09	23.77	511.64	20.23	4.45	536.32
11:00	401.90	20.73	381.17	0.04	22.09	628.45	19.34	5.38	653.18
11:15	426.20	20.93	405.27	0.43	22.97	668.19	19.53	5.71	693.43
11:30	442.40	21.32	421.08	0.55	26.13	694.26	19.89	5.93	720.07
11:45	462.30	21.71	440.59	0.58	31.05	726.42	20.26	6.19	752.87
12:00	475.30	22.10	453.20	0.69	33.45	747.21	20.62	6.37	774.20
12:15	484.90	22.16	462.74	0.41	34.54	762.94	20.68	6.50	790.11
12:30	495.40	22.63	472.77	0.46	35.53	779.48	21.11	6.64	807.23
12:45	502.80	23.36	479.44	0.33	37.33	790.48	21.80	6.74	819.01
13:00	505.60	24.02	481.58	0.67	37.79	794.00	22.41	6.77	823.19
13:15	498.60	24.44	474.16	0.75	37.26	781.77	22.80	6.68	811.25
13:30	496.40	25.11	471.29	0.66	37.15	777.04	23.43	6.65	807.12
13:45	488.20	25.60	462.60	0.24	38.88	762.71	23.89	6.54	793.14
14:00	474.00	26.34	447.66	0.26	39.20	738.08	24.58	6.35	769.01
14:15	445.90	26.12	419.78	0.41	38.75	692.11	24.37	5.97	722.46
14:30	431.90	26.56	405.34	0.89	38.48	668.30	24.78	5.79	698.87
14:45	408.40	26.44	381.96	0.77	38.68	629.76	24.67	5.47	659.90
15:00	373.10	25.90	347.20	1.37	34.23	572.45	24.17	5.00	601.61
15:15	337.10	24.89	312.21	1.92	29.25	514.76	23.22	4.52	542.50
15:30	322.70	24.89	297.81	1.56	24.38	491.01	23.22	4.32	518.56
15:45	278.30	24.10	254.20	1.37	23.59	419.11	22.49	3.73	445.33
16:00	259.20	23.48	235.72	1.53	22.81	388.64	21.91	3.47	414.02
16:15	238.70	24.75	213.95	1.35	23.57	352.75	23.09	3.20	379.04
16:30	193.10	55.15	137.95	1.69	24.24	227.44	51.46	2.59	281.49
16:45	138.30	91.30	47.00	1.57	20.91	77.49	85.18	1.85	164.53
17:00	132.80	96.00	36.80	1.84	20.21	60.67	89.57	1.78	152.02